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ORIGINAL PAPER

Nordic forest management towards climate change mitigation: time dynamic temperature change impacts of wood product systems including substitution effects

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Abstract
Climate change mitigation trade-offs between increasing harvests to exploit substitution effects versus accumulating forest carbon sequestration complicate recommendations for climate beneficial forest management. Here, a time dynamic assessment ascertains climate change mitigation potential from different rotation forest management alternatives across three Swedish regions integrating the forest decision support system Heureka RegWise with a wood product model using life cycle assessment data. The objective is to increase understanding on the climate effects of varying the forest management. Across all regions, prolonging rotations by 20% leads on average to the largest additional net climate benefit until 2050 in both, saved emissions and temperature cooling, while decreasing harvests by 20% leads to the cumulatively largest net climate benefits past 2050. In contrast, increasing harvests or decreasing the rotation period accordingly provokes temporally alternating net emissions, or slight net emission, respectively, regardless of a changing market displacement factor. However, future forest calamities might compromise potential additional temperature cooling from forests, while substitution effects, despite probable prospective decreases, require additional thorough and time explicit assessments, to provide more robust policy consultation.

Keywords Forest management · Climate effects · Forest-based bioeconomy · Sweden · Substitution effects

Introduction

The forest-based bioeconomy of the European Union (EU) is considered a key part of climate change mitigation strategies both by increasing carbon stocks in forests via carbon dioxide (CO_2) sequestration and in harvested wood products (HWP), and by using wood to substitute more greenhouse gas (GHG) intensive materials and energy sources (EC 2021). However, increasing HWP carbon pools and enhancing wood-based substitution through increased wood harvests conflicts with increased forest carbon sequestration.

This highlights the strongly debated trade-off between increasing forest carbon sinks on the one hand and promoting wood substitution on the other (Dugan et al. 2018; Seppälä et al. 2019; Hurmekoski et al. 2020; Jonsson et al. 2021; EC 2021). For assessing this trade-off, an integrative system perspective is thus required to reveal net climate benefits in assessments of forest-based climate change mitigation options.

Within this given trade-off between forest-based carbon sequestrations on the one hand and wood-based substitution and HWP carbon pools on the other lies a strong temporal dimension. Many studies that assess various combinations of increased harvest levels and resulting shifts in the production of HWP commodities conclude that within a short to medium time horizon, the climate benefit from the carbon sink in the productive forest land will exceed additional mitigation from substitution effects and an increased HWP pool

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resulting from increased harvests (Lundmark et al. 2014; Rüter et al. 2016; Matsumoto et al. 2016; Valade et al. 2018; Seppälä et al. 2019; Kalliokoski et al. 2020; Soimakallio et al. 2021; Jonsson et al. 2021; Skytt et al. 2021; Hiltunen et al. 2021; Moreau et al. 2022). If the product portfolio remains stable (i.e. shares among relative HWP distribution keep constant), this conclusion holds also when high substitution effects are assumed (i.e. a displacement factor of < 2.4 Mg C Mg C^{-1}), as mentioned by Seppälä et al. (2019) and Kalliokoski et al. (2020). Within longer time horizons, however (i.e. from minimum 30 years to over 100 years), climate benefits from wood use and associated substitution effects are found to be larger than the net decrease in forest carbon sinks (Lundmark et al. 2014; Skytt et al. 2021; Gustavsson et al. 2021) when assuming static and stable substitution effects over time.

Substitution effects and displacement factors (DFs) vary strongly depending on geographical scope, system boundary, life cycle inventory (LCI) data, and time horizon applied (Brunet-Navarro et al. 2021; Myllyviita et al. 2021). Further, climate change mitigation from wood substitution can be assumed to change in the future, because of, e.g. increased renewable energy use, enhanced production efficiency, or bioenergy and carbon capture and storage (BECCS) (Creutzig et al. 2015). In fact, according to Brunet-Navarro et al. (2021), material substitution effects could decrease by 33% already by 2030, and even by 96% until 2100 when set proportionally to gross anthropogenic CO_2 emission reductions as required to reach the Paris Agreement (Rockström et al. (2017). This stresses expiration of wood product substitution benefits over time.

In Sweden, the forest sector historically plays a key economic role (Lundmark et al. 2013) and is aligned to national environmental quality targets (SME 2019) within the EU's bioeconomy strategy (EC 2018). Swedish forest management is characterized by stable delivery of wood products via extensive long rotation forestry (Eyvindson et al. 2021). Clear-cut harvest and even-aged stand structures dominate the production forest (Egnell and Björheden 2015) with minimum rotations ranging from 45 years in the south to over 100 years in northern Sweden (SME 2019). Over the last century, standing volume, productivity and sustainable harvest levels increased continuously (Lundmark et al. 2013; SFA 2014; Klapwijk et al. 2018; Giuntoli et al. 2020).

However, current Swedish clear-cut forest management is being increasingly debated on its capacity to provide other ecosystem services than wood production, with climate change mitigation at the forefront. The alternatives most frequently put forward to increase the climate benefits of forestry encompass: bioenergy usage of decaying forest residues (tops and branches) (Pukkala 2014; Camia et al. 2021; Eggers et al. 2020), afforestation of set-aside land (Egnell and Björheden 2015), increased harvest rates (Gustavsson et al. 2017), genetically improved seedlings and intensive fertilization (Subramanian et al. 2019; Nilsson et al. 2011), extending rotation periods (Liski et al. 2001; Zanchi et al. 2014; Felton et al. 2017; Eggers et al. 2019; Lundmark et al. 2018; Pingoud et al. 2010), and increased sawlog harvests for augmented long-lived HWP application to substitute emission intense building materials (Churkina et al. 2020; Howard et al. 2021; Dugan et al. 2018; Pingoud et al. 2010).

The effectiveness of different forest-based climate change mitigation alternatives depends largely on the general forest productivity which to a great extent is determined by local climate, soil conditions, and forest characteristics, not the least the age class distribution, i.e. younger forests grow faster than old ones (Petersson et al. 2021). Hence, to more unambiguously analyse climate change mitigation trade-offs between forest carbon storage and increased harvest to promote substitution of GHG intensive non-wood products, regional-level assessments are needed, integrating the interconnected forest eco- and technosystem including the substituted system to avoid conflicting and misleading policy recommendation in order to reach net climate benefits (Smyth et al. 2017; Dugan et al. 2018; EC 2021; Jonsson et al. 2021). In that context, a more nuanced analysis of wood substitution is required to better capture and depict changes in substitution effects following shifts in forest management and ensuing changes in the harvest compositions. Thus, more detailed substitution effect breakdowns are needed in assessments integrating forest eco- and technosystems, to advance over the more aggregated analysis of substitution effects resulting from changed forest management in the studies of, e.g., Cintas et al. (2017), Skytt et al. (2021), or Moreau et al. (2022). The system perspective (EC 2021) further requires inclusion of temporal considerations for which methodological approaches of life cycle assessment (LCA) (ISO 2006a, 2006b) including time dynamic effects (also referred to as time-dependent effects) are appropriate and established methods (Ericsson et al. 2013; Levasseur et al. 2013; Hammar et al. 2019; EC 2021; Hiltunen et al. 2021).

This study provides an integrative time dynamic assessment at regional level, using LCA data to analyse the climate effects of different forest management strategies from a system perspective (EC 2021), to assess the climate change mitigation potential from alternative Swedish rotation forest management. In doing so, the study specifically contributes to the field in (i) deriving detailed substitution effects for an entire HWP portfolio, analysing how these effects change consequential to different forest management regimes and (ii) by advancing common climate assessments of wood product systems given in CO_2 equivalent (CO_2-eq) fluxes into the absolute global temperature change potential (AGTP) that displays climate impacts in terms of temperature change over time (Myhre et al. 2013). By benchmarking

Table 1 Forestry data of all Swedish regions across the North–South climate gradient

Property	Unit	Norrbotten (North)	Värmland (Central/South)	Kronoberg (South)	References
Productive Forest Area	1000 ha	3 930	1 345	666	NFI 2014–2018
Mean Volume (productive land)	m^3 ha^{-1}	110	178	151	NFI 2014–2018
Average Productivity (Bonitet)	m^3 ha^{-1} yr^{-1}	2.5	6.6	9.2	NFI 2014–2018
Average Mean Age	years	76	54	48	NFI 2014–2018
Average Minimum Final Felling Age	years	85	64	58	NFI 2014–2018
Average Final Felling Age	years	116	108	99	NFI 2014–2018
Productive Forest Land for Logging Residue Extraction	%	20	35	45	Adapted from Eggers et al. (2020)

Productive forest land here includes voluntarily and formally set-aside areas

all forest management scenarios to an initial reference forest management across a climate gradient, we seek to increase the understanding as to which, how, and when climate effects of different forest management approaches within a forest-based bioeconomy occur.

Materials and methods

Geographical scope and system boundaries

The study is set in the geographical regions Norrbottens län (67° 08′ 8.98″ N 18° 30′ 3.52″ E), Värmlands län (59° 44′ 59.99″ N 13° 14′ 60.00″ E), and Kronobergs län (56° 14′ 36.06″ N 14° 22′ 51.97″ E) to cover a large latitudinal gradient and thus forest productivity range across Sweden. Table 1 summarizes key information of the initial state of each region, based on Swedish National Forest Inventory (NFI) data from 2014 to 2018. On productive forest land (> 1m^3 ha^{-1} $year^{-1}$), there exist voluntarily and formally set-aside areas which were excluded for the analysis based on statistics from the Swedish Forest Agency (SFA) SFA (2021a) and NFI data. For detailed information on simulated forest characteristics of all regions, including forest age class and species distribution see the Supplementary Material.

The system boundary for each region is shown in Fig. 1. Climate effects are primarily determined by the forest ecosystem, which depends on the forest management strategies

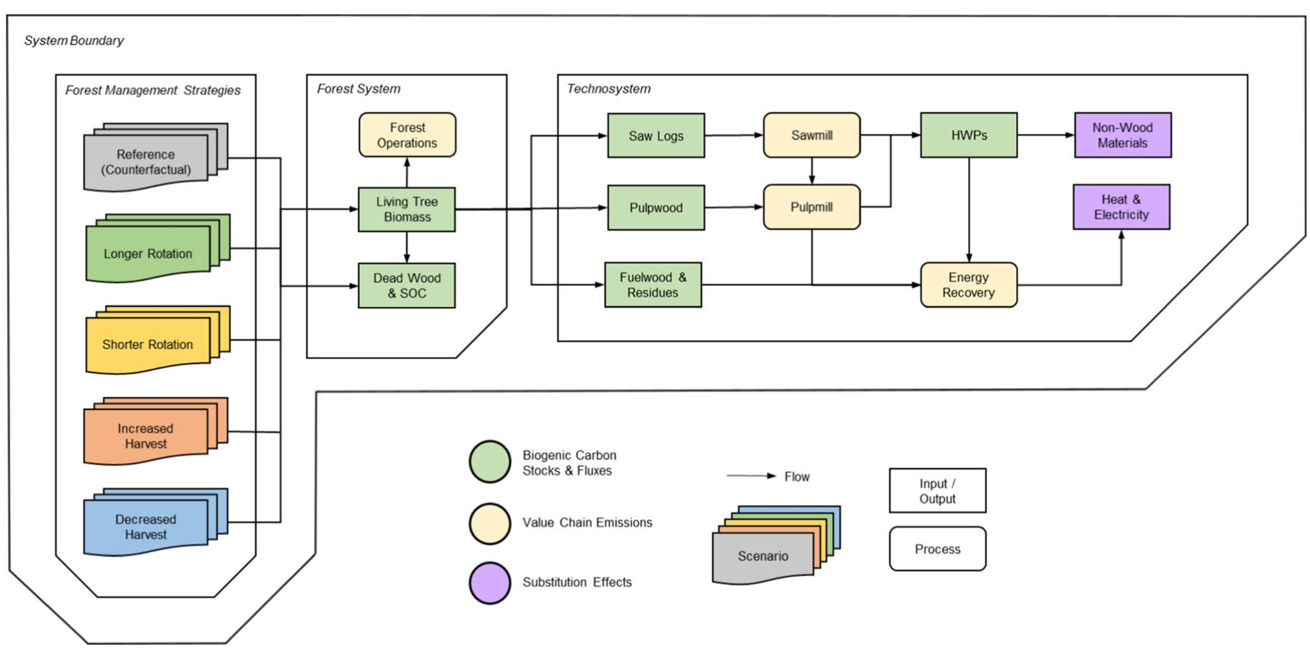


Fig. 1 System boundary for each region including the forest ecosystem and the technosystem influenced by different forest management scenarios. HWP = Harvested Wood Product, SOC = Soil Organic Carbon

and the distribution of biogenic carbon over time ("Section Forest system"). Biogenic carbon from sequestration and decay is allocated between living tree biomass, soil organic carbon (SOC), and dead wood. Forest harvest volumes divide into sawlogs, pulpwood, fuelwood and cullwood (in the following summarized as fuelwood), and harvest residues (branches and tops) which enter the wood product technosystem ("Section Technosystem"). Here, retention, decay and associated biogenic carbon emissions from HWPs are accounted for ("Section HWP portfolio and value chain emissions"). The technosystem comprises processing of harvest volumes into final HWPs in saw and pulp mill facilities, and into energy in a combined heat and power (CHP) plant. Along each wood product value chain, fossil CO_2, methane (CH_4) and nitrous oxide (NO_2) emissions were considered from "cradle to grave" ("Section Substitution effects") and transformed into CO_2-eq using the global warming potential (GWP_{100}) with a 30-fold cumulative radiative forcing of fossil CH_4 and a 265-fold stronger effect of N_2O than that of CO_2 (Myhre et al. 2013). Finally, substitution effects were considered based on a certain HWP portfolio ("Section Climate impact metrics").

Forest system

Forest ecosystem & forestry modelling

The forest management scenarios and biogenic carbon outputs of the forest ecosystem were modelled via the Heureka scenario analysis software RegWise (Wikström et al. 2011) using empirical NFI-based forest data from 2014 to 2018. Heureka RegWise simulates alternative forest management strategies by deterministic models on species-specific forest growth and decay functions, adjustment of silvicultural operations such as final harvest or changing rotation length. Biogenic carbon stocks from living trees (standing biomass) are calculated by biomass expansion factors from the different aboveground compartments of the trees (stem, bark, branches, leaves/needles), and the belowground parts (roots and stumps). SOC is modelled via continuous soil organic matter decomposition by the Q-model that is integrated in Heureka. The carbon stock in dead wood is calculated by additional volume inflow of dead organic matter from tree mortality using an exponential decay rate (Harmon et al. 2000).

Output variables of Heureka simulations for this study were biogenic carbon (Mg C) in standing biomass, dead wood, and SOC, and harvest volumes (m^3) from sawlogs, pulpwood, fuelwood, and logging residues. Harvest volumes and relative distribution among sawlogs, pulpwood, fuelwood, and harvest residues varied depending on the forest age distribution and forest management scenario. Partitioning of sawlog, pulpwood, or fuelwood is predefined in Heureka based on stem diameters greater than 13 cm, 13–5 cm, and smaller than 5 cm, respectively. Values were given in five-year intervals and transformed via interpolation and conversion factors into annual carbon equivalents considering a coniferous softwood density of 415 kg m^{-3} for sawlogs and 400 kg m^{-3} for pulp- and fuelwood, and a dry wood carbon content of 50% (FAO et al. 2020). Given the mass ratio from C to CO_2 of around 1 to 3.67, this equals 732–760 kg CO_2 m^{-3} harvested.

The interpolated and converted values were subsequently used for modelling the technosystem which was kept similar for all regions and forest management scenarios. The time horizon was set to 200 years to include the effects from multiple rotations into the analysis. To assess net impacts on climate change and show additionality, a valid counterfactual "business as usual" (reference) scenario is key to demonstrate how alternative scenarios alter emissions which would have instead occurred (Chomitz 2002). The forest management scenarios for all regions (Table 2) thus include a reference which acted as the counterfactual "business as usual" scenario to prove additionality, and four alternatives: a longer and shorter rotation scenario, and an increased and decreased harvest scenario, to show climate effects from a more and less intensive forestry.

Forest management scenarios

The reference scenario represents recent clear-cut rotation forest management in Sweden as the dominating forest

Table 2 Forest management scenarios on the productive forest land in all regions

Management Practice	Scenarios				
	Reference (Counterfactual)	Longer Rotation	Shorter Rotation	Increased Harvest	Decreased Harvest
Management System	Rotation Forestry				
Harvest Level (% of growth)	83%	83%	83%	100%	66%
Rotation Length (% of min. relative final felling age)	100%	120%	80%	100%	100%
Regeneration	Planting				

management practice in each region. The harvest level amounts to 83% of the growth rate on productive forest land according to the Swedish forest reference level (FRL) (SME 2019). Regeneration under productive forest land occurs via planting, and the rotation length is based on the relative final felling age defined by the Swedish Forestry Act. Thinning is performed according to good practice from the Swedish Forest Agency (SFA 2015). Tree and stump retention after harvest was modelled in accordance with forest certification standards and followed sustainable harvest levels (Jong et al. 2017; SME 2019). Potential final felling area for extracting logging residues was given only under spruce-dominated stands based on the ranging proportions between northern (20%) and southern Sweden (60%) (Eggers et al. 2020). Logging residue extraction comprised 100% tops, 83% of branches, and 38% of needles and was performed only on dry and semi-dry soils, while no stumps were extracted to comply with recommendations from the Swedish Forest Agency (Claesson et al. 2015). Fertilization regimes in Norrland and Värmland amounted to 10,400 ha year^{-1} and to 700 ha year^{-1} in Kronoberg based on average past decade fertilization regimes in Norrland, Svealand, and Götaland, respectively (SFA 2021b).

The longer and shorter rotation scenario was modelled similarly to the reference scenario except for prolonging or curtailing the minimum relative final felling age by ± 20%, respectively. The increased and decreased harvest scenario differed from the reference in terms of an increased or decreased harvest rate by ± 20% reaching a harvest level of 99.6%, and 66% of the growth rate on productive forest land. No climate model and storm model from Heureka was applied in the simulations as both insufficiently represent probable climate change-induced developments.

Table 3 HWP portfolio and substitution portfolio, adapted from Hurmekoski et al. (2020). Replacement rate (R) is expressed in mass units of replaced product per one mass unit of HWP end-use

HWP	End-use	Replaced product	Functional unit	Replacement rate (R)	DF (Mg C Mg C^{-1})	References
Sawnwood	Construction	Concrete Steel	Application in Multi-Family Housing Residentia	9.7 0.2	0.8	Peñaloza et al. (2016), Mehr et al. (2018), Piccardo and Gustavsson (2021)
	Packaging (Pallets)	HDPE	EU Norm Pallett	0.2	0.4	EPAL (2021), APLP (2021)
	Furniture	Steel, PP, PUR, glass, aluminium, PVC	Average Furniture Article	0.1	0.0	Geng et al. (2019)
	Other	-		-	-	
Plywood + Fibreboard	Construction	Gypsum, Mineral Wool, Plaster	Application in Multi-Family Housing Residential	0.2	-0.6	Peñaloza et al. (2016), Mehr et al. (2018), Piccardo and Gustavsson (2021)
	Other	-		-	-	
Pulp & Paper	Graphical Paper	-		-	-	
	Paperboard	PET	Average Paperboard Packaging	0.5	1.1	SCB (2021)
	Viscose	Cotton, Polyester	Mass Based	1	0.4	Peñaloza et al. (2019)
	Other	-		-	-	
CHP	Heat & Electricity	Natural Gas	Energy Content Based	1	0.4	Gode et al. (2011)
Biofuel	HVO	Diesel		1	1.1	Gode et al (2011), Hallberg et al. (2013), Danish Energy Agency (2017)
Weighted Average (DF_m)					0.6	

HWP = Harvested Wood Product, CLT = Cross-Laminated Timber, HDPE = High-Density Polyethylene, PP = Polypropylene, PUR = Polyurethane, PVC = Polyvinylchloride, PET = Polyethylene terephthalate = Combined Heat and Power, DF = Displacement Factor, DF_m = Market Displacement Factor. For more information see the Supplementary Material

Technosystem

HWP portfolio and value chain emissions

Within the technosystem, sawlogs, pulpwood, fuelwood and harvest residues were classified for different applications, comprising a certain HWP portfolio which was further defined by HWP end-uses (Table 3). A Sankey diagram in the Supplementary Material further illustrates the distribution within the portfolio. Sawlog-based HWPs were distributed into 91% sawnwood, 1% plywood, 8% fibreboards and particleboards (in the following summarized as fibreboards), based on SFA (2014). From the 91% sawnwood, 69% were used as construction wood, 19% as packaging wood mainly in form of pallets, 3% as furniture, and 9% as other, undefined products (Hurmekoski et al. 2020). The share of 69% construction sawnwood was further divided into 85% timber light-frame construction, 7.5% cross-laminated timber (CLT), and 7.5% glued laminated timber (glulam) (Rudenstam 2021). Out of the 9% plywood and fibreboards share, 41% were used for construction and 59% for other, unspecified end-uses, based on Hurmekoski et al. (2020). Residues in form of shavings and wood chips from sawnwood production ended up as feedstock in pulp mills, while sawdust and bark were used as fuelwood.

Pulpwood supplied either chemical or mechanical pulp mills with a relative distribution of 75% and 25%, respectively (Skogsindustrierna 2021). Distribution of cellulose-based pulpwood HWP end-uses from the chemical pulp mill comprised 38% paper, 51% paperboard, 2% viscose, and 9% other, based on Skogsindustrierna (2021), CEPI (2020) and Hurmekoski et al. (2020). The remaining pulpwood components hemicellulose, lignin, and extractives were used in form of black liquor for internal energy recovery. A small fraction of crude tall oil (CTO) was extracted from black liquor (0.04 Mg CTO Mg $pulp^{-1}$) (Staffas et al. 2013) and used for hydrogenated vegetable oil (HVO) production, whose properties and emissions were adapted from Gode et al. (2011), Hallberg et al. (2013) and Danish Energy Agency (2017). Viscose-related emissions were taken from Peñaloza et al. (2019). In the mechanical pulpmill, pulpwood was entirely used to produce thermo-mechanically and stone-grounded paper with shares of 50% each.

All harvest residues, residual paper, and fuelwood were assumed to be used for energy recovery in a CHP plant with a heat efficiency of 45% and an electricity efficiency of 30% (EC 2011).

Temporary carbon storage in HWPs was accounted for and calculated with half-life times of 35, 25, and 2 years for sawnwood, wood panels, and pulp-based products, respectively (Rüter et al. 2019). For fuelwood, harvest residues, and by-products within the pulp mills, a half-life time of one year was applied.

Fossil value chain emissions from cradle to grave of CO_2, CH_4, and N_2O were based on process-specific ecoinvent LCI data (version 3.7.1) (Wernet et al. 2016) (Supplementary Material) unless otherwise stated. Emissions connected to a use-phase of all HWP end-uses and the substituted applications were considered similar and thus negligible, including calcination and carbonation processes (Gustavsson et al. 2017, 2021). The end-of-life stage of all HWP end-uses represented energy recovery via incineration within CHP plant facilities which created an energy substitution effect, in addition to the material substitution.

Substitution effects

The portfolio of HWP end-uses replaced a counterpart portfolio of non-wooden construction materials, plastic products, as well as energy sources whose emissions were also based on LCI ecoinvent data (Wernet et al. 2016) (Supplementary Material) unless otherwise stated.

Meeting the same function among non-wood and wood-based products often requires varying mass amounts of each. For construction materials, this can result in substantially different mass replacement ratios (in the following also called replacement rates) (Cordier et al. 2021), e.g., depending on the building type (Peñaloza et al. 2019), or physical properties such as density or the thermal conductivity (Schulte et al. 2021a). Given the variety of construction materials covered in this study, mass replacement rates according to multiple materials were adapted from Peñaloza et al. (2016), Mehr et al. (2018), and Piccardo and Gustavsson (2021) (Supplementary Material). Sawnwood used in timber light frame, CLT, and glulam timber frame multi-storey residential buildings was assumed to substitute for concrete and steel (Cordier et al. 2021), and plywood and fibreboards replaced gypsum boards, plaster, and mineral insulation materials.

Sawnwood used for packaging (pallets) (25 kg $pallet^{-1}$) was assumed to replace high-density polyethylene (HDPE) pallets (5.5 kg $pallet^{-1}$) based on EPAL (2021) and APLP (2021). Wooden furniture replacement built on a representative average of non-wooden furniture, consisting out of steel (67%), polypropylene (PP) (11%), polyurethane foam (PUR) (10%), glass (5%), aluminium (5%), and polyvinylchloride (PVC) (2%) based on Geng et al. (2019). Paperboard packaging replacement of plastic packaging considered an average plastic packaging recycling rate of 67% and recycling from wood packaging to be 41% (SCB 2021). Wood-based cellulose fibre in form of viscose was assumed to replace cotton fibre and polyester (PET) fibre in equal shares, with a simple mass replacement ratio of one to one, similar to Peñaloza et al. (2019). Graphic paper was not assigned any replaceable product, except for energy substitution at the end of life.

Energy substitution was included from incineration of fuelwood and all waste wood products at their end-of-life within a CHP plant to produce heat and electricity, with efficiencies of 45%, and 30%, respectively (Börjesson et al. 2010; EC 2011). Heat and electricity from waste wood, paper and cardboard, and viscose with lower heating values (LHVs) of 16 MJ kg^{-1} and 17 MJ kg^{-1}, respectively (Östlund et al. 2015; ECN 2021a, 2021d) replaced energy recovery within similar CHP facilities from incineration of plastic packaging and cotton textile with LHVs of 40 MJ kg^{-1} and 16 MJ kg^{-1} (ECN 2021c, 2021b), respectively. This resulted in reduced consumption of natural gas as the fossil energy substitute. Fuel replacement was included from diesel towards HVO use. GHG emissions from natural gas and diesel were based on Gode et al. (2011).

Substitution effects were estimated as the product sum of HWP end-use shares, HWP end-use production volumes, LCI emission data for the substituted materials, and finally, mass replacement rates in the different end-uses. Value chain emissions of HWP end-uses were recorded separately in the overall GHG net emission calculations. While substitution effects were accounted for as avoided ("negative") emissions, forgone substitution effects that were not realized, e.g., due to decreased harvest, acted as an emission source. Fossil emissions from the HWP end-use value chains and from substitution effects remained constant over the entire time horizon, albeit this simplifies and neglects that both should be subject to drastic future changes, as mentioned earlier.

Displacement factors & sensitivity analysis

The magnitude of the entire substitution effects can be decisive for whether and when an entire wood product system acts as a CO_2-eq source, or sink. For this purpose, a market displacement factor (DF_m) (Hurmekoski et al. 2021) was calculated from the product DFs (Sathre and O'Connor 2010), to facilitate comparison with similar studies.

The DF_m consisted of the weighted DFs of each HWP end-use with given replacement rates (Table 3) that were assessed similarly as in Hammar et al. (2020) and Schulte et al. (2021b):

$$DF_x = \frac{GHG_{non-wood} \cdot R - GHG_{wood}}{WU_{wood} - WU_{non-wood} \cdot R} \quad (1)$$

where the displacement factor DF of x, a certain HWP end-use, is given in Mg C_{fossil} Mg^{-1} $C_{biogenic}$, $GHG_{non\text{-}wood}$ and GHG_{wood} represent the GHG emissions from cradle to grave of the substituted and wood product, respectively, expressed in mass units of carbon corresponding to the CO_2-eq of the emissions. WU_{wood} and $WU_{non\text{-}wood}$ denote the amount of wood used in the wood product and substituted product, respectively, also given in mass units of carbon, and R is the replacement rate (Table 3 and Supplementary Material). The market displacement factor DF_m was further calculated as

$$DF_m = \frac{\sum_{x=1}^{n} DF_x \cdot W_x}{\sum_{x=1}^{n} W_x} \quad (2)$$

where W_x is the weight, or amount of each HWP end-use x as a share of the total HWP end-use amount (Hurmekoski et al. 2021).

Note that multiplication of the DF_m with harvest volumes is thus not possible as it is derived from the final HWP end-use amount, not the initial harvest volume.

To address connected uncertainty and impact on the results, a sensitivity analysis doubled and halved replacement rates of all HWP end-uses which increased and decreased the DF_m, respectively.

Climate impact metrics

Climate effects from GHG fluxes were calculated using the global warming potential GWP_{100} and the AGTP (Myhre et al. 2013). The GWP_{100} is the cumulative radiative forcing (RF) of other GHGs, here CH_4 and N_2O, relative to the RF of CO_2 for a given time frame, i.e. 100 years (Joos et al. 2013). The metric yet misses to account for the timing of emissions along the assessed time horizon and associated dynamics in the atmosphere.

The AGTP is the response in global mean surface temperature at a certain point in time generated by a change in radiative forcing due to a GHG pulse emission expressed in degrees of kelvin (K). The AGTP was calculated based on annual GHG fluxes from CO_2, CH_4, and N_2O. The perturbation lifetime of CO_2 is based on the Bern carbon cycle model (Joos et al. 2001, 2013), where the molecule remains airborne until it is taken up by oceans or the biosphere. For CH_4 and N_2O, average perturbation lifetimes were 12.4 and 121 years, respectively (Myhre et al. 2013). The AGTP is described by:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H - t) dt \quad (3)$$

where radiative forcing (RF), expressed in W m^{-2}, and the climate response function (R_T) constitute a convolution over the time horizon assessed (H) by a change in RF from a pulse emission of a GHG x. Thus, AGTP accounts for the timing of GHG emissions and their perturbation lifetimes which enables the assessment of time-dependent dynamics within (time dynamic) climate effects. In this study, the term AGTP is used synonymously with the term temperature change.

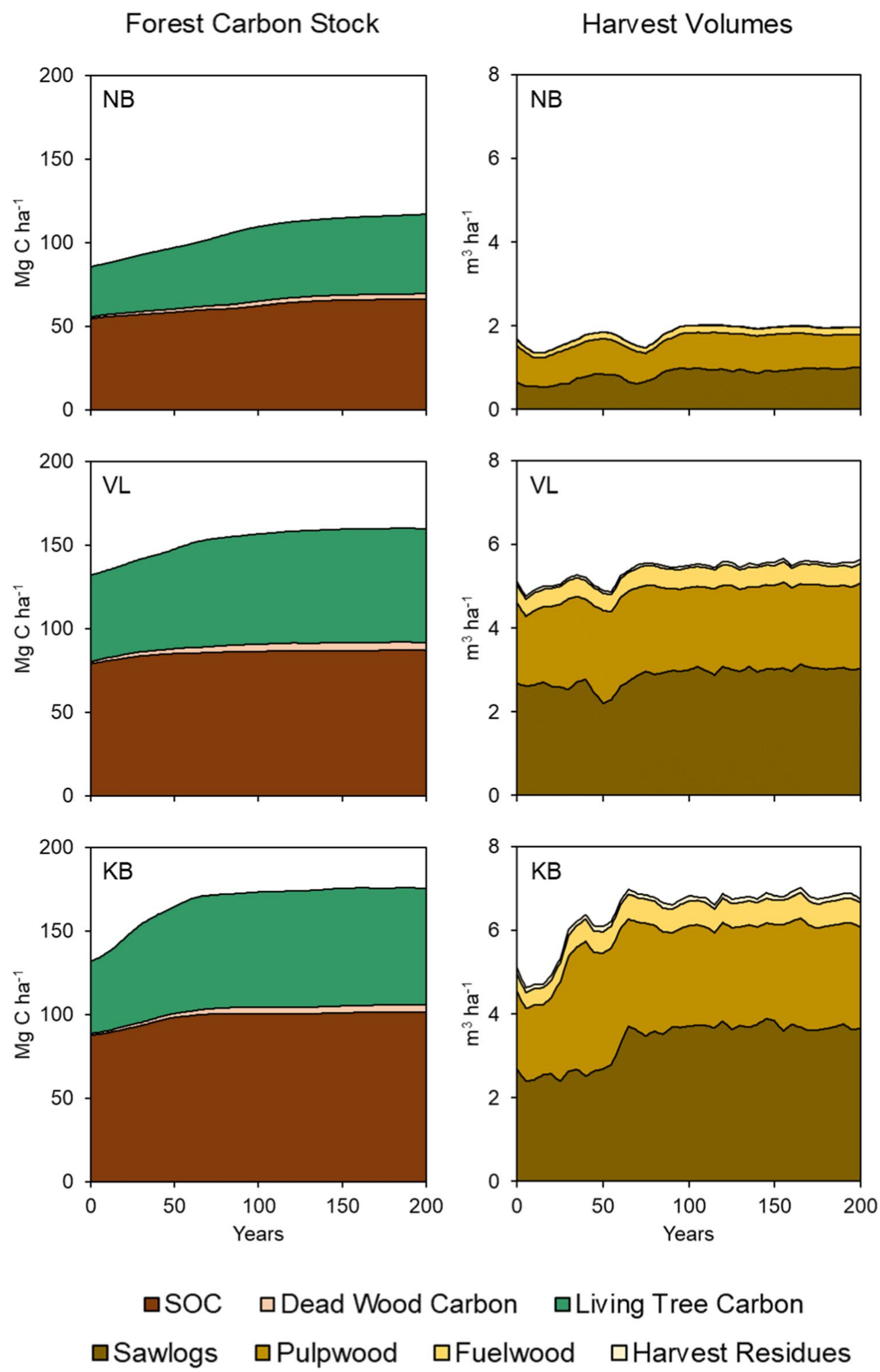


Fig. 2 Simulated forest carbon stock (Mg) and harvest volume (m^3) developments on productive forest land for all three regions per ha over the 200-year time horizon for the reference forest management scenario. NB = Norrbotten, VL = Värmland, KB = Kronoberg

Results

Reference forest carbon stocks and harvest volume developments

Figure 2 depicts simulated forest carbon stocks and harvest volume developments on productive forest land per ha of all three regions for the reference forest management scenario over a time horizon of 200 years. Overall, forest carbon stocks increase in all regions over the time horizon assessed. Across the forest growth gradient from South to North, highest overall carbon stocks and increases in standing biomass are found in Kronoberg (south), while the lowest are found in Norrbotten (north). Simulated SOC stocks initially increase slightly but remain constant over the subsequent time horizon. With growing amount of standing biomass, dead wood carbon amounts rise, however do not reach a substantial part of the overall forest carbon stocks.

Simulated harvest volumes over the time horizon of 200 years among the different regions vary more strongly compared to the forest carbon stocks and do not show continuous increase. Two dips are present after the first decade, and after 50 years which originate from the average age class distribution. On average, harvest volumes in Norrbotten were 1.5 m^3 ha^{-1} $year^{-1}$ over the considered time period, which in total constitute around one fourth of those from Kronoberg, where volumes experience a strong increase in the first six decades. Värmland shows average harvest volumes over the assessed time horizon with around 5 m^3 ha^{-1} $year^{-1}$. In Värmland, the relative harvest volume proportion comprises on average 59% sawlogs, 31% pulpwood, 9% fuelwood and 1% harvest residues. In Norrbotten and Kronoberg, relative average harvest volume proportions are 63% and 51%, 32% and 45%, 3% and 4%, and 1% and 0%, respectively.

Climate impact from a system perspective

Figure 3 shows the simulated climate impact from a system perspective for all assessed regions including the forest ecosystem and technosystem in the unit Mg CO_2-eq ha^{-1}. The results represent the relative outcome from benchmarking the alternative forest management scenarios against the reference scenario.

Overall, the higher the forest productivity, the more influential are changes in forest management on annual CO_2-eq fluxes. Among all forest management options, decreasing harvest intensity leads to cumulatively largest and continuous overall CO_2-eq emission reductions, regardless of the region but with stronger effects the more to the south, i.e. the higher the forest productivity. Considering a 25-year average this is − 0.4 Mg CO_2-eq ha^{-1} $year^{-1}$ in Norrbotten, and − 0.8 Mg CO_2-eq ha^{-1} $year^{-1}$ in Värmland and Kronoberg, and on a 100-year average − 0.2, − 0.6, and − 0.7 Mg CO_2-eq ha^{-1} $year^{-1}$, respectively. Prolonging the rotation period brings a major net average CO_2-eq emission reduction within the first 25 years in all regions, (− 0.7, − 0.9, − 1.6 Mg CO_2-eq ha^{-1} $year^{-1}$ in Norrbotten, Värmland, Kronoberg, respectively) which subsequently is partially offset by a turn into net emissions compared to the reference. This turn into net emissions originates from changes in rotation time, i.e. a changed average forest age distribution and thus timing of harvest, as compared to the reference scenario. Increasing the harvest intensity shows variable, moderate to high CO_2-eq fluxes over time in comparison to the reference. On average, however, the fluxes lead here to an increase in emissions. Shortening the rotation length has the lowest effect on the CO_2-eq balance with a minor heterogenous outcome along the time horizon.

Notably, the forest carbon sink plays the greatest role in influencing the CO_2-eq fluxes from a system perspective. Decreased forest carbon sequestration due to increased harvests is not entirely offset by substitution effects and increased HWP carbon storage. Vice versa, forgone substitution effects and omission of increased HWP carbon storage do not provoke an overall climate burden due to larger forest carbon sequestration and saved fossil value chain emissions, e.g., during scenarios of decreased harvest or increased rotation length. Across all regions and management scenarios, strong temporal variation exists in either forest carbon sequestration or harvest volumes as compared to the reference scenario. These are most pronounced in the longer rotation and increased harvest scenario.

Time dynamic temperature change

Temperature change across time including forest eco- and technosystem due to varying forest management (Fig. 4) is overall more strongly pronounced the more southern the region. The more northern, the weaker and more delayed the climate effects from altering forest management today because of slower forest growth, decomposition, etc. Regardless of the region, strongest cumulative climate cooling over a long time horizon (> 100 years) develops by decreasing harvest levels. In Kronoberg, however, extending the rotation length leads to the strongest cooling effect in the short to medium term (< 50–70 years). In Norrbotten and Värmland, in contrast, climate cooling levels from extending rotation remain overall comparable to effects from decreasing harvest levels until 75 years, and 30 years, respectively. However, afterwards, decreasing harvests induces strongest climate cooling. Shorter rotations lead to comparable effects on the temperature change as the reference scenario. Scenarios of increased harvest in contrast do not provoke additional climate cooling compared to the reference which in the short to medium term shows a heterogenous pattern and in the long term develops into a cumulative trend regardless of the region.

Sensitivity analysis

Figure 5 shows the temperature change impacts of all forest management alternatives until 2070 for an increased DF_m = 1.4 or reduced DF_m = 0.2, due to doubling or halving all replacement rates of all HWP end-uses. Each scenario equals the respective average from all regions under study as compared to the reference.

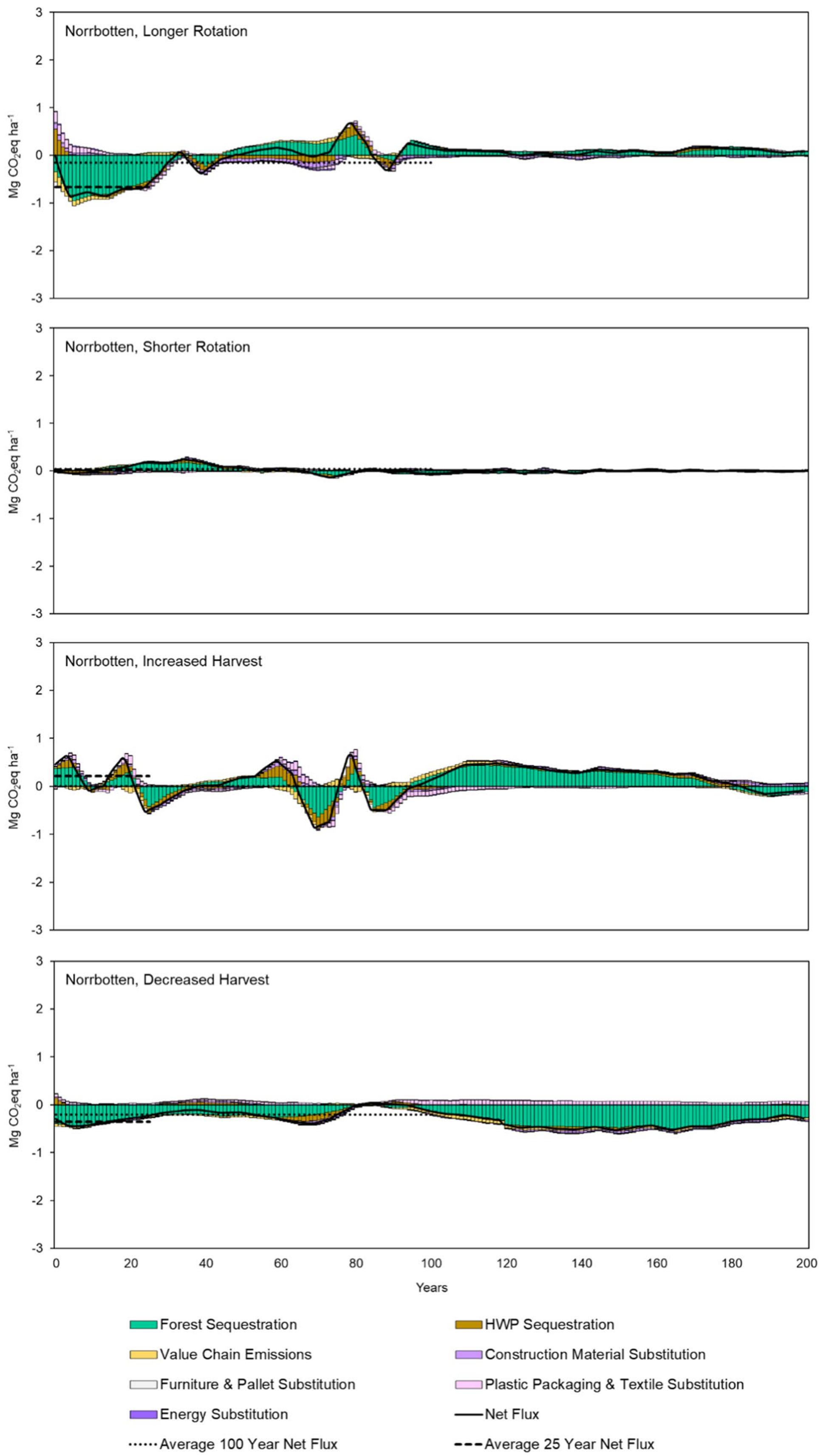


Fig. 3 Annual climate impact (Mg CO_2-eq ha^{-1}) from all forest management scenarios in Norrbotten, Värmland, and Kronoberg over the 200-year time horizon as compared to the reference. Positive values represent emissions to the atmosphere. HWP = Harvested Wood Product

Fig. 3 (continued)

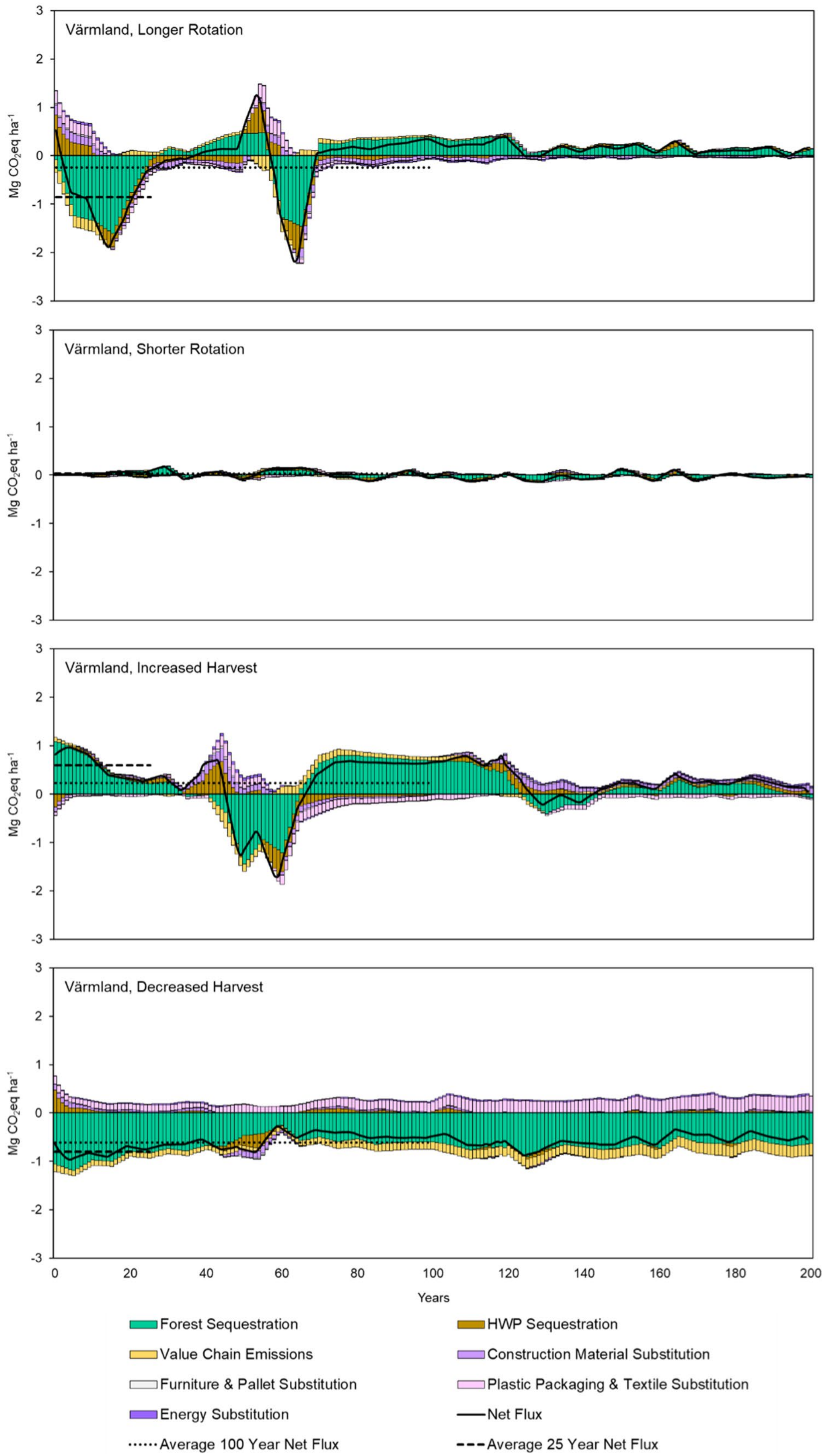
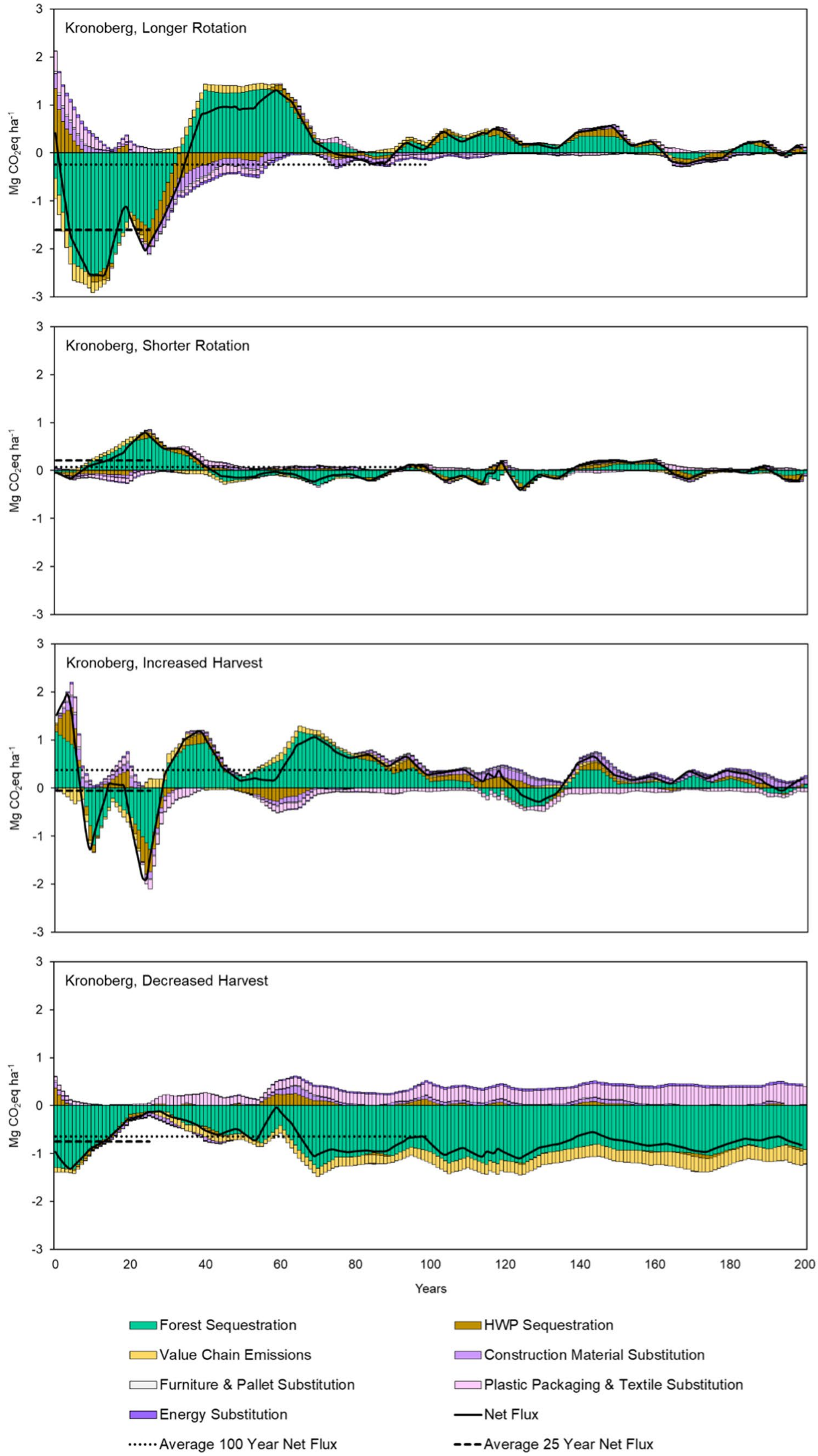


Fig. 3 (continued)



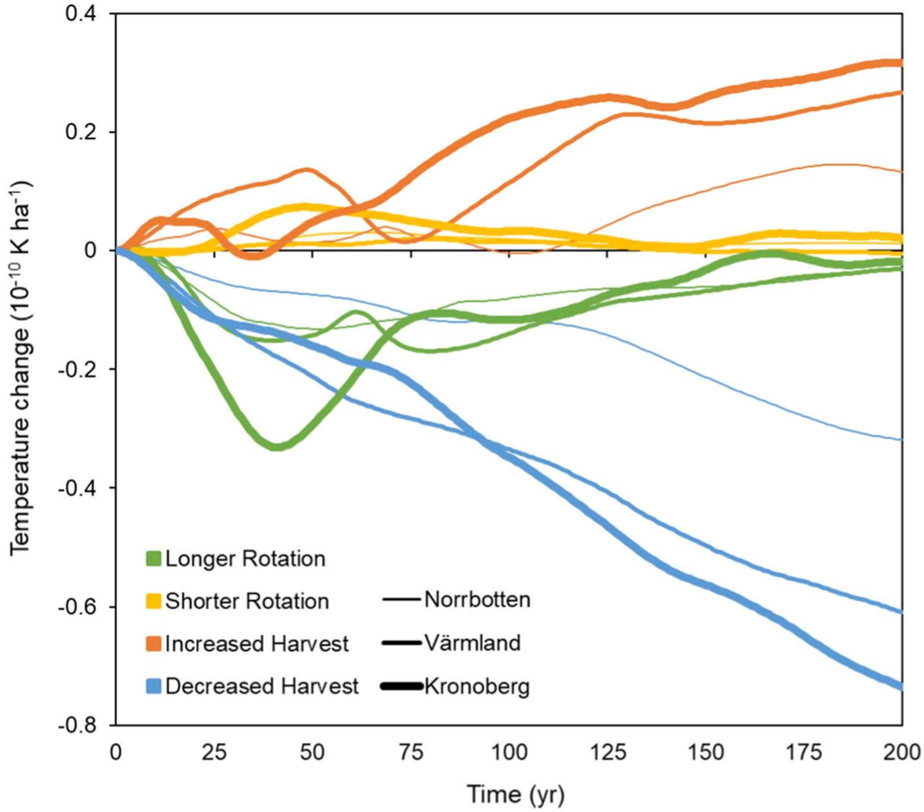


Fig. 4 Temperature change per ha given for all forest management scenarios and regions under study as compared to the reference scenario

An altered DF_m does not change overall temperature change from net cooling towards net warming except during the first decade of the longer rotation scenario. However, in all scenarios apart from shortening the rotation, a higher DF_m leads to decreased cooling effects. For prolonging the rotation and decreasing harvest levels, this is due to larger forgone substitution effects. In the increased harvest scenario, a higher DF_m induces increased climate warming as the temporal variation of surplus and decrease in harvest volumes compared to the reference scenario causes an overall net forgone substitution effect.

Discussion

The Nordic forest sector climate change mitigation trade-off

Despite numerous studies applying a system perspective in analysing climate effects of forest management including substitution effects, the scientific debate on the most effective climate strategy is still not settled.

The results of the present study complement and align with an international body of knowledge indicating that alternative forest management with decreased harvests and increased forest carbon sequestration benchmarked against current reference levels leads to larger net climate benefits (Matsumoto et al. 2016; Skytt et al. 2021; Seppälä et al. 2019; Jonsson et al. 2021; Soimakallio et al. 2021; Biber et al. 2020; Dugan et al. 2018; Hurmekoski et al. 2020) opposed to increasing harvest levels to exploit substitution effects (Gustavsson et al. 2021; Petersson et al. 2021). In fact, across all studied regions, an average additional mitigation potential of -1.0 Mg CO_2-eq ha^{-1} was found over the next 25 years when rotations are prolonged, and -0.7 Mg CO_2-eq ha^{-1} when harvest levels are decreased. This represents additional climate cooling until 2050 of $-0.16{\cdot}10^{-10}$ K ha^{-1} for prolonging rotations, and $-0.10{\cdot}10^{-10}$ K ha^{-1} for decreasing harvest levels.

However, within the Swedish context, it must be recognized that strong forest carbon sinks following prolonged rotations or decreased harvests are, at least partially, a consequence of the present age class distribution (Supplementary Material) characterized by numerous young stands and strong forest growth. This baseline is shaped by decades of active forest management in Sweden, limiting superior climate benefits to several decades, as prolonged rotations may compromise additionality to other scenarios (Lundmark et al. 2018).

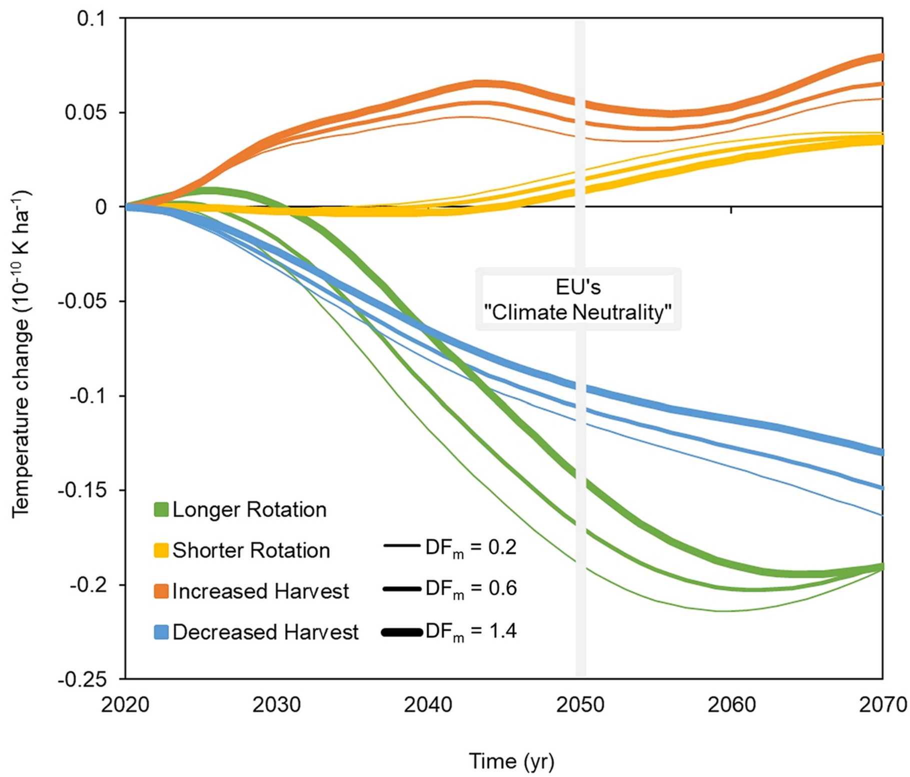


Fig. 5 Temperature change as an average across all regions given per ha for all forest management scenarios when compared to the reference scenario in dependence to a varying market displacement factor (DF_m)

Unless harvest volumes are not used more wisely with considerably larger shares of long-lived wood products (Dugan et al. 2018; Arehart et al. 2021), carbon emissions from bioenergy production are not captured and stored (BECCS), or wood products do not lead to substantially higher substitution effects, for example, by an increasing demand for wood-based housing, a superior climate benefit may originate from a large forest sink (Soimakallio et al. 2021). Furthermore, decreasing harvests and prolonging rotations can provide a higher ratio of sawlogs to pulpwood, resulting in more long-lived products, in a relative sense, as deducible in the decreased harvest scenario across all regions, where mostly pulpwood-based substitution effects are forgone. On the other hand, decreased harvests can result in reduced silvicultural activity as well as decreased economic profitability (Baul et al. 2017), as Swedish forestry today largely relies on wood production (Hiltunen et al. 2021). Thus, climate change mitigation trade-offs among forest management strategies have socio-economic implications, influencing future job opportunities throughout the next decades (Jonsson et al. 2021).

In terms of shortened rotations, the smallest change from the reference scenario and no long-term overall climate benefit was found. However, shorter rotations bear potential to avoid severe forest carbon loss from calamities such as storms (Subramanian et al. 2019) despite being considered to compromise overall forest resilience due to negative consequences for other ecosystem services and biodiversity (Ortiz et al. 2014; Egnell et al. 2015; Felton et al. 2016).

Climate relevance of additional forest management alternatives

Rotation forestry bears additional options for improving climate change mitigation and adaptation. Among them are, increased harvest residue extraction considering biodiversity constraints (Eggers et al. 2020; Camia et al. 2021), retention forestry (Cherubini et al. 2018), or diversifying species composition (Hahn et al. 2021).

Transformation into continuous cover forestry (CCF) is further perceived a promising strategy for improved climate change mitigation and adaptation (Pukkala 2014) for increased forest multifunctionality opposed to rotation forestry (Eyvindson et al. 2021), and thus a more balanced fulfilment of forest policy goals (Eggers et al. 2019) while not constraining forest carbon sequestration (Biber et al. 2020).

No forest management including natural regeneration can be another short- to medium-term climate change mitigation and adaptation strategy to foster forest carbon sequestration and simultaneously increase genetic variation within tree species (Soimakallio et al. 2021), yet it is uncertain regarding long-term climate effects (Knauf et al. 2015; Skytt et al. 2021).

Still, more climate-smart Nordic forest landscapes require mosaics of varying forests including even-, uneven-aged, and natural forests comprising multi-layered mixed stands (Savilaakso et al. 2021; Eyvindson et al. 2021; Soimakallio et al. 2021). Change across all of Europe is urgent given projected climate change and connected economic losses of forests at the end of the century, in the absence of effective counteraction (Hanewinkel et al. 2013). Actual implementation, however, always requires consideration of regional circumstances.

Methodological limitations in wood product climate assessments

Recommended methodological approaches in assessing climate effects from wood product systems across time cover biogenic carbon, valid counterfactual scenarios (Giuntoli et al. 2020), or, examining both, short and long time horizons (Gustavsson et al. 2021). However, additional aspects still leave considerable space for uncertainty.

One is reliance on forest models to process empirical NFI data. In this study, the Heureka RegWise software was applied whose growth models were shown to be reliable within even-aged forest management along extended time periods (Fahlvik et al. 2014). Although available, the climate model and storm model inherent to Heureka were excluded as both insufficiently represent probable climate change-induced developments (Subramanian et al. 2019).

However, Nordic forest growth is expected to increase substantially as a result of climate change (Claesson et al. 2015; Subramanian et al. 2019), at the same time as forest calamities (bark beetle outbreaks, storm events, fires) and biomass decomposition are foreseen to increase in frequency and magnitude, thereby potentially offsetting climate benefits from increased forest growth (Kauppi et al. 2018; Subramanian et al. 2019) as, for example, shown in a Finnish case by Reyer et al. (2017). By omitting these aspects in the assessment, the present study thus can be seen to provide more conservative results as both potentially beneficial (i.e. forest growth-enhancing) and detrimental (i.e. mortality exacerbating) factors were neglected in the model and including these (simplistic) modelling features would add considerable uncertainty.

Wood flow models based on LCA data are likewise subject to assumptions influencing the outcome from forest management scenarios. Among them are fixed vs. dynamic annual harvest volumes and wood product portfolios across time (Hurmekoski et al. 2020; Brunet-Navarro et al. 2021), only approximate half-life times using exponential decay functions for HWPs (Hurmekoski et al. 2020; Brunet-Navarro et al. 2021) improvable, e.g., by gamma decay functions, missing albedo as a climate forcer despite its globally inferior role than CO_2 effects (Pongratz et al. 2010; Cherubini et al. 2018; Kalliokoski et al. 2020), or accounting for indirect land-use changes (Howard et al. 2021). Finally, increased knowledge on consequential modelling of wood product systems relying on LCA data (Helin et al. 2013; Cordier et al. 2021) and a more uniform and nuanced assessment approach for substitution effects are required.

Uncertainties connected to substitution effects

Substitution effects remain a highly uncertain and influential factor in climate assessments of wood products for which until today no universal way of conduct exists. Still, the commonly applied substitution or displacement factor (DF) (Sathre and O'Connor 2010) can be a metric to express the magnitude of avoided fossil C per unit of biogenic C in the wood product. The weighted average displacement factor or market displacement factor (Hurmekoski et al. 2021) found in this study was $DF_m = 0.6$ Mg C Mg C^{-1} and is thus in line with comparable national studies in Nordic contexts such as Lundmark et al. (2014) for Sweden (0.6 Mg C Mg C^{-1}), Soimakallio et al. (2016) for Finland (0.4–0.8 Mg C Mg C^{-1}), or Smyth et al. (2017) for Canada (0.5 Mg C Mg C^{-1}). Further, the value coincides with the average DF_m of the review from Hurmekoski et al. (2021) (0.55 Mg C Mg C^{-1}), which, however, still shows great interval to a required DF_m (2.0–2.4 Mg C Mg C^{-1}) which would mark net zero emissions from increased forest use compared with a baseline harvesting scenario (Seppälä et al. 2019).

However, as summarized by Howard et al. (2021), several assumptions manipulate substitution effects of wood products that impede comparisons of DFs among studies. Spatial assumptions such as equal HWP production with similar energy demands across regions considering changed harvest rates (Smyth et al. 2017), neglection of market and legislative aspects, such as international trade and employment effects from increased wood product consumption (Jonsson et al. 2021) or the emissions trading system of the EU further increase uncertainty.

Since assumptions on substitution effects lacking real-life complexities can result in too optimistic DFs, former conclusions of DFs and substitution effects were regarded to be strongly overestimated (Leturcq 2020; Harmon 2019). In contrast are future substitution effects of wood products considered to decrease, e.g., due to required political climate targets (Brunet-Navarro et al. 2021) and associated decarbonisation of other industrial sectors (Arehart et al. 2021). Climate policy advice solely based on displacement factors bears therefore too much uncertainty to provide reliable consultation (Leskinen et al. 2018; Hurmekoski et al. 2020).

Thus, further studies such as the present one which supply more detailed, time dynamic breakdowns of substitution effects, especially following shifts in forest management, are required, that specify pulpwood, fuelwood, or sawlog-based substitution. In addition, development of dynamic displacement factors is recommended to account for abovementioned shortcomings, e.g., with accounting for political climate targets by assuming an expected increase in renewable energy in line with the Paris agreement (Brunet-Navarro et al. 2021).

Conclusion

The results of the present study suggest that decreasing harvest levels and prolonging rotations would increase net climate benefits compared to present Swedish forestry practices. Across all three regions assessed, prolonging rotations by 20% leads on average to additional climate benefits of − 1.0 Mg CO_2-eq ha^{-1} over the next 25 years, while decreasing harvests accordingly induces − 0.7 Mg CO_2-eq ha^{-1}. This equals additional temperature cooling effects of $-0.16\cdot10^{-10}$ K ha^{-1} until 2050 for prolonging rotations, and $-0.10\cdot10^{-10}$ K ha^{-1} for decreasing harvest levels.

However, forest calamities induced by climate change are likely to somewhat compromise these potential additional climate cooling effects, in which case shorter rotations and increased harvests provide more resilient management approaches. Despite this, resilient long-term climate change mitigation and adaptation strategies for Swedish forests may still be found in increasing more heterogenous forest landscapes. These could include longer rotations, reduced harvests, and changing tree species to those more apt for local site conditions. The transformation of some of the forest area to CCF could be a promising strategy for increased forest multifunctionality, while at the same time not constraining forest carbon sequestration. This transformation still requires considerations of local circumstances. As for policy advice, remaining knowledge gaps and uncertainties—notably, the magnitude and local effects of climate change, substitution effects, carbon leakage effects, and long-term forest growth dynamics given climate change—hinder the formulation of concrete, precise, suggestions. However, the need for changing Swedish forest management is urgent given projections of future climate change and associated ecological, societal, and economic value loss of forests across Europe at the end of the century in the absence of effective countermeasures.

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Author contributions Maximilian Schulte was involved in conceptualization, methodology, formal analysis, writing—original draft, visualization. Ragnar Jonsson contributed to conceptualization, validation, writing—review and editing. Torun Hammar was involved in conceptualization, methodology, resources, writing—review and editing. Johan Stendahl contributed to conceptualization, validation, resources, writing—review and editing. Per-Anders Hansson was involved in conceptualization, supervision, project administration, funding acquisition.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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