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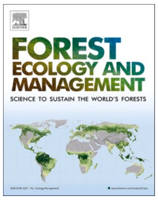

Managing existing forests can mitigate climate change

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ABSTRACT

Planting new forests has received scientific and political attention as a measure to mitigate climate change. Large, new forests have been planted in places like China and Ethiopia and, over time, a billion hectares could become available globally for planting new forests. Sustainable management of forests, which are available to wood production, has received less attention despite these forests covering at least two billion hectares globally. Better management of existing forests would improve forest growth and help mitigate climate change by increasing the forest carbon (C) stock, by storing C in forest products, and by generating wood-based materials substituting fossil C based materials or other CO_2-emission-intensive materials. Some published research assumes a trade-off between the timber harvested from existing forests and the stock of C in those forest ecosystems, asserting that both cannot increase simultaneously. We tested this assumption using the uniquely detailed forest inventory data available from Finland, Norway and Sweden, hereafter denoted northern Europe. We focused on the period 1960 – 2017, that saw little change in the total area covered by forests in northern Europe. At the start of the period, rotational forestry practices began to diffuse, eventually replacing selective felling management systems as the most common management practice. Looking at data over the period we find that despite significant increases in timber and pulp wood harvests, the growth of the forest C stock accelerated. Over the study period, the C stock of the forest ecosystems in northern Europe increased by nearly 70%, while annual timber harvests increased at the about 40% over the same period. This increase in the forest C stock was close to on par with the CO_2-emissions from the region (other greenhouse gases not included). Our results suggest that the important effects of management on forest growth allows the forest C stock and timber harvests to increase simultaneously. The development in northern Europe raises the question of how better forest management can improve forest growth elsewhere around the globe while at the same time protecting biodiversity and preserving landscapes.

1. Introduction

For forests to sequester atmospheric CO_2, new growth must exceed the losses of C following tree harvests, natural mortality and decay, and gaseous and hydrologic fluxes of C from ecosystems (Ciais et al., 2008; Pan et al., 2011). A large potential exists to improve the capacity of established forests around the world to absorb atmospheric CO_2. Forests available for wood production cover about 2.0 billion hectares globally (FAO, 2020). They often intermingle with land used for agroforestry which cover an estimated 0.6–1.2 billion ha (Albrecht and Kandji, 2003). By promoting growth and preventing early mortality and decay better forest management can build up the C stock in living trees, dead trees and in litter and soil (Lundmark et al., 2014; Yousefpour et al., 2019).

Some model simulations have suggested that timber harvest will reduce the rate of C sequestration of forest ecosystems (Holtsmark,

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2012; Hoel and Sletten, 2016). While felling an individual tree interrupts photosynthesis and ends that tree's ability to sequester C, it does not follow that forestry must cause a net C loss across forested landscapes consisting of millions of trees and tree stands of different age. Here we analyze impacts of timber and pulpwood harvests on C sequestration at the national level.

Theoretically, afforestation and reforestation could raise the area of global forest by almost one billion hectares, from 3.5 to 4.4 billion hectares, with substantial new opportunity for sequestering atmospheric C (Bastin et al., 2019). While many parts of the world are engaged in planting and restoring forests, and new plantations can absorb C effectively (Forster et al., 2021), establishing new forests on any grand scale could quickly conflict with other land uses (Song et al., 2018; Delzeit et al., 2019; Doelman et al., 2020). In contrast to planting new forests, improving management practices in forests does not require land-cover change and therefore avoids direct conflicts with food production. Forests host a large fraction of the global terrestrial biodiversity. Establishing new forests will almost certainly change the biological diversity of species. In ideal cases these changes can serve to enrich the nature, however, where afforestation takes place in naturally tree-less ecosystems (grass lands and open wetlands) new tree growth can conflict with established natural habitats.

In this research we focus on *forest C stocks* that include the mass of C embedded in live or dead tissues of trees and in forest soils and exclude the C in other flora, fauna, and harvested wood products. Changes of forest growth can have profound impacts on whether the forest offers a C sink or C source. The *forest C sink* refers to a net increase in the forest C stock, while a *forest C source* refers to a net decrease.

Forests of Finland, Norway and Sweden have been exceptionally well monitored beginning in the years 1921, 1919 and 1923, respectively (Tomppo et al., 2011; Fridman et al., 2014). National Forest Inventories (NFI) of the three countries periodically report observations of forest attributes including the growing stock of the stems of living trees (in volume, m^3), the Gross Annual Increment (net growth in terms of stem volume), and the Gross Annual Decrement (losses of the volume of living trees in harvests, tree mortality and natural disturbances). Similar data on C stocks and sinks exist widely and have been synthesized globally, but the time series tend to be shorter or less nuanced than those available in northern Europe. We emphasize the scientific value of the long-term record of Gross Annual Increment available in northern Europe, which is exceptional internationally.

The objective of this research is to gain insight into the potential of forests available for wood production to contribute to climate change mitigation. We analyze empirical NFI data from forests of northern Europe estimating C stocks and sinks during the period 1960 to 2017. We then analyze the impacts of changing forest growth on changes in the forest C sink and elaborate on the evolution of forest management practices over the period affecting forest growth. Finally, we discuss the significance of forest management in the context of climate change mitigation within the region, by comparing C sink estimates with the respective CO_2 emissions from fossil fuel combustion. We discuss experiences from northern Europe in assessing climate change mitigation in other forested regions of the World.

2. Materials and methods

2.1. Data from national forest inventories

We used data from the open access databases of National Forest Inventories (NFIs) of Finland, Norway, and Sweden (Natural Resources Institute Finland (LUKE), 2020; Statistisk Sentral Byrå (SSB), 2020b; Swedish University of Agricultural Sciences (SLU), 2020). Data for harvested wood volumes in Sweden were retrieved from the Swedish Forest Agency's database (The Swedish Forest Agency (SFA), 2020). *Forested area* was defined as by FAO, i.e., tree canopy cover of more than 10% and patch area of at least 0.5 ha and the trees should be able to reach a minimum height of 5 m. *Productive forest area* was defined as an area, where the forested land has a capacity to produce more than 1 m^3 ha^{-1} yr^{-1} (as stem wood volume). Our data are available in Supplementary Materials. For estimates of C sink, forest growth and forest decrement we used data representing productive forest area. Approximately 95% of growth, decrements and C sink are located within the productive forests. In this research we do not analyze the time lag of C losses associated in the decomposition of harvested material, natural mortality, or disturbances. Some fractions of lost C may persist for decades either as woody debris in ecosystems or as wood-based products in active use.

Gross Annual Increment was derived using empirical observations available from the NFIs that rely on field measurements of the radial and apical growth taken from statistically representative stems. Gross Annual Increment differs fundamentally from the more commonly used concept Net Primary Production (NPP). In annual plants such as agricultural crops, nearly all the C captured in NPP returns to the atmosphere before the next growing season. In trees, a fraction of NPP is integrated into the woody tissues retained in the structure of stems, coarse roots, and branches. Unlike NPP, the Gross Annual Increment refers to the inter-annual gross gain of new biomass of woody tissues that is carried over from one growing season to the next. Gross Annual Increment thus excludes the shedding of leaves/needles, small twigs and fine roots, which constitute a significant part of NPP (Matamala et al., 2003).

The volume attributes of stem wood can be converted to whole-tree C. Forest increment C can be compared with the concurrent decrement C. Whenever increment C exceeds decrement C the surplus C equals the (net) carbon sink. Conversely, a forest C source is observed whenever decrement C is larger than increment C indicating that the C stock of forest ecosystem becomes depleted. In this research we describe a case in northern Europe, where the buildup of C stocks in forest ecosystems has resulted in a persistent C sink for nearly 6 decades.

We used yearly data from 1960 to 2017 on Gross Annual Increment, Gross Annual Decrement, and Growing Stock volume for Finland, Norway, and Sweden. Our data refer to stem wood volume including bark to the top of the stem with the wood volume calculated from stem diameter at breast height and tree height. As an example of how the this volume is calculated, in Sweden, all sample trees from the Swedish NFI 1998–2017 (a total 228 000 trees representing all age classes and tree species) were calculated by applying Näslund's allometric functions (Näslund, 1947).

Specifically for Finland, a delay of 2–6 years has been characteristic of growth observations. During 1960–2001 in Finland, Gross Annual Increment was measured retrospectively from a tree ring sample as the arithmetic mean of the latest five years, combined with observations of the latest five years of apical growth. In other words, the latest available observations of forest growth have been 2 to 6 years old. Interpolations between two consecutive NFI cycles and taking the five-year mean of forest growth smoothens the trajectory of Gross Annual Increment masking inter-annual variations. Tomppo et al. (2011) summarize the collection methods used for the field observations of NFIs in Finland. More recently in Finland, the method of measuring Gross Annual Increment has changed and is now more sensitive to inter-annual variations.

2.2. Volume to biomass; and biomass to whole-tree C

For extrapolating NFI data into units of C, we used a conversion from stem volume to whole-tree C content. All living stems of trees are supported by a canopy and a root system, and the geometry of the roots and canopy follows an adaptive synchrony of stem tissues, a balance referred to as thé pipe-model theorý (Valentine, 1985). Whole tree biomass (dry mass) of trees was estimated based on the concept of the Biomass Expansion Factor (Lehtonen et al., 2004), originally drawing on Marklund's allometric functions (Marklund, 1988) and the models of Repola et al. (2007). The wood density, even for a single species can vary, for example the density of Scots pine varies in extreme cases from 0.274 to 0.697 g cm $^{-3}$ (Auty et al., 2014). Wood density can also vary over time in the same species, for example, early wood within the tree ring of Norway spruce has been measured to 0.396 ± 0.096 g cm^{-3}, then declining while increasing again toward latewood (Jyske et al., 2008). The C content of dry biomass can also vary depending on the chemical composition of woody tissues, although at a relatively narrow range around 48% to 52% (Lamlom and Savidge, 2003).

Noting the uncertainty in determining the Biomass Expansion Factor, wood density, and C content, our analysis progressed in two steps. First, a single and discrete ratio was used linking whole-tree C content to growing stock volume thus ignoring variation sources. Then, a sufficiently large range of uncertainty was introduced to cover all sources of variation. In step one, a ratio of 0.75 t m^{-3} was applied between the total tree biomass and stem volume and a C content of 50% (0.375 t C m^{-3}) was applied to estimate the C stock (Sandström et al., 2007). Because carbon dioxide (CO_2) has a molecular weight 3.67 times higher than elementary C, we obtained a coefficient of 1.375 (=0.375 × 3.67) t CO_2 m^{-3} to convert one cubic meter of stem wood into sequestered carbon dioxide of whole-tree biomass. In step two, to account for the uncertainty of the method we use a range of 1.0–1.5 t CO_2 m^{-3} for this coefficient.

For estimating the C sink, the *flux method* was used that involves subtracting the C content of the annual decrements from the C content of the gross annual increment within the same year. An alternative method of calculation, the *stock method*, estimates the C sink as a buildup of the C stock from one year to the next. For both methods we used identical factors for converting stem volume to whole-tree biomass, and biomass to C.

2.3. *C in forest soils*

Field-based data on the C sink in forest soils are only available for mineral soils from Sweden, which started a Forest Soil Inventory (FSI) in the 1980́s alongside the National Forest Inventory[23]. The Swedish Forest Soils Inventory has monitored soil C since 1990 in the uppermost organic mor-layer and the mineral soil down to 50 cm soil depth. For the other two countries, the values for changes in soil C as well as GHG emissions from organic soils in all three countries are the result of modeling. Emissions of methane (CH_4) and nitrous oxide (N_2O) are reported in CO_2-equivalents. All data are found in the national reports to the UNFCCC (United Nations Framework Convention on Climate Change[24] and in Supplement).

Our data are extracted by combining several columns (i.e. for litter, mineral soils and for organic soils), in the reports to UNFCCC from each country. Out calculations account for the different fractions of forest land on organic soils in each (6% in Norway, 15% in Sweden and 27% in Finland). Though the three countries differ in how they assign data into the different columns, the aggregation yields similar results per unit area for mineral soils (including litter and superficial organic matter on top of the mineral soil) and for organic soils across the study region. A more detailed explanation and key references are available in Supplementary Materials.

3. Results

3.1. *Trends of carbon sink and harvests*

3.1.1. *C sink estimated using a single coefficient converting volume to C*

The C sink in forest trees in northern Europe increased from less than 30 to more than 90 Mt CO_2 yr^{-1} between the 1960s and 2017 (Table 1; using the conversion coefficient 1.375, stem volume to whole-tree C). The estimates of the C sink are shown for two independent calculation methods, stock method and flux method. Positive numbers in Table 1 indicate net transfer of CO_2 from the atmosphere into forest trees, and vice versa.

For northern Europe, the C sink in forest trees was at least three times larger in 2010–2017 than in the 1960́s. With few exceptions, the C sink persisted over all regions, all decades, and independent of the method used for assessment. A large discrepancy between the two methods was detected in the 1960 s for Sweden and may relate to two storm events late in the decade. Using the discrete conversion coefficient and selecting the more conservative flux method in Table 1, the change in the C sink from the 1960 to 2010–17 was estimated as 94.9 – 27.2 = 67.2, a factor of 3.5. By 2017, the C sink for the three countries combined exceeded 90 Mt CO_2 yr^{-1} regardless of the method.

3.1.2. *C sink estimated using a range of coefficients converting volume to C*

Using a range of coefficients for converting stem volume to the mass of C in whole-tree biomass does not change the pattern of increasing C sink. Using the very conservative assumption that the conversion coefficient decreased from 1.5 to 1.0 between 1960 and 2017, we find that the C sink rose from 29.7 to 69.0 Mt CO_2 yr^{-1}, an increase of 132%.

While the long-term change of the C sink is significant and clearly shown, the latest development since 1990 is subtle and more uncertain. Indications of a saturation of the sink can be detected since 1990 in Norway and Finland (Table 1). Nevertheless, the C stock continued to increase until the end of the time series.

3.1.3. *C sink and sources in forest soils*

Reliable empirical records of changes in C content of forest soils are available at national scale only for mineral soils (including litter and soil organic matter on top of the mineral soil) in Sweden since 1990 where these soils sequestered 0.29 t CO_2 ha^{-1} yr^{-1} on average during the period 1990 – 2017. Further back in time, empirical data do not exist for estimating long-term changes of soil C. Estimates for all three countries from 1990 to 2017 show increases in C content in mineral soils do not differ very much among countries, with 0.12, 0.08 and 0.13 t C ha^{-1} yr^{-1} in Norway, Sweden and Finland, respectively.

Drained forested peatlands are modelled to have high emissions of greenhouse gases with an estimated figure of 1.4 t CO_2 ha^{-1} yr^{-1} emitted from all forested peatlands in Sweden and Finland. This figure however encompasses much higher modelled emission from the portion of drained peatlands and is not comparable to the reliable estimates of C uptake in trees and do not merit a detailed analysis. We note, nevertheless, that there are some important trends in the country data reported to UNFCCC (see Supplement) including increases in soil C in

Table 1

Carbon sink in living trees estimated using the flux and stock methods for the tree biomass on productive forestland over decadal periods from 1960 to 2017, Values in Mt CO_2 yr^{-1}.

	Estimation method	1960–69	1970–79	1980–89	1990–99	2000–09	2010–17
Finland	*Flux*	−0.8	13.5	24.6	31.5	38.4	35.3
	Stock	−1.7	17.1	32.9	31.2	28.3	25.4
Norway	*Flux*	4.8	6.9	8.4	14.3	20.8	18.3
	Stock	6.5	7.8	13.9	16.8	25.4	21.7
Sweden	*Flux*	23.2	20.8	48.1	38.9	30.8	41.3
	Stock	3.9	25.7	33.8	30.9	41.9	48.1
northern Europe, total	*Flux*	**27.2**	**41.1**	**81.1**	**84.7**	**89.9**	**94.9**
	Stock	**8.7**	**50.6**	**80.6**	**78.9**	**95.7**	**95.3**

mineral soils in Norway of 300% and in Sweden of 200%. No comparable major change was reported in mineral soils in Finland during the period. With regard to the large contribution to GHG emissions from forested peatlands in Finland we note that these emissions have been estimated to decrease by around 50% during the period studied from −13000 to 5000 kt CO_2 yr^{-1} (see Supplement). We refrain from providing a detailed estimate for the C sequestered in all forest soils in the three countries during the period studied but conclude that on average these soils are a minor C sink, which appears to increase in strength across northern Europe.

3.1.4. *Trends of harvests*

Timber and pulpwood harvests increased by about 40% in the period 1960 – 2017, strongest in Sweden. An increase in harvests, and therefore the Gross Annual Decrement, did not compromise the trends of the rising C sink in living trees. Storms triggered significant natural disturbances with stand-replacing impacts, while wildfires and pest outbreaks occurred only at small scale. Our data indicate that on average about 90% of stem wood decrements were related to harvests while 10% were associated with natural mortality including storm events. Fallen trees were usually harvested after severe storms and thus were included in harvest statistics.

3.2. *Trends of forest growth*

An acceleration of forest growth, outweighing the impact of increasing harvests was a decisive element affecting the C sink (Fig. 1). From 1960 – 2017, the Gross Annual Increment grew 68% from 149 to 251 Mm^3 yr^{-1}, corresponding to a change in carbon dioxide sequestration from +205 to +345 Mt yr^{-1}. The high Gross Annual Increment was sufficient to sustain both the increased harvests and the enhanced C sink. We now focus on the evolution of Gross Annual Increment and on the role of forest management in influencing the trend.

An unusually low ratio of growth-to-decrements prevailed in Finland in the 1960s and in Sweden in the early 1970s (Fig. 1). Events causing growth to lag annual decrements were exceptional and did not distort the sustained long-term trend of the C sink. For instance, a severe storm event in January 2005 triggered a sharp peak in salvage harvests in Sweden (Valinger and Fridman, 2011) that was short lived.

In Finland, increased harvests since 2010 narrowed the gap between increments and decrements. At the same time the average forest growth was highest in Finland in early 21st century, where the age structure of forests favored intensive growth. Nabuurs et al. (2013) have elaborated on similar trends in a wider European context.

Norway offers an example of the average standing stock approaching a steady-state due to its large share of mature forests. In Norway, the Gross Annual Increment nearly doubled from 1960 to 2000, while

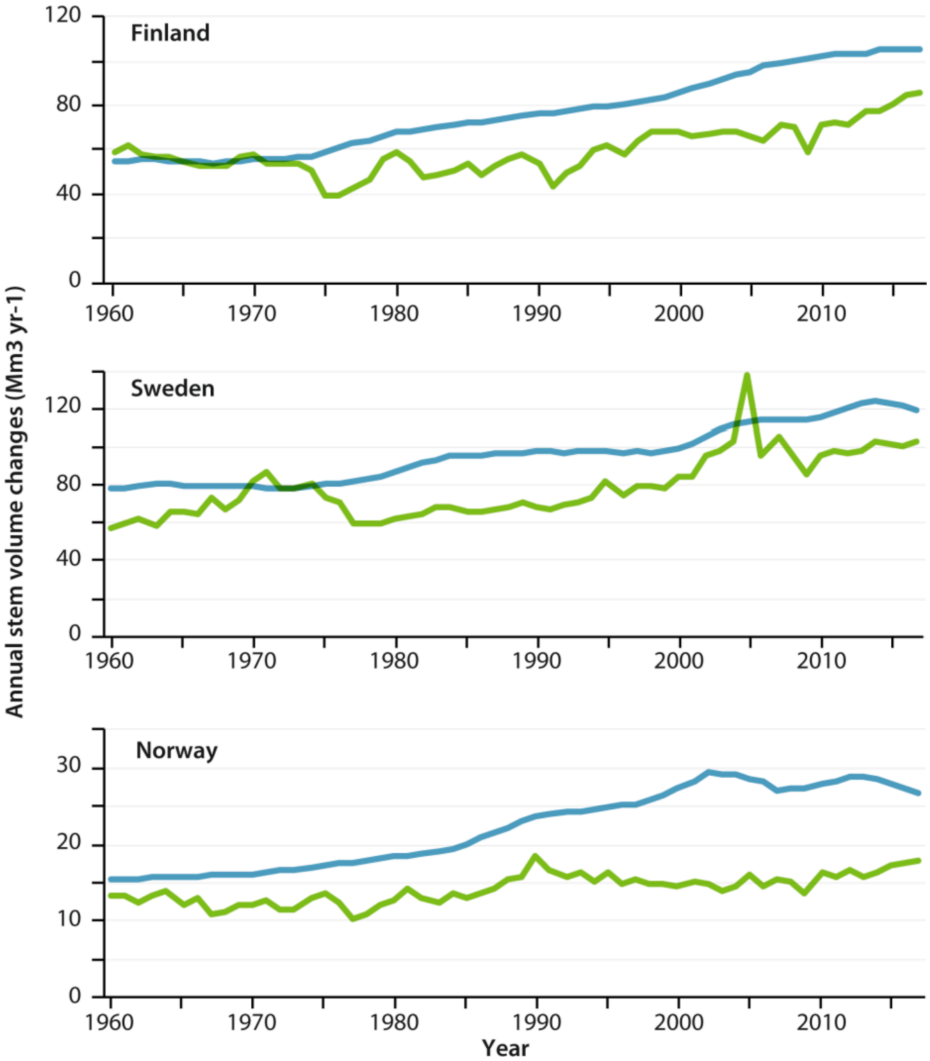

Fig. 1. Gross Annual Increment (blue) and Gross Annual Decrement (green) over time for Finland, Norway, and Sweden on the productive forestland. Note different scales on y-axes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

decrements increased only slightly. Forest growth and the C sink stabilized in Norway or slightly even declined in 2010–2017. This evolution corresponds to the swift transition of Norwaýs economical structure away from agriculture and forestry to the development of oil and gas industries, as well as aquaculture, since the 1970s. Relatively modest timber harvests over the latest decades left Norwegian forests with a large fraction (63%) of mature forests (Table 2). The terḿ maturé does not directly relate to stand age, because maturation age of any stand will depend on climate and soil properties. Rather´Mature forestś refer to stands of trees with a Gross Annual Increment that is rapidly decelerating as the stand age increases.

3.3. *Fossil fuel emissions in northern Europe*

In the context of discussing the contribution of forest growth to mitigating climate change, it is interesting to compare changes in the forest C stock with industrial CO_2 emissions from northern Europe. The carbon sink of forests in Finland, Norway and Sweden matched a significant proportion of the CO_2 emissions from fossil fuel combustion within the region, especially in the latest period of our study. During 2010–2017 combined emissions from fossil fuel combustion averaged 126 Mt CO_2 (excluding emissions of methane, nitrous oxides and other non-CO_2 greenhouse gases from animal husbandry and other activities, bunker emissions from international transport, and emissions from cement production) (International Energy Agency, 2015) (Table 3). Over the same period, forest trees sequestered annually 69–103 Mt CO_2 with a small and uncertain additional sink in forest soils. The system boundaries for calculating emissions are also ambiguous, because international trade has increased and has strongly affected the forest sector and the transport of fossil fuels and the transmission of electricity. Finland and Sweden imported oil, while Norway became a major net exporter of oil and gas.

4. Drivers of increasing forest growth

4.1. *Transitions of forest management*

The rise of forest growth in the forests of northern Europe, a decisive component of the carbon budget, emerged since the mid-20th century. Changes in forest management, land use, and environment influenced forest growth. We draw attention to changes of forest management and the development of forests policies in Sweden described by Enander that also applies to Finland and Norway (Enander, 2011). Fig. 2 illustrates the evolution of forestry policies and practices of northern Europe starting before the 20th century.

From 1850 − 1900, forest industry, at that time mainly saw-mills, evolved with few regulations. Forests were selectively logged, i.e., picking the largest trees with no active regeneration measures. Foresters and landowners relied instead on natural regeneration in the gaps resulting from the felling of individual trees. In the second period, 1900–1950, the increasing economic importance of forests across the three northern European countries resulted in forestry policies that aimed for sustainable production forestry. In the third period, rotation cycle forestry that required active investments in silviculture replaced dimensional logging. The aim of the new approach was to promote forest growth and stocking density, establish efficient harvesting schemes and secure forest regeneration.

Table 2
Structure of forests growing on productive forest land.

Country	Young forests (%)	Middle-aged forests (%)	Mature forests (%)
Finland	17	70	13
Norway	17	20	63
Sweden	27	40	33
Average	**21**	**47**	**32**

Forest management practices thus shifted over time from exploiting degraded and sparse tree populations to promoting fully stocked, even-aged and fast-growing forest stands. Important tools of this approach were mathematical models for growth and yield in combination with using Walter Bitterlichś invention of the relascope in the late 1940′s (Burkhart, 2008). Together these were used to encourage dense stands and vigorous trees intended to realize the potential of each forest site and to respond to local and regional changes in the environment. Taken together these developments accelerated the upgrading production capacity of forests in northern Europe (Henttonen et al., 2017). Detailed tree size distributions are available from Finland, where the frequency of the largest trees (trunks $\geq$ 40 cm diameter at breast height) increased by + 325% from a century before (Henttonen et al., 2019, 2020). Statistics starting in the 1920s show that significant changes did not begin until after the 1950s.

A scientific consensus is emerging on the question: What confined forest growth and C sink of forest ecosystems in northern Europe in the early 20th century? Stems were fewer, smaller, and less vigorous in forests back then, compared to the composition of tree populations in modern forests (Henttonen et al., 2019). Under the regime of selective harvests, small saplings grew slowly underneath the shade of elder trees. As much as 60 years was required for a freshly emerged spruce germinant to ascend to a height of 1.3 m (Eerikäinen et al., 2014). Low stocking density *per se* was a constraint on forest growth as well with earlier stands typically containing an insufficient number of stems (Hynynen et al., 2019). Experimental data show that selective removals not only limited the number of trees per hectare but, in fact, discriminated against dominant and vigorous trees (Bianchi et al., 2020).

The transition of forest management in the 1950s and 1960s was also associated with changes in land use. Cattle grazing in forests was a common practice in northern Europe until mid-20th century, a northern version of agroforestry. Pastoral landscapes were open and benign but sparsely stocked with tall trees. With the abandonment of cattle grazing, such landscapes gradually returned to fully stocked forests. A recent study shows that reduced grazing in Austria, France and the United States also correlated positively with the rate of expansion of forest biomass, while increased harvests did not deplete those forest resources (Gingrich et al., 2022). These results are consistent with our findings from northern Europe.

Especially in Finland and Sweden, forest management has become economically important supporting jobs and livelihoods and meeting the demand for forest products from a large international market. The markets for timber and pulpwood motivated forest owners to invest in forest management; investments that promoted high forest growth (Chudy and Cubbage, 2020). Forest management offered rewards from an economic and social perspective. Tree planting serves an example of the scale of the practices creating jobs within seedling production, soil preparation, manufacturing the required devices and machines, in logistics and planting. Approximately 25 billion trees were planted in northern Europe during 1960–2017 (Table 4). Large programs for constructing forest roads required economic investments in the latter half of the 20th century and assisted in implementing forest management.

4.2. *Other drivers of forest growth*

Changes in the environment also played a role (Henttonen et al., 2017) in increased forest growth reinforcing the impacts of more intensive management. The atmospheric concentration of CO_2 changed from 1960 to 2017 by nearly + 25%. CO_2-fertilization affected Gross Annual Increment at least in some forests, where shortage of nutrients or drought did not limit photosynthesis. It remains difficult to quantify impacts of CO_2 fertilization on forest growth in isolation from impacts of other changes in the environment such as climate warming and nitrogen deposition. In our study region N deposition is on average rather low (Ackerman et al., 2019). Based on references and data shown in this research we conclude that the significant acceleration of the Gross

Table 3

CO_2 emissions (Mt CO_2) from fossil fuel combustion (International Energy Agency, 2015).

Country	2010	2011	2012	2013	2014	2015	2016	2017	Mean
Finland	62.0	54.6	48.9	49.7	45.7	42.4	45.2	42.4	**48.9**
Norway	40.0	38.2	37.1	37.9	37.7	38.1	37.3	36.5	**37.9**
Sweden	46.8	43.2	40.7	37.7	37.7	37.2	37.2	36.8	**39.7**
Total	148.8	136.0	126.7	125.3	121.1	117.7	119.7	115.7	**126.4**

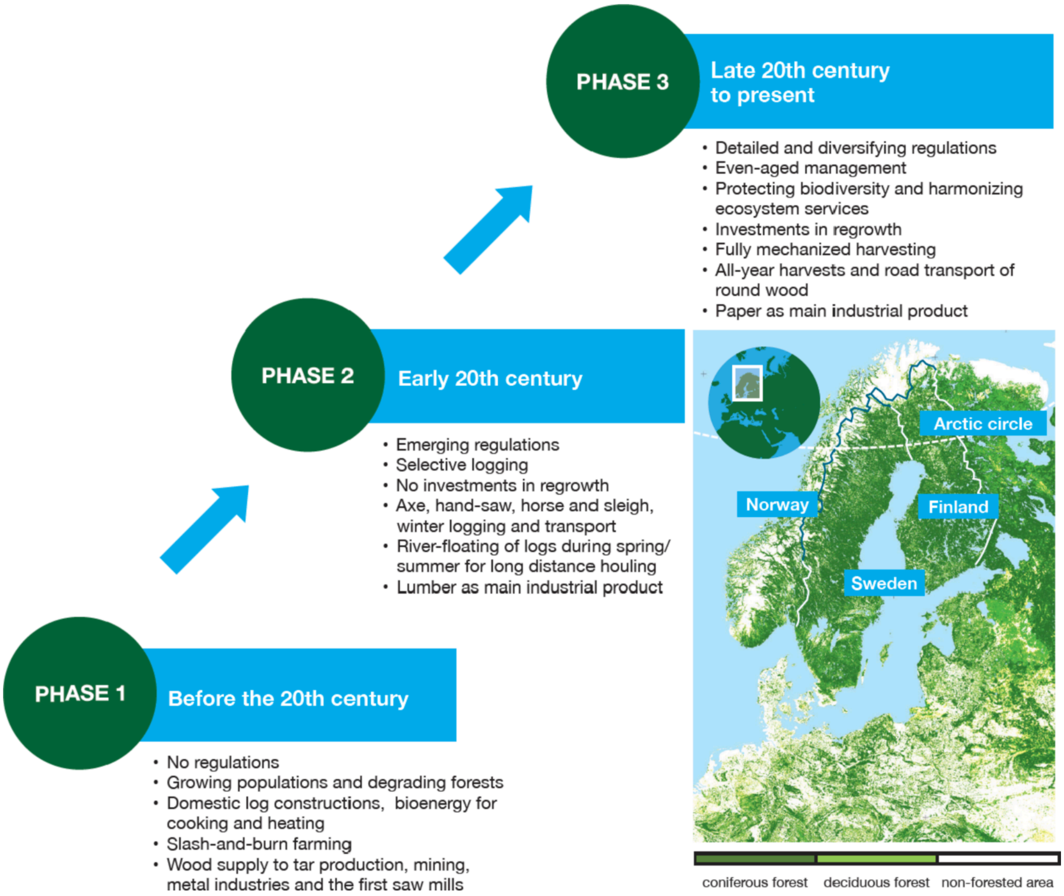

Fig. 2. Main management characteristics and use of northern European forests, classified as three phases, extending over a total period of more than 150 years. Map © ESA Climate Change Initiative.

Table 4

Area of regeneration and total number seedlings planted during 1960–2017 (Natural Resources Institute Finland (LUKE), 2020; Statistisk Sentral Byrå (SSB), 2020a; The Swedish Forest Agency (SFA), 2020).

Country	Planted area (Mha)	Number of planted seedlings (10^9)
Finland	5.1	9.9
Norway[*]	1.1	2.2
Sweden	6.5[**]	13.0[***]
Sum	12.6	25.1

[*] The Norwegian data include 1970–2017.

[**] The Swedish data only contained the total regenerated area, which included both the planted and sown area, hence we used the proportion between the planted and sown area for Finland (73%) to estimate the planted area for Sweden to 70%.

[***] The Swedish data did not contain number of seedlings planted, hence we used the average seedlings planted per ha in Finland (1942 plants/ha) and Norway (2088 plants/ha) to estimate the average in Sweden to 2000 seedlings per ha. We then multiplied this with the planted area to estimate the total number of seedlings planted during the period.

Annual Increment was mainly driven by restoring degraded forests and actively applying forest management practices thus creating stands that were responsive to environmental changes such as surplus CO_2 and longer growing seasons.

In reports from unmanaged forests from Germany, elevated temperatures, raised CO_2 concentrations and increased deposition of nitrogen prompted a 6–7% growth increase during 1960 – 2000 (Pretzsch et al., 2014). In our data, the Gross Annual Increment in northern European forests accelerated much more strongly. Analyses from Finland assigned 30–50% of the accelerated change to environmental changes, while the attribution to restoring degraded forests and changing forest management was 50–70% (Kauppi et al., 2014; Henttonen et al., 2017). Climate warming including elongation of the season of tree growth was a key component of change in the northern European environment (Aalto et al., 2021). Environmental changes reinforced the responses of Gross Annual Increment to altered forest management.

Fire management, draining of peatlands, and – to a lesser extent – forest fertilization also affected the rate of forest growth. Tree breeding programs were implemented but did not yet affect forest growth significantly by the end of our study period. A long response time is required until genetically improved seedlings mature and affect forest growth at large geographic scales.

5. Discussion

Across northern Europe, significantly higher forest growth combined with more moderately increasing harvests (and natural mortality) resulted in a persistent and significant growth of the C sink over this period of 58 years. During the study period 1960–2017 an average sink of 49 – 74 Mt CO_2 yr^{-1} was recorded in living trees allowing for the uncertainty of the estimation method. Cumulatively, from 1960 to 2017, the C stock of living trees increased 50–76%. In forest soils, the concurrent C sink was positive, but much smaller, more uncertain and estimated empirically only in Sweden for the period 1990–2017. Cumulative total transfers of atmospheric CO_2 into the forest ecosystems for 58 years contributed to a net forest sink estimated at 3.5 – 5.0 Gt in wood resources and forest soils. Simultaneously, harvests, and to a lesser degree other forest disturbances and natural mortality generated a total loss of 5.8–6.4 Gt CO_2 from the forest ecosystems.

The concept Negative Emissions of Carbon (NEC) has been introduced as an attribute of C sequestration in terrestrial ecosystems (Houghton and Nassikas, 2018). Our results offer a quantification of NEC in forests available for wood production covering nearly 60 million hectares in northern Europe. In this region approximately five million forest hectares are allocated to nature protection and recreation and are not available to wood production (FAO, 2020). Forest management aiming at growth promotion can contributes to sustainable development at the global scale, noting that the forest available for wood production covers approximately half of World́s forested area.

Rising forest growth has promoted the carbon sink in forests available to wood production of northern Europe. Similar trends are unknown at broader global scales because forest growth cannot be measured using remote sensing and forest inventory programs providing long term records of forest growth are scarce internationally.

Observing forest growth remains an unresolved challenge for remote sensing methods as the rate of cell formation under tree bark and underneath closed canopies cannot yet be observed remotely but must be measured from samples taken *in situ*. Remote sensing instruments change over time and although they improve, such changes of instruments create problems in time series analyses (Breidenbach et al., 2022). Even with challenges to measuring forest growth based on remote sensing, opportunities for international monitoring of especially the growing stock can improve significantly. Combining field measurements with data from remote sensing platforms, introduced in the 1980s, remains the predominant approach for monitoring global forests. Field measurements of the NFI's are essential in validating these techniques (Tomppo et al., 2011).

6. Concluding remarks

Our study area covers about 63 Mha of forests and the question follows: Can management practices affect the forest growth and the C sequestration for the remaining global area (~2000 Mha) of forests available to wood production? New evidence from China shows that along with large recent plantations, existing forests have played a predominant role in enhancing the C stocks in Chinese forest ecosystems (Zhao et al., 2021). The potential role in climate change mitigation of forests available to wood production merits new, intensive research in all forested countries.

Persistent demand for timber and pulpwood motivated and financed forest management in northern Europe, which hosts about one third of the combined forest resources of western Europe (EU + Norway + Britain) and exports wood-based products to the global market. Manufacturing wood-based products has played an exceptional role in financing the national economies of Finland, Norway, and Sweden. These three countries generate 15–30% of the global international trade of printing paper, board, special papers, pulp, lumber, and plywood, depending on product category. More than two thirds of the products are exported out of the region. Besides supporting jobs, export earnings from wood processing industries have assisted in covering the costs of forest management such as building forest roads and planting billions of new trees. Such funding arrangements for financing forest management are not entirely unique internationally but are far from universal. Transport difficulties remain fundamentally challenging to forest management, especially in remote regions of Russia and Canada. The inability to respond to the global demand of wood-based products weakens the economic motivation to invest in forest management for some forests of the world.

Our study shows that a carbon sink in the forests of northern Europe has persisted for almost sixty years. Management practices have strongly contributed to rates of tree growth and C sequestration within forests available to wood production. This strategic approach complements international efforts of planting new forests. Model simulations limited to smaller areas or individual forest stands regularly claim that harvesting wood necessarily increase C sources over time. However, they do so by neglecting the landscape perspective and underestimating impacts of evolving practices of forest management.

In 2020 planted forests covered 293 million ha globally (FAO, 2020). In these forests, forest growth and C sequestration are directly under management control. It is less clear what the impact of management could be on the estimated 2.0 billion ha of existing forests available to wood production. Ideally, forestry could see a new emphasis on selecting suitable combinations of tree species for an area (Messier et al., 2022), encouraging fully stocked stands, improving the rate of success of tree planting, using improved tree genotypes, supplying growth limiting factors, and implementing adaptive management of natural disturbances, which becomes increasing important as the global climate continues to change. Further essential elements of modern forest management include practices and regulations to prevent the spread of insects and pests as well as fire management.

Even more uncertain is what could be the effect of forest management on the estimated 0.6 – 1.2 billion ha of agroforestry systems around the world. In agroforestry, nitrogen fixation, fruit production and fire-wood collection may have high priority. Selecting the best tree species for each site is important, and the list of alternative tree species is much longer in temperate and tropical forests compared to our study region. Plant breeding programs hold promise as well as strategic geographic transfers of plant material to improve the survival and make use of plant material with genetically higher productivity.

Unlike elsewhere in boreal forests, the carbon stock of forest ecosystems has significantly expanded in Finland, Norway, and Sweden (Högberg et al., 2021). We claim that this development has been mainly a response to changes in forest management. In this article we have presented conclusive evidence showing a surprising combination of increasing C sequestration alongside significantly increased harvests. Our analysis suggests that management of already existing forests constitutes an effective, but neglected, tool for increasing contributions of forests to climate change mitigation. Our empirical results call for the continued development of economically sustainable forest management that provides a rationale for maintaining forests for timber production and C sequestration. Economically sustainable management of forest ecosystems can thrive if all ecosystem services are valued and adequately paid for. As the stocks of C in forest ecosystems continue building up, scientists and policy analysts must pay special attention to protecting and restoring the biodiversity of forests and creating adaptive management practices noting the increasing pressure for wildfires, pest outbreaks and storm damages.

Author contributions

P.K., T.L., G.S., H.F.H., A.N., I.W. conceptualized the research, G.S., P.K., T.L., P.H., L.A-C., I.H-S., A.S. collected data and provided data analyses, L.A-C., G.S compiled the Swedish data, carried out calculations and designed Tables and Figures, P.K., P.H., T.L. A.N, I.H-S., H.F.H prepared the first draft. All authors contributed to finalizing the manuscript.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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