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Economic optimization of boreal Norway spruce forest management with coarse woody debris and carbon sinks

Master's Programme in Forest Sciences
Forest ecology and management
Master's thesis

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Abstract:

This thesis investigates how placing social prices on carbon (C) and coarse woody debris (CWD) affects forest management, CWD amounts, C sinks and storages as well as wood production value when the combined value of wood production and C sinks or CWD is maximized. Additionally, it examines the costs related to increasing C and CWD in a boreal Norway spruce forest stand. By examining optimized forest management strategies under different social pricing scenarios, the study reveals trade-offs between wood production, C sinks, and biodiversity targets related to CWD.

The results show that increasing social prices on C promotes management strategies that extend rotation lengths and reduce harvests, enhancing C sinks and gradually increasing CWD amounts. Placing social prices on CWD leads to similar management strategies, but the changes are less gradual and more abrupt as sufficient pricing for promoting natural mortality and CWD accumulation is reached. The results also show that at a 1% interest rate, CWD biodiversity targets of 20 m^3 ha^{-1} can be achieved with less than 10% reductions in discounted wood production value and targets of 40 m^3 ha^{-1} can be reached with under 20% loss. Although higher interest rates or more ambitious CWD targets result in substantial losses in discounted wood production value, CWD targets of 20–40 m^3 ha^{-1} can still be achieved while increasing steady-state net timber revenues under 3% interest rate.

The research confirms earlier findings on the trade-offs between increasing CWD, enhancing C sinks and sustaining wood production. It also highlights the ecological connection between C and CWD, where managing the forest for an increase in either one, inevitably leads to an increase in the other. While the study shows that it is possible to increase both CWD and C services with moderate declines in discounted wood production value, higher interest rates or more ambitious CWD targets will lead to more significant reductions. The cost estimates presented in this study, can support the development of management strategies which balance timber production with C sequestration and biodiversity objectives.

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Tiivistelmä:

Tässä maisterintutkielmassa tarkastellaan, miten hiilen ja järeän lahopuun (CWD) yhteiskunnallinen hinnoittelu vaikuttaa metsänhoitoon, CWD:n määrään, hiilinieluihin ja -varastoihin sekä metsätalouden kannattavuuteen, kun pyritään maksimoimaan puutuotannon sekä hiilinielujen tai CWD:n yhdistettyä arvoa. Lisäksi tutkielmassa analysoidaan kustannuksia, jotka liittyvät hiilen ja CWD:n lisäämiseen boreaalisessa kuusimetsikössä. Optimoituja metsänhoitostrategioita tarkastellaan erilaisissa yhteiskunnallisen hinnoittelun skenaarioissa, jolloin esiin nousevat kompromissit puuntuotannon, hiilensidonnan ja CWD:hen liittyvien monimuotoisuustavoitteiden välillä.

Tulokset osoittavat, että korkea hiilen yhteiskunnallinen hinta suosii metsänhoitostrategioita, jotka pidentävät kiertoaikoja ja vähentävät hakkuita. Tämä lisää hiilinieluja ja kasvattaa vähitellen myös CWD:n määrää. Järeän lahopuun sosiaalinen hinnoittelu johtaa samanlaisiin metsänhoitostrategioihin, mutta muutokset ovat vähemmän asteittaisia. Nämä muutokset tapahtuvat äkillisesti, kun luonnollisen kuolleisuuden ja CWD:n kertymisen edistämiseen riittävä hinnoittelutaso saavutetaan. Tulokset osoittavat myös, että yhden prosentin korkonannalla, lahopuun 20 $m^3\ ha^{-1}$ monimuotoisuustavoite voidaan saavuttaa alle 10 prosentin vähennyksellä puutuotannon diskontatussa nykyarvossa ja 40 $m^3\ ha^{-1}$ monimuotoisuustavoite alle 20 prosentin menetyksellä. Vaikka korkeammat korkokannat tai kunnianhimoisemmat CWD tavoitteet johtavat huomattaviin puuntuotannon nykyarvon menetyksiin, kolmen prosentin korkokannalla 20–40 $m^3\ ha^{-1}$ tavoitteet voidaan saavuttaa samalla, kun tasapainotilan puuntuotannon nettotulot kasvavat.

Tutkimus vahvistaa aiempien tutkimusten havainnot CWD:n ja hiilinielujen lisäämisen sekä puuntuotannon ylläpidon välisistä kompromisseista. Se tuo esiin myös hiilen ja lahopuun välisen ekologisen yhteyden: toisen lisääminen metsänhoidossa johtaa väistämättä myös toisen lisääntymiseen. Tulokset osoittavat, että CWD:n ja hiilipalvelujen lisääminen on mahdollista maltillisilla kustannuksilla puuntuotannon arvossa, mutta korkeammat korkokannat tai kunnianhimoisemmat CWD-tavoitteet johtavat merkittävämpiin menetyksiin. Tässä tutkimuksessa esitetyt kustannusarviot voivat auttaa suunnittelemaan metsänhoitostrategioita, jotka tasapainottavat puuntuotannon, hiilen sidonnan ja luonnon monimuotoisuuden tavoitteet.

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Abstrakt:

Den här magistersavhandlingen undersöker hur social prissättning av kol (C) och grov död ved (CWD) påverkar skogsskötsel, mängden CWD, kolbindning och -lagring samt virkesproduktion när virkesintäkter samt värdet av CWD eller kolbindning samtidigt maximeras. Dessutom analyseras kostnaderna av att öka mängden C och CWD i ett borealt granbestånd. Genom att undersöka optimerade skogsskötselstrategier under olika scenarier med social prissättning, åskådliggörs avvägningar mellan virkesproduktion, kolsänkor och biodiversitetsmål kopplade till CWD.

Resultaten visar att ökande sociala priser på kol främjar skogsvårdsstrategier vilka förlänger rotationslängden och minskar virkesskördarna, vilket stärker kolsänkorna och gradvis ökar mängden CWD. Social prissättning på CWD leder till liknande skogsvårdsstrategier, men förändringarna är mindre gradvisa och sker mer abrupt då en tillräckligt hög prissättning för att främja naturlig dödlighet och CWD-ackumulering uppnås. Resultaten visar också att vid en räntesats på 1% kan ett biologiskt mångfaldsmål på 20 m^3 ha^{-1} CWD uppnås med mindre än 10% minskning av virkesproduktionsnettonuvärdet, medan ett mål på 40 m^3 ha^{-1} kan nås med mindre än 20% minskning. Även om högre räntor eller mer ambitiösa CWD-mål leder till betydande förluster i det diskonterade virkesproduktionsvärdet, kan målen på 20–40 m^3 ha^{-1} uppnås vid en ränta på 3% samtidigt som nettointäkterna av virkesproduktionen i ett jämviktstillstånd ökar.

Den här forskningen bekräftar tidigare resultat om avvägningar mellan ökade mängder död ved, förstärkta kolsänkor och timmerproduktion. Den lyfter också fram det ekologiska sambandet mellan kol och CWD, där skogsskötsel vilken ökar det ena, oundvikligen leder till en ökning av det andra. Studien visar att det är möjligt att öka både CWD- och koltjänster med måttliga minskningar av virkesproduktionens nuvärde, men högre räntenivåer eller ambitiösa CWD-mål leder till större förluster. De kostnadsuppskattningar som presenteras i den här magistersavhandlingen kan stödja utvecklingen av skogsskötselstrategier vilka balanserar timmerproduktion med kolbindning och biologisk mångfald.

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List of abbreviations

BA	Basal Area
BECCS	Bioenergy with Carbon Capture and Storage
BLV	Bare Land Value
COP	Conference of the Parties
C	Carbon
CO_2	Carbon Dioxide
CCF	Continuous Cover Forestry
CWD	Course Woody Debris
DBH	Diameter at Breast Height
ES	Ecosystem Service
EU	European Union
FSC	Forest Stewardship Council
IPBES	Intergovernmental Platform for Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
MDP	Markov Decision Process
MMM	Ministry of Agriculture and Forestry Finland (Maa- ja Metsätalousministeriö)
NFI	National Forest Inventory
NPV	Net Present Value
PEFC	Programme for the Endorsement of Forest Certification
PES	Payment for Ecosystem Services
RF	Rotation Forestry
RL	Reinforcement Learning

1 Introduction

"We can never have enough of nature. We must be refreshed by the sight of inexhaustible vigor, vast and titanic features, the seacoast with its wrecks, the wilderness with its living and its decaying trees, the thundercloud and the rain."

Henry David Thoreau (Walden)

Over the past few years, discussions have extensively focused on climate change and its interconnected issues, such as degradation of habitats, loss of biodiversity, and carbon (C) emission related problems and solutions. The role of the forest sector in mitigating these challenges has also been brought up ever more frequently. For example, the sixth, and most recent assessment report by the the Intergovernmental Panel on Climate Change (IPCC) underscores the significant responsibility of humans in shaping the current scenario and influencing the future outcomes. The report presents improved forest management as a cost-effective option to mitigate climate change (IPCC, 2023a). And with the 2023 Conference of the Parties (COP28) meetings decision to transition away from fossil fuels by 2050, the demand for biofuels also grows, putting increased pressure on sustainable forest use.

Specific concerns on biodiversity are brought up in the latest global assessment report on biodiversity and ecosystem services by The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). According to IPBES, approximately 25 percent of evaluated plant and animal species face threats, potentially pushing around a million species to the brink of extinction worldwide within a matter of decades (IPBES, 2019). Furthermore, the COP-15 biodiversity conference held in 2022 adopted targets including the preservation of 30% of the earth's areas and active restoration efforts for 30% of ecosystems by 2030 (Ainsworth, 2022). Finally, the executive summary of the latest IPCC report emphasizes that the window of opportunity is decreasing rapidly and that strategies to combat climate change should be implemented across various ecological, economic, and social systems (IPCC, 2023b).

In managed forests, economic and ecological matters are undisputedly bound to each other. The Finnish forest sector and Finnish forests provide a clear example of this. The Finnish land use, land use change and forest sector (LULUCF) has had a negative trend regarding C sequestration for the last decade, and in 2021, it became a net source of C for the first time in measured history (Siljander et al., 2023). The biodiversity threats are clearly seen in the Nordic forests too, with over 30 % of the red-listed species in Finland having forests as their main habitat (Hyvärinen et al., 2019). One of the major causes of biodiversity loss in Finnish forest ecosystems is the lack of dead wood, especially coarse dead wood, or coarse woody debris (CWD), and the lack of old growth forest (Hyvärinen et al., 2019). In Sweden, with similar forest management as Finland, this trend can also be seen, with 25 % of the red-listed species being saproxylic (Dahlberg and Stokland, 2004). Not only is CWD important for saproxylic species, but it also plays an important role when it comes to the forest C accumulation and storages (Magnússon et al., 2016; Hyvönen and Ågren, 2001) and general forest resilience. Increasing the amount of CWD in Finnish forests has potential not only to mitigate biodiversity loss, but also to increase the C stocks in our forests. To meet the contemporary and future demands of forests, including climate change mitigation, biodiversity conservation, restoration needs, C sequestration, economic utilization through wood production and various other ecosystem services, an expanded understanding of management options needs to be developed.

The significance of CWD for forest ecosystems is clear, yet its integration into forest management policy and practice is still lacking. This study will employ economic optimization tools to study how social pricing of C and the valuing of CWD changes optimal forest management strategies, wood production value as well as CWD and C dynamics.

The objective of this master's thesis is to better understand the ecological and economic trade-offs in forest management by applying social pricing to C and CWD, and analysing their respective impacts on CWD amounts, C dynamics, and wood production. To address this, the thesis poses the following research questions:

- How does the social price of C affect CWD amounts, C stocks and sinks as well as forest management when maximizing the combined value of wood production and C sinks?

- What influence does an economic value placed on CWD have on CWD amounts, C stocks and sinks as well as forest management when maximizing the combined value of wood production and CWD stock?

- What are the costs related to increasing CWD and C amounts?

2 Coarse woody debris and its significance

Coarse woody debris plays a fundamental part in forest ecosystems, greatly influencing both the structure and processes. It provides habitats and sustenance for a variety of organisms (Harmon et al., 1986), plays a large role in both C and nutrient cycles (Krankina and Harmon, 1995), and serves as a key feature for preserving threatened species in boreal forests (Siitonen, 2001). Decomposing wood contributes to soil formation and can help mitigate soil erosion (Harmon et al., 1986; Hyvönen and Ågren, 2001). Shorohova and Kapitsa (2014) suggest that the role of decomposing wood could be on par with the synthesis of organic matter in ecological importance and Krankina and Harmon (1995) argue that intensive forest management's impact on C sequestration may need re-evaluation, if the effect which woody debris has on the C cycle, is properly accounted for.

As mentioned, one of the major causes of biodiversity loss in Finnish forest ecosystems is the lack of deadwood, especially CWD, and the lack of old-growth forests (Hyvärinen et al., 2019). Especially scarce is large-diameter CWD (Keto-Tokoi, 2018). However, lower diameter decaying wood also plays an essential role in forest ecosystems, hosting a multitude of species (Jonsell, 2008; Jonsell et al., 2007). For example, in Finnish forests, approximately 500 rare or endangered species depend on dead wood, constituting almost 10 % of saproxylic, and 2.5% of all species, and around 25 % of the rare and endangered species (Saaristo & Kaipiainen-Väre, 2010; Korhonen et al., 2016; Hyvärinen et al., 2019). Similarly, in Sweden, 90 % of saproxylic red listed species in Sweden are dependent on CWD (Dahlberg and Stokland, 2004).

As CWD also plays a crucial role for numerous non-saproxylic species, the current low amounts of CWD have a substantial negative impact on forest ecosystems (Seibold et al., 2016). It is clear that CWD is an important part of the soil C cycle, and C sequestration has become an increasingly important part of forest management goals and strategies, both on EU and national level (European commission, 2021; MMM, 2022). Fluxes in C have both indirect economic impact through climate change, and direct economic impacts through emission trading systems.

Next, we explore the definition of CWD, the ecosystem services related to it, ideal levels of CWD in boreal forest ecosystems, as well as the modeling of wood decay.

2.1 Coarse woody debris ecology and dynamics

Each piece of CWD contributes to the overall forest ecosystem, regardless of location and position within a forest stand. For example, logs and branches create a great number of microsites, and promote a diverse range of insects, fungi, microbes, and other organisms. The quantity and characteristics of CWD depend on several factors, especially on tree mortality and decay rate. Mortality due to self-thinning is a natural part of forest succession and targets whole or partial trees, e.g. falling branches. Mortality can also occur due to disturbances such as fires, storms, droughts, floods, insect outbreaks or snow damage (Bobiec, 2005). Finally, silvicultural practices have a significant influence on the availability and behaviour of CWD (Rock et al., 2008, Bobiec, 2005).

2.1.1 Definition of coarse woody debris

The definition of CWD in literature varies depending on the study and the research objective, with no universal definition, complicating comparison of existing literature (Yan et al., 2006). For example, some studies consider CWD standing, leaning, and lying dead woody material, while others focus on specific forms, such as standing trees (snags) or fallen trees (logs). Likewise, the criteria for categorizing woody debris as coarse are not uniform. In North America, typical minimum diameters for CWD vary from 2,5-15 cm (Harmon et al., 1986). A widely adopted definition classified CWD as dead wood with a diameter of ≥10 cm at the large end of a tree or ≥1 cm for roots, drawing a line between snags and logs when the dead tree is at a 45° angle lean (Harmon and Sexton (1996). This approach has been suggested as a potential standard for example by Yan et al. (2006).

Selecting an appropriate definition of CWD will not only affect the comparability of the research but also the applicability and comparability to practical guidelines and forest inventories. Various national forest inventories and regulations offer different interpretations for CWD. For example, the Finnish national forest inventory considers trees with a minimum diameter of 10 cm at 1,3 m height from the root base (“breast height diameter” or DBH) as CWD. It also considers CWD as snags if they have a lean less than 45° (Korhonen, 2009). The Swedish national forest inventory uses the same diameter definition but adds a specific category for leaning trees (SLU, 2023). The Finnish law on preventing forest damage defines CWD as having a minimum diameter of 10 cm at the base of the tree (Laki Metsätuhojen Torjunnasta 1087/2013). The two common forest certification systems in Finland, the Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) employ different definitions for CWD in their guidelines for Finland. While PEFC sets a minimum diameter of 20 cm at DBH (PEFC FI 1002:2024), FSC uses the 10 cm DBH criteria (FSC-STD-FIN-02-2023). Also, the Finnish state-owned environmental service enterprise, Metsähallitus, defines CWD differently in its inventory guidelines, with minimum DBH being 5, 7 or 10 cm, depending on the context (Metsähallitus B 83, 2007; Saano and Koskela, 2015).

To provide a base for meaningful discussions and comparisons of the results against empirical observations from Finnish forests, this thesis uses CWD definition consistent with the Finnish national forest inventory standard. Thus, CWD in this study is defined as all dead trees with a breast height diameter greater than or equal to 10 cm.

2.2 Coarse woody debris ecosystem services

Despite the vital role of CWD in forest ecosystems, the benefits or value of CWD are not widely acknowledged. This lack of acknowledgement has resulted in significantly low amounts of CWD in Finnish commercial forests. In addition to its biodiversity benefits (Jonsson et al., 2005; Stokland et al., 2012; Seibold et al., 2015), CWD also offers other essential ecosystem services (ES). These include an important role in the forest C cycle (Hyvönen and Ågren, 2001; Pan et al., 2011; Seibold et al., 2021), serving as a growth substrate for natural regeneration of trees (Harmon et al., 1986; Zielonka, 2006; Stockland et al., 2012), protecting seedlings from grasses, shrubs and potential pathogens by elevating growth sites (Orman et al., 2016), and preventing soil erosion, litter and snow movement in steep slopes (Harmon et al., 1986; Hyvönen and Ågren, 2001; Holeksa et al., 2008). Moreover, CWD contributes to overall forest resilience, maintains ectomycorrhizal fungi stocks, balances the distribution of nitrogen and other nutrients, and retain soil moisture (Alban and Pastor, 1993; Tonteri and Siitonen, 2001; Mäkipää et al., 2017).

Importantly, since CWD is found in varying stages of decay, its services depend on the specific stage of decay. As decay progresses over time, the duration of specific services is limited. Therefore, the continuation of services requires continuous presence of various types of CWD (Holeksa et al., 2008).

This thesis studies the impacts of increased CWD on forest ES services, including C services. Dead wood plays a critical role in C storage, representing 10-20% of aboveground biomass in mature forests (Brown 2002), and up to 30% of the woody biomass in boreal forests (Tarasov and Birdsey, 2001). Therefore, dead wood represents a substantial C stock, accounting for approximately 8% of the global forest C (Pan et al., 2011).

Around 35% of the global deadwood C stock is in boreal forests. However, due to relatively slow decay, only about 4% of the annual dead wood C release come from boreal forests (Seibold et al., 2021). Thus, boreal forest dead wood C acts as a significant long-term C storage. Recent studies in temperate forests indicate that the presence of dead wood can significantly increase dissolved organic C concentrations in the soil (Shannon et al., 2022). Additionally, it's proposed that a substantial portion of C from CWD transfers to soil through decomposer organisms such as fungi and microbes (Magnússon et al., 2016). Estimates from litter decomposition models like Hyvönen and Ågren (2001), conclude that woody litter contributes between 35 and 75% of the total forest soil C. Furthermore, inclusion of C has been shown to have a major impact on economically optimal forest management (Parkatti et al., 2023). The impact of CWD on soil C is particularly important in boreal forests since boreal forests store 32% of global forest C, up to 60 % of that in soils, and only 20 % in biomass. As a comparison, 56 % of C in tropical forests is found in biomass and only 32 % in soils (Pan et al., 2011).

One way of acknowledging the direct economic values of ES is the use of Payments for Ecosystem Services/Payments for Environmental Services - PES. Although there is no single, adopted definition of a PES, Wunder (2015) revises his own widely adopted definition from 2005 and concludes that PES are: *"(1) voluntary transactions (2) between service users (3) and service providers (4) that are conditional on agreed rules of natural resource management (5) for generating offsite services."* (Wunder, 2015). In other words, PES is a market-based incentive for the provision of ecosystem/environmental services. In practice these agreements have been made both between private parties and arranged through government subsidies.

The programme for protection and restoration of private forests (METSO) in Finland can be placed under the PES definition. The program compensates forest owners for the loss of timber revenues in stands where the state sees fit to promote biodiversity or other non-timber production values. The options in METSO are either a temporary protection via prolonged rotation or a permanent protection. Although protected stands can increase CWD amounts locally, it cannot compensate the widespread lack of CWD in commercial forests. In addition, protection does not guarantee economic efficiency in increasing CWD. For example, Ranius et al. (2005) found that increasing solely rotation length is a costly measure for increasing CWD. This thesis investigates the costs of CWD increase by changes in thinning timing, thinning intensity, and rotation length, considering both rotation forestry (RF) and continuous cover forestry (CCF).

2.3 Optimal amount of coarse woody debris

There is no universal CWD threshold value because different saproxylic species depend on various CWD characteristics as well as other habitat conditions (Ranius and Fahrig, 2006). In practice, forest management considers a range of simultaneous objectives, of which ecological goals are but one. While the ecological minimum for CWD is determined by biodiversity needs, the Finnish forest law restricts the maximum amount of fresh CWD to prevent pest outbreaks. To enable true optimal solutions, this thesis will not approach the question of optimal CWD with fixed constraints, neither minimum nor maximum.

2.3.1 Biodiversity goals

Natural state boreal forests can have CWD amounts up to 200 m^3 ha^{-1} (Siitonen, 2001; Shorohova & Kapitsa, 2015). While such high CWD amounts would be optimal for biodiversity, they may not support other ecosystem services such as wood production, C sinks, and various cultural services. However, the current levels of CWD in Finnish forests are alarmingly low from a biodiversity perspective, due to an emphasis on wood production, which often conflicts with the accumulation of CWD (Díaz-Yáñez et al., 2021; Pohjanmies et al., 2017). In the last decades, the overall average CWD amounts in Finnish forests has risen from 5.8 m^3 ha^{-1} to 6.4 m^3 ha^{-1} according to the Finnish National Forest Inventory (NFI) results from 1996-2022 (Kulju et al., 2023). The NFI results also show that while the amounts of CWD have risen in Southern Finland, they have decreased in the north. Furthermore, the results of the NFI include both protected and commercial forests, and the average CWD amounts in commercial forests may lie between 10-20 % lower than the general NFI average (Korhonen et al., 2020). Given global trends and demands for forest ecosystem services (Reid et al., 2015), forest management changes to further increase the amount of CWD seem necessary. Even small increases in CWD levels can significantly impact species diversity (Díaz-Yáñez et al., 2021). For instance, raising the CWD amount from 3 m^3 ha^{-1} to 13 m^3 ha^{-1} can increase beetle species occurrence by up to 50% (Martikainen et al., 2000).

Studies about threshold values for CWD regarding rare or endangered species are scarce. However, Müller and Bütler (2010) identify threshold values between 10-80 m^3 ha^{-1} for boreal forests, suggesting that a network of forest landscapes with CWD amounts between 20-50 m^3 ha^{-1} is required to upkeep biodiversity. Junninen and Komonen (2011) conclude that the average minimum amount of CWD required for rare and endangered polypores is 20-40 m^3 ha^{-1} and emphasize the importance of large sized CWD. The threshold of 20 m^3 ha^{-1} CWD to promote endangered polypores species is also mentioned in the Finnish national guidelines for good forestry practices (Äijälä et al., 2019).

As mentioned, a sufficient quantity of CWD for biodiversity is not only dependent on the overall amount but also the types of CWD. Larger diameter CWD is generally seen to offer a greater biodiversity benefit (Krumm and Kraus, 2013; Stokland, 2012) even though low diameter CWD may also host a high number of species compared to its volume (Stokland, 2012). For example, Penttilä (2004) suggests that endangered polypores are almost exclusively found on CWD over 20 cm in diameter, while Tikkanen et al. (2006) propose that only 3% of red-listed saproxylic forest species live on CWD with a diameter lower than 10 cm. Junninen and Komonen (2011) propose a practical guideline where in a 20-hectare stand, there should be an average of 20 m^3 ha^{-1} of dead wood, mostly over 20 cm in diameter. This guideline would help ensure an ecologically justified conservation minimum of for example polypore diversity at a stand scale in European boreal forests. The lack of large diameter CWD in Finnish forests is greater than the lack of small diameter CWD (Hyvärinen et al., 2019). In this thesis, the diameter distinctions will not explicitly be considered. Instead, this thesis focuses on studying how social prices for C as well as CWD change the amounts of CWD and try to identify the costs of maintaining 20 m^3 ha^{-1}, 40 m^3 ha^{-1} and 100 m^3 ha^{-1} CWD.

2.4 The decay process of coarse woody debris

The decomposition of wood is governed by a complex interplay of biotic and abiotic factors at temporal and spatial scales and leads to the gradual loss of mass, volume, and density of the wood. The rate at which wood decays is influenced by the characteristics and chemical composition of the woody substrate, as well as its colonization by decaying organisms (Harmon et al., 1986; Mackensen et al., 2003; Laiho and Prescott, 2004). Climatic and environmental factors, such as temperature, precipitation, site quality, aspect, and slope, further influence both the substrate and the decomposer species (Rock et al., 2008).

The species of the tree is fundamental to the decomposition speed, with variations influenced both by genotype and phenotype. Moisture availability on the other hand, is essential for decomposers, while temperature also affects the rate of decay. As decomposition progresses, the substrate and the associated decomposer species change, leading to shifts in the decomposition rates. Site conditions and tree position affect decomposer species and rates, and other factors, such as storms, fires, droughts, floods, and insect outbreaks, can cause rapid changes in decay dynamics. The role of tree diameter on decay rates remains debated. A more detailed breakdown of these factors and their impacts on decay, is provided in Table A1 (Appendix A).

The influence of controlling factors is scale dependent. Shorohova and Kapitsa (2014) show that certain forest attributes regulate decay rates under specific environmental conditions or for particular tree species, but these findings do not apply universally. While fungi are the main decomposers in boreal forests (Jonsson et al., 2005), the role of insects increases significantly in tropical forests (Seibold et al., 2021). Additionally, the chemical composition of wood varies with tree species and environmental conditions, further varying microbial activity and decay rates, even within the same tree species (Edelmann et al., 2023).

Accurately modelling the amount of dead wood in a forest requires predicting or calculating both the rate of mortality and decay. The processes vary across scales, from individual trees to whole forest stands and broader regional or global contexts. Although research has identified several key factors, which influence decay, inconsistencies remain due to the complexity. The challenges and methods for modelling wood decay are discussed further in the next chapter.

3 Decay models for coarse woody debris

There are several approaches for modelling CWD decay. Typically, these models employ negative exponential functions, describing the decay as a continuous process over time. Another common approach is to utilize transition matrices with discrete decay stages through which the wood progresses as the decay advances. The choice of models depends on specific research questions and data availability. To find an appropriate decay model for this thesis, six exponential models (Naesset, 1999; Yin, 1999; Hyvönen and Ågren, 2001; Yatskov et al., 2003; Mäkinen et al., 2006; Zell et al., 2009; Tuomi et al., 2010) and four transition matrix models (Kruys and Jonsson, 2002; Holeksa et al., 2008; Aakala 2010b; Rämö et al., 2020) were considered. Additionally, a model where the volume of CWD is directly related to the volume of living trees was considered (Ranius and Jonsson, 2004). A brief presentation of the models can be found in Table 1.

The objective of this study is to compare the economic outcomes, CWD amounts, and C sequestered and stored in a boreal spruce forest while considering the valuation of timber, C or CWD. The focus therefore lies in providing quantitative data on the forest resources, rather than detailed ecological considerations of the decomposer communities or substrate development.

As discussed, the most common factors influencing CWD decay includes tree species, moisture, temperature, the position of CWD, site type, decay class, substrate quality and diameter. Some existing models include factors such as the tree position, diameter, site type, moisture, temperature and substrate quality (including decay stage and tree species), as well as a time lag or a slow initial decomposition phase as a part of the decay dynamics (Næsset 1999b; Yatskov et al. 2003; Mäkinen et al. 2006; Zell et al. 2009; Tuomi et al. 2010, etc.). While the inclusion of a wide range of factors might improve the model accuracy, the primary criteria for choosing a model for this thesis is the overall model compatibility in stand level optimization.

The model needs to be able to describe CWD development over long-time horizons. In transition matrix models, CWD exits the matrix after a predetermined residence time. In contrast, in exponential decay models, as wood decays, it will reach a point where CWD may still exist in the model, but an actual forest inventory would most likely not be able to identify it. This creates a discrepancy when comparing calculated results with statistical data from forest inventories. For calculation purposes, an explicit endpoint for including decaying wood in the CWD pool, should therefore be defined. Various suggestions exist for defining this endpoint, ranging from 85 %-95 % mass loss from the initial mass (Tarasov and Birdsey, 2001; Shorohova and Kapitsa, 2014; Ranius and Kindwall, 2004 etc.). The most used criterion is 95 % mass loss (Mackensen et al., 2003; Zell et al. 2009: Shorohova and Kapitsa, 2016; Pearson et al., 2017; Edelmann et al., 2023) and this will also be applied in this thesis as the mass loss criteria for CWD.

Similarly to the Finnish National Forest Inventories (Korhonen 2009), in this thesis, only dead trees with initial DBH ≥10 cm are defined as CWD. As in Rämö et al. (2020), this thesis does not consider stumps and other harvesting residue as CWD since they are left in the forest regardless of management regime. Harvesting residues are however included in the soil C model.

Table 1 presents the examined decay models and evaluates their suitability for our optimization setup. The evaluation of these models shows that the models by Mäkinen et al. (2006) are the most suitable for our purposes. Mäkinen et al. (2006) fitted different functions to field data from Finnish boreal forests, and found that the remaining fractions of volume, mass, and density of Norway spruce could be expressed as a sigmoidal curve trough a version of the Gompertz function. The paper also provides specific equations for the different forms of density, mass, and volume decay. The model therefore enables us to predictively calculate the decomposition of the wood for its full lifespan from the point when the decay starts, which is essential for optimization. The decay model and its implementation into the setup used in this thesis will be further discussed in the chapter 5.4.

To summarize, after examining a range of different models, both exponential and transition matrix models, the model by Mäkinen et al. (2006) was found to be the best fit for the purposes of this thesis.

Table 1. Examined decay models for coarse woody debris.

Model	Model type	Model Focus	Findings	Suitability for our setup
Næsset (1999b)	Exponential	Ecological factors affecting decay rates of Norway spruce	Larger diameter and more contact with forest floor will lead to faster decomposition.	Limited suitability due to the focus on factors like tree position and soil moisture which are not included in our set-up.
Yin (1999)	Exponential	Parameterizing substrate quality, environmental, and microbial effects on decay	Emphasizes coupling of substrate quality and microbial activity.	Limited suitability due to intricate ecological considerations like substrate quality and microbial activity which are not included in our set-up.
Hyvönen and Ågren (2001)	Exponential	Explores three different ways to use the structure of litter and the decomposer community to describe the decay.	A simple, single negative exponential model was found to be very limited.	Limited suitability due to the use of colonisation rates of wood which were partly extrapolated from data from Douglas-fir.
Yatskov et al. (2003)	Exponential	Describing three distinct phases of decomposition for logs and snags.	Suggests multiple decay rate constants for different decay stages.	Limited suitability due to geographic differences and the use of multiple decay phases and constants.

Mäkinen et al. (2006)	Exponential	Investigating different functions for predicting decay of wood density, mass, and volume in Finnish conditions.	A second order Gompertz function best described the decay. Considers factors like time since death, tree species, and diameter.	Suitable due to its predictive nature, description of volume and mass, as well as applicability to single tree models and the Finnish conditions.
Zell et al. (2009)	Exponential	Investigating four exponential models.	Sigmoidal curve model best fits data over large regions.	Limited suitability as the study focuses on large-scale modelling and uses data from North America, which may not be applicable to our specific set-up.
Kruys and Jonsson (2002)	Transition Matrix	Tracking transitions between decay classes of Norway spruce, based on data from Northern Sweden.	Importance of using a consistent decay classification system.	Limited suitability due to authors claiming that the model is a crude estimate intended for study of larger areas.
Holeksa et al. (2008)	Transition Matrix	Creating a transition matrix based on observed transitions of sample trees in Poland.	Probability of a log moving to next decay class increases with time.	Limited suitability due to the geographic region of the study.
Aakala (2010b)	Transition Matrix	Modifying a transition matrix for late successional spruce forests.	Includes a decay class for wood covered by ground vegetation.	Limited suitability as the study focuses on late successional forests.

Rämö et al. (2020)	Transition Matrix	Using a transition matrix with 12 size classes and constant decay rate for all sizes and tree species.	Decomposition rates dependent on the state of decay would require different stock for each decay state.	Limited suitability as the model was based on decay rates described in Hyvönen and Ågren (2001) and applies a constant decomposition rate.
Ranius and Jonsson (2004)	Direct Relationship	Describes the amount of CWD in old growth spruce forest in relation to living stem volume, site productivity, mortality rate and residency time.	Not applicable to managed forests.	Not suitable as it does not provide predictive modelling of decay.

4 Previous studies on trade-offs between timber production, carbon sinks, and coarse woody debris

Accumulating and maintaining an optimal amount of CWD in a forest requires maintaining a stock of living trees that ensures a continual provision of new CWD through tree mortality. Since living trees provide valuable timber, each tree which dies before it is harvested impacts wood production negatively. Previous studies have shown a potential trade-off between wood production and other forest ecosystem services.

Díaz-Yáñez et al. (2021) demonstrate the trade-off between wood production and deadwood on a landscape level. They show that maximizing the net present value (NPV) of wood production results in low deadwood amounts, while a similar relationship doesn't exist between C sinks and deadwood. Eyvindson et al. (2021) also found significant trade-offs in multifunctional forestry, with timber harvests often coming at the expense of CWD, C storage, and scenic beauty. These trade-offs being especially evident when examining an individual forest stand. Triviño et al. (2015) identify a trade-off between timber revenues and C, noting that C storages react more strongly to an increase in wood production compared to C sinks. Their results suggests that a 5 % reduction in harvest revenues could lead up to 9 % increase in C storage and 15-23 % increase in C sinks.

Similarly, Mönkkönen et al. (2014) emphasize that a mere 5 % decrease in economic returns can yield considerable ecological benefits. However, they also point out that the creation of deadwood related habitats tends to be more costly than other habitats. They also point out that no single management regime suffices to provide habitats over all different taxa and argue that the best results for biodiversity are achieved by landscape level management. Adding, that the trade-offs between wood production and biodiversity targets are taxon specific.

On a national scale, Mäkelä et al. (2023) found that higher timber harvest levels significantly affect C sinks while some biodiversity indicators are more responsive to specific management practices. The practices can be tree retention, species choice, and deadwood accumulation. The study suggests that additional set-asides are essential for biodiversity support. However, it's important to note that their study excludes CCF and does not account for the potential impacts of a social price on C.

The mentioned studies do not factor in the direct economic valuation of non-timber ES, which could help offer a more comprehensive view of the trade-offs between different forestry objectives. The incorporation of such valuations, through e.g. the social price of C or by using PES, could significantly influence potential forest management strategies and economic outcomes.

Triviño et al. (2015) observed that, within RF, set asides and reduced harvesting increase C sinks, while extended rotations favour C services in general. Studies indicate that including CO_2 pricing generally leads to longer rotations in RF. Assmuth et al. (2018) used a stand level economic-ecological optimization model with size-structured description of forest dynamics and demonstrate how social price of C reduces harvesting and prolongs rotations under a 2% interest rate. However, with CO_2 prices of 20 € tCO_2^{-1} or more, the rotation length is infinitely long with thinning as the only form of harvest, i.e. optimal solution switches to CCF. According to Assmuth et al. (2018), at a higher interest rate, CCF is optimal regardless of CO_2 price. The study also demonstrates that the sawlog to pulpwood ratio in harvested trees increases as CO_2 price is increased. That is, under high CO_2 prices trees are left to grow longer. It is worth noticing, that Assmuth et al. (2018) did not find solutions where the forest is used solely as a C stock, i.e. solutions with no harvests.

Parkatti et al. (2023) expanded the stand level model in Assmuth et al. (2018) to include a detailed model for soil C. According to their results, soil C has a major impact on optimal solutions, particularly under high CO_2 prices. As the CO_2 price is increased, yield diminishes, and rotation length increases. Under 3% interest rate and with per tonne CO_2 prices between €0-20, the optimal solution becomes CCF. However, increasing the CO_2 price to €40 switches the optimal solution back to RF, but with an extended rotation. This switch increases annual yield, decreases the NPV for timber revenues, but increases the discounted value of C sinks. Parkatti et al. (2023) point out that when soil C is omitted, optimal solutions are less responsive to CO_2 prices, resulting in lower bare land values (BLV). Their study suggests that the joint consideration of C sinks and wood production, results in increased BLV and discounted C sinks while lowering NPV for wood production. The result where including C pricing drives a shift from CCF to RF, is also confirmed in Tahvonen et al. (2024).

The question of simultaneous optimization of multiple objectives within a single forest stand naturally extends to a broader landscape, national scale, or even global scale.

This raises the question whether it is more efficient to use forest stands multi-objectively or to divide them into zones with specified purposes such as biodiversity conservation, wood production, and C sinks. However, there remains a lack of consensus on the topic, with studies from boreal forests showing opposite results.

When examining the economy of a single stand and the potential for simultaneous optimization of multiple objectives, one can look at the most cost-effective methods to increase targets other than wood production. In simpler terms, identifying ways to increase for example biodiversity, or CWD, with minimal impact on timber revenues.

Ranius et al. (2003) found that CWD amounts can be increased by forest management measures promoted by the Swedish FSC-certification. Jonsson et al. (2006) and Ranius and al. (2005) found that in Sweden, the most cost-efficient methods vary depending on whether the forest is situated in the north, or south. They argue that generally, more productive forests favour retention methods, while less productive one's favour set-asides. And find that some measures can even be achieved without compromising economic viability at all. Mäkelä et al. (2023) also suggest that, on a national scale, biodiversity can be increased while simultaneously raising harvest levels by applying forest management changes.

Mönkkönen et al. (2011) found temporary small set-asides to be a cost-effective measure for increasing saproxylic species, while in long term, permanent large or small set-asides were seen to be more effective. Moreover, Mönkkönen et al. (2014) pointed out that business as usual (BAU) regimes, with thinnings and clear-cuts, does not only yield suboptimal economic returns. But, in fact, at the same level of returns, ecological benefits could be improved by 100-270% through landscape-scale planning. Their study found green tree retention ineffective, a measure contradicted by later studies such as Triviño et al. (2015). In contrast, Tahvonen et al. (2019) studied the effect of ES on economics in mixed-species forestry by valuing ES through a function of stand state and a biodiversity index, assuming a relationship between biodiversity and ES value. According to their results, increasing the value of ES's favours CCF, increases rotation lengths, and increase the number of broadleaved and non-commercial species trees. Tahvonen et al. (2019) emphasize that to simultaneously produce a range of ecosystem services and optimize harvest revenues, a wide set of management options are needed. That is, oversimplifying the management will narrow the possibility of service provision. The authors also suggest that moderate deviations from CCF solutions which maximize harvest revenues would still increase biodiversity and might not be expensive. However, CWD was not specifically included in their study.

Another strategy for promoting biodiversity while optimizing forest management involves incorporating constraints for CWD amounts. Rämö et al. (2020) investigated the economic implications of increasing CWD with a hard constraint on CWD amounts. Since their stand growth model did not produce enough CWD to meet the targets they had set, an alternative management method was introduced. The method consisted of felling trees intentionally to be left in the forest, so called biodiversity-fellings. They found that increasing the deadwood amounts to 20(40) m^3 ha^{-1} decreased the steady-state net revenues by 17(30) percent.

Tikkanen et al. (2012) suggest that when omitting thinnings, but performing clear-cuts at the time when the trees reach predefined clearcut sizes recommended by Finnish national guidelines, pine stands accumulate CWD amounts over 20 m^3 ha^{-1} and spruce over 10 m^3 ha^{-1}. They also utilized the model by Mäkinen et al. (2006) for wood decay and further added figures identified by Hautala et al. (2004) for the destruction of CWD after harvest. Tikkanen et al. (2012) concluded that a no thinning regime can potentially give a significant increase in CWD amounts at a low cost.

Previous studies have indicated trade-offs between wood production and C or biodiversity services in general, but also shown a potential for cost-effective methods to increase both C services and CWD amounts. Integrating the social price of C to optimization setups generally leads to extended rotation lengths and reduced harvests, both of which potentially contribute to CWD as well as C stocks. Moreover, a social price of C increases BLVs as the C price rises, despite decreases in timber yield and NPV of wood production.

Previous studies also show the need for comprehensive set-ups for finding optimal solutions. While some studies (e.g., Assmuth et al. 2018; Tahvonen et al. 2019; Díaz-Yáñez et al. 2021; Eyvindson et al. 2021 and Parkatti et al. 2023) include both CCF and RF, others (e.g., Jonsson et al. 2006; Ranius et al. 2005 and Mäkelä et al. 2023) do not. Similarly, while some studies incorporate the social price of C (e.g., Assmuth et al. 2018; Parkatti et al. 2023), others do not. Additionally, while for example Parkatti et al. (2023) and Mäkelä et al. (2023) include soil C, most of the literature omits it. Importantly, none of these studies utilizes an individual tree model and optimization of forest management. To be able to optimize forest management without constraints on management methods while accounting for the ecological complexity which an individual tree model offers, advanced optimization techniques are required. Reinforcement Learning (RL) is a machine learning method, which has been proven effective in managing the high dimensionality required to do so.

Malo et al. (2021) applied an actor-critic RL framework to a size-structured matrix model and Tahvonen et al. (2022) extended this framework by using an individual tree model, which added yet another layer of realism to the modelled forest growth. Parkatti et al. (2024) incorporates the Yasso07 soil C model to evaluate the economic costs and benefits of C sinks in boreal forestry. Tahvonen et al. (2024) also examines C sinks and wood production in boreal forests, with the inclusion of bioenergy with carbon capture and storage (BECCS). Both studies apply RL optimization to economically optimize wood production and C sinks simultaneously. Parkatti et al. (2024) focuses on pine in a RF context, while Tahvonen et al. (2024) explores spruce in both RF and CCF.

The principle behind the RL model used in these studies is that an agent chooses the forest management policy which interacts with an environment (the forest ecosystem) and receives feedback in the form of rewards (e.g. NPV value increase). Over time, the agent learns to select actions which maximize cumulative rewards through a trial-and-error process. The RL set-up can handle both a multiplicity of variables as well as stochastic factors like fluctuating pricing or ecological development (e.g. individual tree growth). This ability to find and learn optimal strategies without following predefined rules make RL a particularly powerful tool for realistic forestry modelling, where the problems may have multiple objectives, and the environment is complex.

This thesis builds further upon this advance in ecological-economical optimization done with RL, adding a biodiversity dimension in the form of CWD as a variable to consider. By doing so the aim is to fill literature gaps, both in the trade-offs between wood production and ecosystem services (e.g. Mönkkönen et al., 2014; Tahvonen et al., 2019; Díaz-Yáñez et al., 2021 and Eyvindson et al., 2021) and in the CWD dynamics in economic-ecological models such as Rämö et al. (2020). As well as the mentioned addition of CWD to the RL model used in e.g. Parkatti et al. (2024) and Tahvonen et al. (2024).

5 The optimization setup

The optimization setup consists of a system describing forest growth, management, the flow of C and accumulation of CWD. The model describes a Myrtillus type, single tree species, Norway spruce forest located in central Finland with a mean annual temperature of 3.3°C, a yearly precipitation of 650mm. The stand growth is described using a statistical empirical model by Bollandsås et al. (2008), specifications can be found in Appendix B. A full description of economic-ecological model used, except for the CWD part, is found in Tahvonen et al. (2024).

5.1 Forest growth

Let $x_{t,q,w}$ represent the number of trees per hectare in the developing size classes $q \in \{1, \dots, m\}$, age cohorts $w \in \{1, \dots, n\}$, and time periods $t \in \{1, \dots, \infty\}$ prior to a potential harvest. The number of trees per hectare after a harvest is denoted by $x_{t,q,w}^{+}$ while $h_{t,q,w}$ indicate the number of trees which are harvested, all measured at the start of the five-year periods. The number of trees in various size- and age classes before and after harvests are represented by $x_t \in \mathbb{R}^{m \times n}$ and $x_t^{+} \in \mathbb{R}^{m \times n}$, respectively, with the harvested trees given by $h_t \in \mathbb{R}^{m \times n}$.

The variable $d_{t,q,w}$ represents the breast height diameter of trees in size class q and age w before any harvest and $d_{t,q,w}^{+}$ the diameter after a possible clearcut and the related artificial regeneration. Thus, $d_t \in \mathbb{R}^{m \times n}$ and $d_t^{+} \in \mathbb{R}^{m \times n}$. During each period t, the share of trees which survive from one age class w to the next age class w+1 is given by the function $\alpha_{q,w}$ which satisfies the condition $0 \le \alpha_{q,w}(x_t^{+}, d_t^{+}) \le 1$.

The natural regeneration of trees in the model are again divided into q size classes and the number of seedlings in each size class will be represented by $\phi_q(x_t^{+}, d_t^{+}) \ge 0$. Let $\hat{d}_q$ denote the diameter of newly established trees in size class q. The diameter growth each period is $I_{q,w}(x_t^{+}, d_t^{+})$. A clear-cut is always followed by an artificial regeneration, which then brings the stand to the state $\bar{x} \in \mathbb{R}^{m \times n}$, $\bar{d} \in \mathbb{R}^{m \times n}$. When it comes to management let $\delta_t^{th} \in \{0,1\}$ and $\delta_t^{cc} \in \{0,1\}$ denote Boolean variables which determine the periods when a thinning or a clear-cut takes place. Then, for an initial state x_0, d_0, the stand development is given by:

$$x^{+}_{t,q,w} = (1 - \delta^{cc}_t)x_{t,q,w} - \delta^{th}_t h_{t,q,w} + \delta^{cc}_t \bar{x}_{t,q,w}, \quad q \in \{1,\dots,m\}, \quad w \in \{1,\dots,n\}, \tag{1}$$

$$d^{+}_{t,q,w} = (1 - \delta^{cc}_t)d_{t,q,w} + \delta^{th}_t \bar{d}_{t,q,w}, \quad q \in \{1,\dots,m\}, \quad w \in \{1,\dots,n\}, \tag{2}$$

$$x_{t+1,q,1} = \phi_q(x^{+}_t, d^{+}_t), \quad q \in \{1,\dots,m\}, \tag{3}$$

$$x_{t+1,q,w+1} = \alpha_{q,w}(x^{+}_t, d^{+}_t)x^{+}_{t,q,w}, \quad q \in \{1,\dots,m\}, \quad w \in \{1,\dots,n-1\}, \tag{4}$$

$$d_{t+1,q,1} = \hat{d}_q, \quad q \in \{1,\dots,m\}, \tag{5}$$

$$d_{t+1,q,w+1} = d^{+}_{t,q,w} + I_{q,w}(x^{+}_t, d^{+}_t), \quad q \in \{1,\dots,m\}, \; w \in \{1,\dots,n-1\} \tag{6}$$

$$\delta^{th}_t \delta^{cc}_t = 0, \tag{7}$$

$$x^{+}_{t,q,w} \geq 0, \quad h_{t,q,w} \geq 0, \quad q \in \{1,\dots,m\}, \quad w \in \{1,\dots,n-1\} \tag{8}$$

and $t = 0,1,\dots,\infty$ for all the functions.

5.2 Wood production

Let the gross revenues from clear-cutting be denoted as R_t and the costs associated with clear-cutting and thinning as $C_{cc,t}$ and $C_{th,t}$ respectively. Whenever a thinning or a clear-cut takes place, a fixed harvesting cost C_f is also included, representing both the planning as well as the transporting of logging machines to the site. The inclusion of a fixed harvest cost implies that the harvesting may not be carried out each period. When further adding the regeneration cost C_r, the per-period wood production net revenues are:

$$\pi_t \begin{cases} R_t - C_{th,t} - C_f & \text{if } \delta^{th}_t = 1 \\ R_t - C_{cc,t} - C_f - C_r & \text{if } \delta^{cc}_t = 1 \\ -C_r & \text{if the initial state is bare land} \\ 0 & \text{otherwise.} \end{cases}$$

These revenues depend on the prices of sawtimber and pulp, as well as the size and number of trees harvested. The variable harvesting costs also depend on the size and number of the harvested trees; economic models and parameters can be found in Appendix B.

5.3 Carbon sinks

Let $\rho = 0.83403$ be the factor used to convert commercial stem volume into whole-tree dry mass including the top, branches, leaves, roots, and stump (Lehtonen et al. 2004, Pukkala 2014). The C stock in living trees is given as:

$$\omega(x_t, d_t) = \rho\varphi \sum_{q=1}^{m} \sum_{w=1}^{n} v(d_{q,w,t}) x_{q,w,t}, \tag{9}$$

where $v(d_{q,w,t})$ represent the volume and $\varphi = 0.5$ converts whole-tree dry mass to C mass in tons. When p_c denotes the social price of C in € tCO_2^{-1}, then the periodical C sink value from forest growth is

$$\sigma_{1,t} = \psi p_c \theta \Delta^{-1}(\omega(x_{t+1}, d_{t+1}) - \omega(x_t^+, d_t^+)), \tag{10}$$

where Δ is the period length (5 years), $\theta = 44/12$ converts C into CO_2, and ψ distributes the sink effect evenly over the five-year period and discounts it to the beginning of the period. Over these five-year periods, a continuous process regenerates dead branches, roots etc., giving a C litter flow to the modelled forest soil. The value of this sink is then

$$\sigma_{2,t} = \psi p_c \theta \sum_k b_{tk}, \tag{11}$$

where b_{tk} is the annual soil C input for litter size class k, (specifics available in Tahvonen et al. 2024). In addition to the continuous C flow from living trees into the soil, point inputs occur at the times of harvest (foliage, branches, stumps, roots, and fine roots of harvested trees). Both types of inputs cause CO_2 emissions after a delay, which are estimated using the Yasso07 soil C model (Tuomi et al., 2011). The Yasso07 model, shown in detail as a system of 15 linear differential equations can be found in Tahvonen et al. (2024). The emission values as their present value when the input occurs are given as:

$$\mu_{1,t} = \psi p_c \theta \mathrm{w}^T b_t + p_c \theta \mathrm{w}^T \hat{b}_t, \tag{12}$$

Where the row vector w^T converts the litter input vector and the harvest residue C input vector $\hat{b}_t$ to the present value of emissions computed over an infinite time horizon, using parameters found in Tahvonen et al. (2024). CO_2 emissions from products occur partly during the manufacturing process and partly after a delay, due to the decay of wood products and the use of biomass in energy production. Let $\tilde{b}_t$ denote the C content mass of wood and vector β represent the proportion of manufacturing (forest biomass) C source in four different product classes (1. sawn wood and plywood, 2. mechanical pulp and paper, 3. chemical pulp and paper, and 4. biofuel). The present value of C emissions from products is:

$$\mu_{2,t} = p_c \theta (\beta^T + \widetilde{w}^T (I - diag(\beta))) \tilde{b}_t, \tag{13}$$

where the vector $\tilde{w}$ converts the product C into discounted emission values over an infinite horizon. See Tahvonen et al. (2024) for the full parameter details and calculations.

5.4 Coarse woody debris

5.4.1 Deadwood model

The deadwood model and parameters used in this thesis are adopted from Mäkinen et al. (2006). As follows, let $D_{q,t,w} = x^{+}_{q,t,w}\left(1 - \alpha_{q,w}(x^{+}_{t}, d^{+}_{t})\right)$ represent the number of trees in the size class $q \in \{1, \dots, m\}$ and age cohort $w \in \{1, \dots n\}$ that die during period $t \in \{0, \dots, \infty\}$ and turn to deadwood. A dying tree is classified as CWD if it is ≥10cm DBH at the time of death. When a tree dies, its stem volume $v(d_{q,w,t})$ (commercial volume) is counted as CWD. The tree then continues to be classified as CWD as it decays until 5 % of the initial stem mass is left. Let $i \in (0, \dots, \infty)$ denote the number of years since the tree has died. Now, applying Mäkinen et al. (2006), the duration (years) that deadwood, produced from size class q, and age cohort w, in period t will be considered CWD is determined by:

$$\hat{t}_{q,t,w} = \frac{ln(-\,ln(0.05)) - (-2.017) - (-0.017)d^{+}_{q,t,w}}{0.054}, q \in \{1, \dots, m\}, t \in \{0, \dots, \infty\},$$
$$w \in \{1, \dots, n\}, d^{+}_{q,t,w} \geq 10 \quad (14)$$

Once $\hat{t}_{q,t,w}$ is solved, the remaining portion of CWD volume produced from size class q, age cohort w, at period t, denoted by $W_{q,t,w}(i) \in [0,1]$ at i years after its death, is calculated using the following two equations:

$$W_{q,t,w}(i) = e^{-e^{\left((-2.948)+(0.059)i+(-0.030)d^{+}_{q,t,w}\right)}}, i \in [0, \hat{t}_{q,t,w}] \quad (15)$$

$$W_{q,t,w}(i) = 0, i \in (\hat{t}_{q,t,w}, \infty) \quad (16)$$

Equation (15) describes the decay of a CWD unit from the time of death until $\hat{t}$ years later and equation (16) from that point on. The amount of CWD (m3) produced from size class q and age cohort w, at period t, i years after death is given by $D_{q,t,w}v(d_{q,w,t})W_{q,t,w}(i)$. The tree species specific mass decay parameters (14) and tree species volume decay parameters (15) are taken from Mäkinen et al. (2016).

5.4.2 Economic value of coarse woody debris

In the economic consideration of CWD, each unit of CWD is given a value based on the duration it remains in the forest, representing its ES value throughout its full lifespan. The rate of decay of the CWD from size class q and age cohort w, produced at period t, i years after death is given by:

$$w_{q,t,w}(i) = \frac{d}{di} W_{q,t,w}(i) =$$
$$-0.059 e^{\left((-2.948)+(0.059)i+(-0.030)d_{q,t,w}\right)} e^{-e^{\left((-2.948)+(0.059)i+(-0.030)d_{q,t,w}\right)}}, i \in [0, \hat{t}_{q,t,w}]. \quad (17)$$

Let r represent the annual interest rate. The discounted value of CWD unit originated at time t, from size class q and age cohort w is calculated as:

$$P_{q,t,w}(r) = W_{q,t,w}(0) + \int_0^{\hat{t}_{q,t,w}} w_{q,t,w}(i) e^{-ri} di - W_{q,t,w}(\hat{t}_{q,t,w}) e^{-r\hat{t}_{q,t,w}}, \quad (18)$$

where $W_{q,t,w}(0)$ represents the amount of CWD present at the start of the model, $\int_0^{\hat{t}_{qtw}} w_{q,t,w}(i) e^{-ri} di$ accounts for the decay of the CWD from the death of the tree until the time $\hat{t}_{q,t,w}$ and $W_{q,t,w}(\hat{t}_{q,t,w}) e^{-r\hat{t}_{q,t,w}}$ the CWD which leaves the model at time $\hat{t}_{q,t,w}$.

The discounted values for units of CWD are given for fixed sized trees in Table C1. For arbitrary sized trees linear interpolation is used to approximate the discounted values. Let p_d be the social value of CWD in € per m^3. Now, the periodical economic value of CWD is given as:

$$\zeta_t = p_d \sum_{q=1}^{m} \sum_{w=1}^{n} D_{q,t,w} v(d_{q,w,t}) P_{q,t,w}(r). \quad (19)$$

5.5 Objective function and optimization methods

Let $\gamma = \frac{1}{(1+r)}$ represent the discount factor. The net present value of wood production is:

$$J_w = \sum_{t=0}^{\infty} \gamma^{t\Delta} \pi_t, \quad (20)$$

the present value of C (net) sinks,

$$J_c = \sum_{t=0}^{\infty} \gamma^{t\Delta} (\sigma_{1,t} + \sigma_{2,t} + \mu_{1,t} + \mu_{2,t}), \quad (21)$$

and the net present value of dead wood is

$$J_d = \sum_{t=0}^{\infty} \gamma^{t\Delta} \zeta_t. \tag{22}$$

The overall problem to solve is:

$$J = \max_{h_t, \delta_t^{th}, \delta_t^{cc}, t=0,1,2\ldots} \sum_{t=0}^{\infty} \gamma^{t\Delta} (\pi_t + \zeta_t + \sigma_{1,t} + \sigma_{2,t} + \mu_{1,t} + \mu_{2,t}), \tag{23}$$

Subject to (1)-(19).

This optimization problem can be seen as an MDP, where the agent's actions are determined by the current state, but the objective is maximizing cumulative rewards through an optimal policy. It is solved efficiently with the use of RL, as showed in Malo et al. (2021) and Tahvonen et al. (2022). This approach allows determining the optimal forest management strategies without a need to predetermine or regulate specific methods of harvest. The RL programme effectively discovers the optimal rotations and harvest amounts which best solve the objective function.

6 Results

6.1 Optimal solutions

The analysis begins by studying optimal solutions considering wood production and C sinks (Table 2). With zero CO_2 and CWD price, under 1 % interest rate the optimal management is CCF with 30 years harvesting interval. At 1% interest rate, optimal solution remains CCF for up to €100 CO_2 price per tonne. With CO_2 prices above €100 the optimal solution switches to RF with long rotation length of over 200 years and a low number of thinnings (Table 2). When the interest rate is increased to 2 % all the solutions up to €200 CO_2 price are CCF, while CO_2 prices above €200 render harvesting suboptimal i.e. forest is kept solely as a C storage. Similarly, under 3 % interest the solutions are CCF but only up to €140 CO_2 price after which the forest again is left solely as a C stock.

Omitting C sinks and considering optimal solutions with wood production and CWD pricing per m^3 yield similar results (see Table 3). At 1 % interest, the optimal solutions are CCF up to €300 CWD values, after which the optimal solution switches to RF with 130 to 140 years rotation length and one or two thinning. Further increasing CWD price to €440 produces 230 years optimal rotation without thinning. At 2% and 3% interest rates the optimal solution is similar albeit CCF switches to RF with slightly lower CWD price a CWD price of €420 causes harvesting to stop completely (Table 3).

Table 2. Optimal management regime with changing C prices and interest rates.

	Carbon price € tCO_2^{-1}										
r	0	20	40	60	80	100	120	140	160	180	200
1 %	CCF_{30}	$CCF_{25\text{-}30}$	CCF_{25}	CCF_{30}	CCF_{30}	CCF_{30}	$RFth_{240}$	$RFth_{250}$	$RFth_{250}$	$RFth_{260}$	$RFth_{280}$
2 %	CCF_{25}	CCF_{25}	CCF_{25}	CCF_{30}	CCF_{30}	CCF_{30}	CCF_{35}	CCF_{40}	$CCF_{30/35/250}$**	$CCF_{45/325}$***	NoHarv
3 %	CCF_{25}	CCF_{25}	CCF_{25}	CCF_{30}	CCF_{30}	CCF_{35}	$CCF_{mix^{ƚ}}$	NoHarv	NoHarv	NoHarv	NoHarv

Note: CCF = Continuous cover forestry, RFth = Rotation forestry with thinning, NoHarv = No harvest, *r* = interest rate, *Alternating between 25- & 30-year harvest interval, **Alternating between 4 harvests with 30-35-year interval and 250-year break, ***Alternating between 3 harvests with 45-year interval and 325-year break, ƚThinnings with alternating intervals between 30 and 205 years.

Table 3. Optimal management regime with selected CWD prices

	Coarse woody debris price € m^{-3}										
r	0	40	100	200	300	360	380	400	420	440	500
1 %	CCF_{30}	CCF_{30}	CCF_{30}	CCF_{30}	$RFth_{130}$	$RFth_{140}$	$RFth_{140}$	$RFth_{130}$	$RFth_{140}$	RF_{230}	RF_{250}
2 %	CCF_{25}	CCF_{25}	CCF_{25}	CCF_{30}	CCF_{30}	CCF_{30}	RF_{250}	RF_{280}	NoHarv	NoHarv	NoHarv
3 %	CCF_{25}	CCF_{25}	CCF_{25}	CCF_{25}	CCF_{25}	CCF_{30}	CCF_{30}	RF_{300}	NoHarv	NoHarv	NoHarv

Note: CCF = Continuous cover forestry, RFth = Rotation forestry with thinning, RF = Rotation forestry without thinning, NoHarv = No harvest, *r* = interest rate.

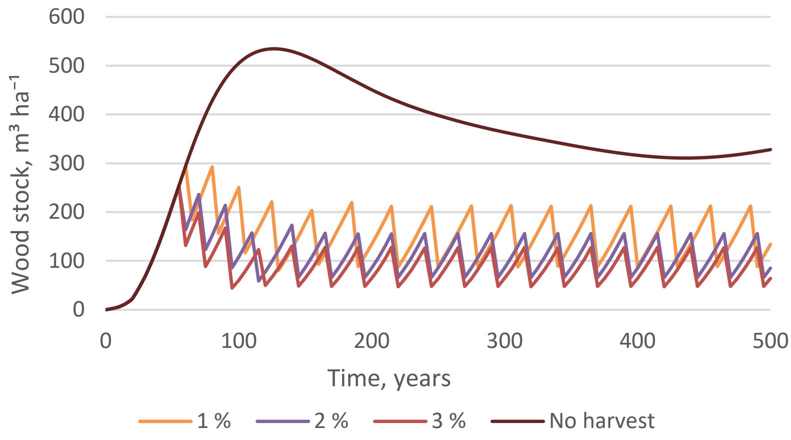

Figure 1. Wood stock with optimal management and no social price on CWD or C, under 1, 2 and 3% interest rates and scenario with no harvests.

Figure 1 demonstrates the wood stock with zero CO_2 and CWD price. With higher interest rates the harvest interval is shorter, and the steady-state stand wood stock is lower. Table 4 demonstrates optimal solution trends which emerge from CO_2 and CWD pricing. Increasing the CO_2 price results in management which increases the stand basal area (BA), as well as the size of harvested trees. The yield also increases with prices up to €40/€60, depending on interest. With 1 % interest and rotation lengths exceeding 240 years, the BA becomes higher than the no harvest BA of 40,1 m^2 ha^{-1}. Overall, the management under C pricing indicates a shift in management towards increased retention of wood stock to enhance C sequestration.

Although raising CWD social prices also leads to an increase in BA and harvest diameters, the shift is more subtle. The yield on the other hand is increased more substantially, showing that with a moderate social price placed on CWD, wood production carries a larger role in the optimal solutions. And only when a certain price is reached does the management clearly shift towards the production of CWD.

When a social price is applied to CWD, harvested diameters are generally smaller compared to when applying a social price on C. This reflects the management objective of keeping large diameter wood for the increasing natural mortality. While harvesting larger trees, as in the case of a social price placed on C, will aid in also promoting younger trees to help increase C sinks.

Table 4. Optimal management, BA, yield and harvested diameters in steady-state under different C and CWD prices.

CWD price, € m^{-3}	C price, € tCO_2^{-1}	Optimal management	Yield, $m^3\ ha^{-1}\ a^{-1}$	BA, $m^2\ ha^{-1}$	Average DBH of harvest, cm
No Harv	No Harv	-	0	40,1	-
	20	$CCF_{25\text{-}30}$ / CCF_{25}	5,1 / 5,0	22,8 / 18,5	34,5 / 30,9
	40	CCF_{25} / CCF_{25}	5,1 / 5,2	25,9 / 25,1	36,7 / 36,1
	60	CCF_{30} / CCF_{30}	4,9 / 4,6	28,4 / 30,4	38,6 / 41,2
	80	CCF_{30} / CCF_{30}	4,6 / 3,8	30,2 / 34,1	40,7 / 46,0
	100	CCF_{30} / CCF_{35}	4,3 / 2,8	31,9 / 36,6	42,7 / 50,8
	120	$RFth_{240}$ / CCF_{mix}	3,5 / 1,1	39,1 / 39,0	37,7 / 52,5
	140	$RFth_{250}$ / NoHarv	3,0 / 0,0	40,7 / 40,1	40,0 / 0,0
	160	$RFth_{250}$ / NoHarv	2,5 / 0,0	41,7 / 40,1	38,6 / 0,0
	180	$RFth_{250}$ / NoHarv	2,2 / 0,0	42,4 / 40,1	39,9 / 0,0
	200	$RFth_{280}$ / NoHarv	1,9 / 0,0	43,4 / 40,1	41,3 / 0,0
0	0	CCF_{30} / CCF_{25}	5 / 4,2	19,3 / 12,1	31,4 / 25,6
40		CCF_{30} / CCF_{25}	5,1 / 4,3	19,6 / 12,4	31,6 / 25,9
100		CCF_{30} / CCF_{25}	5,0 / 4,3	20,0 / 12,8	31,9 / 26,2
200		CCF_{30} / CCF_{25}	5,1 / 4,4	21,0 / 13,4	32,6 / 26,8
300		$RFth_{130}$ / CCF_{25}	5,7 / 4,6	26,0 / 14,3	26,7 / 27,5
360		$RFth_{140}$ / CCF_{30}	5,6 / 4,6	27,9 / 15,0	27,7 / 27,9
380		$RFth_{140}$ / CCF_{30}	5,6 / 4,6	27,9 / 15,0	27,9 / 27,9
400		$RFth_{130}$ / RF_{300}	5,3 / 1,2	29,3 / 44,7	26,5 / 22,0
420		$RFth_{140}$ / NoHarv	5,2 / 0,0	30,7 / 40,1	27,0 / 0,0
440		RF_{230} / NoHarv	1,9 / 0,0	44,3 / 40,1	23,9 / 0,0
500		RF_{250} / NoHarv	1,6 / 0,0	44,1 / 40,1	22,9 / 0,0

Note: The discount rate of the first number is 1% and the discount rate of the second number is 3%. CWD = Coarse woody debris, BA = Basal area, DBH = Diameter at breast height, CCF = Continuous cover forestry, RFth = Rotation forestry with thinning, RF = Rotation forestry without thinning, NoHarv = No harvest

The increase of CO_2 price leads to an increase in the wood stock as a method of increasing the forest C sink. When the social price is placed on CWD, and the price is large enough, the wood stock is also increased. However, the reason is then to promote natural mortality and create more CWD. At a higher interest rate and with a social price on C, the price point required to shift to management prioritizing C sinks is lower than the social price of CWD needed to shift to management favouring CWD. With the social price on CWD the effect is more sudden and drastic, especially as the interest rate increases. According to Figure 2, an increase in the interest rate clearly requires a higher price point of CWD for a shift towards CWD production. The wood stock is also kept lower under higher interest rates. In comparison, with a social price on C, increasing the interest rate clearly decreases harvesting, thus increasing the wood stock.

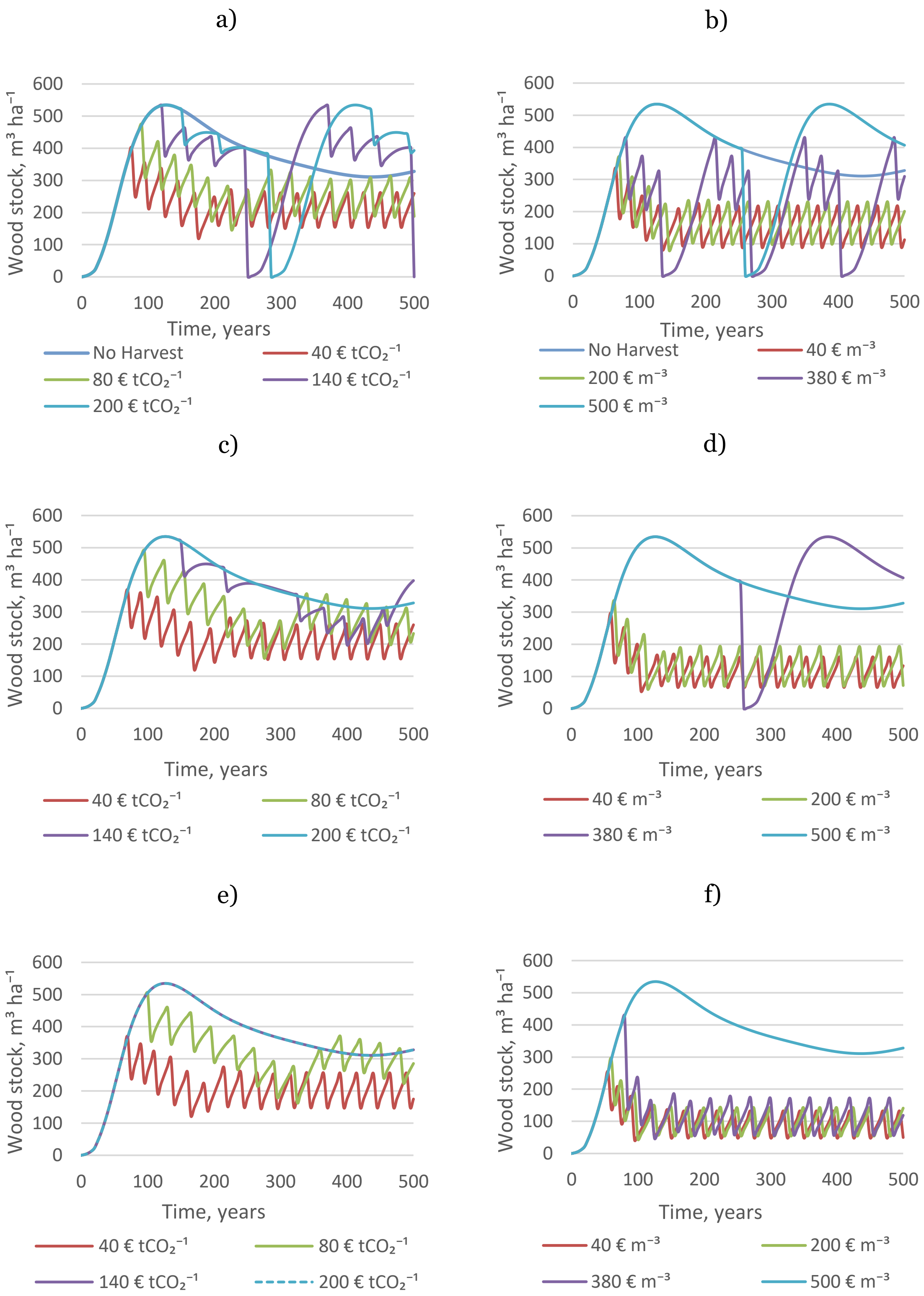

Figure 2. Wood stock under different interest rates and selected social prices for C and CWD. In (a), (c), and (e), the social price on C and interest rates are 1%, 2%, and 3%, respectively. (b), (d), and (f), the social price on CWD and interest rates are 1%, 2%, and 3%, respectively.

6.2 Optimal solution coarse woody debris

Figure 3 demonstrates how optimal solutions without any social price placed on C or CWD have lower steady-state CWD compared to not harvesting at all. The CWD amounts in optimal solutions maximizing net present value of wood production, range between 7,5-14,4 m^3 ha^{-1}, depending on interest rate applied (Table 6). Without any harvest, 200 years from a bare land state, CWD peaks at 200 m^3 ha^{-1} and then decreases towards a steady-state level of around 130 m^3 ha^{-1}. In comparison, in optimal solutions maximizing the net present values of wood production, the CWD peaks are only 20-30 m^3 ha^{-1}, depending on interest rate.

Figure 4 shows how the CWD stock evolves under varying social prices for C and CWD. When a social price is applied to C, the CWD stock increases gradually with higher C prices or interest rates. In contrast, increasing the social price of CWD causes minimal differences between price points, unless the price reaches a level which triggers a clear shift in management. This is particularly evident with higher interest rates, as seen in Figure 4f. Figure 4f also shows that, most prices will exhibit a dynamic, where the CWD levels are increased in the beginning, but the long-term levels will be almost similar, unless the price causes a clear shift in management.

This effect can be seen even more clearly in Table 6, where an interest rate of 3 % and the social price placed on CWD increases the CWD amount only minimally until the CWD price reaches €400. With this price, the mean steady-state CWD amount goes even beyond that of a no harvest scenario, reaching 138 m^3 ha^{-1} compared to the 136,1 m^3 ha^{-1} in the no harvesting scenario.

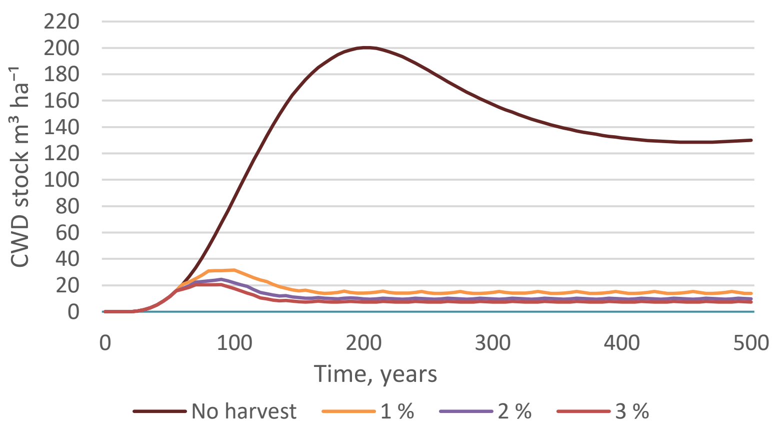

Figure 3. CWD stock with optimal management and no social price on CWD or C.

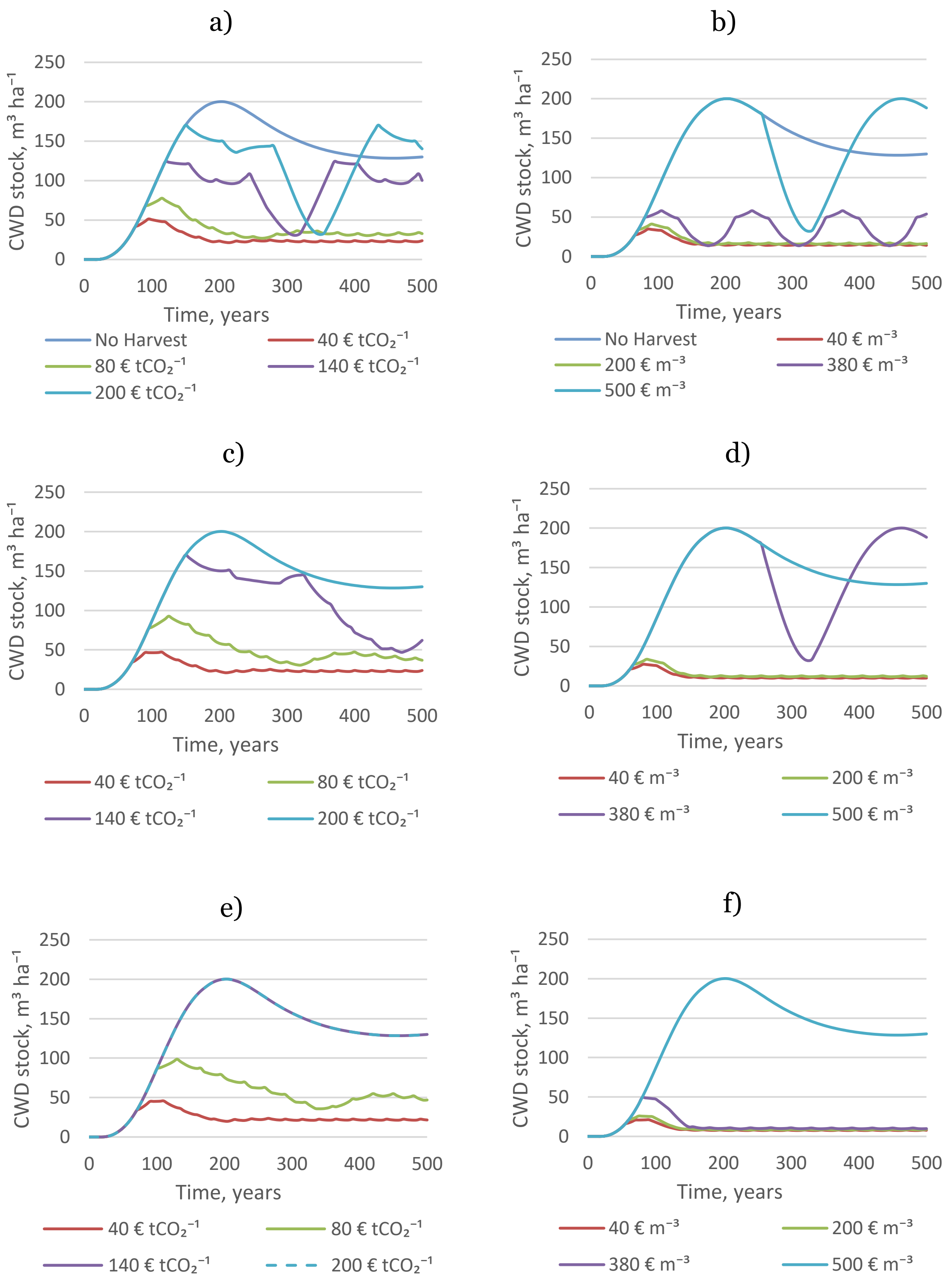

Figure 4. CWD stock under different interest rates and selected social prices for C and CWD. In (a), (c), and (e), the social price on C and interest rates are 1%, 2%, and 3%, respectively. In (b), (d), and (f), the social price on CWD and interest rates are 1%, 2%, and 3%, respectively.

Table 6. Changes is CWD metrics, under different social prices for C and CWD.

CWD price, € m^{-3}	C price, € tCO_2^{-1}	CWD*, m^3 ha^{-1}	Discounted CWD, m^3 ha^{-1}	Peak CWD, m^3 ha^{-1}	Proportion of CWD with DBH 20-40 cm	Proportion of CWD with DBH over 40 cm
'	No Harv	136,1	65,0	200,1	n/a	n/a
	20	18,6 / 13,3	15,8 / 5,6	39,9 / 30,6	63,5% / 55,5%	0,0% / 0,0%
	40	23,1 / 21,8	19,5 / 7,3	51,3 / 45,8	67,6% / 66,6%	0,0% / 0,0%
	60	28,4 / 33,0	22,7 / 8,9	61,8 / 66,8	67,3% / 63,2%	4,1% / 10,9%
	80	32,5 / 45,9	27,2 / 10,7	77,7 / 98,6	63,7% / 48,4%	10,0% / 31,4%
	100	37,6 / 64,1	32,1 / 12,0	94,3 / 133,1	59,1% / 33,5%	17,0% / 51,6%
	120	73,7 / 107,3	40,1 / 12,7	105,8 / 170,3	58,6% / 19,7%	23,1% / 72,6%
	140	85,8 / 136,1	45,3 / 13,0	124,1 / 200,1	58,6% / 19,7%	29,8% / 79,9%
	160	99,3 / 136,1	49,9 / 13,0	141,7 / 200,1	54,0% / 13,4%	38,1% / 79,9%
	180	107,2 / 136,1	53,3 / 13,0	157,3 / 200,1	44,4% / 13,4%	42,8% / 79,9%
	200	114,5 / 136,1	56,3 / 13,0	170,3 / 200,1	42,0% / 13,4%	45,8% / 79,9%
	0	14,4 / 7,5	12,6 / 4,3	31,6 / 20,5	57,6% / 37,6%	0,0% / 0,0%
		14,4 / 7,7	13,4 / 4,4	34,8 / 21,2	58,2% / 39,0%	0,0% / 0,0%
		14,7 / 8,0	13,8 / 4,5	35,6 / 21,9	59,0% / 40,3%	0,0% / 0,0%
		15,1 / 8,5	15,2 / 5,0	41,1 / 25,8	60,5% / 42,3%	0,0% / 0,0%
		16,3 / 9,2	19,3 / 5,7	49,4 / 32,6	54,1% / 45,2%	0,0% / 0,0%
		31,2 / 10,0	21,5 / 6,7	56,6 / 41,9	58,0% / 47,7%	0,0% / 0,0%
		35,3 / 10,0	21,9 / 7,2	58,1 / 49,1	58,7% / 47,9%	0,0% / 0,0%
		36,2 / 138,0	25,0 / 13,0	67,1 / 200,1	61,0% / 36,1%	0,0% / 53,4%
		42,2 / 136,1	26,8 / 13,0	76,6 / 200,1	63,3% / 13,4%	0,0% / 79,9%
		126,9 / 136,1	59,2 / 13,0	200,1 / 200,1	43,9% / 13,4%	31,7% / 79,9%
		133,7 / 136,1	61,9 / 13,0	200,1 / 200,1	38,9% / 13,4%	48,8% / 79,9%

Note: The discount rate of the first number is 1% and the discount rate of the second number is 3%. CWD = Coarse woody debris, DBH = Diameter at breast height, *steady-state mean

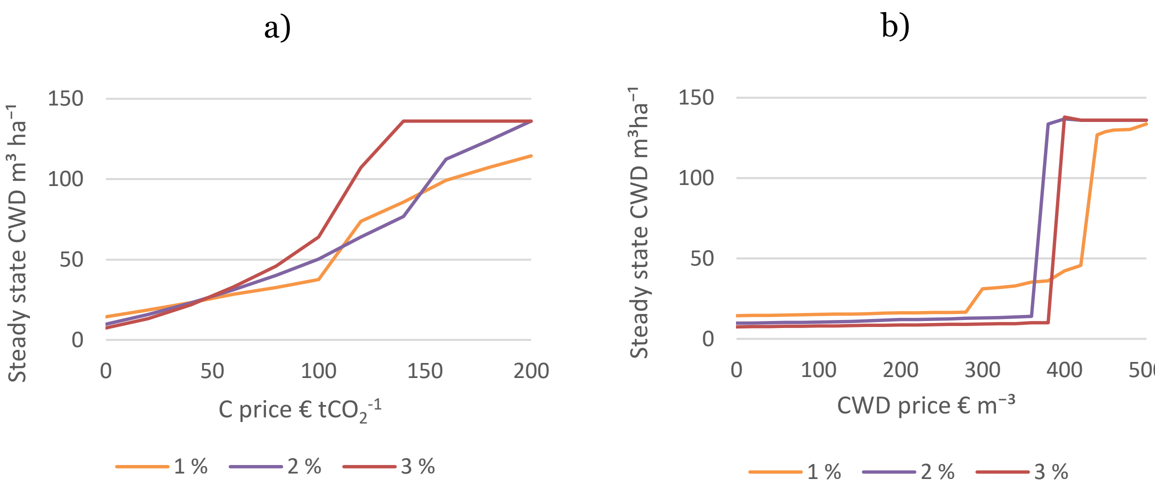

Figure 5. Mean steady-state CWD amounts with different (a) C and (b) CWD prices and different interest rates.

Table 6 presents the steady-state mean CWD, discounted CWD, maximum CWD peaks, and the proportions of CWD with DBH between 20 and 40 cm and over 40 cm DBH. While the steady-state CWD provides ecological insights, the discounted CWD is useful for comparing the results of the optimization. The CWD can peak at ~200 m^3 ha^{-1} under several management scenarios, both with, and without timber production. The no harvest scenario results in a steady-state CWD of ~136 m^3 ha^{-1}, which can be surpassed, as seen in the case with a CWD price of €400. Discounting the CWD leads to higher values at lower interest rates.

Overall, the proportion of large-diameter CWD is high. With a social price on C, a gradual shift towards a management focused on growing large timber and maintaining high wood stocks starts at low social prices. This results in an immediate increase in CWD both over 20 cm and 40 cm in diameter. In contrast, a social price on CWD causes a more abrupt shift towards forests emphasizing large-size timber and increased mortality for CWD production. Figure 5 illustrates this sudden effect on CWD amounts when a social price is placed on CWD instead of C. The highest steady-state mean CWD amount occurs at 3 % interest rate and a CWD price of €400.

6.3 Optimal solution carbon sinks and stocks

Figure 6 shows that, without a social price placed on C, higher interest rates lead to shorter harvest intervals and smaller fluctuations in the annual net C sink. Despite this, the overall annual sinks are quite close to each other. The no-harvest scenario provides a higher short-term sink effect. However, over the long term, the steady-state sinks naturally converge towards zero, whether the forest is managed or not.

In general, without a price on CO_2 or CWD, a higher interest rate intensifies harvesting, leading to lower wood- and C stocks (Table 7). However, as the social price on C increases, the initial trend with decreased C storage is reversed, and the management is shifted towards increasing C sinks, and thus storage increases too. A higher interest rate will shift the management towards increasing C sinks sooner. Interestingly, in the optimal solutions found in this thesis, the highest C storage at 3 % interest rate is lower compared to the highest C storage at 1 % interest rate (Table 7). The fact that this occurs is due to higher interest rates and high enough C prices promoting no management scenarios, while under high C prices and low interest rates, the long rotations with few thinnings is found to be a more effective way to increase discounted C sinks.

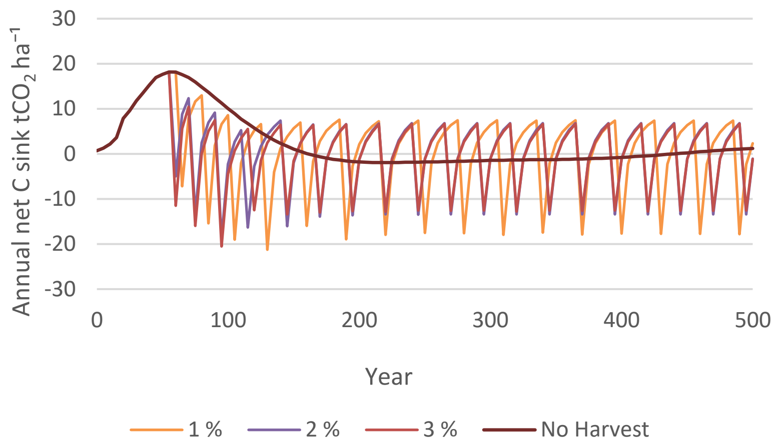

Figure 6. Annual net C sink under different interest rates and no harvest scenario.

Table 7. C storage metrics including soil, products, trees, and the total, alongside the discounted net C sink.

CWD price, € m^{-3}	C price, € tCO_2^{-1}	C in soil, tC ha^{-1}	C in products, tC ha^{-1}	C in trees, tC ha^{-1}	C in total, tC ha^{-1}	Discounted net C sink, tCO_2 ha^{-1}
No harv	No Harv	234	0	143	377	740
	20	158 / 134	26 / 25	80 / 64	264 / 222	518 / 209
	40	174 / 170	26 / 26	92 / 89	292 / 285	564 / 232
	60	186 / 195	25 / 24	102 / 109	313 / 328	596 / 247
	80	193 / 209	24 / 20	108 / 123	326 / 352	629 / 257
	100	201 / 218	23 / 14	115 / 133	338 / 365	658 / 262
	120	239 / 229	18 / 6	138 / 141	395 / 375	687 / 263
	140	246 / 234	15 / 0	145 / 143	406 / 377	705 / 264
	160	253 / 234	13 / 0	148 / 143	414 / 377	716 / 264
	180	257 / 234	11 / 0	151 / 143	419 / 377	724 / 264
	200	259 / 234	10 / 0	154 / 143	423 / 377	729 / 264
0	0	138 / 93	25 / 20	67 / 40	230 / 153	463 / 181
40		140 / 96	25 / 20	68 / 41	233 / 157	473 / 183
100		142 / 98	25 / 20	70 / 42	237 / 161	480 / 185
200		147 / 102	26 / 21	73 / 45	246 / 168	499 / 194
300		177 / 108	27 / 22	86 / 48	294 / 179	525 / 204
360		186 / 112	27 / 22	94 / 51	306 / 185	548 / 216
380		187 / 112	27 / 22	95 / 51	309 / 185	552 / 221
400		194 / 267	26 / 6	98 / 159	318 / 431	565 / 263
420		199 / 234	25 / 0	103 / 143	328 / 377	579 / 264
440		267 / 234	10 / 0	156 / 143	432 / 377	725 / 264
500		267 / 234	8 / 0	156 / 143	431 / 377	734 / 264

Note: The discount rate of the first number is 1% and the discount rate of the second number is 3%. CWD = Coarse woody debris

Further, Table 7 shows that the total C storage is highest with a low interest rate and a CWD price over €440. With a CO_2 price of €200, the C storage comes close to that. The results also show that soil C is the largest part of the total C stock. The C in living trees is the second highest C stock and C in products holds only a minor part of the total C stock. While the no harvest scenario sacrifices product C storage it manages to produce the highest discounted C sink. A no harvest scenario leads to the highest percentage of C stored in trees, and therefore also a substantial discounted net C sink.

Optimized solutions balance C storage across soil, products, and trees. Higher CO_2 prices lead to more trees, and less harvesting, allowing the stand to store more C. As the price of CO_2 increases, the value of maintaining forest C sinks becomes greater, leading to solutions where the forest's ability to act as a C sink improves, demonstrated by the higher discounted net C sink at higher CO_2 prices. However, at higher interest rates this effect diminishes. Higher interest rates favour more frequent harvests, reducing the ability of forests to act as C sinks and store C. The shorter harvest intervals which come with higher interest rate limit the growth of trees, leading to less biomass for C sequestration and a diminished overall C sink and storage. In contrast, with 1% interest rate, the system favours longer rotations, allowing increased C sequestration by trees. Putting a price on CWD on the other hand incentivizes the accumulation of CWD, which slightly increases the soil C stocks as the CWD accumulation C into soil.

Figure 7 shows the C stock with selected C and CWD prices and different interest rates. As the interest rate is increased, higher C prices make the solution converge towards the no harvest scenario and the C stock increases. However, with a low interest rate and a high social price on C or CWD, optimal management with long rotations produces even higher C stocks compared to the no harvest solution. Raising the interest rate in the CWD price scenarios lead to solutions where timber harvest is emphasized more strongly, which can be seen in lower C storages. With a high enough social price on CWD the optimal solutions inducing natural mortality will however also lead to increased C sinks and high C stocks.

In summary, high forest C sinks, and stocks are favoured by a combination of low interest rates, moderate to high C prices or high CWD prices, and policies that incentivize conservation of wood over frequent harvests. Product C then plays a relatively small role in C stocks, while managing forests for long-term storage in trees and soil provides the greatest potential for C sinks, particularly when C prices rise beyond €120, or CWD prices reach beyond €440/400, which also enables the total C stock to reach beyond that of the no harvest scenario.

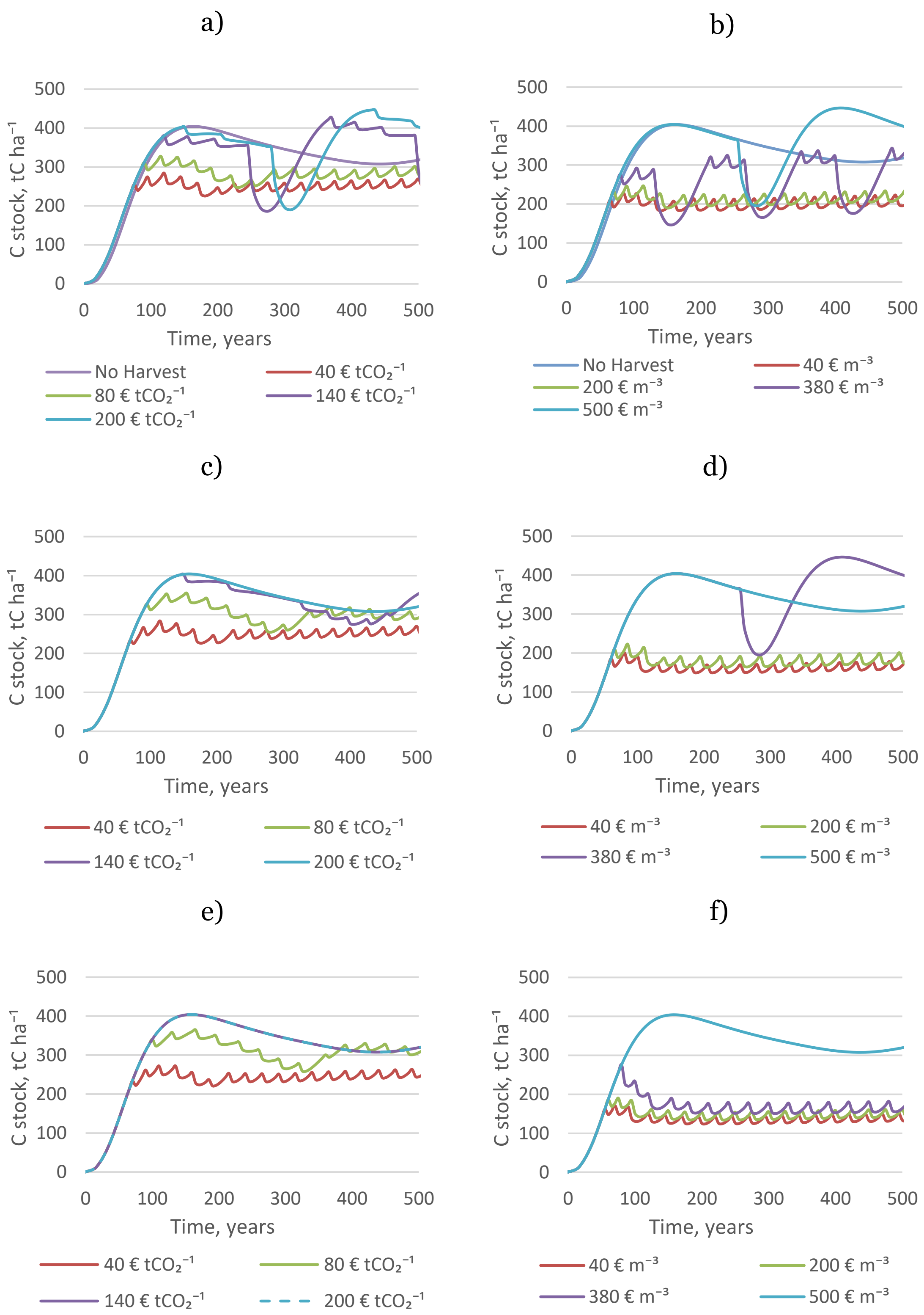

Figure 7. C stocks under selected C and CWD prices and different interest rates. In (a), (c), and (e), the social price on C and interest rates are 1%, 2%, and 3%, respectively. In (b), (d), and (f), the social price on CWD and interest rates are 1%, 2%, and 3%, respectively.

6.4 Costs of increasing carbon and coarse woody debris

Figures 8 and 9 shows the loss in wood production BLV per additional unit of discounted m^3 CWD or tCO_2, when a social price is placed on C or CWD. The unit costs are calculated as wood production BLV change divided by additional units of discounted CO_2 or CWD. In Figure 8 we see that the dynamics are similar both under 1% and 3% interest rates. Since the discounted value of combined wood production and CWD increase is maximized with a social price on CWD, the unit price will naturally be lower than with a social price placed on C. This can be seen especially with a moderate or large increase in CWD. However, as the increase in CWD moves towards its maximum, this difference tends to disappear. This is particularly seen in the 3 % interest rate scenario, and can be explained by the management shifting towards keeping the forest solely as a stock for C or CWD, with no harvests performed. This renders the CWD increase and loss in wood production value similar regardless of placement of social price. The discrepancy at the beginning of Figure 8b, where the CWD unit cost under CWD pricing exceeds that under C pricing, is due to the gap of data points with a social price placed on C, drawing a straight line instead of a curve.

In Figure 9 the unit costs per discounted CO_2 unit is shown. Here the trend is reversed compared to the case of CWD increase, with a social price placed on CWD giving higher unit prices per increase in CO_2 tonne. The explanation is the same, maximizing the joint discounted value of wood production and C sinks favours a social price on C. Interestingly, the overall difference between the two social pricing scenarios tends to be moderate, especially at 3% interest rate. Also, at 1% interest rate with low increase in C sinks, the management under a social price on CWD tend to be close to optimal in terms of C sink increase. This suggests an ecological connection between these two management scenarios.

In Figure 10, the costs of increasing steady-state C storage are shown as a loss of total BLV wood production value. At 1% interest rate, the results under a social price placed on CWD are quite close to those with a social price placed on C. However, at 3% interest rate, the costs are significantly lower when the social price is placed on C.

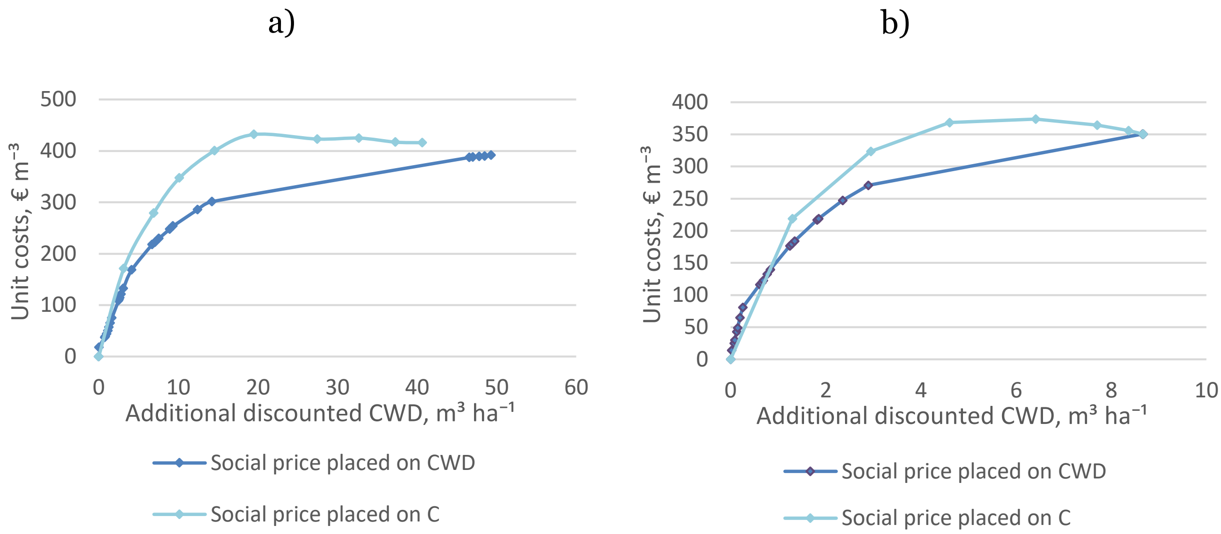

Figure 8. Costs of an increasing CWD amount with a social price placed on CWD or C and under (a) 1% and (b) 3 % interest rate.

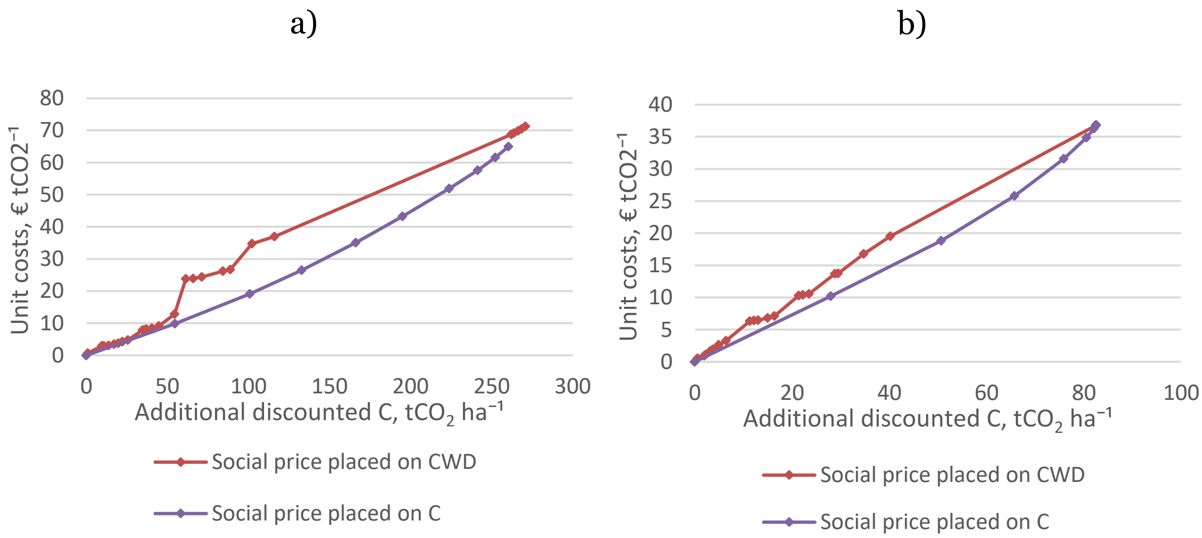

Figure 9. Costs of an increasing C sink with a social price placed on CWD or C and under (a) 1% and (b) 3 % interest rate.

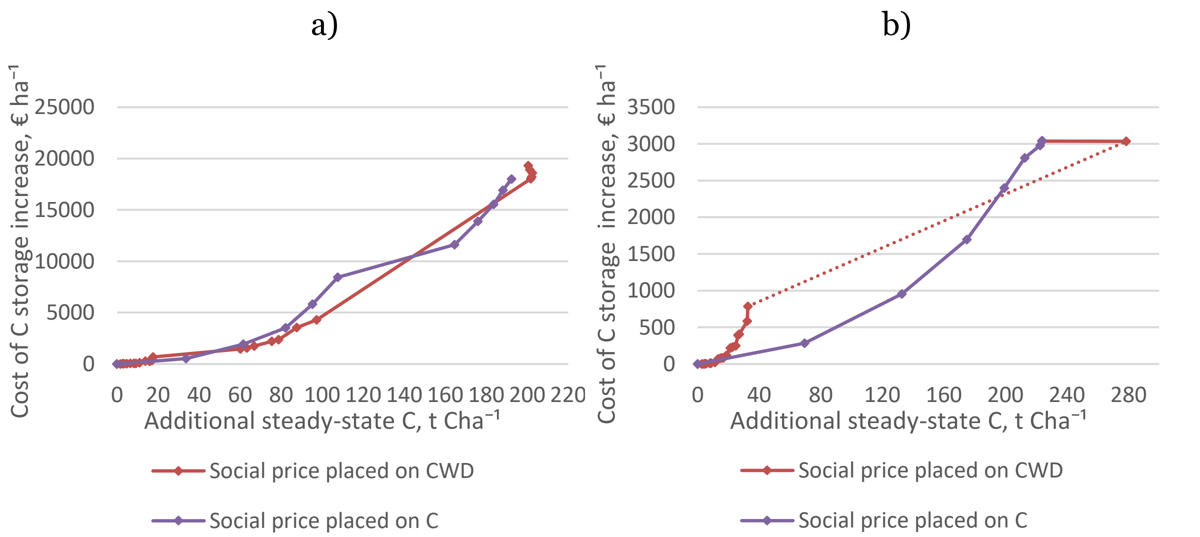

Figure 10. Costs of an increasing steady-state C storage with a social price placed on CWD or C and under (a) 1% and (b) 3 % interest rate.

The slight turn at the end of the red curve in Figure 10a, which becomes more pronounced in Figure 10b, reflects a shift in management strategies. The management under a high social price on CWD changes into one which is less effective in increasing steady-state C stock. The dotted line in Figure 10b illustrates a discontinuity, where no optimal management alternatives were found when balancing the value of CWD and wood production. The discontinuity arises when the CWD price rise from €390 to €391, and the management shifts from CCF with 30 years intervals to focusing on CWD production. This shift causes a major jump the C storage.

Although maximizing steady-state C stocks is not the objective of the optimization, managing for an increase in discounted CWD amounts or C sequestration also results in higher C stocks. Figures 8-10 all carry traits of this ecological connection between CWD and C services, as management strategies to increase one, inevitably increase the others.

6.5 Costs of achieving coarse woody debris thresholds

Ecological CWD thresholds of 20, 40, and 100 $m^3\ ha^{-1}$ can be achieved with sufficient social price on C or CWD under all examined interest rates (Figure 11). However, the costs increase with higher CWD demands. Figure 11 illustrates the costs of increasing steady-state CWD as the decrease in BLV of wood production. The costs are presented for both social prices on C and CWD, at interest rates of 1% and 3%, with the thresholds represented by vertical green (20 $m^3\ ha^{-1}$), yellow (40 $m^3\ ha^{-1}$), and orange (100 $m^3\ ha^{-1}$) lines. The striped, red line shows the maximized timber production achieved with no social prices.

The results in Figure 11 illustrate the costs of achieving steady-state ecological thresholds under 1% and 3% interest rates. At low interest rates (1%), achieving the ecological CWD thresholds is more cost-effective when a social price is placed on CWD rather than on C.

At 1 % interest, all the thresholds can be achieved without fully losing the timber revenues, illustrated by the red dotted line. However, at 3% interest, only 20 $m^3\ ha^{-1}$ can be reached without NPV of wood production turning negative, and placing a social price on CWD fails to meet the thresholds while producing any considerable amount of timber.

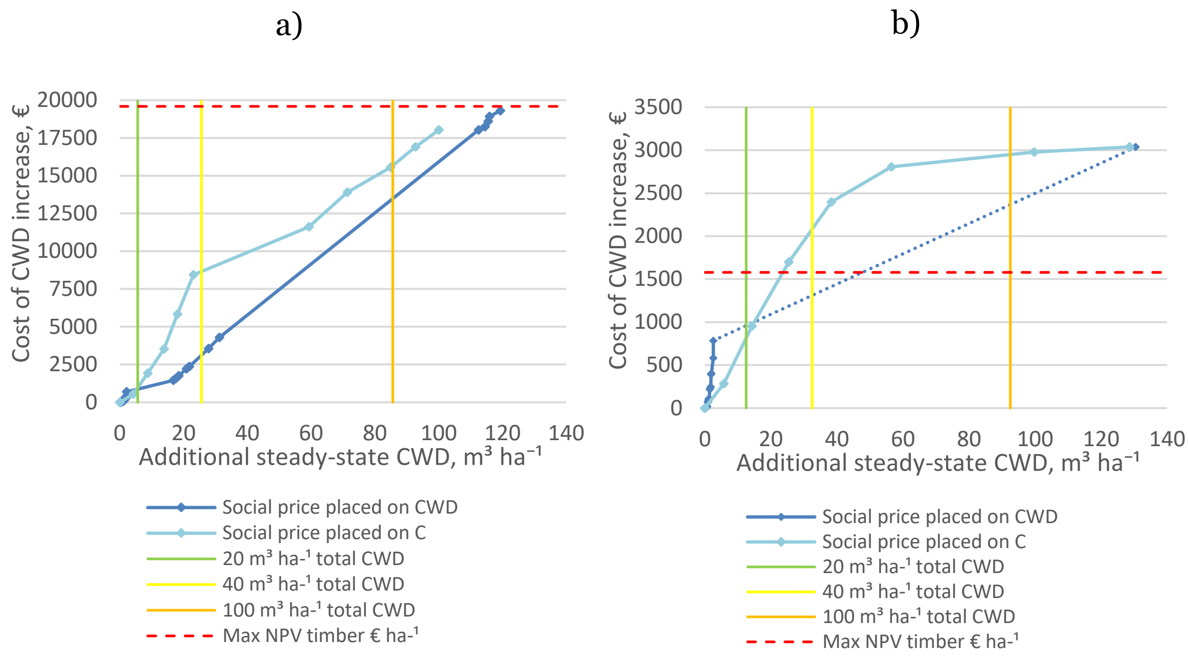

Figure 11. Costs of achieving steady-state CWD thresholds at (a) r=1% and (b) r=3%.

At 1% interest, there is greater variation in optimal management strategies which maximizes the joint value of discounted wood production and CWD (Figure 4b). This results in the smoother and more gradual cost curve for steady-state CWD seen in Figure 11a. In contrast, at 3% interest, even though raising CWD prices does cause an initial increase in CWD, the long-term equilibrium levels of CWD remain low (Figure 4f). These levels show little variation across price points unless the price is high enough to trigger a significant shift in management practices. This dynamic is seen in Figure 11b as a steep rise in the cost while barely increasing CWD under a social price for CWD at 3% interest, followed by a large jump in the data points. Similarly to Figure 10b, the dotted line in Figure 11b, does therefore not correspond to any actual management alternatives found in the optimization. This can occur because the objective is not to maximize steady-state CWD or C stocks.

For the 20 m^3 ha^{-1} threshold, the costs at 1% interest rate are modest and management remains close to baseline regimes. As thresholds increase to 40 and 100 m^3 ha^{-1}, the costs rise notably, as bigger changes in management strategies are required. However, the results still indicate, that the 20 m^3 ha^{-1} thresholds can be reached with less than 10 % reduction in wood production BLV and 40 m^3 ha^{-1} with less than 20 % (Figure 11a).

Table 8 shows the dynamics between steady-state CWD, mean annual steady state timber revenues, total BLV and BLV of wood production, as well as the management strategies leading to these outcomes. In general, the BLV differences reflects the model's optimization focus. Under C pricing, the value of wood production and CO_2 sink is maximized, with higher C prices further rewarding sequestration options. In contrast, CWD pricing targets wood production and CWD increase, which slightly limits the economic potential, since the number of trees dying from natural mortality is low in comparison to C sinks by living biomass.

Table 8 shows that although the discounted timber production value decreases, average steady-state timber revenues may still rise with management shifts. This is due to the aim of maximizing net timber income, along with CWD or C services. This can lead to an increase in average harvest DBH and even yield (Table 4). Larger DBH suggests less wood is harvested as pulpwood, and more as valuable sawlogs.

Table 8. Optimal management, steady-state CWD increase, BLV of timber production and total BLV under different C and CWD prices at (1%/3%) interest rates.

CWD price, € m^{-3}	C price, € tCO_2^{-1}	Optimal management	Steady-state CWD, m^3 ha^{-1}	Steady-state mean annual timber revenues, € ha^{-1} a^{-1}	BLV of timber production, € ha^{-1}	BLV total, € ha^{-1}
No harv	No Harv	-	136,1	0	-1555	-1555
	20	CCF_{25-30} / CCF_{25}	18,6 / 13,3	302 / 285	19052 / 1294	29412 / 5472
	40	CCF_{25} / CCF_{25}	23,1 / 21,8	299 / 304	17662 / 625	40229 / 9891
	60	CCF_{30} / CCF_{30}	28,4 / 33,0	291 / 272	16072 / -118	51838 / 14688
	80	CCF_{30} / CCF_{30}	32,5 / 45,9	275 / 225	13764 / -818	64122 / 19736
	100	CCF_{30} / CCF_{35}	37,6 / 64,1	257 / 163	11162 / -1230	77000 / 24923
	120	$RFth_{240}$ / CCF_{mix}	73,7 / 107,3	210 / 62	7972 / -1398	90439 / 30171
	140	$RFth_{250}$ / NoHarv	85,8 / 136,1	176 / 0	5692 / -1459	104359 / 35437
	160	$RFth_{250}$ / NoHarv	99,3 / 136,1	150 / 0	4041 / -1459	118551 / 40708
	180	$RFth_{250}$ / NoHarv	107,2 / 136,1	125 / 0	2683 / -1459	132942 / 45978
	200	$RFth_{280}$ / NoHarv	114,5 / 136,1	109 / 0	1570 / -1459	147447 / 51249
0	0	CCF_{30} / CCF_{25}	14,4 / 7,5	293 / 226	19590 / 1579	19590 / 1579
40		CCF_{30} / CCF_{25}	14,7 / 7,7	294 / 228	19562 / 1577	20097 / 1753
100		CCF_{30} / CCF_{25}	15,1 / 8,0	294 / 233	19532 / 1572	20908 / 1929
200		CCF_{30} / CCF_{25}	16,3 / 8,5	299 / 241	19305 / 1494	22339 / 2497
300		$RFth_{130}$ / CCF_{25}	31,2 / 9,2	310 / 253	18131 / 1331	23923 / 3032
360		$RFth_{140}$ / CCF_{30}	35,3 / 10,0	319 / 260	17381 / 996	25129 / 3402
380		$RFth_{140}$ / CCF_{30}	36,2 / 10,0	319 / 260	17222 / 794	25560 / 3539
400		$RFth_{130}$ / RF_{300}	42,2 / 138,0	297 / 68	16036 / -1456	26054 / 3737
420		$RFth_{140}$ / NoHarv	45,6 / 136,1	303 / 0	15299 / -1459	26575 / 3997
440		RF_{230} / NoHarv	126,9 / 136,1	108 / 0	1560 / -1459	27599 / 4257
500		RF_{250} / NoHarv	133,7 / 136,1	90 / 0	288 / -1459	31240 / 5036

Note: The discount rate of the first number is 1% and the discount rate of the second number is 3%. CWD = Coarse woody debris, BLV = Bare land value

6.5.1 Achieving the 20 m^3 ha^{-1} coarse woody debris threshold

Under a social price on C, the threshold of 20 m^3 ha^{-1} will be reached at a C price of €40 under both 1% and 3% interest rate (Figure 11, Table 8). At a 1% interest rate, the management transitions from the baseline optimal solution with no harvest, which is CCF with 30-year harvest intervals, to CCF with a 25-year interval (Table 8). The loss of wood production value is relatively modest at €1 928 (approximately 10 % of the baseline solution). At 3 % interest rate, however, the decline in BLV of wood production grows more significant, exceeding 60 % of the baseline solution. The management regime remains CCF with a 25-year harvesting interval (Table 8).

When a social price instead is placed on CWD, the trend is slightly different. At a 1% interest rate, only a price of €300 and a shift to RF with thinnings breaks the 20 m^3 ha^{-1} threshold (Figure 11, Table 8). The decrease in the value of wood production is however smaller, at €1459 or 7,4 % of the baseline optimum. Table 8 also shows that, at 3 % interest rate, the required CWD price rises to €400, with a shift to RF without thinning and a 300-year rotation, leading to a negative value of wood production due to initial costs of soil preparation and planting. However, this management alternative makes the CWD amount exceed the threshold of 100 m^3 ha^{-1}.

6.5.2 Achieving the 40 m^3 ha^{-1} coarse woody debris threshold

Reaching the 40 m^3 ha^{-1} CWD threshold with a social price on C requires significantly higher costs than achieving 20 m^3 ha^{-1} (Figure 11, Table 8). At a 1% interest rate, this threshold shifts the management regime from CCF to RF with a 240-year clear-cut interval and three thinnings. The decline in wood production value is significant, at nearly 60% of baseline BLV (Table 8). At a 3% interest rate, the management remains CCF with 30-year intervals, but the wood production value turns negative. However, the total BLV increases over tenfold compared to the baseline (Table 8).

Table 8 also show that, when applying a social price on CWD, a 1% interest rate and a price of €400 achieves the 40 m^3 ha^{-1} threshold. This results in a roughly 18% decrease in wood production value and leads to a shift from CCF to RF with 130-year rotation length and one thinning. Interestingly the timber yield increases despite the loss in discounted wood production revenues.

6.5.3 Achieving the 100 m^3 ha^{-1} coarse woody debris threshold

Achieving a threshold of 100 m^3 ha^{-1} can be seen as an extreme scenario, mimicking natural old-growth forests. This state can be reached by halting timber harvests completely. However, according to the results in this thesis, it is possible to achieve this amount of CWD while also producing small amounts of timber (Table 8). Table 8 shows, that at a 1% interest rate and a C price of €180, the threshold is exceeded with an 86% reduction in wood production BLV. At a 3% interest rate, a C price of €120 reaches the same CWD level, but the wood production value becomes negative. With a social price on CWD, the 100m^3 ha^{-1} marker is met at a price of €440 under a 1% interest rate, causing a 92% reduction in wood production BLV.

These results highlight a clear trade-off between wood production and increasing CWD levels. Moderate social prices for C and CWD allow simultaneous increase in timber yields and CWD amounts, but higher prices will shift the focus towards prioritizing C sinks and CWD increase. In these scenarios CWD amounts are increased, either on purpose, or as a by-product of managing for increased C sinks. In both cases however, the BLV of wood production decreases. Despite reduced wood production revenues, the total BLV increases significantly with higher social prices (Table 8).

7 Discussion

The aim of this study is to investigate how placing social prices on C and CWD affects forest management, CWD levels, C sinks and storages, as well as economic outcomes when maximizing the combined value of wood production and C sinks or CWD. This includes examining the costs of increasing C and CWD to better understand the trade-offs between C, CWD, and wood production. The goal is to support the integration of these essential ES into forest management policies and practices.

Placing a social price on C will significantly affect optimal forest management. Raising C prices encourage a shift towards management which maximizes C sinks by extending rotation lengths and reducing harvesting, thereby increasing the wood stock. For example, at a 1% interest rate and C prices up to €100, CCF becomes optimal. At higher prices (up to €200), RF with rotations over 200 years and few thinnings are preferred. At higher interest rates, CCF remains optimal until C prices rise to the point where no harvests are performed, and management shifts solely to the production of C services. At 3 % interest, this transition occurs at a C price of €140 (Table 3). These findings differ from Assmuth et al. (2018), who did not include soil C and found that low C prices (€0-20) and a 2% interest rate favoured RF, and a higher C price (>€20) or higher interest rate shifted the optimal management to CCF. Parkatti et al. (2023), expanded the model by Assmuth et al. (2018) with soil C and found that raising C prices up to €40 increased rotation lengths or shifted management from CCF to RF depending on interest rate. In this thesis, using an optimization set-up based on Tahvonen et al. (2024) with the addition of a CWD component, the results show that increasing C prices lead to a shift towards RF, similar to Parkatti et al. (2023) but at higher price points. This is also consistent with Tahvonen et al. (2024), which also found higher C prices to result in shifts towards RF or managing solely for C with higher C prices.

As the social price on C increases, management increasingly focuses on maximizing C sinks, which also raises C stocks and CWD levels. Extended rotations and increased wood stocks enable greater C sequestration. Placing a social price on CWD leads to similar trends but differs in that the overall wood stock is kept lower compared to the C price scenario. Management strategies aimed at promoting CWD through natural tree mortality leads to a larger proportion of C being allocated to soil compared to placing social price on C. This demonstrates the ecological link between CWD and soil C. This difference becomes even more pronounced with higher interest rates. Higher interest rates and social price on C tend to favour a gradual increase in wood-stock and decline in yields, whereas a social price on CWD favours wood production more strongly, until a distinct threshold price is reached to shift the management completely.

Previous studies (e.g. Mönkkönen et al. 2014; Rämö et al., 2020; Yáñez et al., 2021; Eyvindson et al., 2021) have examined trade-offs between wood production and ecosystem services, but, to my knowledge, the direct effects of optimized management on CWD amounts under social pricing of both C and CWD have not been studied. In this study, placing a social price on C results in a steady increase in CWD stock as the C price is increased, with higher interest rates making the increase more pronounced due to the smaller relative cost of reduced wood harvest. In contrast, applying a social price directly to CWD causes some CWD increase at low prices, but only high prices result in a substantial increase. Again, this dynamic is seen more clearly under a higher interest rate (Table 8).

The optimization process reflects a balance between increasing either the CO_2 sink or CWD amounts until the marginal cost of adding more, equals the social price assigned to it. The set-up offers a greater capacity in increasing C sink units, compared to CWD units (Table 6 and 7). This reflects how ecological factors influence economic outcomes, as the availability and flexibility of the target unit (C or CWD) affect the costs. This also gives some insight into one possible development of the optimization set-up. Including stochastic disturbance events with large wood stock loss, equalling CWD increase but temporary C sink loss, could potentially alter the outcome of the optimal management and costs.

The results of this thesis show that although increasing CWD and C services generally reduces wood production, moderate increases in these services are achievable alongside timber production. At a 1% interest rate, CWD levels can reach the biodiversity target of 20 m^3 ha^{-1}, argued as critical for supporting rare species (Junninen & Komonen, 2011; Müller & Bütler, 2010), with less than a 10% reduction in wood production value. This increase in CWD will also enhance C services (Table 7). Achieving this can be accomplished by either implementing CCF with 25-year cycle, or a 130-year RF rotation with two thinnings (Table 8). RF achieves the target with smaller wood production losses and higher timber yields but offers lower benefit in C services (Table 7) and smaller CWD diameter size than the CCF option (Table 6). In both cases however, over 50 % of the CWD will be larger than 20 cm in diameter.

If the interest rate is kept at 1%, a biodiversity target of 40 m^3 ha^{-1} CWD is also achievable while still raising the timber harvests, but at a 18 % loss in BLV of wood production. To achieve 40 m^3 ha^{-1} CWD, the rotation length is kept at 130 years but only one thinning per rotation is carried out. Higher interest rates or higher CWD targets result in more substantial costs and may render a negative wood production value considering the initial investment costs of soil preparation and plantation (Table 8). Under 3% interest rate, the lost value of discounted wood production when achieving the CWD is substantial, rendering the BLV of wood production negative in most cases. However, when evaluating steady-state net revenues from wood production at 3% interest, achieving 20 m^3 ha^{-1} of CWD led to a 35% increase in average steady-state net timber revenues, and achieving 40 m^3 ha^{-1} resulted in no change in mean steady-state net timber revenues (Table 8). These outcomes were achieved with a social price of €40 and €80 for C and require CCF management in a steady-state forest with high BA and DBH of harvested trees (Table 4).

These findings differ from Rämö et al. (2020) who found that achieving 20 to 40 m^3 ha^{-1} CWD to be possible with 17-30% steady-state net timber revenue loss at a 3% interest rate. Rämö et al. (2020) acknowledged that their model was restricted by fixed harvest intervals, which limits optimization compared to approaches which include flexible harvest timing and management methods, such as the one used in this thesis. They suggested that future studies could explore optimal forest management with biodiversity considerations by jointly optimizing harvest timing and intensity. This difference in the optimization is likely the explanation for the large difference in the results between these two studies. Additionally, their model struggled to produce sufficient CWD amounts. This led them to add the possibility of performing biodiversity fellings, where commercially valuable timber was felled to increased CWD, which may have reduced the average timber revenues further.

This thesis looks at CWD and C as socially valued ES. The findings partially align with Mönkkönen et al. (2014), who suggests that a 5% decrease in discounted economic returns could significantly increase ES. According to the results of this thesis, under lower interest, this holds true. However, at a 3% interest rate (as used in Mönkkönen et al. 2014), a 5 % decrease in wood production BLV results in only a 10-15% increase in CWD and C amounts compared to the baseline optimal solution. It is however important to note that Mönkkönen et al. (2014) used a BAU benchmark scenario, instead of an optimized one, and examined taxon-specific ES, making direct comparisons difficult.

Despite the decline in wood production BLV, the total BLV increases with the inclusion of social prices. Provided that these social prices are regarded as prices for ES, this thesis partially contradicts the findings of Tahvonen et al. (2019), where a higher value of ES was found favouring CCF and increasing rotation lengths. Their study used a transition matrix model for forest growth and based their ES valuation on the Simpson biodiversity index. While the results found in this thesis does favour increasing rotation lengths, higher social prices will eventually shift the management towards RF with increasing harvesting intervals and decreasing thinning intensities, and ultimately cease harvests altogether.

Ranius et al. (2003) demonstrated that CWD amounts can be increased by following Sweden's national FSC guidelines, which aim at balancing economic returns with ecological consideration. Similarly, this thesis suggest that forest owners can increase both C and CWD services to an ecological minimum without substantial losses in wood production revenues, but mostly at lower interest rates. Reaching more substantial increases in CWD, would require some form of valuation mechanisms for these services to maintain or enhance forest economic value.

Tikkanen et al. (2012) found that a no-thinning regime could increase CWD at low cost. This thesis suggests that no-thinning regimes are only optimal when social prices for ES are high enough for wood production to become a secondary revenue source. However, unlike this study, Tikkanen et al. (2012) accounted for the destruction of CWD during logging operations. Hautala et al. (2004) has showed that the impact of logging and soil preparation on CWD can be considerable. Thus, future development of the set-up used in this thesis could include this as a possible improvement for ecological precision.

This thesis also reveals that the trade-offs between CWD and wood production intensifies as CWD levels or C sinks rises. Likewise, it reveals the opposite trend between CWD and C services, where the increase of either, increases the other. This is in line with previous studies such as Díaz-Yáñez et al. (2021) and Eyvindson et al., (2021), who found that maximizing wood production revenues or increasing wood production reduces CWD amounts, and with Triviño et al. (2015) who showed that harvest reductions increase C storage and sinks. The result of this thesis however suggests an opposite pairing compared to Triviño et al. (2015) who found that 5% reduction in NPV harvest revenues under 3 % interest can increase C storage 9% and C sinks 15-23%. This study instead suggests that optimal management leading to a decrease in harvest revenues in general increases C storages more than (discounted) C sinks. The direct comparison is still difficult, as the study by Triviño et al. (2015) refers to C storage as the size of the C pool at a certain point in time, and C sink as the amount annual transfer of C to the forests and considers these C metrics without discounting.

The findings of the C impact of CWD increase seen in this thesis align with more general ecological statements about the importance of CWD in the forest C cycle (Krankina and Harmon, 1995; Hyvönen and Ågren, 2001; Pan et al., 2011; Seibold et al., 2021). This thesis also shows, that in moderation, the possibility to balance both wood production and other ES objectives simultaneously does exist when employing optimal management. Somewhat similar results are also discussed e.g. in Mäkelä et al. (2023), who found that on a national scale, biodiversity could be increased under current harvest intensity through management actions. Their study did however not include optimization of forest management, nor social pricing.

The value of C sinks surpasses that of wood production at CO_2 price of €20-40, depending on the interest rates. For CWD to have similar effect on value, prices need to reach €300-440 (Table 8). Figure 10 shows that the ecological bond between CWD and stored C can enhance steady-state C storages at a low cost when managing forests for increased discounted CWD, particularly at a low interest rate. If the value added through social pricing are interpreted as a potential PES scheme, supporting an increase in either C sinks or CWD could enable forest owners to maintain economic viability while also achieving specific ecological goals. Since CWD and C services are interconnected, directing a PES towards either one, will still increase the other.

Placing a social price on CWD or C results in distinct forest management priorities, focusing either on enhancing CWD amounts or C sinks. Although these priorities differ, the management strategies share similarities, particularly in their trade-offs with timber yield and changes in forest structure. A higher social price on C leads to a gradual and steady increase in BA and tree size, resulting in greater living biomass but reduced timber yields. In contrast, CWD pricing promotes increased natural tree mortality and maintains a lower overall wood stock. At low CWD prices, timber yields can increase slightly alongside a moderate increase in BA and natural mortality. Higher CWD prices further increase BA, reduce timber yields, and promote mortality in the stand. Compared to CWD pricing, C pricing more directly enhances living biomass and C sinks. Including more management possibilities, such as multiple tree species with different wood production values or biodiversity fellings aimed at creating CWD as in Rämö et al. (2020), could possibly alter these outcomes.

To summarize - no prior study has combined CWD and C models to explore the impact of placing a social price on CWD or C. The results found in this thesis reveal that, while placing a social price on CWD or C share some similarities, there are also clear distinctions in managing the forests towards an increase in CWD or C sinks. Overall, although an increase in C sinks and CWD both affect wood production negatively, this study suggests that to some extent, these services can be increased without substantial losses in wood production, especially under low interest rates. Also, CWD and C services can be increased simultaneously without considerable trade-offs, offering additional benefits, when managing for an increase in either one.

Given the insufficient CWD levels in Finnish managed forests to support biodiversity (Hyvärinen et al., 2019), and the LULUCF sector's failure to sustain much needed C sinks (Siljander et al., 2023), this thesis provides some valuable insights. It shows the potential for optimizing forest management to deliver both CWD and C services while also maintaining raw material supply for the forest industry. It gives some insight into both the costs of the wood production decline associated with these ES increases, as well as the potential role of social pricing in support of CWD and C services.

For future studies it is important to acknowledge the limitations of the current set-up which focuses on a single stand of Norway spruce. Expanding the model to include additional tree species with varying economic and ecological value would add a possibility for more management strategies. Further, incorporating natural disturbances, CWD losses during harvesting and climate change projections would improve ecological realism. More intricate process models could potentially allow for integration of other ecosystem services provided by CWD such as moisture retention, mycorrhizal fungi stocks and tree regeneration microsites. The current model could also be improved by differentiating between standing and lying CWD, which has been suggested as an important factor contributing to the rate of decay, especially for conifers (eg. Shorohova and Kapitsa, 2014; Yatskov et al., 2003; Krankina and Harmon, 1995).

Finally, it is good to note, that the optimal solutions without any social price on CWD or C, yields somewhat higher CWD amounts than the current Finnish national average. This can be due to the Bollandsås (2008) ecological model, or suboptimal management in terms of CWD in current Finnish forests – the BAU scenario being RF with relatively short rotations and regular thinnings from below, resulting in low amounts of CWD. Future studies could compare results under a BAU scenario aligned with Finnish national forestry guidelines and explore mixed species stands across various regions.

While scientific understanding of forest ecosystems is constantly developing, actions for improving forests can still be taken based on the best knowledge available. This study advocates for the possibility of multiple use forest management which more strongly balance economic, ecological and social objectives. The thesis also touches upon the potential of policy instruments such as payments for ecosystem services to play a role as tools in achieving more sustainable use of forests. Ultimately, large-scale change requires coordinated efforts from researchers, policymakers, the forests industry, forest owners and society in general. This thesis provides a glimpse into the possibilities of balancing wood production with increased CWD levels and enhanced C sinks.

8 Conclusion

This master's thesis studies the impact of placing social prices on C and CWD on optimal forest management, wood production, forest C dynamics, CWD accumulation and economic outcomes. The findings show that including social prices significantly influences forest management by postponing and reducing harvests, enhancing C sinks and increasing the CWD amounts in the forests. Placing a social price on C results in gradual changes to improve sinks already at low prices, while placing a price on CWD results in more distinct management shifts once a certain price threshold is reached.

Key insights of the thesis reveal that C and CWD services can be increased simultaneously with moderate decrease in wood production value, particularly under low interest rates. At a 1% interest rate, achieving CWD biodiversity targets of 20 m^3 ha^{-1} can be achieved with less than 10 % loss in discounted value of timber production and 40 m^3 ha^{-1} with less than 20 %. The synergy between CWD and C has also been shown, where the increase of one inevitably leads to the increase of the other. This shows the potential of balancing economic and ecological objectives as well as forest climate benefits. However, at higher interest rates or more ambitious CWD targets, the economic viability of wood production has here been shown to suffer. This finding is important for policy making and long-term goals of forest management which include strategies that aim at increasing CWD and C services.

In conclusion, this thesis supports the idea that through thoughtfully designed forest management strategies, Finnish forests can deliver multiple ecosystem services – wood production, C services, and biodiversity conservation – simultaneously. By optimizing management practices, forests can sustain both economic viability and ecological resilience, especially when supported by policy instruments such as payments for ecosystem services. Integrating CWD and C management into forest practices not only improve climate benefits and ecological resilience, but also strengthens the long-term economic potential of these landscapes. Therefore, future forest policies should more strongly encourage a balance between social, economic and environmental goals, promoting a stewardship of truly sustainable forest ecosystems.

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Appendices

Appendix A Decomposition factors

Table A1. Decomposition factors and their influence on decay rates of wood.

Factor	Description	Impact on decay rate	Additional notes	References
Tree Species	Different tree species have different physical, and chemical properties and will host different decomposer communities.	Significant influence: in general conifers decompose slower than deciduous trees. Within species variation is also observed.	Tree species is often considered the primary factor for decomposition rates since it strongly influences both the decomposer communities and decay dynamics in general.	Edelmann et al. (2023); Shorohova and Kapitsa (2014); Stokland et al. (2012); Yatskov et al. (2003); Tarasov and Birdsey (2001); Harmon et al. (2000); Krankina and Harmon (1995)
Moisture	Crucial for decomposer activity. An optimal range of moisture for microbial activity can be found; insufficient or excessive moisture can inhibit decomposers.	Non-linear relationship with decay rates; moderate moisture levels promote highest decomposition rates.	Higher moisture content facilitates microbial activity, but excess moisture can create low oxygen environments inhibiting decomposition. If the general site conditions provide moisture, precipitation might not affect decay rates further.	Brischke and Rapp (2008); Shorohova and Kapitsa (2014); Pearson et al. (2017)

Temperature	Directly affects microbial activity; has a non-linear relationship with decay rates. The importance varies depending on scale.	Crucial factor globally. Temperature range is sometimes more significant than mean temperature, especially in boreal forests. An optimal range and stable temperatures promote faster decomposition. Small litter types more sensitive.	Higher temperatures generally accelerate decomposition. Above +15°C every 10 °C increase doubles the rate until 40 °C. Extreme temperatures can hinder decay, and freezing temperatures virtually halts it.	Chambers et al. (2000); Hyvönen and Ågren (2001); Yatskov et al. (2003); Mäkinen et al. (2006); Shorohova and Kapitsa (2014); Bradford et al. (2014)
Site Conditions	Influences local climatic factors such as temperature and moisture levels. Nutrient availability also affects decay rates.	Significant influence: site fertility, moisture, and canopy openness affect decomposition rates. Deciduous trees and trees in early decay states suggested to be more sensitive to site conditions.	If there is sufficient moisture, canopy removal may accelerate decay. Site conditions in general interact with climatic factors to influence decay.	Yin (1999); Næsset (1999b); Kruys and Jonsson (2002); Shorohova and Kapitsa (2014); Pearson et al. (2017); Edelmann et al. (2023)

Tree Position	Suggested by some to be the second most important factor after tree species. Tree species may affect tree position dynamics.	Standing trees (snags) generally decay slower than fallen trees (logs) but site-specific variations are observed. Ground contact accelerates decay.	Tree position interacts with moisture and its decomposition dynamics. Snags often decay slower due to lower moisture content and ground contact increases moisture and accelerates decay.	Shorohova and Kapitsa (2014); Holeksa et al., (2008); Mäkinen et al. (2006); Yatskov et al., (2003); Krankina and Harmon (1995); Næsset (1999b)
Diameter	Ambiguous impact. Studies showing all possible outcomes: no impact, larger logs decay faster, smaller logs decay faster.	Smaller logs may decay faster due to higher surface-to-volume ratio while larger logs may decay faster due to increased ground contact.	Impact of diameter on decay rates is complex and varies depending on factors like tree species, position, and site conditions leading to ambiguous findings across studies.	Shorohova and Kapitsa (2014); Zell et al. (2009); Holeksa et al. (2008); Tarasov and Birdsey (2001); Yin (1999); Næsset (1999b); MacMillan (1988); Harmon et al. (1986)
Decay Class	Indicates decay stage of wood. Affects decomposition rates through substrate quality and decomposer community.	Significant influence: wood in advanced decay classes decomposes slower. Change in substrate characteristics affects decomposition rates.	Different species have different decay dynamics, some species have an almost linear decay, while others are best described by a sigmoidal curve, with a slow start, moving into a rapid phase and finishing in a slower phase.	Shorohova and Kapitsa (2014); Tuomi et al. (2009); Mäkinen et al. (2006); Yatskov et al. (2003); Harmon et al. (2000); Næsset (1999b)

Substrate Quality	Chemical composition and physical structure of wood influences microbial activity and decomposition rates.	Rate-controlling factor: substrate quality affects decomposition dynamics at single tree scale. The efficiency of wood-inhabiting fungi depends on substrate quality.	Substrate quality influences microbial activity and decomposition efficiency. This varies with tree species and decay stage.	Edelmann et al. (2023); Shorohova and Kapitsa (2014); Tuomi et al. (2009); Yatskov et al. (2003);
Decomposer Community	Composition and activity of fungi and other decomposer organisms.	Directly affects decomposition rates trough species-specific decomposition strategies. Community is influenced by tree species, moisture, and substrate quality.	Decomposer community composition varies with tree species, site conditions, and substrate quality and influences decomposition efficiency and dynamics.	Edelmann et al. (2023); Stokland et al. (2012); Shorohova and Kapitsa (2014); Siitonen (2021)

Appendix B Stand growth and economic parameters

The function forms and parameters for the individual tree model are given in Bollandsås et al. (2008). For specific parameter values applied, see Tahvonen et al. (2019). After a 20-year artificial regeneration period, the stand includes 1750 trees over 50 size classes (diameters from 5 to 10 cm, at equidistant intervals), with volume growth assumed linear in the first 20 years. The natural regeneration depends on the stand basal area as specified in the original paper by Bollandsås et al. (2008).

The roadside pulp and sawlog prices are p_1= €38.55 m³, p_2 = €69.07 m³, and the revenue at period t is

$$R_t = \sum_{q=1}^{m} \sum_{q=1}^{n} (p_p v_p(d_{q,w,t}) + p_s v_s(d_{q,w,t})) h_{q,w,t}$$

where $h_{q,w,t} \equiv x_{q,w,t}$ for clear-cut and $h_{q,w,t} \in (0, x_{q,t,w})$ for thinning for all q = 1, ..., m and w = 1, ..., n. The functions v_p and v_s give pulp and sawlog volume yields corresponding to tree diameters using linear interpolation between values given in Table B1

Table B1. Commercial sawlog and pulpwood volumes for spruce.

DBH (cm)	Pulpwood (m^3)	Sawlog (m^3)
6.5	0	0
7.5	0.01374	0
12.5	0.06664	0
17.5	0.16690	0
22.5	0.08080	0.23419
27.5	0.06482	0.44578
32.5	0.05975	0.68392
37.5	0.04978	0.96304
42.5	0.05039	1.25313
47.5	0.04324	1.57421
52.5	0.03925	1.89981
57.5	0.03317	2.21442

Note: DBH = tree diameter at breast height. Volumes are estimated by linear interpolation, based on values in Heinonen (1994).

The costs for harvesting include a fixed cost $C_f = €500\ ha^{-1}$ covering planning and equipment transportation and variable costs which are based on tree volume and depend on thinning and clear-cut, with functions as follows:

$$C_{j,t} = \xi_{j0}\xi_{j1}\sum_{q=1}^{m}\sum_{w=1}^{n} h_{q,w,t}\left(\xi_{j2} + \xi_{j3}v_{q,w,t} + \xi_{j4}v_{q,w,t}^{2}\right) +$$
$$\xi_{j5}(\xi_{j6}\sum_{q=1}^{m}\sum_{w=1}^{n} h_{q,w,t}v_{q,w,t} + \xi_{j7}(\sum_{q=1}^{m}\sum_{w=1}^{n} h_{q,w,t}v_{q,w,t})^{0.7})$$

Where $j \in \{th, cl\}$ denotes thinning or clear-cut,$v_{q,w,t} = v_s\left(d_{q,w,t}\right) + v_p(d_{q,t,w})$ is the commercial stem volume of a tree with diameter $d_{q,w,t}$, and parameters ξ_{ji} are found in Table B2.

Table B2. Parameters for thinning and clear-cut variable costs.

j	ξ_{j0}	ξ_{j1}	ξ_{j2}	ξ_{j3}	ξ_{j4}	ξ_{j5}	ξ_{j6}	ξ_{j7}
th	1.620	1.150	0.412	0.758	-0.180	1.150	2.272	0.535
cl	1.620	1.000	0.412	0.758	-0.180	1.150	1.376	0.393

Note: Parameters are based on Nurminen et al. (2006) and Tahvonen and Rämö (2016). *th = thinning. cl = clear-cut.*

The costs for artificial regeneration are €1555, €1504, and €1459 for interest rates 1%, 2%, and 3%, respectively.

Appendix C Net present value of coarse woody debris

Table C1. Net present value for a unit of Norway spruce CWD in the model.

Norway Spruce $P(r)$ values			
Diameter	1% interest rate	2% interest rate	3% interest rate
10 cm	0.3452836	0.5558150	0.6863544
15 cm	0.3595065	0.5746689	0.7056582
20 cm	0.3734269	0.5927803	0.7238802
25 cm	0.3870082	0.6101265	0.7410319
30 cm	0.4002601	0.6267355	0.7571654
35 cm	0.4131978	0.6426411	0.7723367
40 cm	0.4257870	0.6578274	0.7865637
45 cm	0.4380651	0.6723508	0.7999181
50 cm	0.4499977	0.6861972	0.8124184
55 cm	0.4616076	0.6994079	0.8241233

Note: The diameter of an arbitrary size CWD unit is found by linear interpolation.