On the role of forests and the forest sector for climate change mitigation in Sweden

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Abstract

Long-standing debate over the benefits of forest conservation vs. those of forest resource use and substitution continue to occupy attention in Europe and beyond. To study this question, we simulate the short- and long-term consequences for atmospheric greenhouse gas (GHG) concentrations of different forest management strategies and forest product uses in Sweden. We compare the projected short- and long-term consequences of increasing forest use vs. increasing land set-asides. In all scenarios but one, forest management for wood production results in higher net GHG reduction than the alternative to set-aside forests for conservation. In all scenarios, annual carbon dioxide (CO_2) sequestration rates in conservation forests decline as maturing forests eventually reach a steady state, while they rise in all other forest management strategies. Thus, there is an apparent tradeoff between wood production and nature conservation. Forest set-asides are associated with sizable long-term opportunity costs corresponding to the foregone wood production capacity. Retained in the circular bioeconomy system over the long-term, forest management for wood production eventually stabilizes at significantly higher amounts than a management system which promotes greater shares of forest protection and conservation. In all cases, the long-term mitigation gains from wood production are cumulative and significant. Likewise, the indicative level of wood supply for biobased production that can be maintained without causing systematic loss in land carbon stocks is large. Such long-term consequences, however, are not properly accounted for in the European Union's (EU's) legislative LULUCF (Land Use, Land-Use Change and Forestry) carbon accounting framework, which effectively encourages land set-asides at the expense of forest wood production capacity.

Keywords: Substitution, Conservation, Mitigation, Adaptation, Forest, LULUCF, Land Set-Asides.

Introduction

Sweden aims to become a fossil-free welfare society with net zero GHG emissions by 2045 and negative emissions thereafter. Biomass is already the largest energy source in Sweden and a nation-wide initiative to develop business sector roadmaps towards a fossil-free future[1] indicates that biomass-based solutions are increasingly being considered. Most of this biomass is expected to come from forests. The European Union (EU), on the other hand, seems intent on restricting forest use and on reducing, or at the very least restricting, further increases in forest use intensity (Grassi et al., 2019; Matthews, 2020).

Forests and forestry influence atmospheric carbon dioxide (CO_2) concentrations through removing CO_2 from the atmosphere and storing carbon in forest biomass and forest products (Pilli et al., 2015). Forestry also affects atmospheric CO_2 concentrations through forest processes that return carbon to the atmosphere, i.e., respiration and combustion. Further, greenhouse gas (GHG) savings arise when forest products substitute other products which cause GHG emissions, such as cement, steel and fossil fuels (Gustavsson et al., 2017; Lundmark et al., 2014; Sathre & O'Connor, 2010). There is an apparent tradeoff between the objectives of storing carbon in the forest, on the one hand, and harvesting wood to produce forest products, on the other. These two objectives, however, are not mutually exclusive and forest management decisions reflect the balancing of these and other objectives.

How best to balance forest carbon storage and wood production with respect to the climate has long been a subject of debate and scientific discussion (Cowie et al., 2021a; Eriksson & Klapwijk, 2019; Klapwijk et al., 2018). Forest owners tend to favor the harvesting of wood to produce forest products, while more nature-oriented groups tend to favor conservation, facilitating forest carbon storage and improving biodiversity (Eriksson & Klapwijk, 2019). Disagreements may also arise due to opposing views concerning short- term vs. long-term climate objectives, expectations concerning society's future dependence on carbon-based energy and materials, and whether these needs can be met in climate friendly ways without using biomass (Cowie et al., 2021b; Gustavsson et al., 2017, 2021).

A range of additional concerns compound the relative emphasis on natural and production forests, including; employment and income generation (Nambiar 2019; Li, Mei, and Linhares-Juvenal 2019), bioeconomy development (Toivonen et al., 2021), leakage effects (Kallio & Solberg, 2018; Solberg et al., 2019; Grassi et al., 2018), biodiversity (Parrotta et al., 2012), forest resilience (Liang et al., 2016; Oliver et al., 2015), the role of services for conducting business (Näyhä Annukka et al., 2015; Pelli et al., 2017) and the preservation and protection of natural habitat and wildlife corridors to assist species survival and migration (Dinerstein et al., 2019; Jonsson et al., 2019). Continued debate surrounds the amounts of set-aside forests required to ensure the protection of wildlife habitats and wild species (Dinerstein et al., 2019; Ellis, 2019; Roberts et al., 2020) with some studies identifying important, frequently neglected weaknesses to arguments in favor of set-asides (Schulze, 2018).

In the current study, we assess how different forest management strategies in Sweden influence the forest carbon stock and wood harvest over time. Forest management strategies are discussed

[1] 22 roadmaps produced so far, see https://fossilfrittsverige.se/en/roadmaps/.

in relation to their climate change mitigation potential, while possible climate change impacts on forests are also considered. More specifically, the study aims to analyze:

- the role of forests and forestry by comparing how atmospheric change in CO_2 concentrations are affected both by storage in forests, in forest products (HWP) and substitution over different time scales (given a fixed management system)
- forest protection, nature conservation and their long-term impacts on forest-based climate change mitigation
- the potential for improved forest management to sustainably increase net CO_2 substitution and removals
- the potential benefits and/or increased risks associated with a changing climate (we simulate both positive and negative climate effects on growth based on the rise in global temperatures and potential nutrient deprivation)
- the difference between the *real* effect of forests and forestry on atmospheric CO_2 concentrations and the *reported* and *accounted* climate reporting estimates implied by different accounting frameworks

Materials and Methods

Forest management in Sweden

Forest management in Sweden involves harvesting (final felling) about 1% or less of total Managed Forest Land (MFL) per year and legally requires immediate, active regeneration after harvest (Forest agency 2020a; Forest agency 2020b). Tree species composition has not been significantly altered over the course of the 20^{th} century (Forest statistics 2021), but there is concern about a gradual decline in the area of virgin old growth forests (B. G. Jonsson et al., 2019) and that the targeting of biologically young stands for harvest will limit delivery of several ecosystem services, resulting in less multifunctional forest (M. Jonsson et al., 2020). In parallel with increasing wood harvesting levels, forest management has resulted in significant increases in forest carbon stocks. Following a historic period of declining forest resources, forests in Sweden have continuously accumulated carbon since the early 1920s, resulting in more than a doubling of carbon stocks over the past century (Forest statistics 2021). The focus on forest policies and management strategies has over time integrated securing wood supply for the forest industry with other objectives, such as climate change mitigation and adaptation, biodiversity conservation, social aspects and water resource management (Eriksson et al., 2018).

As highlighted in Figure 1, forest stands are traditionally harvested when annual growth rates decline and mean annual carbon accumulation rates begin to plateau (Eriksson, 1976).

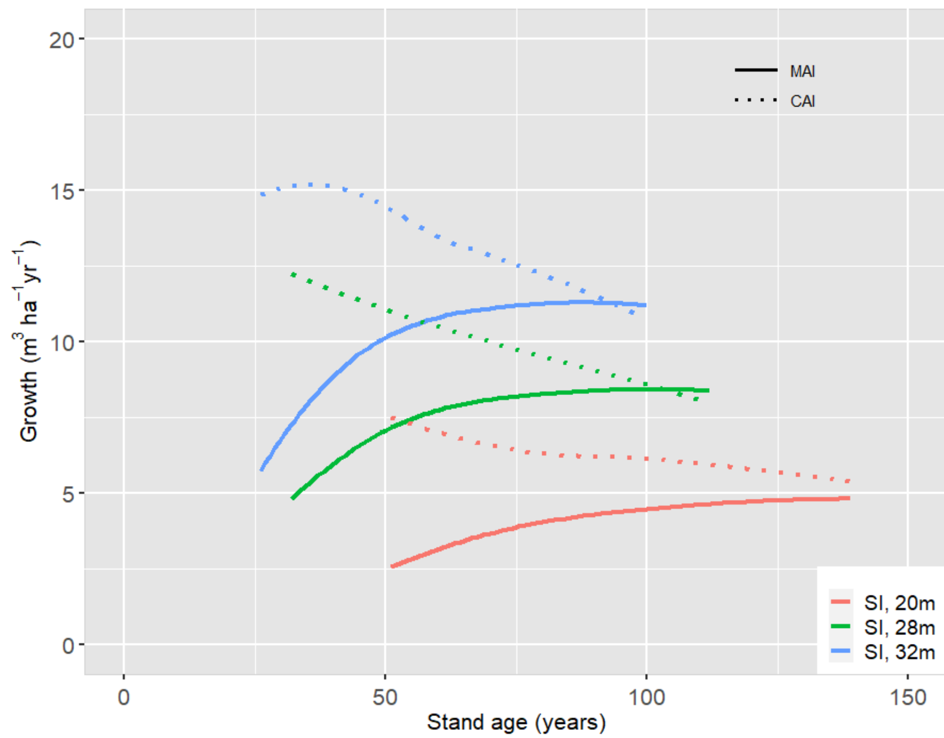

Figure 1: Measured Development of Mean Annual and Current Annual Increment in three common Norway spruce stands (1 m^3 stem wood roughly corresponds to 1.4 tonnes $CO_{2}e$, SI = Site Index and refers to tree height at 100 years).
Note: After stand establishment, a tree stand first grows slowly, then more rapidly, then peaks, and after this point the growth rate begins to decline (see e.g., Eriksson 1976; Figure 1). The optimal rotation period which maximizes growth occurs when the MAI line crosses the CAI line. Growth will be lost if harvest occurs before or after this optimization point. Current annual increment (CAI) is the total annual growth in any given year. Mean annual increment (MAI) is the average annual growth a stand exhibits at a given age and is calculated as the cumulative growth divided by the stand age.

For a given site (site index) in Sweden, the optimal harvest should occur after the year in which growth culminates. The optimal rotation period is the period which maximizes growth (or carbon uptake) in trees. On average, this occurs after approximately 100 years of growth and carbon sequestration (later in the North and earlier in the South). After this peak, each additional year of forest growth sequesters less additional carbon. Over time, failure to harvest is therefore assumed to yield declining amounts of additional biomass and slowing rates of carbon uptake. In the long term, and given an approximately even-aged stand distribution, carbon uptake will eventually become equal to decomposition rates, yielding a steady state, net zero rate of carbon sequestration. Over time, older standing forests therefore provide no significant climate benefit.

In principle, forestry is considered an atmospherically acceptable practice because wood supply is ideally and traditionally harvested when annual growth rates slow and mean annual carbon accumulation rates begin to plateau (H. Eriksson, 1976). In place of the harvested wood supply, forests are immediately and actively regenerated and begin accumulating and sequestering additional carbon from the atmosphere. Young forests rapidly increase overall rates of carbon sequestration. Growth rates can further be improved by introducing new, fast-growing species, with genetic improvements in native species, fertilization, intensive forest management and planting density modifications. Given an even-aged stand distribution, constant fertility over the forest landscape and harvest at the optimal rotation period for all stands, net tree growth will eventually stop increasing (saturation point). This point defines a steady state equilibrium where tree growth and harvest removals are balanced and equal. Though both equilibria described above can be affected by "natural disturbances" (ND) such as insect attacks, wildfires and storms (Forzieri et al., 2021; Senf et al., 2020; Senf & Seidl, 2021a, 2021b), the concept of a more or less stable, long-term equilibrium remains relevant.

Because net rates of carbon sequestration decline over time, it is preferable to harvest growth, store it in long-lived HWPs and use forest residues for bioenergy production. Following a cascading model, both long and short-lived HWP's should be recycled as many times as possible and should also be used at the end of their life cycle for bioenergy production. Directly after felling, there is a net loss of carbon as harvest residues left on site decay. But regrowing forest turns into an increasingly strong net sink after a couple of decades. Growth rates can further be improved by introducing new, fast-growing species, via genetic improvements in native species, fertilization, forest thinning and planting density modifications.

Scenarios for future forest management

To study the cumulative climate impacts of harvest and standing forest-based stocks over time in Sweden, future developments are simulated using five different scenarios. The total Managed Forest Land (MFL) area is estimated at 27 Million hectares (Mha) in 2010. MFL is subdivided into productive MFL (average growth>1 m^3/ha/yr; around 23 Mha) and unproductive MFL (average growth <1 m^3/ha/yr, around 4.0 M ha). Productive forests are separated into 20 Mha of forests used for wood supply and another 3.6 Mha of formally and voluntarily protected forests in which harvest is not permitted. Low productive forests covering another 4 Mha are also considered "protected". Thus, a total of 7.6 Mha of forest are currently protected and excluded from harvest.

We focus on MFL defined as forest land remaining forest land (e.g., Lundblad et al. 2019), i.e., we include land use conversions to forest land and exclude forest land converted to other land use categories. Land transitions from and to MFL are simulated based on the average conversion rate over the period 1990-2017 (Lundblad et al. 2019; afforestation rates are approximately 15 kha/yr and deforestation rates 11 kha/yr). Land actively converted to forested land is first classified as Afforested Land for 20 years and thereafter included under MFL. Land actively converted from MFL is immediately considered and reported as Deforested Land for 20 years and thereafter reported in the land category it was converted to.

In all scenarios, we assume 100 % of the growth on productive MFL used for wood supply, minus self-mortality, is harvested. We assume zero harvest in protected forests. We further assume an equilibrium stem volume (biomass) will emerge, as well as a steady state on land set-asides after approximately 200 years.

Table 1: Scenarios and Assumptions

Scenarios	Assumptions
Maximum Potential Harvest	Base scenario
Increased Nature Conservation	Study effects of increasing forest land set-asides (3.7 Mha]
Improved Forest Management	Fertilization (restricted by law)
Negative Climate Effects on Growth	Double mortality
Positive Climate Effects on Growth	Growth based on IPCC RCP 4.5 scenario

In the *maximum potential harvest* scenario*,* areas of different land-use classes as well as management practices (excluding harvest intensity) are assumed to simulate the conditions specified by the Forest Agency for the period 2000-2009 (Forest Agency 2008; Claesson et al. 2015; Forest Agency 2015). To study the consequences of setting aside additional MFL for nature conservation, we assume an additional 3.7 Mha of mainly productive MFL is set aside for nature conservation in the simulation. This amount is equivalent to approximately 18.5% of currently available, productive MFL, bringing the total protected forest area to 11.3 Mha. In the *increased nature conservation* scenario, except for the area set aside for nature conservation, all parameters remain the same as in the *maximum potential harvest* scenario. (Under regulation (EU) 2018/841, set aside forests will still be reported and accounted under MFL).

To study the consequences of increased investments in forestry on net removals in carbon pools and substitution of fossil fuel-based alternatives, we simulate the *improved forest management* scenario. Since the lack of nitrogen limits growth in Boreal forests, this scenario primarily involves fertilization. This model specification presents a moderate fertilization scenario approximating traditional fertilization practices on a larger area, but within the legal fertilization guidelines (intended to promote biodiversity). The simulated fertilized area is thus about 200 kha per year or approximately 1% of productive MFL, roughly 7 times more fertilization than assumed in the other scenarios. This strategy primarily targets middle aged/older coniferous forests. The simulated fertilization thus considers the effect of adding 150 kg N/ha (ammonium nitrate) per occasion, in a five-year cycle. Apart from fertilization, all other parameter settings are identical with the *maximum potential harvest* scenario.

To study the potential risks of negative climate effects on growth, net removals in carbon pools and assumed substitution of fossil fuel-based alternatives, we modify the *maximum potential harvest* scenario by assuming a doubling in natural mortality. For the *negative climate effects on growth* scenario, all other parameter settings remained identical (currently mortality is estimated at around 11% of the growth in Sweden; Forest statistics 2021). To estimate the potential consequences of positive climate effects on tree growth, we use the corresponding IPCC RCP 4.5 pathway (IPCC, 2013) to simulate the *positive climate effects on growth* scenario. In both the negative and positive climate effects scenarios, all other parameter settings remain identical.

For all scenarios, the initial state is set by adopting the existing measured data on the permanent sample plots of the Swedish National Forest Inventory (NFI) in 2010 (Fridman et al., 2014). The Swedish NFI employs area-based sampling on 30,000 permanent sample plots and each sample plot measures 10 m in radius. All plots together represent the total land and freshwater area of Sweden. The NFI is an annual, systematic cluster-sample inventory organized as a systematic grid of sample clusters. The square-shaped clusters are distributed in a denser pattern in the southern than in the northern part of the country. Each cluster consists of four to eight sampling plots. Each sample plot is occasionally delineated into more than one land use category. A variety of tree, stand and site variables are registered on the plots. On each plot, all trees with DBH >= 4 cm are calipered, height is measured and damages recorded on sample trees. Dead wood with diameter >= 10 cm is calipered and stumps are measured (Marklund, 1987; Näslund, 1947; Petersson & Ståhl, 2006)). Land use is assessed in the field with the help of site and stand variables and the existing vegetation cover.

Modelling of biomass, carbon flows and pools

The NFI data used to simulate these scenarios consists of the following parameters. Stem volume and living tree biomass in 2010 is estimated with the help of allometric models (Marklund, 1987; Näslund, 1947; Petersson & Ståhl, 2006; Wikström et al., 2011). The dead wood state is measured on the plots (Sandström et al., 2007; (Lundblad et al., 2019). Changes in carbon pools (living biomass, dead wood, stumps, litter, soil and HWP) are estimated using the stock difference method (Eggleston et al., 2006). Inflows to the HWP-pool are estimated based on simulated harvest. For the substitution effect, harvested roundwood is assumed to yield logging residues for direct bioenergy use. All forest industry processing residues, including a representative share of tops and branches, are assumed used for bioenergy. Since there is considerable debate regarding appropriate substitution factors, we estimate a range, where one m3 harvested stem wood is assumed to result in 0.5, 1 and 1.5 tonnes of *avoided CO_2-emissions* per cubic meter of harvested roundwood (Leskinen et al., 2018; Lundmark et al., 2014). We return to the debate on substitution factors in the Discussion. Other emissions (Tables 4(I) to 4(V); (Eggleston et al., 2006)) are generally minor (under Swedish conditions) and were assessed as a constant emission of 0.096 $MtCO_2e$/yr for all years and scenarios.

The Heureka decision support system simulates the future given initial natural resources, biological limitations on growth (measured on the plots) and assumptions about forest management practices (Wikström et al., 2011). The specification of forest management between two consecutive points in time may include: e.g., fertilization, harvest type and intensity, regeneration type and areas set aside for nature conservation. We model ingrowth, growth (with varying growth equations for young stands, productive forests, unproductive stands (growth less than 1 m^3/ha/yr) and natural mortality. The models are empirical in character and build primarily upon data from the NFI. An algorithm (based on forest owner behavior identified on NFI sample plots) was used to select stands for harvest.

Changes in pools for dead wood, litter and soils were modeled using the Q-model (Ågren et al., 1996). The Q-model is a process-based model built on empirical data. The inflow of organic material is assumed to originate from dead organic matter after harvest, natural mortality and from non-tree vegetation. Model parametrisation settings for 4 Swedish climatic regions were applied. For the initiation of the model, carbon stock level estimates from the Swedish Forest Soil Inventory were assumed to be close to steady state with organic matter input at the first period. A 20-year spin-up period was also used. Inflow/turnover rates were modelled for branches, needles and root fractions and constants assessed for grasses, herbs, shrubs, mosses and lichens. Inflows from harvest residues were estimated per fraction of needles, branches, stems, tops, stumps and roots, and excluded stemwood. In Sweden, roundwood is harvested. But a minor share of the stems is left on harvest sites. A proportion (equivalent to approximately 10 TWh) of tops and branches are also harvested for bioenergy. Stumps are not extracted. Natural mortality is empirically modeled. Stumps and harvest residues are assumed to decompose at an annual rate of 4.6% (Melin et al., 2009) and 15% (Lundblad et al. 2019), respectively. The Q-model is only applied to mineral soils and emissions from drained organic soils are estimated using activity data (area multiplied by emission factors, Lundblad et al. 2019). Different emission factors are used per nutrient status and climate region (Lundblad et al. 2019).

Results

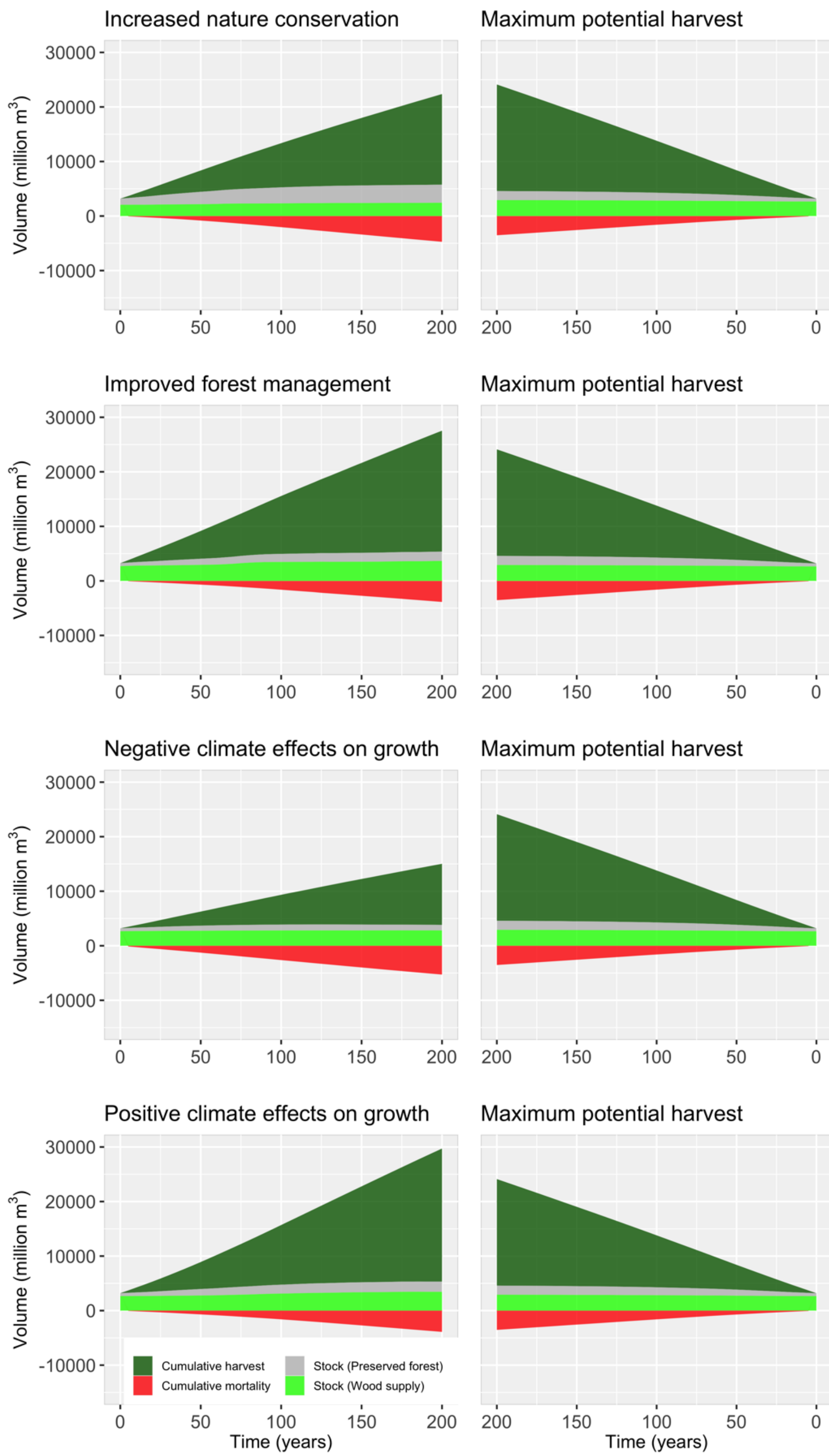

Figure 2) The simulated cumulative stem volume [Mm^3] stored in MFL forests, cumulative harvest and (decomposed) cumulative mortality over a period of 200 years, assuming that 100 % harvest of net growth in MFL is used for wood supply and no harvest in

preserved forests. Note that stand age on the x-axis is represented in mirrored directions in the left- and right-hand figures. In all scenarios, after 200 years, cumulative harvest is greater than storage. From a pure climate perspective, if harvest is used for substitution or stored (where no decomposition occurs), harvesting mature trees and using *maximum potential harvest* provides greater climate benefits than storing carbon in standing forests. This is explained by the higher mortality in protected forests (as represented by the *increased nature conservation* and *maximum potential harvest* scenarios). The *improved forest management* scenario simulates the possibility that intensive forest management may increase the climate benefits associated with forest use. Finally, the *negative* and *positive climate effects on growth* scenarios simulate outcomes depending on whether climate change is negative or positive for tree growth. Since 100% of the net growth is harvested, after peaking at 200 years, the yearly additional growth for harvest remains linearly constant. The differences in the magnitude of the positive volumes are primarily explained by variation in mortality rates.

The *maximum potential harvest* scenario (Figure 2; upper right-hand panel) finds that after around 200 years both stocks (storage) and growth become linear, reflecting our equilibrium predictions. This occurs because we assume 100 % harvest of the net growth on MFL and 0 % harvest in protected forests. After peaking, the constant annual sustainable harvest is estimated at 99 Mm^3/yr. After 200 years, approximately two forest rotation periods, the cumulative harvest is 4.3 times greater than stocks (we assume mortality, due to decomposition, is emitted to the atmosphere). Total gross growth is estimated at 119 Mm^3 per year, similar to current gross growth in Sweden (Forest statistics 2021). Assuming forests remain viable over the very long-term, this relationship will continue in a linear fashion over time.

The *increased nature conservation* scenario (Figure 2 upper left-hand panel), on the other hand, finds that, after peaking, the constant annual sustainable harvest (growth) is estimated at 85 Mm^3/yr. The long-term loss from setting aside an additional 3.7 Mha of productive forest land for nature conservation compared to the *maximum potential harvest* scenario is 14 Mm^3/yr, from peak to perpetuity (a loss of 3.8 m^3/ha/yr of additional forest growth per year over the entire scenario period). Since the two scenarios generate similar total amounts of forest growth, after 200 years estimated stocks + cumulative mortality + cumulative harvests were not significantly different. An important share of the growth in the *increased nature conservation* scenario, however, is lost to cumulative mortality and eventually becomes an emission. In the *maximum potential harvest* scenario, on the other hand, it is never really lost. In the *increased nature conservation* scenario, more volume is also stored in the forest and harvest is smaller than in the *maximum potential harvest* scenario.

The *improved forest management* scenario (Figure 2, second left-hand panel) finds that, after 200 years, the long-term harvest increases to approximately 112 Mm^3/yr (Figure 2, second left-hand panel), or approximately 13 Mm^3/yr more than in the *maximum potential harvest* scenario (and about 27 Mm^3/yr greater than in the *increased nature conservation* scenario). As noted above, however, since significant restrictions on the use of fertilization apply, fertilization is only simulated on about 1% of available MFL. This point raises interesting questions about the possible outcome of greatly increasing MFL fertilization rates.

The *negative climate effects on growth* (Figure 2, third left-hand panel) and the *positive climate effects on growth* (Figure 2, fourth left-hand panel) scenarios both suggest powerful impacts on forest-based mitigation potential. After 200 years, total sustainable harvest growth was significantly lower under the *negative climate effects on growth* scenario (57 Mm^3/yr) and emissions from mortality were higher. On the other hand, the *positive climate effects on growth* scenario, primarily because this scenario affects all MFL equally, resulted in the highest sustainable harvest levels and the largest cumulative impact (137 Mm^3/yr).

Table 2: Total climate benefit across carbon pools for two scenarios given "1 to 1" substitution. (The shaded year refers to reporting under EU/2018/841 for the period 2021-2025).

	[M tonne CO2/yr] Increased nature conservation (Maximum potential harvest)								
Year	living biomass	soil litter	other emissions	(stumps) dead wood	(lying/ standing) dead wood	long lived HWP	short lived HWP	"1 m3 to 1 tonne CO2" substitution Harvest	SUM
10	-26.8 (-11.6)	-5.41 (-4.47)	0.10 (0.10)	-1.14 (-3.23)	-2.97 (-2.47)	-2.79 (-4.65)	0.05 (-0.52)	-77.9 (-89.0)	**-117 (-116)**
15	-33.3 (-16.9)	-5.32 (-5.44)	0.10 (0.10)	-0.02 (-2.25)	-2.63 (-2.07)	-1.96 (-3.88)	0.27 (-0.25)	-75.3 (-88.1)	**-118 (-119)**
30	-31.3 (-17.1)	-3.40 (-1.87)	0.10 (0.10)	-1.50 (-2.24)	-2.47 (-1.52)	-2.29 (-3.30)	-0.43 (-0.44)	-80.3 (-92.3)	**-122 (-119)**
50	-22.9 (-13.8)	-3.74 (-0.97)	0.10 (0.10)	-1.47 (-1.97)	-2.28 (-1.21)	-0.83 (-1.45)	-0.54 (-0.56)	-83.5 (-96.5)	**-115 (-116)**
70	-18.3 (-9.38)	-2.34 (0.20)	0.10 (0.10)	-1.27 (-1.33)	-2.07 (-1.06)	-1.11 (-1.29)	-0.37 (-0.17)	-84.4 (-99.7)	**-110 (-113)**
90	-14.2 (-7.78)	-0.87 (0.86)	0.10 (0.10)	-0.49 (-0.92)	-1.36 (-0.73)	-0.66 (-1.26)	-0.04 (-0.14)	-84.9 (-101)	**-102 (-111)**
110	-10.5 (-5.58)	-0.81 (0.39)	0.10 (0.10)	-0.40 (-0.48)	-0.81 (-0.51)	-0.64 (-1.17)	0.03 (-0.07)	-86.0 (-101)	**-99.0 (-109)**
130	-7.33 (-2.79)	-1.00 (0.69)	0.10 (0.10)	-0.29 (-0.30)	-0.48 (-0.25)	-0.19 (-0.44)	-0.01 (-0.03)	-85.8 (-101)	**-95.0 (-104)**
150	-3.36 (-3.46)	-0.38 (0.35)	0.10 (0.10)	0.26 (0.22)	-0.10 (-0.06)	0.02 (-0.14)	0.07 (0.07)	-84.7 (-99.6)	**-88.1 (-103)**
170	-0.26 (-0.97)	0.36 (0.76)	0.10 (0.10)	-0.40 (-0.23)	0.13 (0.06)	-0.20 (-0.29)	-0.12 (-0.07)	-86.5 (-101)	**-86.8 (-101)**
190	-3.34 (-1.62)	-0.02 (0.86)	0.10 (0.10)	0.49 (0.26)	0.24 (0.15)	0.19 (-0.19)	0.16 (0.10)	-83.4 (-99.1)	**-85.6 (-99.5)**

Table 2 provides more detailed information on the direct climate impact/benefit of change across all carbon pools in the *increased nature conservation* and *maximum potential harvest* scenarios over the same 200-year period, but expressed in terms of their climate impact in carbon equivalents ($MtCO_2e$/yr). In the short-term (i.e., by 2025) the climate benefits are similar in both scenarios. However, in the long-term, i.e., after the carbon pools peak within a period of approximately 200 years, significant differences arise between the two scenarios. In this case, the climate benefit in the *maximum potential harvest* scenario is 16% greater per year (-99.5 $MtCO_2e$/yr) than in the *increased nature conservation* scenario (-85.6 $MtCO_2e$/yr). The climate benefit from the *maximum potential harvest* scenario is represented by net removals of -99.5 $MtCO_2e$/yr from peak to perpetuity, an amount greater than carbon removals in the *increased nature conservation* scenario by -14 $MtCO_2e$/yr. Setting aside an additional 3.7 Mha MFL for nature conservation thus reduces the growth/harvest cycle in the circular bioeconomy, thereby impacting future mitigation opportunities.

The results in Table 2 are further sensitive to the assumed substitution effect (here 1 m^3 to 1 tonne CO_2e). Depending on the assumed rate of substitution, projected outcomes for the total annual net forest-related impact on climate change mitigation vary dramatically (see Figure 3). In most cases, however, the short-term impact of setting aside an additional 3.7 Mha of land for nature conservation is relatively minor compared to the long-term impact of forest use, carbon sequestration in long-lived products and substitution. Only in the most conservative case (1 to 0.5), is the additional carbon sequestration in standing forests simulated by the *increased nature conservation* scenario greater in the short-term than the sequestration/substitution impact of *maximum potential harvest*. The difference in impact is measured as the space between the *increased nature conservation* impact (blue line) and the *maximum potential harvest* impact (green line). As the estimated sequestration/substitution impact increases in size, however, the respective substitution benefits of *maximum potential harvest* increase relative to *increased* *nature conservation*. (In the discussion section we further elaborate the logic behind different estimated substitution impacts).

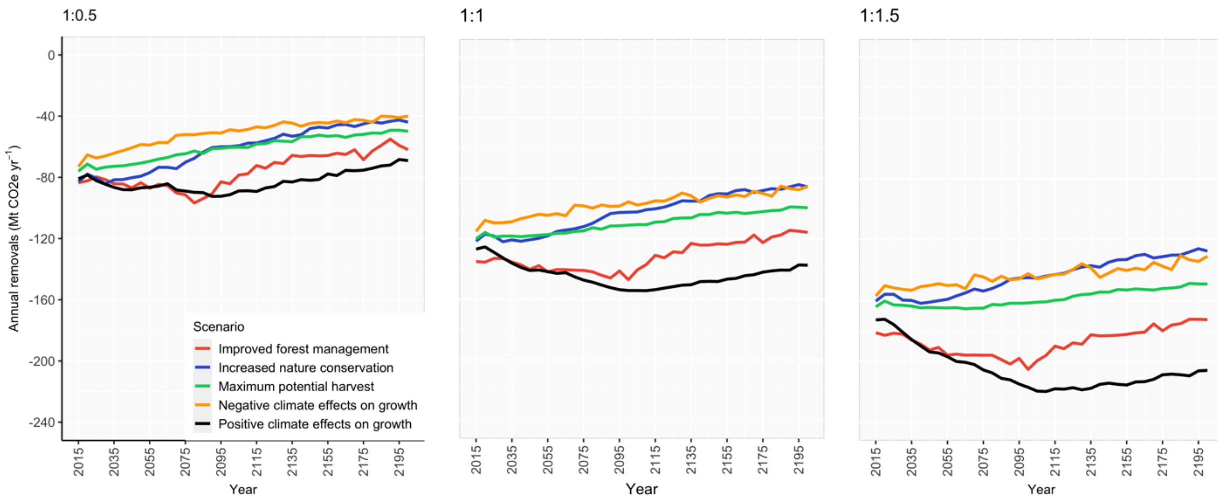

Figure 3) Total Annual Estimated Net Carbon Sequestration and Substitution, Selected Scenarios (2015-2195). The scenarios include changes in all carbon pools (see Table 2) and substitution for three different assumed substitution effects (0.5, 1, and 1,5 tonne CO_2e per m^3 wood). (Observe that, generally, annual removals decline over time for all scenarios.

The *positive climate effects on growth* and *improved forest management* scenarios likewise have very large, continuous impacts on the total net annual sequestration/ substitution potential. While the *positive climate effects on growth* are larger, due to legal restrictions in Sweden, we assume fertilization only on a total of 1% of the available MFL in the *improved forest management* scenario. The *positive climate effects on growth* scenario, however, is not similarly restricted in extent. We cannot really say, however, what might happen if fertilization were permitted on an additional 10% or more of the Swedish MFL.

The Impact of Accounting Rules on Mitigation Incentives

The above results suggest a strategy that maximizes forest use potential tends to yield better climate results. Surprisingly, both UNFCCC *reporting* and EU-level carbon *accounting* rules create important disincentives vis-à-vis Land Use, Land-Use Change and Forestry (LULUCF) and favor net removals in standing forest and land set-asides by constraining harvest levels (FRL) and by disincentivizing benefits for promoting additional forest growth (cap). As political compromises between competing interests and visions of how terrestrial resources should ideally be used, the UNFCCC reporting and EU LULUCF accounting agreements are imperfect. Though they may be required to address multiple societal goals and interests (i.e., climate benefits, food security, wood supply, biodiversity, erosion, water regulation and recreation), their climate impacts are not neutral.

UNFCCC reporting on LULUCF focuses only on the net change in carbon pools and does not assess effects beyond the impact on carbon pools (e.g., substitution, https://unfccc.int/land-use-land-use-change-and-forestry-lulucf). Thus, UNFCCC accounting does not tell the whole story behind the climate impact of forestry. All biomass used for bioenergy production is assumed "oxidized" and fully accounted as harvest. Avoided emissions from reduced fossil fuel dependence, however, are not attributed to the LULUCF sector. Since harvest is already accounted as a decline in living biomass (i.e., as an emission), to avoid double counting and despite measurable emissions, the combustion of tree biomass is accounted as zero in the energy sector. In this sense, though these *avoided* emissions are not strictly counted, by replacing/substituting other fossil fuel emissions, bioenergy use does help countries meet their UNFCCC targets and thus provide real, positive contributions to the global carbon budget.

The same is true for all HWP-based substitution of fossil fuel-intensive products such as steel and cement and for carbon sequestration in the HWP carbon pool. When avoided emissions occur, they are indirectly accounted only as reduced emissions in the energy sector. Harvest, on the other hand, always has a negative impact on total *reported* LULUCF emissions/removals. Thus, UNFCCC reporting on the LULUCF sector fails to reflect what an ideal forest and forest resource-based climate accounting model might look like and thus fails to encourage mitigation actions based on forest use.

Like UNFCCC reporting, EU LULUCF carbon accounting likewise ignores all LULUCF impacts on avoided emissions resulting from substitution. The EU LULUCF regulation (2018/841), however, further creates a separate LULUCF pillar. The creation of pillars limits the role of climate-promoting incentives by making it possible to strictly limit “flexibility” across sectors (the trading/offsetting of credits/debits across sectors). By limiting impacts on other sectors of the climate policy framework, setting limits on forest resource use with the Forest Reference Level (FRL), and by placing a crediting cap on MFL, the EU policy framework represents one of the most restrictive forest frameworks in the world. For another, debits are imposed for harvesting beyond (failing to achieve) the FRL. This strategy explicitly discounts and sets strict limits on the offsetting potential of the forest and forest resource-based sector. Likewise, not achieving the FRL (no-debit rule) is perceived as a failure. The EU LULUCF regulation does, on the other hand, promote long-lived HWP-based carbon sequestration. The remaining components of the carbon accounting framework, however, fail to incentivize the climate benefits of forest growth and substitution (Ellison et al., 2013, 2014, 2020; Nabuurs et al., 2017).

By excluding a share of the forest resource from harvest, the FRL has the effect of increasing uncertainty regarding future forest resource use, thereby weakening future forest investment incentives. While the potential to gain carbon credits from afforesting unmanaged forest lands may make up for this in some cases, the new regulation requires afforested lands outside forest management be integrated into MFL after a period of 20 years (EU 2018/841). Because new forest growth can only be accounted for the first 20 years but then presumably becomes subject to the MFL-based FRL and cap strategies, both public and private sector investment incentives are likely reduced: Since the forest resource can eventually be used for other “purposes”, investors interested only in the long-term set aside effects on biodiversity, for example, may lose interest, while profit-seeking initiatives are weakened through the FRL and the cap.

UNFCCC *reporting* and Paris Agreement-based EU *accounting* practices have different impacts with respect to reputation and the potential impact of sanctions. UNFCCC *reporting* outcomes are reputational in character and do not weigh heavily on individual Parties. EU *accounting* outcomes, on the other hand, can result in penalties (i.e., debits). Parties (or EU Member states) who fall short of their commitments are expected to purchase surplus carbon credits from other countries/Parties.

Table 3 highlights the UNFCCC and EU level reporting and accounting consequences of the respective LULUCF frameworks based on each of the five simulated scenarios for the period 2021-2025. Ideally, the optimal choice is the scenario that both sequesters the most carbon over both the short- and the long-term and has the greatest potential climate impact. Based on our scenario results, the short-term benefits are marginal, while the potential long-term gains are significantly greater. However, both the UNFCCC reporting and the EU accounting frameworks entirely ignore any of the climate effect that arises from the avoided emissions associated with HWP carbon sequestration and bioenergy use. In this regard, however, it may make more sense to pursue long-term strategies.

Table 3: UNFCCC Reported and EU Accounted LULUCF Impacts Relative to their Pure Climate Change Mitigation Effects, 2021-2025
Changes in carbon pools are reported to the UNFCCC. For MFL, changes in carbon pools, living biomass, soil + litter, other emissions and short lived HWP are accounted with a cap compared to the FRL, while dead wood and long-lived HWP are accounted without a cap compared to the FMRL (under CP2). For Sweden, the cap, which limits credits from MFL, is –2.5 M tonnes CO_2e/yr. The total climate effect is calculated as the reported net change in carbon pools, plus the substitution effect. Three alternative substitution effects have been used.

UNFCC Reporting	**NET change in pools [M tonne CO2/yr]**								1 m³ to 0.5 tonne CO2		1 m³ to 1.0 tonne CO2		1 m³ to 1.5 tonne CO2	
Sweden: MFL 2021-2025					long	short	*REPORTED*							
Scenario	living biomass	soil litter	other emissions	dead wood	long lived HWP	short lived HWP	Total		Harvest	Total Climate Effect	Harvest	Total Climate Effect	Harvest	Total Climate Effect
Maximum Potential Harvest	-16.9	-5.4	0.1	-4.3	-3.9	-0.2	**-30.7**		-44.0	**-74.7**	-88.1	**-118.7**	-132.1	**-162.8**
Increased Nature Conservation	-33.3	-5.3	0.1	-2.7	-2.0	0.3	**-42.9**		-37.6	**-80.5**	-75.3	**-118.2**	-112.9	**-155.8**
Improved forest management	-9.3	-4.7	0.1	-7.7	-6.1	-1.2	**-28.9**		-50.8	**-79.7**	-101.7	**-130.6**	-152.5	**-181.4**
Negative Climate Effects on Growth	-10.6	-5.7	0.1	-5.6	-3.3	-0.1	**-25.2**		-42.1	**-67.3**	-84.2	**-109.5**	-126.4	**-151.6**
Positive Climate Effects on Growth	-19.1	-5.8	0.1	-5.6	-4.4	-0.5	**-35.3**		-46.8	**-82.1**	-93.6	**-128.9**	-140.4	**-175.7**

EU Accounting	**NET change in pools relative to the required Reference Level**						
Sweden: MFL 2021-2025	**[M tonne CO2/yr]**				long	short	*ACCOUNTED*
Scenario	living biomass	soil litter	other emissions	dead wood	long lived HWP	short lived HWP	Total
Maximum Potential Harvest	13.4	-4.0	0.0	-1.6	-0.6	0.8	**8.1**
Increased Nature Conservation	-3.1	-3.8	0.0	0.1	1.3	1.4	**-1.1**
Improved forest management	20.9	-3.2	0.0	-5.0	-2.8	-0.1	**9.9**
Negative Climate Effects on Growth	19.6	-4.2	0.0	-2.8	0.0	1.0	**13.5**
Positive Climate Effects on Growth	11.1	-4.3	0.0	-2.9	-1.1	0.6	**3.4**
Reference Levels (effective caps)	-30.2 (cap)	-1.5 (cap)	0.1 (cap)	-2.7 (no cap)	-3.3 (no cap)	-1.1 (cap)	**-38.7 (Total FRL)**

Both UNFCCC reporting and EU accounting encourage short-term impacts. Both for the UNFCCC *reporting* framework and the EU *accounting* frameworks, the scenario yielding the largest benefits is *increased nature conservation*: this strategy provides -42.9 MtCO_2e/yr in UNFCCC reporting benefits and -1.1 MtCO_2e/yr in EU accounting benefits. The principal difference between the UNFCCC and EU outcomes derives from the decision to harvest 100% of the annual net increment. Since the EU accounting framework penalizes harvesting below the FRL, this framework yields an emission in all the scenarios except increased nature conservation. Harvesting even less to fulfill the FRL would improve accounted removals in all cases but would not alter the linear relationships between the different scenarios. Moreover, this would only serve to further raise lost net potential harvest to a point even further below the increased nature conservation scenario over the longer term. Harvesting less (FRL) is essentially equivalent to increasing the relative share of protected forest and would yield outcomes comparable to those predicted by this scenario, with a comparable reduction in the substitution effect. Apart from the *negative climate effects on growth* scenario, both frameworks (UNFCCC and EU) encourage strategies that provide smaller total climate benefits relative to the alternatives.

The long-term future loss from adopting an *increased nature conservation* scenario is significant. Given constant climate conditions, compared to the *maximum potential harvest* scenario and based on the 1-to-1 scenario, the future lost opportunity is estimated at -13.9 MtCO_2e/yr, from peak to perpetuity. The *increased nature conservation* scenario is only capable of producing net removals of approximately -85.6 $MtCO_2e$/yr from peak to perpetuity, while the *maximum potential harvest* scenario can produce as much as -99.5 $MtCO_2e$/yr from peak to perpetuity. Finally, if we consider the potential climate effects across the different substitution effects, the opportunity costs of failing to choose either the *maximum potential harvest* or the *improved forest management* scenarios may be substantially greater.

Discussion

Substitution Effects

Considering short- and long-term alternatives, the potential substitution impact rapidly becomes important. At very low levels of substitution, (1 m^3 to 0.5 tonne CO_2e), the *increased nature conservation* scenario may perform better than the *maximum potential harvest* scenario in the early years of the simulation. However, as soon as we increase the magnitude of the substitution effect, the *maximum potential harvest* scenario quickly becomes the better short- *and* long-term scenario. The only scenarios that perform better vis-à-vis the climate are the *positive climate effects* and the *improved forest management* scenarios, the performance of which are likewise strongly affected by the magnitude of the substitution effect.

Hudiburg et al. (2019) recently suggested that, at least in places like the US, large shares of HWP simply end up in landfills and are never used for substitution. While such outcomes clearly represent *missed opportunities*, the study likewise misses the substitution that occurs at previous points in the HWP life cycle. HWPs can substitute for a range of more fossil fuel intensive products (cement, steel, plastics, glass). And long-lived HWPs simultaneously sequester carbon over extended periods of time, while newly planted forests simultaneously sequester large amounts of new carbon. Where end-of-life-cycle wood resources are squandered, the circular bioeconomy clearly falters. Prior substitution effects, however, are not thereby eliminated: only the opportunity for additional substitution is lost. Moreover, the fact that HWP resources end up in landfills is by no means a justification for increasing rates of forest protection and conservation. It is instead a signal of failed policy intervention and inefficient resource use. This requires a different kind of correction.

Several factors can clearly influence the magnitude of substitution effects. The first is the *quality* of the circular bioeconomy measured in terms of the number of times wood (and other) resources can be used and reused for different purposes, the relative efficiency of wood resource use, as well as the longevity of storage in long-lived wood-based products. Improving the quality of the circular bioeconomy presumably requires public policy intervention. The presence/absence of adequate policy frameworks which encourage or require specific circular behaviors (e.g., fines on wood resources in landfills or legal requirements on paper and used wood resource recycling) matters. Where policy inadequately incentivizes recycling, long-lived HWPs and end-of-life-cycle use and re-use, much can still be done to close the loop and improve the efficiency and effectiveness in the circular bioeconomy and thus its substitution potential. Policy interventions can of course both impose legal requirements on the use and reuse of construction materials, as well as provide public goods to support research on improving the quality of the circular bioeconomy (e.g., improving its efficiency and effectiveness).

The second factor concerns what is meant by the carbon sequestration and substitution impacts of HWP resources. Much substitution, for example, does not require the combustion of the available biomass material. Where HWP products substitute for fossil fuel intensive materials such as cement, steel, plastics or even glass (e.g., as construction materials, furniture or kitchen utensil substitutes), the HWP carbon content remains unaffected (apart from wood processing losses). Thus, the extent to which HWP products can be used and reused, the extent to which HWPs can be improved and used more efficiently (Lundmark et al., 2014), and the extent to which short-lived HWPs can be traded for long-lived HWPs, the greater are the related substitution effects. These substitution effects are additive and independent of the amount of carbon stored in the individual HWP resource.

The calculation of different substitution rates begs the question of which substitution rates are most appropriate? There is, however, no easy answer to this question. In a recent analysis of the Swedish marketplace, others estimated a substitution potential of 0.47-0.75 tonnes CO_2e/ 1 m^3 stem volume (Lundmark et al., 2014). This represents a relatively modest substitution impact from forest resource use. Since the Swedish study was conducted, the forest industry has become more resource and energy efficient and also developed the portfolio of products, which is why the substitution factor is probably higher today. Leskinen et al. (2018) provide a review of some 51 studies which provide estimates of different substitution factors ranging from -0.7 to as much as 5.1 kg C / kg C, or approximately -0.53 to 3.83 tonnes CO_2e/ 1 m^3, with an average of 0.9 tonnes CO_2e/ 1 m^3 and 90% of estimates on the positive side of this range (Leskinen et al., 2018). To the extent substitution effects can be compounded and added together by shifting to longer-lived HWPs, increasing the efficiency of wood resource use, reuse, and ensuring that end-of-life-cycle wood products are used for bioenergy, the related substitution effect will be larger.

Others question substitution effects for various reasons (Harmon, 2019). One of the most appropriate concerns addresses what happens to substitution once countries manage to achieve net-zero targets, whether by 2045, 2050 or later (see also (Brunet-Navarro et al., 2021)). For climate-based reasons, the role of forestry will likely continue to provide biomass-based HWP and bioenergy resources (substitution). Moreover, even after net-zero has been achieved, both negative emissions (either carbon sequestration via forest and forest product-based net removals) and substitution will be required elements of any climate strategy for many years. And strategies such as BECCS could further help accelerate the impacts of substitution and negative emissions, even long after societies have managed to achieve real zero (Burns & Nicholson, 2017).

Even if fossil fuel-based anthropogenic emissions approach zero sometime in the future, hydropower, solar energy, bioenergy and other resources will be needed to provide humankind's energy needs. Where only forest residues and end-of-life cycle HWPs are used to produce bioenergy, this clearly represents a more meaningful use of forest resources than simple decay in forests and landfills. Thus, as long as the net annual exchange of biomass use and net annual biomass growth is zero (i.e., harvest does not exceed gross growth), HWP and forest residues will continue to provide carbon neutral energy resources as a part of the foundation of the circular bioeconomy.

There is, moreover, a certain danger in suggesting that circular bioeconomy concepts rise and fall with concepts of substitution potential. Of course, a key circular economy issue is how best to take advantage of *renewable* resources and avoid, or drastically reduce, the use of scarce, *non-renewable* resources. Since forest products are replenishable over time, the key is to recognize the limits of sustainable forest production and use, not to eliminate their use. Though substitution may no longer be meaningful in the future, the availability of renewable resources is of great significance, especially under the more general conditions of limited resources, peak resource production and declining resource availability. Precisely because wood resources will likely continue to meet with rising demand, in particular due to their circular bioeconomy benefits, more emphasis should ideally be placed on better understanding the real limits of sustainable forest resource use, as well as biodiversity needs.

Finally, the problem of leakage must also be considered. Reducing forestry in some parts of the world where it is already heavily practiced may negatively impact the deforestation of primary forests and significantly increase the intensity of forestry in other parts of the world. The releases of carbon that would result from shifting wood resource production to the tropics should not be ignored.

Can climate benefits be increased through improved forest management (fertilization)?

Although the *improved forest management* scenario increased growth from about 99 (*maximum potential harvest* scenario) to about 112 Mt CO_2e/ year, fertilization was only applied on 1% of the forest area per year. Due to legal restrictions in Sweden, only older forests were assumed fertilized about 10 years before final felling (a common practice in Sweden for fertilized Scots pine stands). Gustavsson et al. (2019) investigated a more intensive management scenario, where growth increased by 40% after one hundred years. Presumably there is great potential to increase growth with the help of fertilization. In the same study Gustavsson et al. (2019), ran a scenario where as much as 50% of the forest land area was protected. Fertilization may thus provide an opportunity to preserve larger areas for biodiversity, while simultaneously managing forests more intensively in other areas, thereby maintaining total growth. Though most fertilizers are fossil-based, from a climate perspective fertilization will become more attractive if organic fertilizers or non-fossil-based processes are used.

Consequences of a changing climate

Discussions about the possible positive and negative climate effects on tree growth trigger divergent responses. For the Nordic boreal forests, the prevailing assumption is that gradual climate change will be positive for growth due to higher CO_2 concentrations and extended growing seasons. This assumption is, for example, supported by analyses of growth trends based on NFI data from Finnish forests (Henttonen et al., 2017; Kauppi et al., 2014). Changes in climatic conditions and resource availability have direct and indirect substantial impacts on the growth and productivity of forests over time through abiotic and biotic factors and mechanisms (Keenan, 2015). Changes in abiotic conditions in the boreal regions, such as increasing temperature, precipitation and atmospheric nitrogen deposition may likewise improve opportunities for growth (Appiah Mensah et al., 2021; Keenan, 2015; Kellomäki et al., 2008; Koca et al., 2006).

From a Nordic boreal perspective, the single most growth-limiting factor in upland soils is nitrogen (N) availability (Tamm, 1991). How N availability develops in a changing climate will likely be critical for the future forest response (Etzold et al., 2020; Kauppi et al., 2014; Tamm, 1991). Compared to current levels in Sweden, climate effects suggest positive future productivity increases of about +300% and +100% in the northern and southern regions respectively, resulting in shorter rotation periods (Bergh et al., 2005). Finally, though we have not estimated this using the HEUREKA framework, forested northern regions are expected to expand further northward, yielding larger areas of forest cover and increasing forest density (Claesson et al., 2015).

On the other hand, other climate-related factors may challenge the positive effects of CO_2 fertilization and longer growing seasons (Hanewinkel et al., 2013; Reyer et al., 2017). A Canadian study based on tree ring analyses showed both negative and positive growth responses depending on tree species, with no strong, overall average effect across the Canadian forest landscape (Girardin et al., 2014). Changes in water availability provided one possible explanation for the divergent responses. Water availability was also highlighted as a factor that could level out or even reverse positive effects on growth in boreal tree species (Reich et al., 2018). Single-factor studies, e.g., the impact of increased CO_2 concentrations, have highlighted the importance of nutrient availability for benefitting from these increased concentrations (Norby et al., 2010; Sigurdsson et al., 2013). In their review of likely impacts from elevated CO_2, N deposition, increased temperature and forest management-based carbon sequestration, some conclude that single-factor responses can be misleading due to intervening interactions between factors (Hyvönen et al., 2007).

In Sweden, increases in evapotranspiration may result in more persistent drought during the growing season, potentially counteracting growth (Koca et al., 2006). Higher groundwater levels and shorter winter soil frost seasons may increase the risk of soil and storm damages from off-road timber transport (Oni et al., 2017). And increasing disturbances from wind, bark beetle and wildfires at European level (Seidl et al., 2014), may become greater concerns in Sweden. For example, (Pinto et al., 2020) found that both climate and vegetation correlate with fire size, whereas human-related landscape features shape ignition patterns. Hence, the boreal forest growth response and carbon cycle feedback to climate change remain uncertain.

Extreme and frequent changes in abiotic conditions could have damaging effects on trees, thereby affecting growth capacity in succeeding years (Keenan, 2015). Tree growth rates in Sweden, for example, were found to be about 20% lower than expected in 2018 due to summertime hot and dry conditions. While temperature effects on tree growth can be severe, precipitation effects may be minimal during the growing season due to the recharge of the ground water table from melted winter snow (Bergh et al., 2005). On the other hand, future events such as storms, frosts and droughts can trigger wildfires, pest and disease outbreaks (e.g., root rot and bark beetles) that may reduce forest growth and productivity (Björkman et al., 2011; Blennow & Olofsson, 2008; Subramanian et al., 2015).

Under specific climatic conditions, forest growth could exhibit varied risks depending on stand age, development stage and management practices (Blennow, 2012). Adaptive forest management practices could be essential for mitigating negative effects, while maximizing forest growth and production (e.g. (Bolte et al., 2009; Keenan, 2015). For instance, reducing the intensity of forest thinnings and rotation lengths have been suggested as the best practice to enhance stem volume production and the profitability of Norway spruce in southern Sweden due to reduced storm risk, root and butt rot (Subramanian et al., 2015). Additionally, the incident rates and magnitude of forest damage by spruce bark beetle are higher in older stands (Martikainen et al., 1999). Forests managed for nature conservation, on the other hand, will be highly susceptible to the associated risks of climate change and may not be suitable for climate improvement in the long term. In this context, intensive forest management for wood production seems plausible.

Suggestions that old-growth forests arrive at a steady state with stable C-stocks have been challenged by studies providing evidence that old-growth forests continue to act as C sinks (Hadden & Grelle, 2016; Luyssaert et al., 2008; Seedre et al., 2015), though Luyssaert et al. have been challenged (Gundersen et al., 2021). Such studies, however, are often based on single stand measurements over limited time periods. Longer-term measurements over entire landscapes which also capture small- and large-scale disturbances may provide more robust determinations about old growth forests. Derderian et al. (2016), for example, resampled a 700-year chronosequence three decades after the initial sampling, only to discover that while the old-growth part of the chronosequence still acted as a moderate sink, C-stocks, due to high mortality among the spruce trees caused by a bark beetle attack had declined compared to thirty years earlier. Likewise, one Canadian study illustrates that national parks with large shares of old-growth forests have large C-stocks but low annual CO_2 uptake, whereas parks with a large share of younger forests had reduced but still large C-stocks and relatively high annual CO_2 uptake over the period 1978-2008 (Sharma et al., 2013). Thus, in national parks, where natural disturbances are rare, existing C-stocks can be preserved. These findings should, however, be considered in light of a changing climate and the increased risk of natural disturbances (e.g. (Seidl et al., 2014).

In a recent study, based on data from the Norwegian NFI, the rapid drop in current annual increment (CAI) at a certain age (cf. Figure 1) was challenged (Stokland, 2021a). The methodology behind that study has been questioned (Brunner, 2021), but Stokland defends his findings and suggests more studies looking into the fate of CAI after the point where CAI crosses MAI (Stokland, 2021b). A more stable CAI over some decades would, from a climate mitigation perspective, speak for extended rotation periods in managed forests. Yet another recent study based on the Finnish NFI confirms the rapid drop in CAI and hence in MAI, with the exception of very poor sites showing a flatter CAI development with age (Repo et al., 2021).

The Swedish NFI compiles detailed, robust and constantly updated information about the state of the forest. Multiple types of data are recorded at the tree, site and stand level, and the quality of the data is checked in several steps after the inventory. The models in the Heureka system are mainly built on empirical NFI data. The models for basal area growth, mortality, and ingrowth for instance, are constructed using data from the permanent plots, i.e., the same plots that form the underlying data for the simulations. The growth and mortality modeling has been validated and Heureka has been shown to generate trustworthy results (Fahlvik et al., 2014). Given regular harvests and no natural disturbances we assume that no unknown variable would change the principal findings. As with all empirical models, precision diminishes if the aim is to simulate the development under circumstances that deviate from the prevailing circumstances at data collection. The positive climate effects from assuming RCP 4.5, for example, rely on process-based assumptions, whereas the future climate impact on tree vitality and growth is uncertain. The outcome of possible negative climate effects is also uncertain.

Tradeoffs between biodiversity & mitigation?

Tradeoffs between biodiversity-driven set asides and climate change mitigation potential may arise from the choice of land set-asides. Immediate biodiversity goals are better achieved with older forests (Gao et al., 2015; Martikainen et al., 2000). As we have demonstrated, since younger forests sequester more carbon, this will have a negative impact on mitigation potential. Thus, the choice of land set aside type is not a neutral choice. Older forest set asides will result in arriving at a steady state much earlier than is optimal for promoting short-term mitigation potential. In our increased conservation scenario, we assume comparatively younger forest set-asides. However, the common practice in Sweden is to set aside remote, little used forests and older high biodiversity potential forests (such as the primary forests highlighted in the *EU Biodiversity Strategy for 2030*). To the extent set asides occur exclusively or even primarily in older forests, this will weaken the short-term benefits shown in this study.

Policy Frameworks

The FRL reference established in the context of the EU's LULUCF regulation (2018/841) represents a significant burden for Member states that make use of their forest resources for bioenergy purposes. While emission reductions are indirectly accounted in the energy sector, harvest (for whatever purpose) is accounted only in the LULUCF sector. Since gains (avoided emissions) are not weighed directly against harvest-related emissions, this strategy conflicts with the bioeconomy interests of many Member states.

The FRL strategy essentially requires Member states to set limits on the total share of the forest resource to be harvested. Theoretically, the FRL is set in order to protect annual net removals (sinks) and to limit the increasing intensity of forest use (Matthews, 2020). However, this calculation neglects the fact that bioenergy-based *avoided emissions* in the energy sector fulfill the same goals and may even do this more efficiently and effectively. Part of the answer to this question lies in the magnitude of the actual, realized substitution effect. To the extent that the FRL has the effect of increasing forest protection, as mimicked under the *increased forest conservation* scenario, it is likely to increase mortality and reduce the production of usable forest biomass and its related substitution effects. We have highlighted the significant losses in terms of the future biomass resource.

The strategy for establishing the FRL further sets limits on countries that have regularly been harvesting comparatively low shares of the available net increment across the 2000-2009 period. The LULUCF ruling essentially locks in behavior and suggests countries should continue to harvest at the same rate: harvest intensity should not increase. The Netherlands, for example, harvested approximately 55% of the annual net increment over the period 2003-2013 (Arets & Schelhaas, 2019), while Sweden has typically harvested a significantly larger share of its overall net increment (on average, approximately 82% over the period 2000-2009, excluding commercial thinnings) (Swedish Ministry of the Environment, 2019). This approach thus reduces the potential for countries that use smaller shares of their forest resource to increase production and promote greater total amounts of substitution.

Though the FRL strategy may help promote additional forest protections and conservation, and potentially increase the immediate forest sink while reducing land use intensity, there is little evidence this will promote climate change mitigation at comparable rates. Our results suggest the opposite. Moreover, as noted above, there are important implications for the leakage that will result from increasing protections on European forests, thereby reducing the amount of European forest available for harvest (Grassi et al., 2018; Kallio & Solberg, 2018; Solberg et al., 2019). This strategy is likely to unleash consumer demand pressures on international trade that will drive biodiversity loss in parts of the world that still host the principal share of global primary forests and some of the richest carbon stores. If trade in wood products releases these stores, it will have far greater negative climate impacts than the continued and increased use of European forest resources.

On the other hand, to the extent land set-asides and increased forest protections do not affect the practice of forestry, unless they involve the regeneration of degraded forest lands, they will likely have little effect on overall mitigation potential. In Sweden, for example, newly proposed land set-asides may not involve intensively managed lands. Similarly, the plan to set aside some of the remaining primary forests in Europe, because of their age, is not likely to significantly affect carbon sequestration rates in standing forests. This could, however, have significant positive impacts for protecting what remains of European forest biodiversity (Sabatini et al., 2018, 2020).

To optimize the climate effects of forestry, it is preferable to consider substitution effects and enable flexibilities in trade across sectors. To evaluate what is best for the climate requires studying all land and atmosphere fluxes over a longer period. Current consideration of the next version of the EU LULUCF policy framework (COM(2021) 554 final) provides opportunities to address these concerns.

Conclusions

Though storing carbon in standing forests clearly contributes to climate change mitigation, this strategy has definable limits that emerge once forests achieve a long-term steady state where carbon sequestration is essentially equal to forest-based emissions. To the best of our knowledge, the long-term net impact of standing forests on the annual net carbon balance is at or very near zero.

To achieve long term reductions of atmospheric CO_2, on the other hand, it may be best to view the forestry enterprise – the circular forest-based bioeconomy – as the mechanism by which the net forest impact on the climate can be maximized by progressively increasing the magnitude of total annual forest growth, as well as potential carbon sequestration and substitution effects. As our scenarios suggest, the net forest impact on the climate is maximized when forest growth and the potential annual substitution effect have been maximized.

We have calculated the net effect of increasing forest set-asides on a relatively modest share of productive forest land (18.5%). Given constant climate conditions and compared to the *maximum potential harvest* scenario, the future lost opportunity is estimated at -13.9 $MtCO_2e$/yr. This effect is not small. Current net removals in standing forests, and thus the total net carbon sequestration impact of Swedish LULUCF during the 2nd Commitment period, is approximately -49 MtCO_2e/yr. Based only on this total (and ignoring potential additional impacts from the related substitution effects), this would suggest a future mitigation loss from increased forest protections of approximately 28%/yr from peak to perpetuity. Cumulated over longer periods of time, this would represent the loss of a substantial share of the negative emissions required to continue extracting carbon from the atmosphere. Moreover, if we include substitution effects and consider their potential magnitude, this amount could be much greater.

It is entirely possible to pursue forest management as a strategy for maintaining and strengthening the forest role as a "regulator" of atmospheric GHG concentrations. Moreover, concepts of the circular (bio)-economy have long been founded on the idea that naturally recurring resources should be used, while scarce and non-renewable resources should be protected. Since forests represent a quintessential and naturally renewable resource, they should be used carefully and judiciously. The sustainable management of forest resources will thus provide societal benefits through harvested wood for biobased products long after the urgent need for immediate mitigation benefits has begun to subside.

Policy interventions that could meaningfully mobilize the climate benefits of forest use are, however, currently hamstrung by a misplaced and misguided emphasis on reducing the decline in the forest carbon sink and harnessing pressures to increase forest use intensity. Pressures to reduce forest use intensity likewise do not augur well for thinking through other potentially interesting scenarios, such as bargains focused on trading reduced forest use in exchange for increased fertilization on equal shares of land. As the above scenarios suggest, policy interventions could indeed go a long way toward better mobilizing forest use in favor of the climate. If current policy initiatives are maintained, especially at the EU level, we expect the opposite to happen. Significant lost opportunities would likely reverberate across the broad range of EU member states. Key policy and research innovations that could further help mobilize forests in favor of the climate are: achieving greater flexibility in the trading of carbon credits across the multiple sectors of the climate policy framework, eliminating the "no-debit role", along with the FRL and the cap, and improving the accounting of and knowledge about substitution effects.

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