NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

Case study on impacts of large-scale re-/afforestation on ecosystem services in Nordic regions

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Executive Summary & Policy relevant messages

This deliverable presents a case study on the role of forest-based carbon dioxide (CO_2) removal (CDR) as Negative Emission Technologies and Practices (NETP) and their effect on regulating, provisioning, and cultural ecosystem services in the Nordic countries Finland, Sweden, and Norway. The focus is on re-/afforestation and changes in forest management practices, bioenergy production potentially combined with carbon capture and storage (BECCS), and wood products storing carbon for long time.

The Nordic natural environment is far more dominated by forest than the rest of Europe, with relatively unfavourable climate for forest growth especially regarding short growing seasons. The soils are less fertile, and the pool of soil organic carbon (SOC) is high. Still, increasing biomass of the Nordic forests has a significant role as carbon trade-offs in national carbon budgets, i.e. carbon uptake in forests balanced roughly between 20-40% of the annual anthropogenic CO_2 emissions since 1990. The Nordic Prime Ministers have jointly signed the 2019 Helsinki Declaration on Nordic Carbon Neutrality and have thus established ambitious net-zero CO_2 emission targets. Without the forest sector, the Nordic countries will not be able to meet their net-zero emission goals.

Land area for afforestation (i.e., forest on land that is not previously forest-covered) is limited in the Nordic countries. Reforestation and afforestation are therefore not separately assessed in this deliverable. In Finland, the re-/afforestation potential is mainly found on former agricultural land and on peatlands formerly used for peat production for energy purposes. In Norway planting of forests are considered on recently abandoned and former pasture. CDR in standing forest can be increased through changes in forest management and harvesting regimes.

The forest's potential for CDR differs greatly with different forest management measures. Nitrogen and ash fertilization is used to a greater extent in Sweden and Finland than in Norway. In Finland, the estimated average CDR potential of fertilization could be more significant than re-/afforestation plus conservation potential. While Norwegian authorities identify rejuvenation of forests with optimum tree species and increased tree density, followed up by young forest care as actions that have the largest CDR potential. Increased forest conservation is estimated to have CDR potentials of similar magnitude as re-/afforestation in both Finland and Sweden because standing forest is an active carbon sink.

In addition to a significant carbon sink, the forests provide harvested wood products (HWP) that partly are used to substitute fossil carbon-based products, and biomass for bioenergy substituting fossil fuels. This dual role can lead to intensified harvesting, which inherently will lead to a lower carbon sink and stock in forests. The three Nordic countries have plans to increase their use of HWP. In addition, forest-based bioenergy account for about a quarter of the energy production in Sweden and Finland. This bioenergy is mostly produced from side streams in the forest industry. An additional common characteristic for Finland and Sweden is the widely distributed district heating systems, which allow for combined heat and power production plants, and thereby high efficiencies in bioenergy use.

The large forest industry and comprehensive use of bioenergy in Sweden and Finland creates especially advantageous conditions for the deployment of BECCS, with the already existing point sources for biogenic CO_2 representing record high CDR potentials. In Norway the capacity for transport and storage of CO_2 under the North Sea seabed will by mid-2024 be 1.5 million tonnes CO_2 per year, with the capacity to increase up to 5 million tonnes CO_2 per year. For comparison, recent anthropogenic CO_2 emissions summed for Finland, Sweden and Norway are in the order of 150 million tonnes CO_2 per year.

Highest CDR potentials within the forestry sector are reported for restoration of drained peat soils, the increased production of long-lasting wood products and leaving harvest residues in the field. The CDR by re-/afforestation and forest management may in the Nordic region be offset by changes in the large SOC stores. In boreal forests the SOC pool has a turnover time of 250 years and can in size be 2 to 5 times that of the standing biomass. This entails that a small loss of SOC can substantially offset the CDR potential. Given the relatively slow forest growth rates and the large pools of SOC in high latitude Nordic countries, the net CDR effect of re-/afforestation as NETP remain under scientific debate. Especially, the common forestry on ditched and drained organic peatlands represents potentially loss of SOC. A main forest management practice to limit greenhouse gas (GHG) emissions is thus the rewetting of these drained forested peatlands. Although a reduction of GHG fluxes is achieved on the short term, a CDR effect is probably only relevant on longer timescales.

The climate effect by re-/afforestation may in Norway, Sweden and Finland also be offset by changes in surface albedo due to changes in seasonal snow cover. The climate effect of loss in albedo is larger than the effect of CDR by increased biomass where there is a long period with snow cover during winter, such as in the mountains, while the effect of increased biomass is larger than the effect of albedo in the lowlands.

All assessed NETPs have significant effects on regulating, provisioning, and cultural ecosystem services. The measures with the most positive impacts are those that promote stable forests i.e., conservation and reduced deforestation. By contrast, the largest negative impacts on environmental and social values are associated with re-/afforestation and intensified forest management. In a Nordic perspective, it is especially the effect on terrestrial biodiversity, water quality, and recreation that are pertinent. The loss of semi-natural grasslands habitat and fragmentation of old-growth boreal forests are both conceived as a major challenge for biodiversity in managed forests in the Nordic countries also effect the water quality by generating higher fluxes of nutrients and dissolved natural organic matter (DOM), leading to increased eutrophication and GHG emissions from lakes, respectively. As Nordic water supply is commonly based on surface raw water sources the increase in DOM is a challenge as it is costly to remove. Re-/afforestation has also an effect on how landscapes are valued for recreation and tourism, as pasture landscapes are the most favoured, while densely planted spruce forests are the least favoured.

Key policy relevant messages:

- Bioenergy with carbon capture and sequestration has a very high CDR potential due to already existing large point sources of biogenic CO_2 (from forest industry and bioenergy production).
- The potential for climate change mitigation of re-/afforestation is rather limited.
- Restoration of ditched and drained peatlands is a highly effective measure for reducing CO_2 emissions but may increase the risk of methane release.
- Increasing the share of long-lasting HWP (compared to short-lasting products, such as pulp and paper) is an effective CDR measure with few direct negative effects.
    - An important exception is if increased demand for HWP leads to more intensive harvesting and forest management, the CDR potential will drop and negative impacts on other ecosystem services will increase.
- No regret NETP measures for increased CDR are reduced deforestation, increased forest conservation and longer forest rotation time.
- Re-/afforestation of especially former pasture lands is negatively perceived in terms of recreational, touristic, and cultural values.

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Abbreviations

BAU = Business as usual

BECCS = Bioenergy production combined with carbon capture and storage

BVOC = Biogenic volatile organic compounds

CDR = Carbon dioxide removal

CH_4 = Methane

CHP = Combined heat and power production plants

CO_2 = Carbon dioxide

DOM = Dissolved natural organic matter

EU = European Union

GHG = Green House Gas

HWP = Harvested wood products

IPCC = Intergovernmental Panel on Climate Change

LULUCF = Land Use, Land-Use Change and Forestry sector

Mt = Million tonnes

N_2O = Nitrous oxide

NETP = Negative Emission Technologies and Practices

SDG = Sustainable Development Goals

SOC = Soil organic carbon

SOC = Soil organic carbon

SOM = Soil organic matter

TOC = Total organic carbon

UNFCCC = Nations Framework Convention on Climate Change

WEM = With Existing Measures

Introduction

The Intergovernmental Panel on Climate Change (IPCC) considers afforestation as one of the key strategies available to the forestry sector for mitigating climate change (Nabuurs et al., 2007; IPCC, 2022). The forestry sector also has a crucial role in European Union's climate targets.

This deliverable presents a case study on the role of forest-based carbon dioxide (CO_2) removal (CDR) practices available and their specific features in the Nordic region. The focus was originally on potential of re-/afforestation and its impacts on carbon sequestration and ecosystem services, but the scope of the deliverable is extended to cover also other potential forest and forest biomass-based CDR practices in the Nordic countries. This includes increased forest carbon uptake by changes in management practices, bioenergy production potentially combined with carbon capture and storage (BECCS), and biobased products storing carbon for long time e.g., in building materials. These are evaluated in the context of wider bioeconomy targets in Nordic countries. The geographic scope of the study is Finland, Sweden, and Norway.

These three countries have extensive forest cover and forests play a significant role in their national carbon budgets. When we consider climate change and its mitigation, two functions of Nordic forests have been highlighted: they act as significant carbon sinks and storages, and they provide biomass that partly is used to substitute fossil carbon-based products with biobased carbon-based products and fossil fuels with bioenergy. There is thus an ambition by the Nordic governments to increase the sustainability of their bioeconomy by increasing the forest biomass in the quest to meet climate obligations. However, there are trade-offs between the targets to increase the CO_2 sink and the use of biomass to replace fossil carbon with biogenic carbon.

In addition to their functions in the climate system, forests impact several other regulating, provisioning, and cultural ecosystem services. Moreover, the intended climate benefits from CO_2 removal by increasing carbon stocks in forests may in the Nordic region be offset by changes in soil organic carbon (SOC) stores and changes in other climate forcings such as albedo. A better understanding of such negative side-effects is a prerequisite for the development of a knowledge-based policy to abate climate change within the forest sector, ensuring a sustainable management of natural resources and ecosystem services.

Chapter 1 presents an overview of the Nordic forestry sector, and the Nordic government plans regarding the role of the forestry sector in climate change mitigation. The current targets for re-/afforestation, as well as possibilities for increasing forest biomass and associated C sequestration in biomass and soils through different management practices are reviewed. Based on this assessment, the potential for enhanced CO_2 removal practices through forest management is discussed.

Chapter 2 presents a literature review of potential environmental effects of the forest-based CO_2 removal practices on local climate and ecosystem services, and conflicts with existing environmental policies. This includes the negative side-effects on climate targets, due to reduced albedo and loss of SOC, and detrimental as well as favourable effects on ecosystem services related to terrestrial biodiversity, water quality and other ecosystem services.

In Chapter 3, we discuss the potential and role of forest Negative Emission Technologies and Practices (NETPs) for CDR in the Nordic countries in the European context.

1 Potential for forest-based CO_2-removals in Nordic countries

The recent IPCC 6th assessment report from Working group III on mitigation measures (IPCC, 2022) highlights that the deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 emissions are to be achieved. In this, the use of forests for CDR is a central topic being mentioned 50 times throughout the Summary for policymakers.

Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods. Moreover, there is globally a large economic mitigation potential within the agricultural, forestry and land-use sector at costs below USD100 tCO_2 eq^{-1}. Up to half of this is available at less than EUR20 tCO_2 eq^{-1} and could be upscaled in the near term across most regions according to the IPCC report. The largest share of this economic potential comes from the conservation, improved management, and restoration of forests. The improved and expanded use of sustainably sourced wood products to replace more Green House Gas (GHG) intensive products is also stated in the IPCC report to have some CDR potential through the allocation of harvested wood to longer-lived products, increasing recycling or material substitution.

As a basis for the literature search on potentials of forest related NETPs in Nordic countries (1.4-1.6), this chapter first introduces general aspects on re-/afforestation and forest management (1.1), Nordic net zero targets (1.2), and provides an overview on the forestry sector within the three assessed countries (1.3).

1.1 Reforestation, afforestation, and forest management

At a global level, re-/afforestation are generally considered as affordable practices to create negative CO_2 emissions and are thus already readily included in the mitigation scenarios from cost-optimizing integrated assessment models summarized in the IPCC reports. NEGEM Deliverable 8.1 present a summary on the role of various NETPs used in the IPCC report on the impacts of global warming of 1.5°C (IPCC, 2018). Afforestation was the second most used NETP in these scenarios after bioenergy combined with carbon capture and storage (BECCS), with a median uptake of about 3.8 $GtCO_2$ $year^{-1}$ in 2050 (Table 1). Based on systematic literature review, Fuss et al. (2018) estimated the global sustainable re-/afforestation potential to be lower, at 0.5–3.6 $GtCO_2$ $year^{-1}$ by 2050.

Table 1 Summary of for the contribution by negative emission technologies and practices (NETPs) in reaching global mitigation scenarios in the IAM 1.5°C Scenarios Database (Huppmann et al., 2019; NEGEM D8.1, Koljonen et al., 2022).

NETP	Number of scenarios	Median value in 2050, $MtCO_2$ yr^{-1}	Median value in 2100, $MtCO_2$ yr^{-1}
BECCS	266	3,300	10,840
DAC – CCS	8	50	6,420
Afforestation	51	3,790	4,740
Enhanced weathering	1	1,200	2,500
Soil carbon / biochar	1	3,600	3,500
Total NETPs	275	11,940	27,950

NEGEM Deliverable 1.1 point out that a clear distinction between reforestation and afforestation is often missing in the literature. A common differentiation refers to afforestation as planting trees on land not covered by forest during the previous 50 years. In contrast, reforestation consists of replanting trees on recently deforested land (NEGEM D1.1, Cobo et al., 2022). It was also noted that it is more cost-efficient to reduce deforestation than focus on re-/afforestation and reforestation activities. In the Nordic context re-/afforestation are not major issues. They are thus not separately assessed in this deliverable.

Forests are considered a non-permanent carbon pool since carbon stored in trees can return to the atmosphere through fire, mortality caused by insect outbreaks, windfalls, or land-use change. Moreover, decay of dead wood and litter will eventually release all the sequestered CO_2 back to the atmosphere. Thus, to what extent re-/afforestation removes atmospheric CO_2 depends on the time frame relative to the duration of locked atmospheric CO_2 in 'safe storage'. The issues related to permanence of "nature-based" carbon storages are discussed in NEGEM Deliverable 2.2 (Mitchell-Larson and Allen, 2022).

The potential for re-/afforestation in the Nordic countries is limited compared to other European countries, as a large proportion of their land is already forested, with relatively limited areas suitable for agriculture. However, carbon accumulation in standing forest can be increased through several measures related to forest management and harvesting regimes. Northern forest soils store large amounts of organic carbon, so avoiding loss of this SOC to the atmosphere (i.e., as greenhouse gases) caused by forest-based CDR is important for the climate effect of these measures.

1.2 Nordic net-zero targets

The Nordic Prime Ministers have jointly signed the 2019 Helsinki Declaration on Nordic Carbon Neutrality. They announced that Nordic countries want to lead by example and to intensify cooperation related to removing CO_2 from the atmosphere (NORDEN, 2021). All Nordic countries have thus established ambitious net-zero CO_2 emission targets for their climate policies. It must be noted that the Nordic countries use different approaches for incorporation of CDR by forests to achieve net-zero targets, e.g. Finland includes total sink to its 2035 target, whereas Sweden accounts only for an additional sink compared to a reference level (Table 2).

The role of the forest carbon sink is important in the national greenhouse gas inventories for all Nordic countries, as the remaining anthropogenic emissions are planned to be balanced at least partly with the carbon sink within the Land Use, Land-Use Change and Forestry (LULUCF) sector. Without their forests, the Nordic countries will likely not be able to meet their net-zero emission targets. This is due to emission reductions in other sectors, such as industry, agriculture, and transport, do not appear to be rapid enough considering their present substantial fossil fuel-based energy dependence (Figure 1).

Table 2 Nordic emission reduction targets (NORDEN, 2021)

Country	Net-zero GHG emissions
Denmark	2050
Finland	2035
Iceland	2040
Sweden	2045
Norway	80-90% reduction by 2050

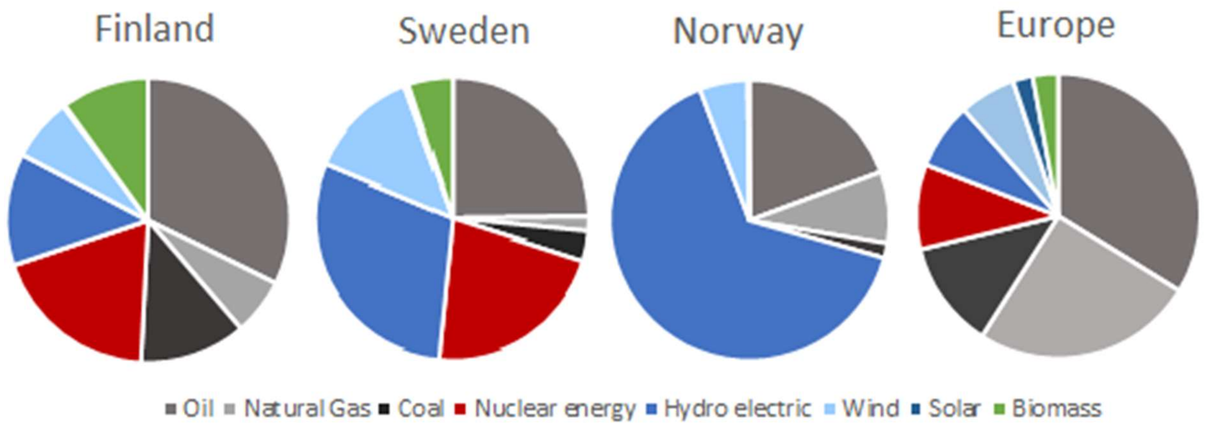


Figure 1. Share of the main primary energy sources in Finland, Sweden, and Norway (Data extracted from British Petroleum (2022). Note the share of biomass, displayed in light green.

1.3 Background on Nordic forests and forest industry

Finland, Sweden, and Norway have extensive forests, covering 71% of the land surface in Finland, 66% in Sweden and 44% in Norway (OECD 2022) (Figure 2). The large forest industry sector, especially in Finland and Sweden, plays an important role in climate mitigation. Foremost, forests act as important carbon sinks and thus balance emissions from other sectors in the national greenhouse gas inventories (Figure 3). The forest carbon sink will thus have a crucial role in achieving the nations net-zero carbon targets. In addition, forests provide biomass feedstock for pulp and paper industry, for various mechanical wood products and construction, for the energy sector, and in future for various sectors of bioeconomy (e.g., advanced biofuels, bioplastics, textiles, chemicals, medication, food etc.) (MMM, 2022). This additional role of forests allows to replace existing fossil-carbon-based products with green biogenic-carbon based ones, thus creating substitution benefits. However, this requires that the total climate impact of the biobased production chain in question is smaller than those of the fossil counterfactual products. Moreover, when assessing the substitution benefits, also the potential impacts on forest carbon sinks and stocks on short and long terms need to be estimated.

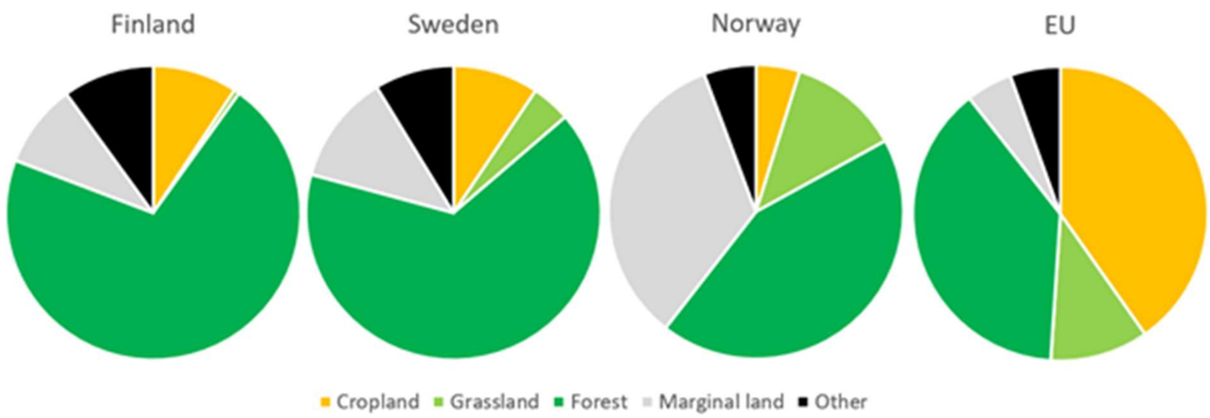


Figure 2. Land use cover in the Nordic countries and EU. Land use types are according to the fractionation used in Deliverable 4.2. Data on land cover are from OECD.Stat (2022).

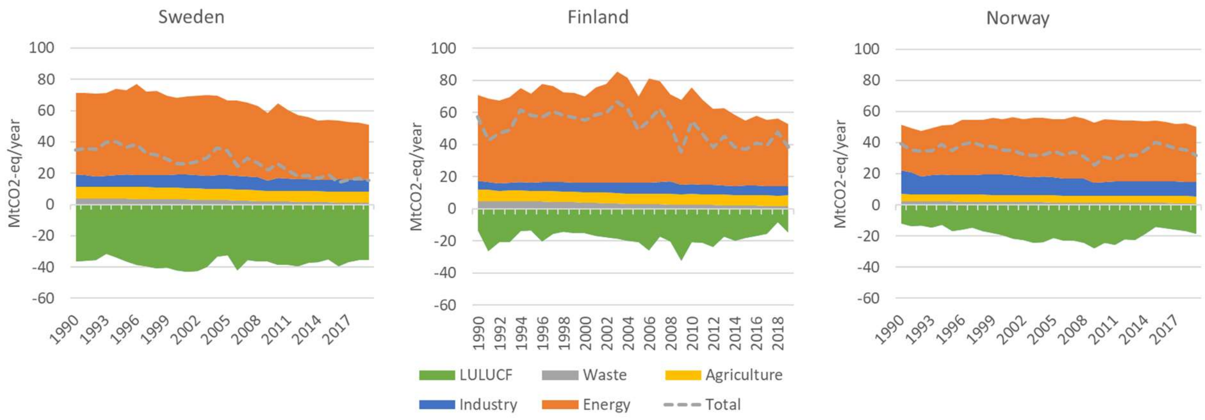


Figure 3. Development of LULUCF sink and total emissions in Nordic countries (UNFCCC, 2021).

Forest harvest levels in Finland, Sweden and Norway have historically been on a sustainable level relative to forest growth (i.e., the harvest is lower than forest increment) (Figure 4). The LULUCF sector in Finland, Sweden and Norway has thereby balanced roughly between 20-40% of the annual anthropogenic CO_2 emissions since 1990. However, the dual role of the forests in climate change mitigation can lead to a possible trade-off: more intensive harvests can lead to more substitution benefits, but this intensified harvesting will inherently lead to a lower carbon sink and stock in forests. This trade-off needs to be understood better as the role of carbon sinks becomes more important to meet the national targets of net zero emission (Table 2), while the demand for biomass for substitution of fossil products in various sectors is similarly on the rise.

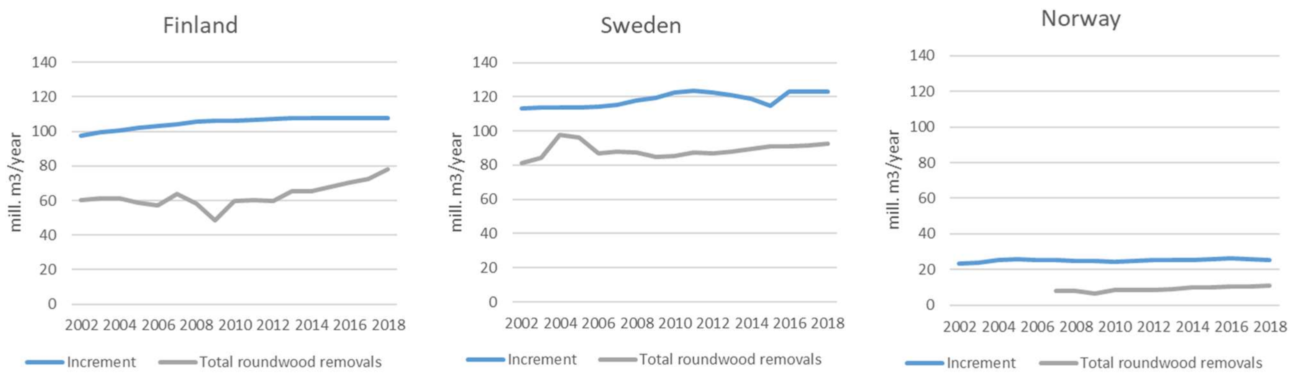
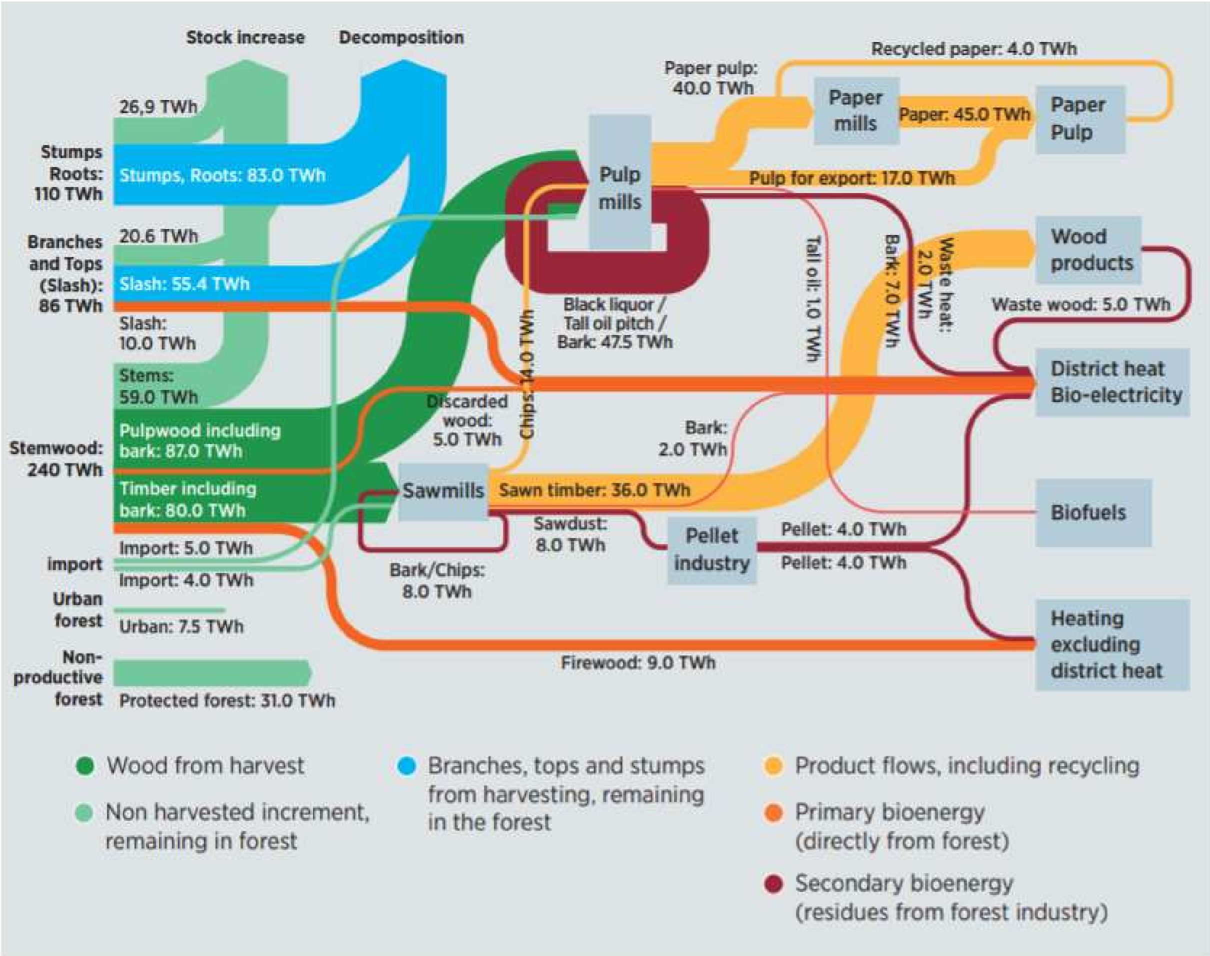


Figure 4. Total roundwood removal and forest biomass increment in Finland (LUKE, 2021), Sweden (Riksskogstaxeringen, 2022) and Norway (Statistics Norway, 2021).

Forest growth is partly rebounding from intense use of forest resources in the beginning of the 20th century. Moreover, climate warming, elevated CO_2 concentrations, and accumulation of reactive nitrogen deposition from long-range transported NOx, further stimulate forest growth. Climate warming has resulted in longer growing seasons due to higher fall and spring temperatures. However, future projections depict, on the contrary, a downward trend in annual net uptake from the sector towards 2050 (Bright et al. 2020). This is due to a combination of an increasing share of old-growth forest (forest that is no longer in its most productive phase), increased logging due to more harvest-mature volume becoming available in the future, and lower investments in forestry in recent decades.

Figures 5 and 6 depict how the harvested forest biomasses are currently utilized in Sweden and Finland, respectively. The figures illustrate that most of the biomass harvested goes to different uses of forest industry, whereas only a smaller fraction is directly used for bioenergy. Bioenergy is mostly produced from side streams (such as black liquor from pulp production, sawmill residues, bark, logging residues/slash, wood from thinnings, and damaged wood through rot or wildfires). This is substantially different from the bioenergy options available in many Central-European regions. The role of forest-based bioenergy in overall energy production is important in both countries; 25% and 26% of total energy supply in Sweden and Finland, respectively (Energimyndigheten, 2019), which slightly deviates from data reported to British Petroleum (Figure 1). An additional common characteristic for Finland and Sweden is the widely distributed district heating systems, which allow for combined heat and power production plants (CHP), and thereby high efficiencies in bioenergy use (e.g. 95%, based on higher heating value). This is also a specific feature for these two countries, as district heating networks are much less common in Central-Europe. In Norway forest-based bioenergy is much less developed, as the local conditions allow to produce renewable electricity from hydro- and wind power (Figure 1). As renewable electricity is abundantly available, heating is largely based on electricity in Norway, and the role of bioenergy is marginal compared with Sweden and Finland (British Petroleum, 2022).



Source: Svebio analysis of data from Statistics Sweden (SCB), Swedish Energy Agency (SEA), Swedish Forest Industries (Skogsindustrierna), Swedish Forest Inventory, SLU, Swedish Pellets Council (Pelletsförbundet) and others (2018)

Figure 5. Harvested biomass uses in Sweden 2015 (Cowie et al., 2021).

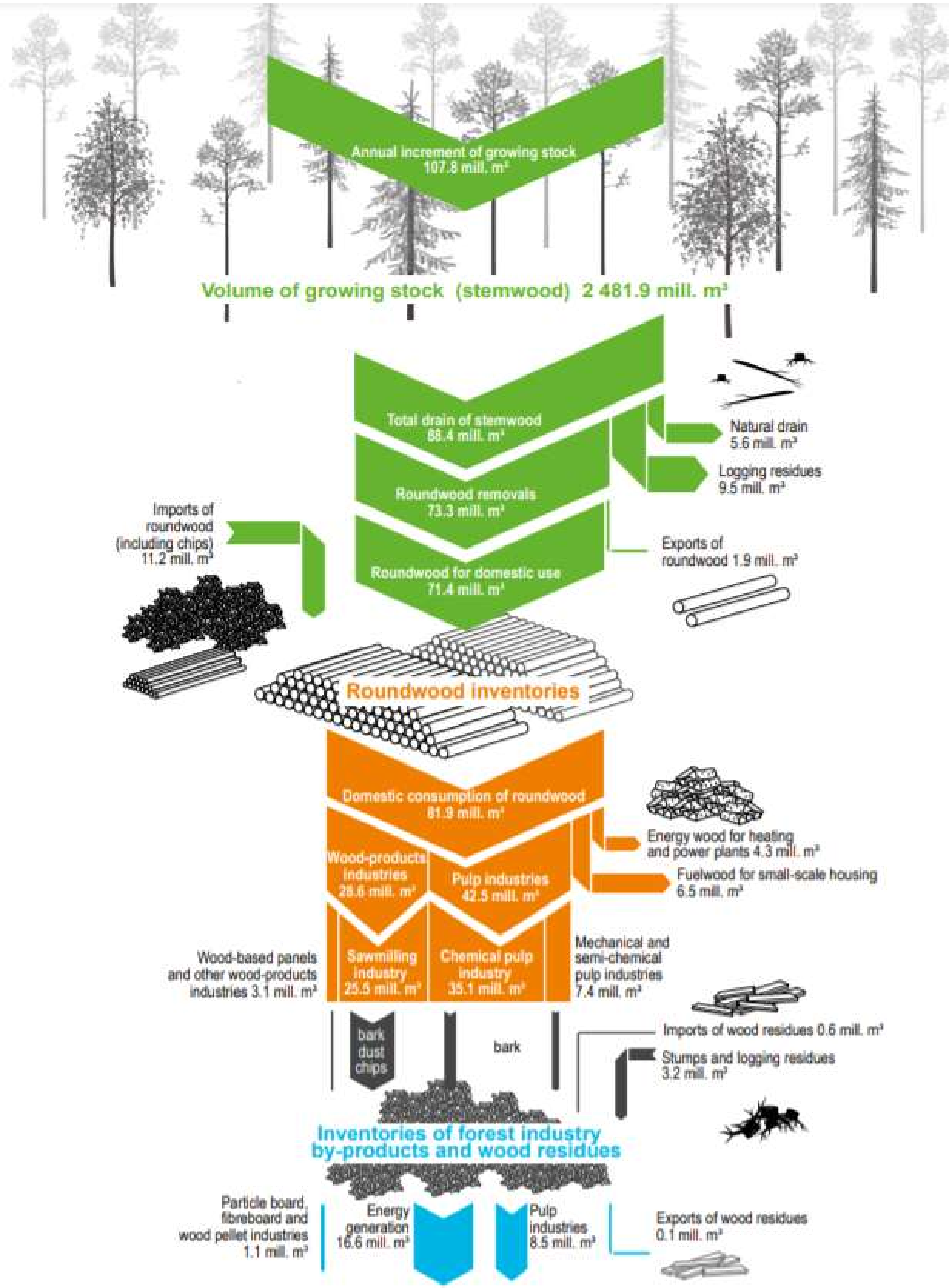


Figure 6. Harvested biomass uses in Finland 2019 (LUKE, 2020)

Against the backdrop of the outlined current situation of Nordic forests and the associated industry, as well as governmental plans and targets, the following sections will take a closer look at the different potentials from specific CDR actions in the forestry sector.

1.4 Potential to increase carbon storage in forests in each country

Recent reports and white papers from Finland, Sweden, and Norway list the potential for re-/afforestation, increased conservation, and intensification or modification of forest management to create additional carbon sinks within the LULUCF sector to support the transition towards zero-carbon societies (Lehtonen et al., 2021; Regeringskansliet, 2020; MD, 2020).

The effects on CDR from the different practices need to be considered in a short- and long-term perspective, which is a qualitative distinction. Boreal forests have rotation periods of at least half a century. Due to this long rotation periods of the boreal forests, some measures are expected to have short term impacts (S)[1], while others have long-term perspectives (L)[2] (Table 3). Here we present a summary of the potential CDR potential by different practices, followed by a closer look at the different measures. Impacts on other climate forcers (such as albedo) and other ecosystem services will be discussed in Chapter 2.

For Finland, the CDR potential of LULUCF sector was summarized by Lehtonen et al. (2021). Table 33 presents the forest-related actions by year 2035. In addition, reduced deforestation, while not a CDR practice per se, is estimated to have a short- term impact by avoiding the emission of 0.68 $MtCO_2eq.\ year^{-1}$ through saving 6.5 kha of forest yearly.

Table 3 Annual CDR potential of forests in Finland in 2035 (Lehtonen et al., 2021. Figure 18)

FINLAND for year 2035 Measure	Land area (kha $year^{-1}$)	CDR potential ($MtCO_2eq.\ year^{-1}$)	Time period short (S)/long term (L)
Re-/afforestation	6	0.19	L
Increased conservation	6	0.17	S
Seedling care [a]	30	0.31	L
Nitrogen fertilization	50	0.62	S
Drained peatland soils	75	2.40	S
Ash fertilization [b]	77	0.28	L
Wood products [c]	22000	1.50	S
Decaying wood [d]	22000	1.26	S

Footnotes: a) Early treatment, clearing and thinning; b) Spreading of ashes from incineration of side stream of forest industry; c) Increased share of long-lasting Harvested Wood Products (HWP); d) Reduce the harvest of forest residues to increase soil carbon.

A proposal for Swedish strategy for a climate positive future (Regeringskansliet, 2020) summarises similar potentials in Sweden (Table 4 and 5). Table 4 shows estimated absolute CDR potentials per year of various measures, while Table 5 shows cumulative relative effects of various management measures compared with a ‘no change in forest management’ scenario.

[1] I.e., relevant impacts before 2035.
[2] I.e., impacts take place over decades.

Table 4. Annual CDR potential of forests in Sweden (Regeringskansliet, 2020. Table 6.1)

SWEDEN Measure	Land area (kha)			CDR potential ($MtCO_2eq.\ year^{-1}$)		
Year	**2030**	**2040**	**2045**	**2030**	**2040**	**2045**
Re-/afforestation, direct [a]	100	100	100	0.1	0.4	0.8
Re-/afforestation, passive [b]	50	50	50	0.04	0.1	0.2
Agroforestry [c]	50	50	50	0.03	0.06	0.1
Rewetting of drained peatland soils [d]	50	100	100	0.4	0.8	0.8

[a] planted; [b] self-rejuvenated; [c] planting of trees and shrubs on agricultural land; [d] filling of ditched drainage channels.

Table 5. Change in CDR potential of increased conservation and forest rotation period in Sweden (Regeringskansliet, 2020. Table 6.2) compared with a reference scenario of no change in forest management. Note that here cumulative effects (in $MtCO_2eq$) are presented, contrary to annual effects.

SWEDEN Measure	Cumulative CDR potential ($MtCO_2eq.$)		
Year	**2030**	**2045**	**2100**
Increased conservation (4.5 Mha)	12	13	13
Increased conservation (0.5 Mha)	1.3	3.1	1.1
Increased rotation period (full potential)	4	2.9	0.8
Increased rotation period (careful estimation) (0.5 Mha) [a]	0.2	0.1	0.04
Increased deciduous and mixed forests [b]	2.2	4.5	8.4
Increased production [c]	2.8	3.1	1.3

[a] equivalent of an increase in turnover time by 10 yrs. on half million hectares; [b] increased mix with deciduous forest; [c] through e.g., re-/afforestation.

Table 6. CO_2 removal (CDR) potential of increased conservation and forest rotation period in Norway (KLD, 2020-2021).

NORWAY Measure	CDR potential ($MtCO_2eq.\ year^{-1}$)	
Year	**2030 (S)**	**2100 (L)**
Existing measures		
Nitrogen fertilization [a]	0.14–0.27	0.14–0.27
Forest breeding [b]	0.1	1.1
Increased forest density [c]	0.0	0.0
Possible measures		
Minimum age of logging [d]	0.3	0.3
Young forest care [e]	0-0.5	1.5 – 3.3
Reduced damage of root rot [f]		1.0
Right tree species when rejuvenating [g]	0.1	1.3
Afforestation [h]	Depends on extent	Depends on extent

[a] Fertilization with calcium ammonium nitrate (Opti-KAS Skog from Yara) at the same level as present. Lime is added to counteract acidification. [b] Produce seeds with better traits for volume production, CO_2 sequestration, wood quality and climate adaptation. [c] Increase number of trees in areas with sub-optimal forest density. [d] Requirements for minimum age for logging in line with today's requirements of the Program for the Endorsement of Forest Certification (PEFC). [e] Selection of species with good quality and ensure an optimal density so that the growth and the quality of the forest becomes the best possible. [f] Limit the spreading of wood-destroying fungi (*Heterobasidion parviporum i.e., Rotkjuke in Norwegian).* [g] Require that only the optimum tree species for the growth habitat is included in the requirement for minimum legal forest density. [h] Planting of forest on land, which is not, or to a low extent forested today.

The Norwegian forests store about 2 billion tonnes of organic carbon (Grønlund et al., 2010). The Norwegian Environment Agency (MD) has proposed several new climate measures in the LULUCF sector that are addressed in the “Climate cure” (Klimakur) 2030 white paper (MD, 2020). These are assessed in the Norwegian Climate plan for 2021 – 2030 (KLD, 2020-2021), providing the summarised CDR potentials for Norway presented in Table 6.

Following this overview on country-specific potentials for CDR within forests, the next two sections will take a closer look at similarities and differences in re-/afforestation (1.4.1) and forest management options (1.4.2) across the three countries.

1.4.1 Re-/afforestation and reduced deforestation

Tables 3, 4 and 6 showed re-/afforestation potentials in Finland, Sweden, and Norway, respectively. The average land area estimated to be available for re-/afforestation in Finland and Sweden is small compared with the total forest area, e.g., 6 kha $year^{-1}$ in Finland by 2035 (0.026% per year of the total forest surface of 22.8 Mha in Finland) and around 10 kha $year^{-1}$ in Sweden by 2040 (0.025% per year of the total forest surface of 40.8 Mha in Sweden).

In Finland, the re-/afforestation potential is mainly located on former agricultural land and on peatlands formerly used for peat production for energy purposes. The CDR potential per hectare of re-/afforested land significantly depends on the former land use, land type (mineral, organic, peat land), and tree species planted. Furthermore, the carbon accumulation varies over time. LUKE (2020) has estimated that the CDR potential of re-/afforested land can be from 3.8 to 17.1 tCO_2eq. ha^{-1} $year^{-1}$, depending on the former land use, soil type, tree species, and the time passed since the re-/afforestation effort. For example, re-/afforestation on former agricultural land on mineral soil can remove 3.8 tCO_2eq. ha^{-1} $year^{-1}$ compared to the original land use in the period of 15 years since re-/afforestation. Re-/afforestation of former agricultural land on organic soil can remove 9.8 tCO_2eq. ha^{-1} $year^{-1}$, and re-/afforestation of land used for peat production for energy purposes 7.8 tCO_2eq. ha^{-1} $year^{-1}$ for the same period (Lehtonen et al., 2021). Behind these rates, there are some key assumptions on soil carbon dynamics that are subject to uncertainty (see Chapter 2).

In Finland, reduced deforestation, although not causing any CDR, is estimated to have a more significant impact on the carbon balance (0.68 $MtCO_2$eq. $year^{-1}$) than re-/afforestation (0.19 $MtCO_2$eq. $year^{-1}$; Table 3). This is especially true in peatlands, where avoided deforestation more efficiently prevents additional emissions than re-/afforestation of agricultural land can remove CO_2 (Kärkkäinen et al., 2019). Currently deforestation takes place mostly due to construction of roads, houses, and infrastructure and due to land needs for agriculture (e.g., for feed production and manure treatment) (Lehtonen et al., 2021). In agriculture, the increased need for land is related to the centralisation of production, e.g., larger animal farms and need for a new field area in their proximity.

The Norwegian government’s white paper on climate policy (MD, 2011-2012) and plans (KLD, 2020-2021) clearly expresses an intent to strengthen the nation’s existing climate measures in forests, including a policy of large-scale planting of spruce (Picea abies (L) H. Karst). The areas that are to be used for re-/afforestation in Norway are mainly previously outfield pastures that are now open areas or regrowth areas with suboptimal forest production. These areas, generally referred to as semi-natural grassland, are historically open landscapes traditionally managed by grazing husbandry that are in various states of natural succession towards native forest vegetation dominated by deciduous broadleaved tree species (Mooney et al., 2020). The decline of grazed grasslands has mainly been driven by farm-level economic efficiency and profitability interests, which have been related to agricultural policy measures (Luoto et al., 2003). It is also due to urbanization, with decreasing population in the countryside for running the farms. This land suitable for re-/afforestation is estimated by Haugland et al. (2013) to be 978 kha, which is 6.8% of the present forest area of 14 325 kha in Norway (ForestEurope, 2022). A tentative estimate of re-/afforestation rate for spruce in Norway is 5 kha per year over a 20-year period (Haugland et al., 2013), or 3.5% of the current forested area (i.e., 0.07% per year). This somewhat conservative estimate for Norway considers the limitation for re-/afforestation posed by loss in albedo, loss in biodiversity, and other environmental, ethical, social, and cultural values, as well as economic feasibility limitations. Moreover, according to the guidelines from the Norwegian Environment Agency (Haugland et al., 2013), re-/afforestation in Norway should be realized on soils with high site index. The area in Norway that is considered suitable for planting forest as a Nature based solution for CDR is referred to as *semi-natural areas of the cultural landscape* and is mainly located on the west coast and in mid-Norway (Haugland et al., 2013). Haugland et al. (2013) estimated the additional uptake of carbon in relation to re-/afforestation in Norway to be between 14 to 16.8 tCO_2eq. ha^{-1} $year^{-1}$.

1.4.2 Forest management practises for increased forest-based CDR

Various forest management measures can have great influence on the forest's potential for CDR.

Nitrogen and ash fertilization.
To increase productivity, nitrogen fertilization of forests is a well-studied management practise. Fertilisation is most useful where other factors, such as temperature or water, do not limit the forest growth (Lehtonen et al., 2021). In young and old stands of Norway spruce and Scots pine, nitrogen (N) fertilization with 150 kg N ha^{-1} usually gave increment increases in the range of 1-2 m^3 ha^{-1} yr^{-1}, for a period of 6-8 yrs. after application (Nilsen, 2001). This effect clearly exceeds the CO_2 emissions from production, transport and spreading of the fertilizer. The effect also exceeds the possible additional emissions of nitrous oxide. Likewise, Routa et al. (2012) demonstrated that the CDR due to nitrogen fertilisation of forests is greater than the emissions due to the fertilizer production and application. Nitrogen fertilizers are used to a greater extent in Sweden and Finland than in Norway. The average annual fertilized area during the period 2008–2012 was in Finland 45 kha (Metla, 2013). During the same period an average of 59 kha were fertilized in Sweden (Skogsstyrelsen, 2013). In Norway, only about 0.8 kha were annually fertilized between 2009 – 2013 (MD, 2014). In Norway, 5 – 10 kha $year^{-1}$ of forest is assessed to be suitable for nitrogen fertilization (e.g., not already receiving high loading of atmospheric nitrogen deposition; MD, 2014).
In addition to nitrogen fertilization on mineral soils, ash fertilisation of peatlands has been assessed. For ash fertilisation, wood ash from wood combustion is used. There are large amounts of wood ash available in Finland and Sweden, from the use of side streams of forest industry for energy production (See Figs. 5 & 6). Table 3 shows that the estimated average CDR potential of nitrogen and ash fertilization regimes could be more significant than re-/afforestation plus conservation potential in Finland. In Norway fertilization with ash is not a legal practice.

Increased forest density and seedling care
Currently, the standard forest management practise in Finland aims for production of commercial timber and merchantable wood. This requires thinning during the forest growth phase. However, thinning the seedling stands can reduce the carbon accumulation to the biomass. Growing the forests denser would increase the carbon sink and carbon accumulation on forest soils. However, this would likely reduce the income for forest owners due to lower quality wood and higher harvest expenses. Thus, providing subsidies to support carbon accumulation in forests would be needed to make denser forests profitable (Lehtonen et al., 2021). Another forest management option is the use of increasingly refined seeds (i.e.,

forest breeding) when planting new forests. However, the impact of this on the forest growth and thus CDR does not occur in the period of first 30 years of forest rotation. Still, the Norwegian MD (2020) identifies rejuvenation of forests with optimum tree species and increased tree density, followed up by young forest care, as actions that have the largest CDR potential (Table 6).

Less intensive harvesting.

While less intensive use of forests and/or conservation may increase carbon stocks in forests, thus positively influencing the forest's capacity for carbon storage, intensified forest management to increase productivity will also be associated with increased carbon removals by logging. This may in turn lead to reduced carbon stores in the forest (see e.g., Figures 7 and 8). Decreasing forest harvests and prolonging the forest rotation periods has thus a direct impact on the carbon sinks (Stokland, 2021). The SOC stock in forests vary with geographical location (southern or northern Finland), tree species and the age of forest to be conserved. It has been documented that the SOC stock in forest conservation areas is higher than in forests in economic use (Lehtonen et al., 2021). Framstad et al. (2013), providing an overview of the role of old Nordic forests on the carbon cycle, found that old forests continue to store atmospheric carbon. This entails that shifting forests from active economic use to conservation increases the biomass carbon stock and can increase the carbon sink depending on the phase of rotation of the forest. Increased forest conservation is expected to lead to increased CDR simply because standing forest is an active carbon sink. Increasing forest conservation is thus estimated to have CDR potentials of similar magnitude as re-/afforestation in both Finland and Sweden (Table 3 and 5). These impacts are several magnitudes larger than those of other changes in forest management practices. In addition, changes in the amount of forest residues left behind after harvesting have impacts on the soil carbon accumulation. Here the trade-off comes with the potential substitution impacts of the use of the harvested side lines from forest industry for energy production in combination with carbon capture i.e., BECCS. This is further discussed in Chapter 1.6.

Forest management scenarios in Nordic countries.

For Finland (Figure 7), three scenarios for future forest management have been developed i.e., With Existing Measures (WEM), Continuous Growth, and Savings. These scenarios vary in several assumptions e.g., on the role of bioenergy and development of forest industry and the agricultural sector, which all impact on the amounts of wood harvested, and land area available for re-/afforestation or other CDR methods. For example, Continuous Growth and Savings scenarios include assumptions of increase in the area used for bioenergy crops and a sharp reduction in the area of arable land. As a result, more arable land will be converted to forest land or grassland than in the WEM scenario. In Savings scenario the harvests increase compared to Continuous growth scenario, and the increased carbon stock in Harvested Wood Products (HWP) does not compensate the lost sink in forests, even though long-lived products are emphasised (Koljonen et al., 2020). All the scenarios produced divergent trajectories for the LULUCF sector, but in all scenarios the sector remains as a net sink i.e., the removal of greenhouse gases, is higher than emissions. The figure is shown here to illustrate that the variation of forest harvest within the scenarios is of high importance and can have a several magnitudes higher impact on the carbon sink formed by forests than some of the CDR methods listed in Table 3. The level of harvests is largely defined by the demand by forest industry, and decisions by private forest owners, so policy interventions can be challenging to apply.

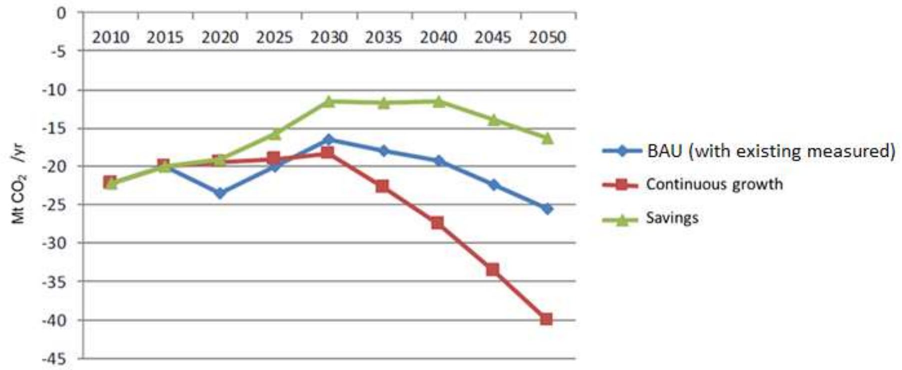


Figure 7. Development of LULUCF sink in Mt CO_2-eq. per year in Finland, in different scenarios (BAU denotes Business As Usual. I.e., with existing measures) (Modified from Koljonen et al., 2020).

For Sweden (Figure 8) four scenarios have been modelled. I.e.: 1) "BAU" denotes the reference values with business as usual I.e., with existing measures; 2) "Production" reflects the use of growth-enhancing measures (e.g., re-/afforestation of arable land, fertilisation, rejuvenation measures and increased use of the tree species Contorta); 3) "Environment" denotes increased environmental ambition (e.g., increased provision for land conservation); and 4) the combined effect of "Environment+production". The measures contribute to an increase in net storage in LULUCF by 2050, but the effect on increased net storage of production-enhancing measures compared to the reference subsides beyond 2050 and ends in 2070 (Swedish EPA, 2012; Regeringskansliet 2020), though this is not the case for the "Environment" measures. The results range from reduced net storage of 11 Mt CO_2-eq. per year in 2050 (in the case of high felling) to increased net storage of 20 million tonnes (environment+production scenario, with low felling and high storage in wood products) compared to the forecast reference scenario. In practice, more storage in wood products is a result of more sawn timber. This requires more thinning to grow trees better suited for timber production. Combining high yield of sawn timber with low felling is thus not straight forward. The calculations include the growth effect of a warmer climate but not increased risks of reduced net storage from future forest damage that may arise from a changing climate (Swedish EPA, 2012).

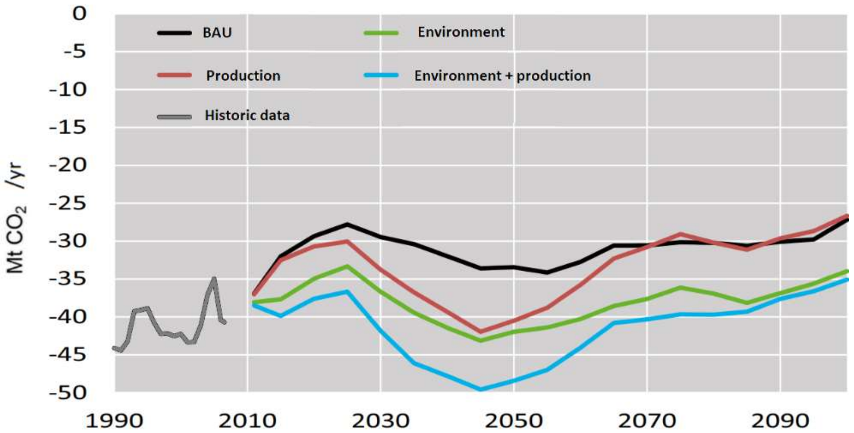


Figure 8. Net CDR by 2100 within the LULUCF sector in Sweden. Four alternative national development scenarios are modelled: "BAU" denotes the reference values with business as usual I.e., with existing measures; "Production" reflects the use of growth-enhancing measures; "Environment" denote increased environmental ambition; and the combination "Environment+production" include comprehensive measures. Among other things, in the form of increased provision for land conservation ("environment") as well as re-/afforestation of arable land, fertilisation, rejuvenation measures and increased use of the tree species Contorta ("production"). Please note that the figure does not account for the entire LULUCF, but only forestry (Modified from Swedish EPA, 2012).

The simulated effect in Norway of increased forest management activity compared with business as usual, including nitrogen fertilization, and the use of HWP on net CDR within the LULUCF sector, is shown in Figure 7. The impact may be seen after 2050 and increases up to 3.5 Mt CO_2 yr^{-1}. in 2100. Several measures will also have synergistic effects for each other, such as increased area planted after felling, increased plant density and use of processed plant material. The effect of nitrogen fertilization can be relatively significant per unit area, but with the limitation of maximum area as specified by the MD (2014), the effect will remain limited on a national scale. However, there is a significantly larger area that may be relevant for fertilization (Søgaard et al., 2020).

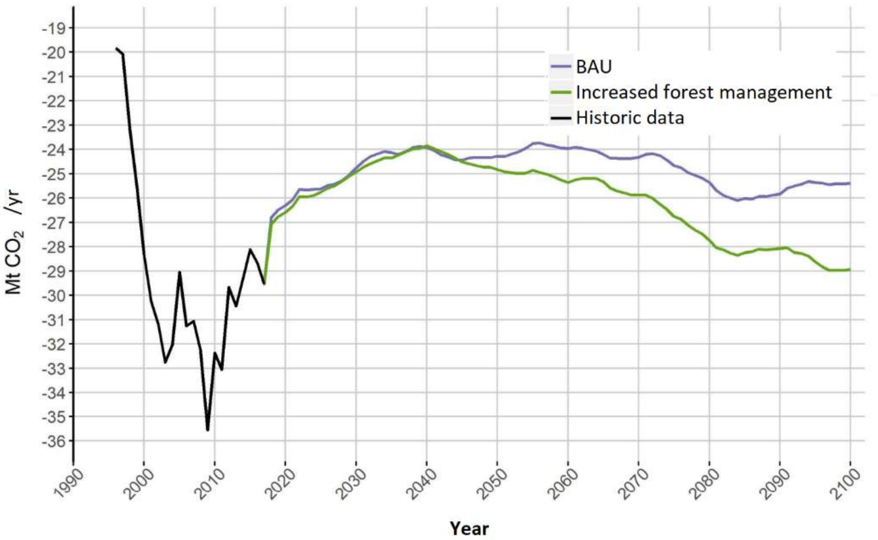


Figure 9. Net CDR within the LULUCF sector in Norway based on RCP 4.5 climate scenario comparing business as usual (BAU I.e., with existing measures) and with increased forest management intensity (Modified from Søgaard et al., 2020).

1.5 Potential of wood products to store carbon

Harvested wood products (HWP) are already currently included in the national greenhouse gas inventories (Figure 10). This carbon storage can be increased e.g., by increasing the use of long-lasting wood products (e.g., construction materials) compared to short-lasting ones (e.g., paper and paper board). The share of long-lasting products (solid wood products) is 78-100% in Finland, 53-79% in Sweden, and 0-100% in Norway between years 2010-2019. The large range in Norway is due to a small sawmill industry. Biofuels are not included in HWP, as the carbon is directly released in their combustion. Formally under UNFCCC the carbon is reported as emitted on the moment of felling, not at combustion which could be a few years after felling. The issue of permanence is thus crucial when considering the potential of HWP to create CDR. Using wood in buildings and in furniture can form long lasting carbon storages that may last from decades to centuries (UNFCC accounts for 35 years half-life). All countries have plans to increase their use of HWP by e.g., increasing building using wood, which could increase the share of more permanent storage. However, in recent scenarios for Finland, the HWP stock is estimated to vary between -2.9 and -3.9 $MtCO_2$-eq. per year between 2025 and 2050, thus not increasing compared to current state (Maanavilja et al., 2021). This is based on estimation by Finnish Lumber Industry association, which foresees only moderate changes in harvests of solid wood and production of HWP.

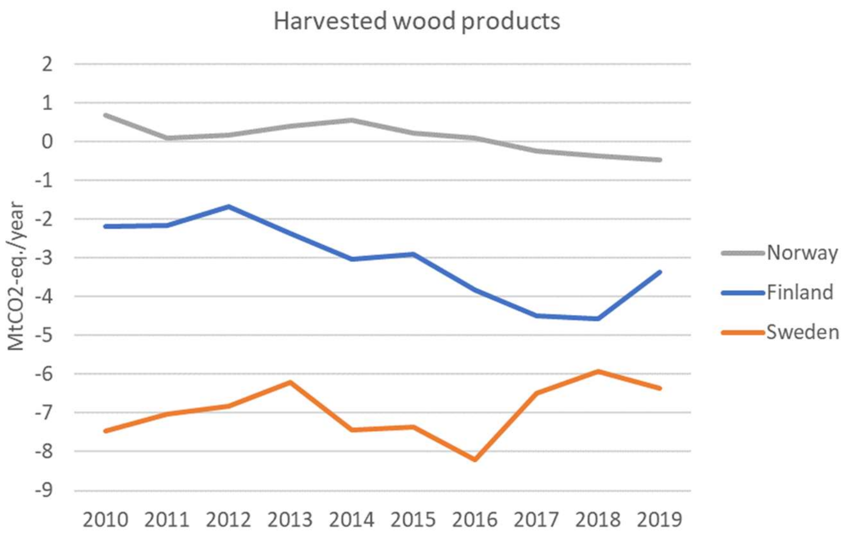


Figure 10. Contribution of harvested wood products (HWP) in GHG inventories in Finland, Sweden, and Norway (Source: UNFCCC, 2021).

Overall, increasing wood harvest for carbon storage may reduce carbon stocks within the forests, as shown in scenarios for Finland (see above). To manage forests both for maximizing carbon storage and for replacing fossil carbon with biogenic carbon, is thus a daunting task as these two aims present a trade-off.

1.6 Potential for BECCS in the Nordic countries

In Finland and Sweden, the large forest industry and comprehensive use of residual (and other) biomass sources for bioenergy, creates especially advantageous conditions for the deployment of Bioenergy with Carbon Capture and Storage (BECCS). In Norway the potentials are more restricted due to a small forest industry sector and a large hydropower sector. There are already several significant point sources of biogenic CO_2 from the combustion of side stream biomass waste from the forest industry for energy production. Thus, BECCS can be deployed based on existing sources. Moreover, it does not require large-scale cultivation of energy crops, as in the European or global context. I.e., in IPCC mitigation scenarios BECCS is mainly based on energy crops cultivated on former agricultural land.

The favourable "low-hanging" opportunities for BECCS in the Nordics are for example:

- BECCS in forest industry waste-based CHP plants (producing power and heat for district heating)
  - In CHP plants, energy efficiency benefits from BECCS deployment are especially advantageous, as the possible loss in electric efficiency due to carbon capture and sequestration deployment can be gained back in heat efficiency.
- BECCS in pulp mills
  - BECCS could be retrofitted to pulp mills, which are large biogenic CO_2 point sources (Onerheim et al., 2017).
- BECCS in biorefineries
  - BECCS could be installed in future biorefineries, producing e.g., biofuels from residual cellulosic feedstocks. In biofuel production there are often high-concentration CO_2 streams readily available for very cost-efficient capture (see NEGEM Deliverable 1.4).

Rodriguez et al. (2021), mapping the large biogenic point sources in Finland and Sweden, disclosed that in 2017 there were 51 CHP-plants and pulp mills that each emitted at least 300 000 tonnes of biogenic CO_2 per year (Figure 11). This summed up to at least 46 million tonnes of biogenic CO_2 per year.

There are planned BECCS projects in Finland, Sweden, and Norway (Norden, 2021). In Helsinki, Finland, there is a BECCS facility under construction within the bio-heat sector. Sweden is planning the Stockholm Exergi BECCS project, with a vented pilot study that started in 2019, and a full-scale plant planned for 2025 with a capacity of 800 kt yr^{-1}. Norway has the *Langskip project* (CCS Norway, 2022), which is based on a cement plant and a waste incineration with CHP plant. A large-scale plant is planned for 2023 – 2024 with a capacity to capture 800 kt CO_2 yr^{-1} (20 – 50% biogenic) (Norden, 2021).

Fuss and Johnsson (2021), studying the implementation of BECCS in Sweden, concluded that in principle it should be possible to implement BECCS with the currently envisaged deployment scales, but this would require rapid and rigorous introduction of political and economic incentives. They see that the main barriers are not due to technological readiness level (TRL), but rather due to socio-economic, political, and institutional restraints. For example, in order to achieve e.g., 6.4 Mt CO_2 removal target by year 2045, 7 pulp and paper mills and 7 CHP units utilising biomass should be converted to BECCS plants (Fuss and Johnsson 2021). This entails a new investment on both every 2.5 years, starting from 2025. This illustrates the scale of implementation required, and the current gap in implementation. In the latest carbon neutrality scenarios for Finland, a need for 8.3 Mt of BECCS for 2050 is envisaged (Koljonen et al., 2021), meaning that similar actions need to take place in Finland. In Norway, a significant governmental bid (1.7 billion EUR) has been allocated to the realisation of the full-scale capture of CO_2, including biogenic CO_2, as well as infrastructure for CO_2 transport and storage (Norden, 2021).

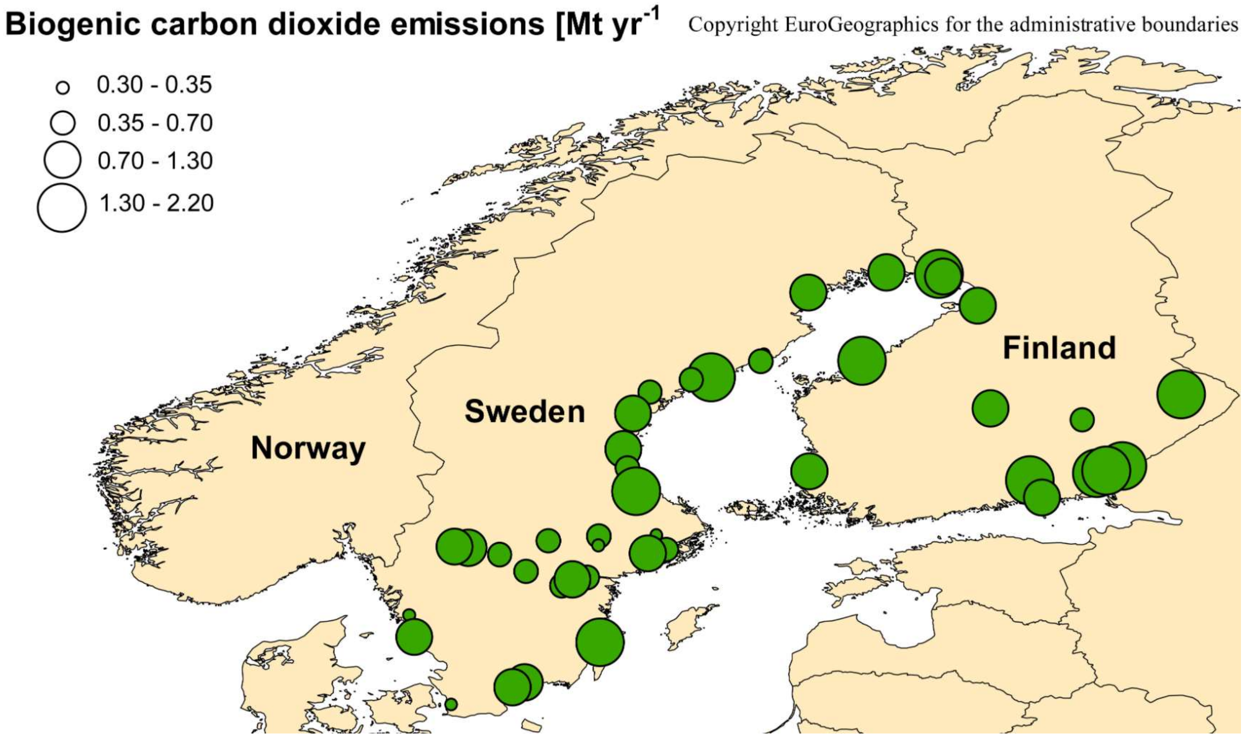


Figure 11. Point sources of biogenic CO_2 in Finland and Sweden during the period 2014–2016 (Figure from: Rodriguez et al., 2021).

There are currently several initiatives working in parallel on the storage and transport of CO_2. In Sweden, Cinfracap (Port of Gothenburg, 2022) will deal with transport of CO_2 on land. Transport and storage logistics of CO_2 under the North Sea seabed is to be handled by the *Northern Lights* (2021). Phase one of *Northern Lights* will be completed in mid-2024 with a capacity of up to 1.5 million tonnes of CO_2 per year.

The project has the potential to increase the transport and storage capacity up to 5 million tonnes CO_2 per year (total storage capacity is around 100 million tonnes). This will provide an open access storage solution for industrial facilities around Europe (Government of Norway, 2021; Northern lights, 2021). According to Levihn et al. (2019), CO_2 transport contracting is readily available, and the choice of transport system is to a large extent a matter of logistics optimization. Still, it takes a few years to order ships, so to optimize ship size and costs there might be a lag of 2-3 years from order to delivery.

There are likewise plans for new geological CO_2 storages under development in Norway, Denmark, and Iceland, as well as in other sites in Northern Europe. The region, therefore, has unusually favourable conditions for testing and proving the feasibility of the entire BECCS value chain (Norden, 2021).

2 Effects of Nordic forest-based CO_2 removal practices on climate feedback and ecosystem services

2.1 Net climate effects of forest-based CDR practices

In this chapter we assess climate feedbacks, such as change in albedo as well as vegetation feedbacks on SOC, impacting the overall net climate effect of forest-based CDR practices.

2.1.1 Effects of re-/afforestation on CDR and climate

On average, carbon resides in the vegetation and soil for a longer time at latitudes above 75° north than near the equator, with mean whole ecosystem turnover times of 255 and 15 years, respectively (Carvalhais et al., 2014). Knorr et al. (2005) found that soil organic matter (SOM) in northern forests has a turnover time of 250 years, which is long compared with aboveground biomass that has a turnover time between 70 and 120 years. In boreal forests, the SOC stock can be 2 to 5 times that of the standing biomass (Ameray et al. 2021; Bradshaw & Warkentin 2015) implying that small losses of SOC can offset carbon accumulation in biomass. The effect of re-/afforestation on SOC is thus potentially considerable. Still, there is an inadequate knowledge regarding the stability of SOC under different land-use, soil texture and climate conditions. There is likewise a lack of data on the SOC in Nordic semi-natural grasslands. Due to this, there is no consensus on effects of re-/afforestation on SOC storage. In the following, results from site studies on effects of re-/afforestation on SOC in Nordic countries are briefly summarized.

The net CDR effect of re-/afforestation as NETP in high latitude Nordic countries thus remain under scientific debate (Kalliokoski et al., 2019) given the relatively slow forest growth rates in cool climates and the large pools of SOC. Moreover, when also considering possible effects on energy budgets through changes in reflectance (surface albedo) by alterations in seasonal snow cover, surface roughness, evapotranspiration, and in cloud formation from emissions of biogenic volatile organic compounds (BVOC), the net climate effect becomes uncertain. Forest cools the local climate through increased surface roughness (increased turbulence) and evapotranspiration (Bonan, 2016). BVOCs, such as monoterpenes, emitted from the trees produce secondary organic aerosols (SOAs), which also cool climate through promotion of cloud cover enhancing the cloud albedo (Spracklen et al., 2008). On the other side, BVOC increase the lifetime of methane (CH_4), a highly potent climate gas, because these organic compounds compete for the hydroxy radical that removes CH_4 (Kaplan et al., 2006). Regardless, the emissions of BVOC are likely low in colder climates (Grote and Niinemets 2008) compared to tropical forest.
Still, due to decreased albedo and/or potential loss of SOC, the overall effect of planting forests on reducing the atmospheric levels of GHGs may be offset in boreal and arctic tundra. To determine the total impact of re-/afforestation on climate change mitigation, all the climate forcers need to be included in the analysis. However, this is rarely done, partly due to lack of simple methods by which various climate feedbacks (CO_2 and non-CO_2 radiative forces) can be compared.

When re-growing mountain forest in tundra ecosystems, Clemmensen et al. (2021) pointed out that the mycorrhizal composition will change, possibly causing an increased mineralization of SOM and resulting in loss of SOC. The changes in soil fungi by planting of spruce on grassland may thus lead to decreased SOC (Clemmensen et al., 2021). Likewise, Kammer et al. (2009) did not find an increase in SOC upon an altitude increase in treeline – leading to higher litter inputs to soils. Instead, they noted accelerated carbon and nitrogen cycling and a change in SOM quality. Abandoned out-field boreal grassland soils are conceived to

have very high SOC content. Strand et al. (2021) did not find an increase in soil carbon of a pasture 50 years after re-/afforestation with spruce, which could be in part related to shifts in mycorrhizal community between grass (arbuscular mycorrhiza) and spruce (ectomycorrhiza).
Soil type and organic matter content appears to be a crucial factor for predicting effects of re-/afforestation on soils (Søgaard et al., 2019). Sandy, organic matter poor soils are likely to benefit from re-/afforestation while fertile, humic soils are more likely to lose SOC (Friggens et al., 2020), especially if the soils are drained. Re-/afforestation of intensively used agricultural fields with high water tables, that have lost significant amounts of organic matter during decades of cultivation, could be an effective strategy for soil carbon accumulation (Regina et al., 2019). Moreover, combined with re-/afforestation using tree species, such as alder or birch that have tolerance for high groundwater table level, may also be favourable (Wichtmann et al., 2016).

Regarding the net climate effect of re-/afforestation, Bright et al. (2020), studying the effect of planting spruce forest on land overgrown by birch, found a net release of carbon during the first 30 years after planting, due to the necessary removal of birch prior to planting. Net CDR would then take place, with maximum benefits occurring 130 years after planting. Note that the practices studied by Bright et al. (2020) are termed 'accelerated forest conversion' to distinguish them from re-/afforestation, which is limited to unforested areas. Bright et al. (2020) concluded that planting of spruce forest in Norway has a net cooling effect, as forest-based CDR dominates the warming effect of reduced albedo in a ratio of 15 to 1. This contrasts with most studies that indicated a neutral or warming feedback from re-/afforestation of grasslands. The difference may be because Bright et al. (2020) compared the transition of broadleaved to spruce forest, with more similar albedos (Mooney et al., 2021). By contrast, De Wit et al. (2014) found that the albedo effect was 10 to 17 times stronger than CDR effect of regrowing mountain birch forest on tundra and heath in Norway, thus resulting in a net climate warming effect.

Models are commonly used to assess the climate feedback of re-/afforestation, including both carbon uptake and changes in albedo. Several modelling studies in mid- to high latitudes document small or neutral climate feedbacks of re-/afforestation, or even a warming effect (Betts, 2000; Montenegro et al., 2009; Davin & de Noblet-Ducoudre, 2010; Arora & Montenegro, 2011; Longobardi et al., 2016; Bonan, 2016; Keller et al., 2018). Mooney et al. (2021) modelled that re-/afforestation on grassland or shrubland in Norway will locally lead to an additional warming of surface temperatures in winter and spring (between 1.0°C and 1.5°C), due to loss in albedo. On the other hand, enhanced evapotranspiration of a forest compared to grassland has a cooling effect in the summer (between −1.6°C and −1.3°C), though the significance of this is low in cool boreal regions (Arora and Montenegro, 2011). Moreover, the decrease in albedo is less when replacing deciduous forest with spruce (Mooney et al., 2021). The effect of albedo is thus determined by the geographic location of the planted forest. It is modelled that the effect of reduced albedo is greater than the CO_2 uptake in areas with low productivity, such as in the mountain region with alpine climate. The opposite is the case in warm temperate climate zones, as found along the Norwegian coastline. The positive climate feedback of reduced albedo will be weakened in the future due to global warming (implying shorter seasonal snow cover).

Table 7. Qualitative assessment of the relative significance of re-/afforestation governed by the main climate and vegetation feedbacks.

	Re-/afforestation of abandoned pastures		
Effect	**Lowland forest**	**Tundra**	**Confidence**
Biomass CO_2 removal			High
Albedo			High
SOC change	Neutral	Loss	Uncertain
Net effect	Cooling	Warming	Intermediate

That rules of thumbs are missing makes it difficult to evaluate how cooling effects from forest-based CDR balance warming effects. A qualitative assessment of the importance of main climate and vegetation feedbacks is presented in the Table 7. The table is illustrating that the loss of albedo is higher than the effect of CDR by increased biomass where there is a long period with snow cover during winter, such as in the mountains, while the effect of increased biomass is larger than the effect of albedo in the lowlands. What is missing are the effects of increased aerosol emissions and increased evapotranspiration as the effect of these are assumed to be low in the Nordic forests. In addition, the effect of a transition of broadleaved to coniferous forest, which results in an initial loss of CO_2 is not assessed. Replacement of broadleaved with coniferous forest, however, is not considered as a policy option by the Nordic governments.

2.1.2 Effects of forest management on CDR and climate

Re-/afforestation are less effective from a climate change perspective due to reductions in albedo from changes in land cover, and potential loss of SOM. Forest management, on the other hand, does not change land cover but can change forest structure and therefore the exchange of energy and water vapor. However, a model assessment by Naudts et al. (2016), comparing managed with natural forest, concluded that the climate impact of historical change in forest structure related to management was of little significance in the Nordic countries compared with the rest of Europe. Kumkar et al. (2021) found in a model study for Nordic forests that management can lead to both regional cooling and warming related to energy fluxes. However, the large-scale forest management that were assessed in this study are beyond what is proposed by Northern governments.

Northern forest soils are rich in organic matter with well-developed organic forest floor layers, high content of humic matter, and large amounts of roots and fungi (Callesen et al., 2003), so avoiding loss of SOC as a consequence of forest management-based CDR is important for the overall-effectiveness of these practices. Liski et al. (2002), calculating the carbon budget of soils and in trees in the European forests, found that standing forests are a sink for carbon in soils albeit at lower rates (<20%) than in biomass (De Wit et al., 2006). Forest management can be optimised to increase soil carbon storage, especially through increasing productivity and thereby litter inputs to soils and by avoiding disturbances, but empirical evidence on effects of forest management on soils is mixed (Jandl et al., 2007). Carbon in bogs is believed to be most vulnerable to human intervention (Grønlund et al., 2010). The measures listed in Tables 3 to 6 include several practices with potential effects on SOC (e.g., increased conservation period, longer rotation periods, nitrogen, and ash fertilization, leaving harvest residues rather than exporting them, and restoration of drained peatland soils).

Forestry on ditched and drained organic peatland soils is common with potentially negative effects on SOC. Moreover, natural peatlands support rich biological diversity at the genetic, species, ecosystem, and landscape levels. Peatland ecosystems capture carbon by primary production into long-term storage within a peat layer, and thus establish a structural and functional basis for biodiversity maintenance that is not found elsewhere (Yu et al., 2017). Large peatland areas were ditched and drained throughout the Nordic countries during the 20th century with the aim to promote forest productivity. This has led to increased decomposition and mineralization of the SOM to GHG as the high water table is crucial to sustain soil carbon storage in peatland soils (Ojanen et al., 2010). Ongoing restoration of these peatlands is expected on the long term to increase soil carbon storage. On the other hand, the very reason to lower water tables was to promote forest productivity, and consequently, restoration with higher water tables will have the opposite effect. Additionally, higher water table will increase CH_4 emissions (Maljanen et al. 2010). Abdalla et al. (2016) estimated that CH_4 emissions increase by 46% upon rewetting of peatlands.

Maljanen et al. (2010) estimated that restored forested peatlands are smaller sinks for CO_2 (190 gCO_2 eq. m^{-2}) than drained forested peatlands (780 gCO_2 eq. m^{-2}) but highlighted that CH_4 and nitrous oxide (N_2O) emissions were not accounted for. Minkkinen et al. (2020) assessed that rewetting of northern peatlands (forested and cultivated) reduces N_2O emissions. Nevertheless, a global assessment of GHG balances of rewetted organic soils, extending the assessment of the 2014 Intergovernmental Panel on Climate Change (IPCC) Wetlands Supplement, suggested that rewetting peatlands in the short-term mainly reduces CO_2 emissions. Restoration of these peatlands thus result in a net lowering of GHG emissions (Wilson et al., 2016). Moreover, on long time scales it may also provide CDR through increased soil carbon storage.

Fertilization with nitrogen is done to increase forest growth. Such a treatment can also promote soil carbon storage (Makipaa, 1995), possibly through suppression of SOM mineralization (Hasegawa et al., 2021). Wood ash addition promotes forest productivity by addition of base cation nutrients. However, it also increases soil pH which leads to enhanced SOM decomposition rates (Mortensen et al., 2019; Pitman, 2006), but it is not clear if this effect is transitional. Another concern regarding nitrogen fertilization of these typically acid forest soils in the Nordics is the increased production of Nitrous oxide (N_2O) (Wang et al., 2017), a highly potent greenhouse gas. Hakansson et al. (2021) found a short-lived increase in N_2O emissions in fertilized forest plots on acidic soils in Sweden and longer-lasting reduction of the CH_4 soil sink. Still, the productivity increases however compensate for the N_2O increases (see Chapter 1.4.2). The main uncertainties connected with effectiveness of forest management to promote CDR are thus for rewetting of drained forested peatlands. Although it seems rather certain that a reduction of GHG fluxes is achieved on the short term, a CDR effect is probably only relevant on very long timescales.

From a climate perspective, it would usually be wise to cautiously consider potential reductions of SOC and avoid practices that lead to disturbance of soils as SOC stocks are much larger than C stocks in trees in Nordic forests.

2.2 Effects of forest-based CO_2 removal on ecosystem services

The NETP within the LULUCF sector, that have been assessed in terms of their CDR potential and efficiency, have moreover significant impact on environmental, cultural, and ethical functions and values, especially regarding ecosystem services (Filyushkina et al., 2016). The IPCC report on mitigation of climate change (IPCC, 2022) points out that the impacts, risks, and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale. Re-afforestation, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure. On the other hand, re-/afforestation, forest conservation, avoided deforestation, and improved sustainable forest management and soil carbon management, can have multiple synergies with the UNs Sustainable Development Goals (SDGs). The recent IPCC report evaluates the global synergies and trade-off effect of NETPs regarding the 17 SDG (IPCC, 2022. Figure SPM.8). The report concludes with high confidence that there are clear synergies of reduced deforestation on health (SDG 3), water (6) and biodiversity in water (14) and on land (15). Likewise, re-/afforestation is clearly good for sustainable cities (11) and aquatic biodiversity (14). Moreover, improved sustainable forest management has clear positive effects on poverty (1), industry (9), and life on land (15), while increased use of wood products has global industrial (9) synergies.

In a Nordic perspective, it is especially the effect on terrestrial biodiversity (Nilsson et al., 2001), water quality (Kreutzweiser et al., 2008), and recreation (Hansen and Malmaeus, 2016) that are pertinent.

The measures listed in Tables 3 to 6 that have the largest potential impacts on biodiversity include those with an impact on dead wood, forest disturbance and old forests (i.e., removal of harvest residues, forest management intensity, and conservation). For water quality, harvesting methods and fertilization are especially important.

2.2.1 Effects on terrestrial biodiversity

Forests represent an important ecosystem for the biodiversity of the Nordic countries, harbouring more than 50% of all known terrestrial species in Finland, Sweden, and Norway, and almost an equally large share of the threatened species (Framstad et al., 2013). Still, in Norway, forests, open lowlands, and mountain ecosystems have the lowest state of biodiversity, i.e. below the values that define good ecological status (Jakobsson and Pedersen, 2020).

Re-/afforestation will increase forest cover at the cost of other types of land cover, such as semi-natural grasslands that generally sustain a higher biodiversity (Wilson et al., 2012). The loss of semi-natural grasslands habitat (Silva et al., 2008) and fragmentation of old-growth boreal forests (Kouki et al., 2001) are both conceived as a major challenge for biodiversity in Fennoscandia. Regarding the Nordic region, Søgaard et al. (2019) conclude that planting with spruce on abandoned pastures with ordinary vegetation types of medium quality has limited impact on biodiversity. This conclusion is nevertheless challenged by Aarrestad et al. (2013) who emphasize that areas with high densities of red-listed species, such as red-listed habitat types and habitats of specific action plans (wildflower meadows), will be particularly negatively affected by spruce planting. Rewetting of peatlands can be positive for restoration of fen vegetation although tree removal is often needed to increase light availability (Hedberg et al. 2012), reducing thereby the CDR potential.

Spruce is not a natural specie in southern Norway, nor on the Norwegian west coast. The natural forests in these parts of Norway are deciduous or pine. The planting of Norway or Sitka Spruce in these regions furthermore enable these species to spread, invading neighbouring peats and abandoned pastures (Vollering, 2021). However, planting of spruce in areas where spruce does not have its natural distribution, may provide a higher biodiversity than in homogeneous landscapes, consisting of birch and pine forests, although the indigenous diversity can be reduced (Aarrestad et al., 2013).

Intensifying forest management will threaten biodiversity by loss of old growth and native forests, by replacement of natural stands with homogeneous conifer plantations (monocultures), and by increased dead wood removal (Pötzelsberger et al., 2021; Framstad et al., 2013). An old-growth forest, also termed primary forest or virgin forest, is a climax community without significant disturbance and thereby include diverse tree-related structures that increases biodiversity of forested ecosystems. The use of land for forest may nevertheless provide several positive side-effects on biodiversity if it is conducted in an environmentally sound and sustainable manner, as well as on the right scale. In a general assessment of ecological status of Norwegian forest, Framstad et al. (2021) thus conclude that forest management and technical infrastructure are the largest threats to forest biodiversity, and that similar challenges exist in Sweden and Finland.

Nitrogen fertilization of forests to boost productivity can likewise reduce biodiversity of understory herbs and shrubs (Aarrestad et al. 2013; Sullivan and Sullivan 2018). Increased nutrient availability by nitrogen fertilization may consequently have effects on biodiversity and ecosystem functioning. The magnitude and duration of these effects depend on initial species composition, nutrient status, and intensity of the fertilization regimen (Hedwall et al., 2014). Boreal forest has generally low biodiversity, thus the decrease in number of species due to fertilization may be less clear or even inverted (Hedwall et al., 2013). Fertilization may on the other hand cause large and long-lasting decreases in lichens and shifts in composition of the bryophyte community (Strengbom et al., 2001). Moreover, nitrogen fertilization has been shown in numerous studies to decrease the biomass of ectomycorrhizal fungi (Bahr 2013, and references herein). Likewise, reviewing the use of wood ash in forestry, Pitman concluded in 2006 that in British upland conifer plantations high ash doses could be very detrimental to the overall biodiversity of the stands.

2.2.2 Effects on water

Managed forests in the Nordic countries are associated with higher runoff of nitrogen and phosphorus than natural forests (de Wit et al., 2020), most likely because of a post-harvest, temporary decline in plant demand for nitrogen and phosphorus. Additionally, production and runoff of potentially toxic methylmercury to surface waters can increase because of forest management practices (Porvari et al., 2003; Eklöf et al., 2016). These effects can last for several years up to a decade (Kreutzweiser et al., 2008). Re-/afforestation increases the standing biomass and thereby litterfall, that in the longer term eventually serves to increase the leaching of dissolved natural organic matter (DOM) to the water i.e., Browning (Finstad et al., 2016). Moreover, replacing deciduous forest with coniferous forest significantly increases the leaching of DOM (Thieme et al., 2019). Although water is an abundant commodity in the Nordics, the water supply is commonly based on surface raw water sources (Eikebrokk et al., 2018), rendering the waterworks vulnerable to changes in water quality. Especially increases in DOM are problematic since DOM-removal is a common and costly step in drinking water treatment (Eikebrokk et al., 2004). In addition, brownification has impacts on the local ecosystems and leads to increased greenhouse gas emissions from the lakes (Tranvik et al., 2009). A possibly longer-lasting effect is the depletion of base cations in acid-sensitive regions in Fennoscandia through whole-tree harvesting, leading to soil and surface water acidification (Valinia et al., 2021). Swedish Forest Agency recommends compensation fertilization with wood ash to ensure that unwanted effects are avoided in the nutrient balance of the forest soil and in the quality of surface water. The wood ash application has not been found to cause any significant effect on the pH in the stream water (Norström et al., 2022).

Generally, the presence of wetlands is associated with nutrient retention and flood mitigation (Kieckbusch et al., 2006), while drained areas of forests are hotspots for the export of total nitrogen, total phosphorus and total organic carbon (TOC) (Finér, et al., 2021; Lepistö, et al. 2021). However, rewetting (restoration) of drained peatlands poses a risk to water quality depending on nutrient status of the peatlands (Koskinen et al., 2017; Nieminen et al., 2020), similar to forest management. Eutrophication and increased export of DOM are common effects. On the other hand, restoration is likely to decrease erosion and transport of suspended solids from ditched and drained peatlands (Haahti et al., 2016; Hokka et al., 2016). The effects of restoration might be limited in time, but few long-term studies are available. For the Nordic countries, we were not able to find studies that justified wetland restoration with the aim to reduce flood risk, suggesting that flood risk mitigation is not deemed to be of key national importance when considering impacts of wetland restoration.

Nitrogen fertilization of forests is a common practise in Finland and Sweden, though in Norway this is only conducted once about 10 years before the forest is harvested. This late-rotation nitrogen fertilization gives, in most cases, a small and transient increase in biomass and in nitrogen runoff (Haugeland et al., 2014; Valinia et al., 2021). Due to poorly buffered soils in the Nordic countries, the nitrate leaching resulted in a brief, but significant decline in acid neutralising capacity and pH (Valinia et al., 2021). Nitrogen fertilization in Norway is limited to regions that do not already receive elevated atmospheric N deposition based on an assessment of risk for eutrophication and acidification of surface waters (Haugeland et al., 2014; Kaste et al., 2021). More intensive fertilization regimens, as practiced in Finland and Sweden, with intensive fertilization starting in young forests may, on the other hand, considerably increase the biomass supply and value for the industry. The economic and environmental risks of this type of fertilization may, however, be larger and more research is needed on the effects on the stand level, and especially on the landscape level, including late rotation management of the forest (Hedwall et al., 2014). Increased nutrient levels, browning and decreased concentrations of base cations have detrimental effects for the biodiversity of freshwater biota (Lindholm et al., 2018; Wang et al., 2021; Smedsrud et al., 2018).

2.2.3 Effects on recreation, tourism, natural and cultural heritage

Ecosystem services supplied by forests in the Nordic countries are amongst others timber and pulpwood, bioenergy, game, climate regulation, purification of water and recreation and training. These different ecosystem services in multipurpose forests are relevant to consider for forest management relative to the CDR potential. For Swedish forests, each of these services is estimated to have a monetary value of several billion SEK (Hansen and Malmeaus, 2016). Monetization of these categories is challenging but Hansen and Malmeaus (2016) document that other services than timber production also have significant economic value. Moreover, increased use of wood products is conceived to also have aesthetic, anthropological, archaeological, cultural, historical, scientific, and technological heritage values (ICOMOS, 2017).

Esthetic value of landscapes can be assessed by studying preferences. Afforestation occurs at the cost of other types of landscapes, especially semi-natural grasslands. Appreciation of the cultural landscape qualities and landscape history are important for recreation and tourism. Liu et al. (2021), studying the landscape preferences among the Norwegian population, found that pasture landscapes are the most favoured (55%), while densely planted spruce forests are the least favoured (8%). The choices were mainly driven by the preference for landscape openness and aesthetic properties of cultural landscapes, and depended on gender, age, and nationality. The forest landscape preferences in the Nordic countries are closely linked to place identity and stewardship (Gundersen et al., 2016), and afforestation on former agricultural lands is viewed more negatively than the reforestation with non-native species within established native forests (Gundersen & Frivold, 2008). Thus, re-/afforestation can have significant effects on how landscapes are valued for recreation and tourism. How humans perceive and judge nature and relate it to their life is shaped by emotional, cognitive, cultural, and social factors. Whether a species is considered native, non-native, or invasive interacts with our emotions. Consequently, how humans perceive and judge the presence of non-indigenous species, or how they judge an ecosystem or landscape change triggered by them, is not fixed and easy to define (Kueffer & Kull, 2017).

The forests have been affected by several centuries of human action and are a part of the European cultural heritage (Agnoletti & Santoro, 2015). In these times of rapid change, escalating threats from loss of habitat to agriculture and resource extraction and the threat of climate change, there is an increased focus on the strong cultural values of forest conservation. This is rallying targeted, sustained and more effective conservation action (Infield & Mugisha, 2013) of primeval and virgin forests.

In some cases, preferences for scenic landscape do not align with the dynamics of natural forest where forests with little dead wood were rated higher than forests with abundant dead wood (Gundersen et al. 2017), but this effect was ameliorated by adding information on the value of dead wood for biodiversity. Likewise, peat restoration by rewetting drained peat soils has ecological, and intrinsic cultural benefits, though it is often perceived to require the abandonment of traditional rights of landowners (Bullock & Collier, 2011).

3 Nordic countries in a wider European context

The IPCC report on mitigation of climate change (IPCC, 2022) points out that re-/afforestation within the forest sector, although not sufficient to limit global warming to below 2°C, is currently the only widely practiced and economically profitable CDR action. Responding to the urgency for climate action, highlighted in the successive assessments of the IPCC, the European Union (EU) has set into law its objective of economy-wide Climate Neutrality by 2050 (EU, 2021). EU forests, covering approximately 42% of its land area, are already contributing to mitigate climate change through their annual increment of wood, which is currently equivalent to approximately 10% of Europe's fossil fuel emissions. It is unclear for how long this carbon sink in EU forests will continue to increase, considering that historical records show significantly lower carbon storage (Kaplan et al., 2012) and Nabuurs et al. (2013) have reported the first signs of carbon sink saturation in European forest biomass. Moreover, growth in some species (especially beech) has been reversed in recent years (Kint et al., 2012). Also, net removals from terrestrial ecosystems in the EU have been on a declining trend over the last decade, largely driven by the deteriorating situation in forest ecosystems. Solutions are available to reverse this decline and to return quickly to past levels of net carbon removals.

With this in mind, the Commission proposed to amend the LULUCF Regulation with the aim to reach climate neutrality in the entire land sector by 2035, which means that carbon removals in terrestrial ecosystems should balance the greenhouse gas emissions from all land, livestock and fertiliser use. This would imply the wide-scale adaption of carbon farming practices, a green business model that rewards land managers for taking up improved land management practices, resulting in the increase of carbon sequestration in living biomass, dead organic matter and soils, while often providing important co-benefits for biodiversity and other ecosystem services. Next to carbon farming practices on agricultural land, such as use of cover crops, conservation tillage or agroforestry amongst others, re-/afforestation, as well as improved forest management may provide important contributions to climate neutrality in the EU. There may at least in some regions be potential for increasing the CDR by changing forest management practices to increase the levels of standing biomass (EASAC, 2017). Moreover, it has been estimated that some 15 million hectares of abandoned farmland in the EU could be available for planned re-/afforestation up to 2030 (Keenleyside and Tucker, 2010).

The management options that are used may lead to different outcomes regarding CDR pending on the initial state of the forest, and the end use of the harvested wood, so that complex trade-offs emerge. Forest ecosystems in the EU are diverse, spanning from the boreal and temperate (Atlantic and continental), to the Mediterranean biomes. Each zone exhibits different species, growth rates and contrasting management traditions, which have evolved according to forest type and management approaches. In contrast to the northern EU countries, Southern Europe exhibits a lower level of economic activity in forestry, though forests in Central European countries have high stocks and higher annual increments compared with the European average. The EU white paper on Sustainable Carbon cycles (EU, 2021) focuses on the short-term actions to upscale carbon farming. These actions will all contribute to the climate mitigation effort of the Union, with strong co-benefits for the Union's ambition to reverse biodiversity loss and pollution.

In the Nordic countries the natural environment and other premises are very different compared to the rest of Europe. The Nordic climate is colder and wetter with shorter growing seasons. The soil materials are glacially eroded from igneous rock, rendering thin acid soils that are less fertile than the European soils. However, due to the slow decomposition of organic matter, the pool of SOM accumulates, leading to high organic carbon content in the soils. Below the alpine zone in the Nordic countries, the dominating land use is the boreal conifer forest, while in Europe the forest is less dominating and instead populated by Nemoral deciduous forest. The forest industrial sector is large in the Nordic countries, especially in Finland and Sweden. This is mainly because forestry is the dominant land-use, while cropland is the dominating land use in EU. Land in the Nordic countries that is suitable for agriculture is limited and basically entirely used for farming. The option to convert this limited fertile land to forest is generally not considered an option. The potential for re-/afforestation is thus small in the Nordic countries in contrast to other European countries.

Biodiversity in EU forests is in decline and very few biodiversity ‘hotspots’ such as old-growth forests remain in Europe. Mainly as a consequence of maximising volume yield in timber production, one-third of European forest stands are dominated by only one type of tree species, and only 20% harbour more than three different species (Nabuurs et al., 2015). According to EEA (2016), only 26% of forest species and 15% of European forest habitats were in ‘favourable conservation status’ in 2007–2012, and 27% of mammals, 10% of reptiles and 8% of amphibians linked to forest ecosystems are under threat of extinction within the EU. In Scandinavia and the Baltic countries, the percentage of forest area undisturbed by man, as well as the semi-natural forests, are the highest in Europe (EEA, 2016).

Overall, European wood is used in almost equal proportions (40%) for energy and products. The remaining 20% is used for pulp (EASAC, 2017). EU policies towards the use of forest biomass for energy production have been under discussion for over a decade. This is especially due to concerns on potential negative effects on the climate over the short to medium term, when using wood directly for energy purposes. One of three EU key NETP strategies is to recycle carbon from waste streams, from sustainable sources of biomass or directly from the atmosphere, to use it in place of fossil carbon in the sectors of the economy that will inevitably remain carbon dependent (EU, 2021). Another key EU target is to upscale carbon removal solutions that capture CO_2 from the atmosphere and store it for the long term, either in ecosystems through nature protection and carbon farming solutions, while ensuring no negative impact on biodiversity or ecosystem deterioration in line with the precautionary and “Do No Significant Harm” principles. The Nordic Forest sector plays an important role in the government’s CO_2 budgets and to reach their national zero emission targets. In Finland and Sweden, the large forest industries play an important role in the production of renewable green energy, with biomass accounting for 10% and 5%, respectively, of their total energy production. This production of bioenergy is mainly from side streams, such as logging residues and forest industry side streams such as sawn dust and black liquor. This is substantially different from the bioenergy options available in Europe, where the production of energy from biomass accounts for only 3%. In Norway less energy is generated from biomass than in Finland and Sweden. Instead, the energy production is dominated by hydropower (58%) (British Petroleum, 2022). The extensive use of bioenergy in Finland and Sweden generates many biogenic point sources of CO_2 suited for BECCS. Combined with the Norwegian government projects *Northern Light* and *Longship*, providing CO_2 transport and sequestration into North-sea reservoirs, this provides the full process chain for BECCS, contributing to the EU target of upscaling CDR options.

4 Conclusions and further steps

The forestry sector in the Nordic countries is important for balancing their anthropogenic CO_2 emissions. All countries have assessed measures to further increase the importance of the forestry sector for negative CO_2 emissions. We have compiled and compared data for CDR potentials of main NETPs in the Nordic countries (Table 8). Such a comparison is challenging because of differences in forest and management types (for example, forestry on peatlands is common in Finland but far less so in Norway) and in methods employed for assessing various forest-related CDR measures, in terms of definitions, time periods, land area available for the measure and methodological approaches. We have attempted to describe how CDR practices were defined and assessed in each country based on these reports but cannot claim to have done full justice to each practice. Not every CDR measure was assessed in each country. Nevertheless, comparing them in a single table provides an overview of proposed practices, which are assessed to have most CDR potential. Practices are, where possible, also evaluated in terms of 'climate-effectiveness' i.e., by including effects on albedo, SOC and other GHG emissions, and on their effect on other ecosystem services in particular biodiversity, water quality and recreational and cultural services. We have subjectively rated the confidence in the effects from high to low, depending on the support from the assessed literature. This was based on our arbitrary judgement, which is grounded on the assessed literature, rather than any specific thresholds. This may therefore to some degree be subjective as probably not all available literature was systematically included. Likewise, the qualitative categories of confidence levels are inspired by the IPCC guidelines. I.e., it "*synthesizes the author teams' judgments about the validity of findings as determined through evaluation of evidence and agreement*" (Mastrandrea et al., 2010).

Table 8 shows the CDR measures in declining strength of CDR potential for all Nordic countries. The order is slightly subjective as CDR potential was not available for each measure in each country. The highest CDR potentials have been estimated for restoration of drained peat soils, the increased production of long-lasting wood products and leaving harvest residues in the field for decay. As measures with intermediate CDR potentials, forest conservation, longer rotation times, change in tree species and re-/afforestation have been identified. The lowest CDR potentials have been estimated for ash fertilization and increased forest density. The climate feedback when including other effects than CDR, such as albedo and BVOC emissions, is reduced especially for re-/afforestation. The measures with the most positive impacts on other ecosystem services than climate regulation are those that promote stable forests i.e., conservation and reduced deforestation. By contrast, the largest negative impacts are associated with re-/afforestation. Short explanations are provided by footnotes under Table 8.

We conclude that the potential of re-/afforestation as a CDR practice is rather limited in the Nordic countries. This is partly because most area suited for forests is already used for forestry. Also, Nordic countries have climate with seasonal snow cover and soils with high stores of organic matter, both of which are important factors that reduce the climate-effectiveness of increasing forest cover.

A particular Nordic feature, especially in Sweden and Finland, is forestry on ditched and drained peatlands. Restoration of such ditches is a highly effective measure for reducing emissions but increases the risk of methane release. Increased use of wood for long-lasting products (e.g., wood in buildings and furniture) is an effective NETP measure with few negative side effects. It has been assessed in Finland, but not in Norway and Sweden. However, if this NETP measure would require intensification of forest management or harvests it may lead to negative impacts on other ecosystem services, hence the 'low confidence' assessment of 'other ecosystem services' effects.

Loss of biodiversity (Chapt. 2.2.1) is perhaps the ecosystem service of highest concern globally, as reflected by the Sustainable Development Goal 15. In a Nordic perspective, wildflower meadows with high biodiversity are under threat in Norway while forest monocultures in all Nordic countries are associated with low biodiversity. Intensified forest residues harvests, leaving less dead wood in forests, are also a significant risk for biodiversity.

The most diffuse and evasive qualities to assess in terms of the effects of NETP are the effects on recreational, tourism, and natural values, as well as cultural heritage. The confidence levels of our assessments are thus generally lower than for the other ecosystem services. Still, there is little doubt that re-/afforestation of old pasture lands / other open areas and increased forest density are perceived to be strongly negative in terms of recreational, touristic, and cultural values.

Table 8. Overview of CDR potential (rounded off to 1 decimal) of the main NETPs in Finland, Sweden, and Norway along with assessed positive (in green), variable (in orange), negative (in red) or no (none) effects on climate (including other climate feedbacks than CDR) as well as effects on ecosystem services. Effect strengths are discretionary indicated as Strong, Medium, Weak, None, Unclear or Variable, with confidence level denoted by cell fill (dark grey: high; medium grey: medium; light grey: low; white: very low confidence). n.a. denote not available.

	CDR potential (for 2035-2040) in Mtonn CO_2eq. yr^{-1}				**Assessed Positive or Negative overall effect on:**			
Measures	**Finland**	**Sweden**	**Norway**	**CDR**	**Net climate**	**Bio-diversity**	**Water quality**	**Societal values**
BECCS	5-20[e]	10-20[f]	n.a.	High	Variable[26]	Variable[26]	Variable[26]	Variable[26]
Intensify forest management*	n.a.	n.a.	n.a.	High	High	Strong	Medium	Medium
Restoration of peatlands	2.4[a]	0.8[b]	n.a.	High	High[1]	Medium[6]	Variable[13]	Weak[19]
Increase wood products	1.5[a]	n.a.	n.a.	High	High[2]	None	None	Weak[20]
Leave residues for decay	1.3[a]	n.a.	n.a.	High	High	Strong[7]	None	Weak[21]
Reduce deforestation	0.7[a]	n.a.	n.a.	High	High	Medium	Weak[14]	Weak[22]
N fertilization	0.6[a]	n.a.	0.1-0.3[d]	Medium	Medium[3]	Medium[8]	Medium[15]	None
Increase forest conservation	0.2[a]	High[c]	n.a.	Medium	Medium	Strong[9]	Weak[14]	Strong[23]
Longer rotation time	n.a.	Low[c]	0.3[d]	Medium	Medium	Weak[9]	Weak[14]	None
Change of tree species	n.a.	Medium[c]	0.1[d]	Medium	Medium	Variable[10]	Variable[16]	Variable[24]
Re-/afforestation	0.2[a]	0.4[b]	0.2	Medium	Weak[4]	Strong[11]	Weak[17]	Strong[25]
Ash fertilization	0.3[a]	n.a.	n.a.	Medium	Waek[5]	Strong[12]	Weak[18]	None
Increase forest density	0.3	n.a.	0.0[d]	Low	Weak	Medium	None	Weak

[a] From Table 3; [b] From Table 4 (for 2040); [c] From Table 5 (for 2030), which indicates potential relative to 'no extra measures'; [d] From Table 6 (for 2030); [e]Estimation for technical potential from Kujanpää et al. 2023; [f]Lower limit a "feasible potential" from Swedish Energy Agency, upper limit a "total potential# from Zetterberg, et al. 2021. The aim of figures here is to illustrate that BECCS potential is high compared to other measures.[1] Increase in nitrous oxide and methane emissions, and reduced forest productivity (Ch. 2.1.2); [2] Uncertain turnover time of wood products (Ch. 1.5); [3] Risk of increased N_2O emissions and reduced CH_4 sink (Ch. 2.1.2); [4] Albedo effect, reduced SOC (Ch. 2.1.1); [5] Enhanced SOM mineralization (Ch. 2.1.2); [6] Fen vegetation (Ch. 2.1.2); [7] Dead wood important for biodiversity (Ch. 2.2.1); [8] Understory vegetation (Ch. 2.2.1); [9] Old growth forest (Ch. 2.2.1); [10] Introduction of new species increase biodiversity but may become invasive (Ch. 2.2.1); [11] Loss of species-rich habitats (Ch. 2.2.1) as forest restoration is not an issue in the Nordic countries; [12] Reduced biodiversity (Ch. 2.1.2); [13] Depending on nutrient status (Ch.2.2.2); [14] Reduced number of clear cut pulses (Ch. 2.2.2); [15]Eutrophication, acidification (Ch. 2.2.2); [16] Less DOM from birch; [17] Eutrophication, browning, acidification (Ch. 2.2.2); [18] Browning and increased K (Ch. 2.2.2.); [19] Value as cultural landscape vs. value of traditional land-use (Ch. 2.2.3); [20] Aesthetical value of wood products (Ch. 2.2.3); [21] Lack of literacy (Ch. 2.2.3.); [22] Cultural heritage (Ch. 2.2.3); [23] Environmental conciseness (Ch. 2.2.3); [24] Native or non-indigenous species (Ch. 2.2.3); [25] Preference for scenic landscapes and esthetical value of open cultural landscape (Ch. 2.2.3); [26] Depends on how the biomass for BECCS has been produced (e.g., is it residual streams from forest industry or wood from intensified harvests in forests); * Intensified forest management refers to increased resources to promote growth and is a common denominator for various practices, mentioned in various studies but not supported by particular references.

The Nordic countries rely on the forest in their national carbon budgets and have increased their attention towards maximizing the role of their forests to mitigate climate change. This report shows that each country has their own priorities, partly related to biogeographic differences and the economic importance of the forest sector. What also becomes visible is that comparing national forest related NETPs between the countries is difficult and would benefit from harmonization of terminology and approach. Additionally, the emphasis on forests as tools to sequester carbon or assist in the switch between fossil and biogenic carbon can lead to underestimating effects of forest-related NETPs on other than climate-regulating ecosystem services. This would be key for a nuanced balance of forest management for increased CDR and production of forest products to support the shift from fossil-based to biobased products.

Considering the further modelling work to be done in NEGEM, this deliverable adds the Nordic point of view on forest-related CDR potentials. For example, the models used by WPs 3, 4 and 7 (LPJmL5 and MONET) mainly rely on BECCS produced by bioenergy crops such as miscanthus and willow, whereas in Nordic countries the main potential for BECCS could be from currently existing CO_2 streams in forest industry and bioenergy production. The results from this deliverable will thus complement the modelling work of these WPs. This deliverable will also feed in the NEGEM scenarios to be modelled in WP8 by the VTT-TIMES model, which will also include a closer description of the Nordic energy systems.

For preparing this report, the following deliverable/s have been taken into consideration:

D#	Deliverable title	Lead Beneficiary	Type	Dissemination level	Due date (in MM)
D1.1	Justification of NETPs chosen for the NEGEM project	ETH	Report	CO	6
D1.4	Comprehensive sustainability assessment of Bio-CCS NETPs	VTT	Report	Public	12
2.2	Interactions and trade-offs between nature-based and engineered climate change solutions	UOXF	Report	Public	17
8.1	Stocktaking of scenarios with negative emission technologies and practises. Documentatio n of the vision making process and initial NEGEM vision	VTT	Report	Public	8

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