B4EST

Adaptive BREEDING for productive, sustainable and resilient FORESTs under climate change

Deliverable D5.4

Layman's report on benefits, costs and risks related to use of improved FRM in the Nordic countries

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1 Summary

The changing climate is an important driver of change in forests. It can increase forest vulnerability to damage and disease occurrence and intensity, reduce forest health and productivity, and cause economic losses. Depending on the region, it can also have positive effects, such as increasing forest growth due to increased temperature in Northern Europe.

This deliverable focuses on benefits, costs and risks related use of improved forest reproductive material (FRM) in the Nordic countries. The analyses cover tree species relevant to regional tree breeding objectives and programmes in case study areas. They have been executed through simulations to address the long-term impacts of deployment of improved FRM. Especially, the role of improved FRM and forest management in maintaining and improving health, resilience and productivity of Nordic forests under climate change was emphasized. Because of the high socioeconomic importance of forests to Finland and Sweden, the effects on industrial wood production and profitability of forest management was assessed as well.

Three alternative deployment and management scenarios were constructed and analyzed for both countries. Business as Usual scenario (BAU) is a reference scenario, which assumes that the deployment of improved FRM, as well as the intensity of silviculture and harvesting levels in production forests will remain at the current level also in the future. Scenario of Wood Production (PROD) aims to increase forest growth, wood production and profitability of forest management by intensifying silviculture in a cost-efficient manner and increasing the use of artificial regeneration with improved FRM. Adaptation and mitigation to climate change and biodiversity of production forests are emphasized in scenario Combined (COMB) with the help of adapted forest management together with the intensive use of improved FRM.

Results suggest that an increased use of improved FRM may provide not only improved wood-production and economy but also a tool to handle the trade-offs between production, biodiversity and other important ecosystem services. The use of tailored FRM together with tailored site-and species-specific silviculture seems to be a feasible way to promote the vitality and resilience of production forests under changing environment (COMB scenario). Alternatively, increased use of seedlings from the tree breeding programmes has the possibility to notably increase long-term wood-production and wood-removals as well as the economic performance of forestry (PROD scenario).

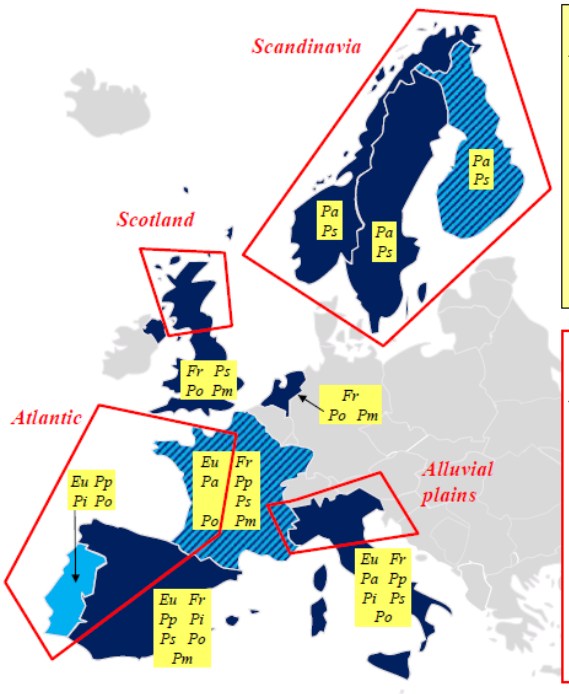
Throughout the work, cooperation within B4EST project between WP's and collaboration with stakeholders beyond B4EST was an indispensable part of the implementation of the work. Intensive cooperation with WP1 addressed the effects of climate change on the study regions on growth conditions in Sweden and Finland. The deployment strategies of FRM with tailored silvicultural management regimes applied were the result of cooperation between WP5 and WP4. Preliminary scenarios as well as main results were discussed with national stakeholder groups throughout the project.

2 Tree breeding and deployment of FRM to meet challenges of European forestry

The changing climate is an important driver of change in forests. It can increase forest vulnerability to damage and disease occurrence and intensity, reduce forest health and productivity, and cause economic losses. However, it can also have positive effects, offering opportunities for growing trees in previously suboptimal regions.

The strategic goal of B4EST is to increase forest survival, health, resilience and productivity under climate change and natural disturbances, while maintaining genetic diversity and key ecological functions and fostering a competitive EU bio-based economy. B4EST has provided forest tree breeders, forest owners, managers and policy makers with: 1) better scientific knowledge of adaptation profiles to increase sustainable forest productivity, and added value of raw materials for economically important tree species, 2) new and flexible adaptive tree breeding strategies and tools, 3) decision-support tools for the choice and use of Forest Reproductive Material (FRM) for balancing production, resilience and genetic diversity, 4) robust management and transfer recommendations for FRM deployment at stand and landscape levels, 5) policy recommendations to adapt European forest production systems to the challenges posed by climate change and natural disturbances, and to meet societal demands set to sustainable and multifunctional utilization of forest resources.

Benefits, costs and risks related to the deployment of improved FRM in Europe have been assessed by carrying out analyses indicating the impacts of revised deployment strategies in four different regions of Europe focusing on regionally prevalent challenges. The four different regions differ for growth conditions, tree species, structure of forests, operational environment of forestry, and expected biotic risks and other impacts of environmental change.



Tree species resources available for B4EST in the consortium countries

Tree species	Breeding populations (for WP1, 2, 3)	Multi-environment genetic experiments (for WP1, 2, 3, 4)
Eu	FR, PT, ES, IT	FR, PT, ES, IT, UK
Fr	FR, UK	FR, NL, UK
Pa	FI, NO, SE	FI, NO, SE, FR, UK
Pp	FR, ES, IT PT	FR, PT, ES, IT, UK
Pi	PT, ES	FR, PT, ES
Ps	FI, NO, UK, SE	FI, NO, SE, UK, FR, ES
Po	FR, IT	FR, IT, ES
Pm	FR, IT	FR, IT, ES, UK

EU zones with regionally prevalent challenges selected for the socio-economic impact analyses related to the deployment of improved FRM

Zones	Species	Indicators analysed
Scandinavia	*Pa, Ps*	Biomass production, financial performance, carbon sequestration, forest resilience and biodiversity
Scotland	*Ps*	Forest resilience, carbon sequestration, biodiversity, biomass production
Atlantic zone	*Eu, Pi, Pp*	Biomass production, carbon sequestration, forest resilience, biodiversity, seed production
Alluvial plains	*Po*	Biomass production, carbon sequestration, biodiversity

This report presents the main results from Nordic countries, Sweden and Finland.

3 Context and regional prevalent challenges

3.1 Nordic forests and forestry under climate change

The most abundant forest resources in Europe can be found in the boreal forest zone of Nordic countries. Almost 30% of the European forest area and nearly 20% of the growing stock of European forests is located in Finland, Sweden, and Norway (State of Europe's Forests 2015). In Finland and Sweden, the proportion of forests of the total land area is 73% and 68%, respectively, while the European average is ca. 33%. Socioeconomic importance of forest is significant in Finland and in Sweden. These two countries produce almost 30% of sawn goods, and 60% of pulp for paper and paperboard in EU.

Climate change is expected to be the most significant driver affecting forests and utilization of forest resources in Nordic countries during the coming decades. As climate gets warmer, the growing season is getting longer, and the effective temperature sum of growing season increases. Climate change has already affected dynamics of forests. Most notable changes have been observed in forest growth. During the last 50 years (1971 – 2020), total volume of the growing stock in Finland has increased from 1 520 millions m^3 to 2 506 millions m^3. According to Henttonen et al. (2017), 63 % of the growth increase from 1970 to 2010 was attributed to growing stock volume and forest structure, which both changed due to differences in forest management. However, 37 % of the volume increment increase was environment-induced, which coincided with increase in temperature sum. Increasing growth rate is beneficial to raw material supply from production forests. Increasing growth rate also means increasing uptake of carbon dioxide by trees from the atmosphere.

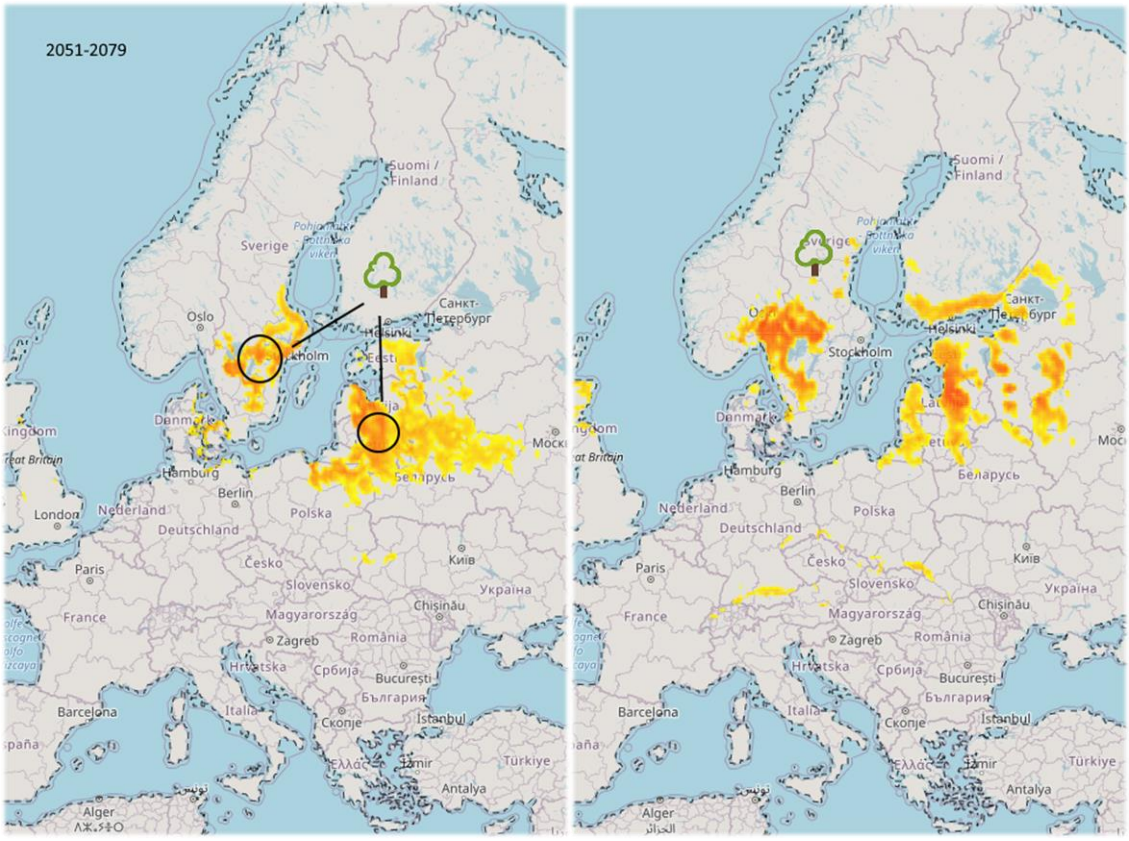


Figure 1. Prevailing climate in south-central Finland and Central Sweden in years 2051-2079 according to Climate Matching Tool (B4EST- WP1).

Climate change may affect differently projections for the different tree species and thus may change the tree species structure of forests. Survival of coniferous (Norway spruce and Scots pine) seedlings from winter is expected to become more difficult. After the mild winter, Norway spruce growth is weaker in early summer than in the summer after frosty winter. Birch is assumed to benefit from warming climate, because of the increasing concentration of carbon dioxide in the atmosphere is bringing forward the beginning of birch growing season. For all tree species, preparation for the winter, as well as the eruption of the winter break in spring can be disturbed.

Climate change brings along also increasing risks to health and vitality of forest ecosystems. There will be more newcomer and invasive species and their chances of survival are improving. Damage risk by insects such as bark beetles can increase due to more favorable reproductive and growing conditions. From fungal diseases, root rot caused by *Heterobasidion* spp. in conifer trees can increase and spread towards the north. Further, the risk of more severe storm damage is expected to increase.

Loss of biodiversity is another alarming trend, which has been globally identified. In Nordic countries, it has been seen as a consequence of prevailing forest management, but it is also affected by climate change.

Concern about the negative impacts of climate change and prevailing management on forests has brought about the need to change forest management so that forests could better adapt to and mitigate climate change and meet wider range of sustainable development goals.

3.2 Tree breeding in the Nordic countries

Although there are some minor differences, the tree breeding programmes for Scots pine and Norway spruce in Sweden and Finland are very similar in strategy and design and the key features are described below. The breeding programmes were initiated in the 1940's and 1950's with the selection of superior individuals, so called plus-trees, by visual assessment in natural stands. In the 1980's and 1990's an additional round of plus-tree selection was performed in both countries to broaden the base of trees to select from. These plus-trees were subsequently tested in field trials and the best plus-trees were selected after genetic evaluation to constitute the next breeding generation. These selected trees were crossed, and their offspring tested in field trials, whereafter the new candidates are evaluated, and the best performers selected. This then continues with a complete generation turnover of 20-30 years, with a genetic gain of 10-15% per turnover, and can be illustrated as a circular process (Figure 2).

At different steps in the process, the elite material identified in the breeding process is transferred to the deployment population dedicated to forest reproductive material (FRM) production which, so far, almost exclusively has been made up of seed orchards. After the plus-tree selection, many of these trees were also used as parents in first generation (1g) seed orchards with a genetic gain about 10% compared to unimproved stand seed. After the genetic evaluation of those plus-trees, the best trees were selected to the one-and-a-half generation seed orchards (1.5g) with a genetic gain about 20-25% compared to unimproved stand seed. The most advanced parts of the breeding programmes have now reached the genetic evaluation of a new breeding generation and some early second-generation seed orchards (2g) are planned for establishment in a few years.

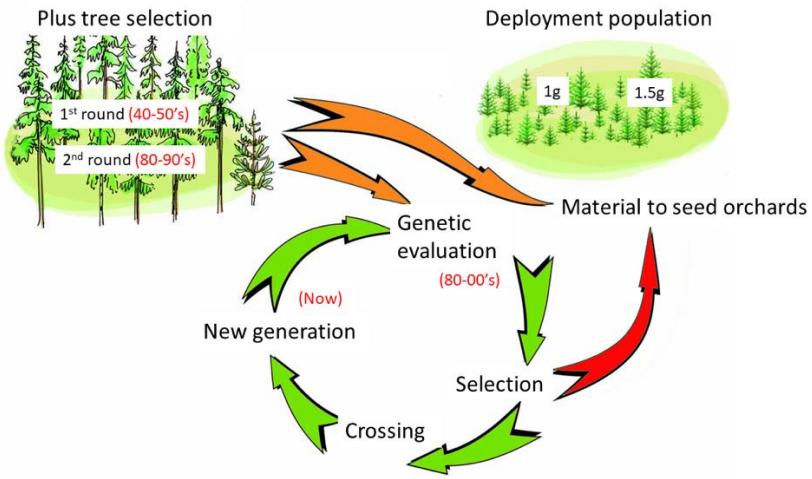


Figure 2: ***The different steps of the Scots pine and Norway spruce breeding process in nordic countries*** and approximately when those steps were reached/performed (red text). The seed orchard definitions are described below.

The breeding programmes aim to combine and integrate: (i) improvement in several traits included in the breeding goal; (ii) preparedness for climate change; (iii) dynamic management of genetic diversity.

The breeding programmes have so far aimed for general purpose goals where most of the focus has been on increased growth and vitality (so indirectly on local adaptation) and the genetic gains we have presented earlier refers to predicted production over a rotation in environmental conditions experienced in the area. However, especially for Scots pine, stem and branching traits have also been considered and for Norway spruce growth rhythm traits have been included in some situations. For both species, wood quality traits (e.g. density, stiffness) and resistance to biotic threats (e.g. Cronartium, Root rot, Pine wood nematode) have been evaluated but not yet fully included in the breeding goal.

The breeding programmes are based on MPBS (Multiple Population Breeding System) with several different sub-populations covering different regional targets. Breeding managements of these sub-populations are unrelated to each other and adapted to different combinations of photoperiod, temperature and altitude, which are known drivers of interactions between the genetic material and the environment. This results in a differentiation of adaptation patterns between the sub-populations and consequently a preparedness for a warmer climate.

The inherent long-term trade-off between potential genetic gain and level of genetic diversity is key for each breeding programme. The MPBS-system where each sub-population and its 50-100 founder trees are unrelated is part of a dynamic management of genetic diversity. At each generation turnover, the selection process and crossing system are carefully designed to achieve maximum possible genetic gain while preserving additive genetic variation, maintaining low inbreeding and reduced loss of rare alleles, allowing for a sustainable genetic improvement over many generations.

Figure 3. ***Controlled crosses of Norway spruce in a greenhouse to recombine elite genotype and manage genetic diversity***. Photo: Matti Haapanen

The testing strategy consists of 4-6 field trials for each sub-population, that are spread across different climatic conditions within the target area of that population. In the subsequent genetic evaluation, only trees that exhibit good performance at all different trial sites are selected. This multisite selection increases the robustness and stability of performance of the selected trees in the intended deployment area. Furthermore, new analysis methods and trial designs with better connection between different trial series allow for joint analyses with much more data to evaluate the trees, resulting in better estimates of their future performance.

The improvement of performances provided by the breeding programmes are transferred to forestry by the production population, providing at large scale improved FRM. This deployment strategy of genetic gains and tailored genetic diversity has been dominated by seed orchard deployment systems. The currently available seed orchards of Scots pine and Norway spruce have different genetic composition, different levels of genetic gain and adaptive properties, which means that correct and climate adapted deployment of the improved FRM is necessary to transform potential genetic gain in realized improvement of performances. Therefore, deployment guidelines and decision support tool have been and are under continuous development to integrate changes.

3.3 Stakeholder demands and perceptions

Stakeholder views on improved forest reproductive material (FRM) was collected through an online survey in 2019 that was open to all stakeholders of the European forest-based bio-economy and more specifically eight important forest tree species in Europe. From the Nordic countries, Finland, Norway and Sweden, there was 87 answers from public administrators as well as public and private forest managers. For the Nordic countries the two relevant species are Norway spruce and Scots pine.

We can sum up and say that the negative effects of climate change are perceived by the stakeholders today and are expected to increase until 2050. A balance of negative and positive

effects is observed and expected in the Nordic countries in contrast to the more negative effects observed and expected in Southern Europe and Germany.

The reported data show that there is an expectation and confidence that future changes will be manageable across Europe. To be able to cope with climate change, the three most important forest management strategies are, first, diversification of tree species, which is a common strategy to distribute risk. Second, artificial regeneration with improved FRM tested and recommended for adaptation to climate change and the third strategy is enrichment of natural regeneration with FRM better adapted to future climate changes.

As criteria for selection in Norway spruce tree breeding programmes, the resilience to biotic disturbances ranks on the top, with bark beetle and root rot (*Heterobasidion*) as the two major threats. As the most important climate condition to consider, the drought- and storm resistance was indicated. The most important issue preventing the use of Norway spruce improved FRM is the limited availability of improved FRM.

For Scots pine, the most important selection criteria considered was also resistance to biotic disturbances. Abiotic disturbances as drought and wind also need to be considered. The most important issue preventing the use of Scots pine improved FRM was the preference towards natural regeneration among forest managers.

Lastly, the outlook for the use of improved FRM in the next 20 years is positive. Across all species the use of improved FRM is expected to increase. In Sweden, Finland and Norway the view of the benefits using improved FRM outweighing the benefits of using non-improved FRM is the most prominent in Europe indicating that stakeholders rely on tree breeding in general.

4 Methodology for the analysis of future FRM deployment and forest management scenarios

4.1 The goal of the scenarios

The ultimate goal of scenario analysis is to provide decision support for regional-level forestry planning and decision making in by indicating the impacts of deployment of improved FRM in Nordic countries. In Finland and Sweden, the emphasis of long-term scenarios is on the effects of improved FRM on biomass production, carbon sequestration, resilience and biodiversity of forests under changing climate and changing operating environment in a selection of forest areas (Figure 4, 3 counties in Sweden and five regions in Finland). Performance of improved FRM in multifunctional and sustainable forest management have been analyzed with two decision-support systems (DSS – Heureka and Motti) both incorporated with the effect of genetic gain in growth models.

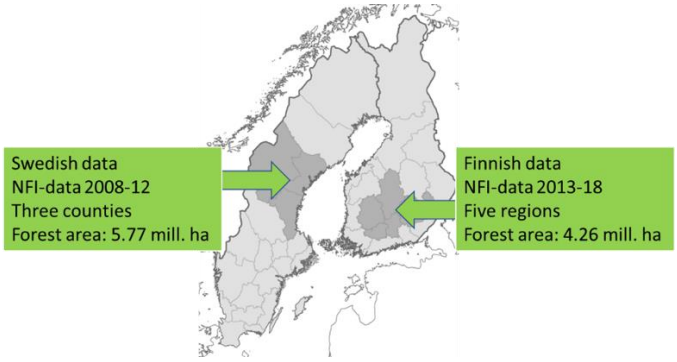


Figure 4. ***Description of target areas for simulations in Sweden and Finland***.

4.2 Simulation tools and data from national forest inventories

Finland, Mottis (DSS)

Stand projections were produced by Motti stand simulator (Salminen et al. 2005). The simulator includes two sets of models for predicting stand dynamics (Hynynen et al. 2014). Stand-level growth models are used to predict juvenile stand development (until 7 m dominant height) after which individual-tree distance-independent models are applied. Motti stand simulator has been widely applied to analyze the effects of different forest management alternatives under different growing conditions (Hynynen et al. 2015, Ahtikoski et al. 2018; Juutinen et al., 2018). Genetic gain was modelled as an endogenous variable in existing individual growth models for tree diameter and height via application of a Chapman–Richards type function (Ahtikoski et al. 2012, 2013). The procedure corresponds to applying a genetic multiplier (e.g. Gould and Marshall 2010). The genetic gains applied in the models were initially derived from the results for existing, mature seed orchards (Haapanen et al. 2016, 2020).

In the simulation process, national forest inventory (NFI)-sample plot data was used as input. Motti automatically selected a set of management regimes for each sample plot according to site-species-climate classes for each scenario and predicted stand developments according to these pre-defined management regimes. After the simulations linear programming (LP) was applied using software J (Lappi and Lempinen 2014). Linear programming was needed to include the predefined regional goal and constraints set each scenario. With the help of linear programming, the final set of management scenarios, one per each stand, was selected resulting in a feasible solution for each scenario (e.g. Huuskonen et al 2020).

Sweden, Heureka (DSS)

The Swedish simulation tool Heureka Regwise was used for the analysis (Wikström et al. 2011). It is adapted to large scale scenario analyses, aiming at answering questions like “what happens if…”. A wide range of settings when it comes to management, harvest levels, climate and so forth makes it possible to analyze the consequences of different assumptions about the future. The core of the system is empirical models. For young stands (height<7 m) the models for stand structure and height growth is based on data from the HUGIN young stand survey and data from the national forest inventory (NFI). For established stands the models are based on the development on permanent plots from the NFI. The models simulate growth on individual tree level and stand level, ingrowth and mortality.

Effect on growth from a prolonged vegetation period and increasing CO_2 -concentrations in the atmosphere according to the climate scenario RCP4.5 (IPCC 2013) was added in all scenarios. The built-in climate effect in Heureka regwise have been estimated using the process-based model BIOMASS (McMurtie & Landsberg 1992) and concerns positive growth effects only and no negative effects of climate change were simulated.

NFI data, Finland

Currently, National Forest Inventory (NFI) measurements are conducted within five years. In practice, measurements are done in the entire country each year through measuring one-fifth of the plots. Further, about one-fifth of all plots are measured as permanent. Information from the Finnish NFI has traditionally been used in large area forest management planning, such as planning regional and national level cutting, improving silviculture and forest regimes, making decisions concerning forest industry investments, and providing a basis for forest income taxation (Tomppo 2006). For this study the NFI sample plot data to represent current forest resources were derived from a sub-sample consisting of 12 062 systematically located NFI sample plots in the region of five provinces located

in South-Central Finland. The forest area corresponding the NFI sample plots was ca. 4.26 Mha, and the average temperature sum ranged from 1 180- 1 350 d.d.

NFI-data Sweden in the three studied counties

NFI is a stratified sample of circular plots (7 or 10 m radius) arranged along the sides of squares, so called tracts, systematically distributed over all kinds of land. A total about 11 000 plots are inventoried each year. On each plot trees are calipered and site and stand data is registered. Additional measurements are made on a subsample of the trees, such as height and registration of damages (Fridman et al. 2014).

The studied area was southern Norrland in central Sweden, including the three counties Jämtland, Västernorrland and Gävleborg (Fig. 4). Total land area is 8.8 Mha of which 5.6 Mha is productive forests, dominated by Norway spruce (42%) and Scots pine (38%).

Since it takes five years to cover the whole sample, data from 2008-2012 were used as the base for the simulations, meaning that the start year was set to 2010. Only productive forest land (growth >1 m3/ha/yr) was included. The plots were put in different domains: formally protected areas, voluntary set aside areas, retention patches and wood production land (Table 1). Management and harvest were simulated on wood production land only.

Table 1. ***Areas of the different domains in the three Swedish counties*** included in the scenarios (Jämtland, Västernorrland and Gävleborg).

Forest Domain	Area, ha
Voluntary set aside areas	327 045
Retention patches	538 399
Nature reserves	101 069
Wood production land	4 801 534
Total	5 768 047

4.3 Scenarios

Finland

For assessing the benefits, costs and risks related to the deployment of improved FRM three management scenarios were established in Finland:

1. Business as Usual scenario (**BAU**) is a reference scenario, which assumes that the deployment of improved FRM, as well as the intensity of silviculture and harvesting levels in production forests will remain similar to the present even for decades to come. The intensity of silvicultural practices was expressed as the relative amount of accomplished vs. recommended treatment areas. The actual areas were obtained from the NFI12 field data. Harvesting level was defined as mean annual harvesting removals from 2016 to 2020 obtained from forestry statistics (stat.luke.fi). Treatment areas and harvesting levels were used as constraints in the optimization.
2. Scenario of Wood Production (**PROD**) aims to increase forest growth, wood production and profitability of forest management by intensifying silviculture in a cost-efficient manner and increasing the use of artificial regeneration with improved FRM. Timing and allocation of commercial cuttings are in the key role in maximising profitability.Net present value (NPV) of cutting incomes using commonly applied interest rates was used to depict profitability. Maximising NPV at 3% interest rate was set as a goal in LP for finding an optimal solution for PROD scenario. The focus of PROD scenario is on the economic sustainability. It aims to

show the profitable potential of wood production and forest based raw material supply enabled by intensive use of improved regeneration material and intensive silviculture of production forests.

3. Adaptation and mitigation to climate change and biodiversity of production forests are emphasized in scenario Combined (**COMB**) with the help of adapted forest management and intensive use of improved FRM. Goal is to improve the resilience of forests and increase biodiversity in production forests. COMB scenario aims to reconcile different objectives of forest management under changing environment and secure the provision of wide range of sustainable development goals set to the utilization of forest resources. Carbon sequestration of forests is promoted by lengthening rotation periods and using improved FRM always when forest is regenerated by planting or sowing. The share of broadleaved tree species is favoured in coniferous dominated stands by maintaining at least 20 % broadleaved mixture in production forests, whenever possible. Goal is to improve the resilience and increase biodiversity. In LP phase, management regimes promoting broadleaved mixture and extended rotations were favoured.

With respect to FRM material (seed origin) there was a difference between BAU and PROD & COMB scenarios. The proportions of unimproved, 1st generation and 1.5th generation seed orchard seed are presented in Table 2 in evolving time for both tree species, Scots pine and Norway spruce. In brief, the proportion of 1.5th generation seed orchard seed gradually increased in evolving time for both tree species (Table 2).

Table 2. ***Proportion of unimproved, 1st generation and 1.5th generation seed orchard seeds*** in artificial regeneration of Scots pine and Norway spruce related to BAU, PROD and COMB scenario. *Note that identical proportions were applied for PROD and COMB scenarios.*

Time interval	BAU	PROD & COMB
2021-2025	Unimproved: 15%[a)] (35%)[b)] 1st generation: 46% (43% 1.5th generation:39% (22%)	0% (10%) 54% (59%) 46% (31%)
2026-2030	15% (35%) 35% (33%) 50% (32%)	0% (10%) 42% (45%) 58% (45%)
2031-2035	15% (35% 9% (18%) 76% (47%)	0% (10%) 10% (25%) 90% (65%)
2036-2040	15% (35%) 330% (0%) 85% (65%)	0% (10%) 0% (2%) 100% (88%)
2041-2045	15% (35%) 0% (0%) 85% (65%)	0% (10%) 0% (0%) 100% (90%)
2046 →2100	15% (35%) 0% (0%) 85% (65%)	0% (10%) 0% (0%) 100% (90%)

[a)]the value, 15% is for Scots pine, [b)] percentage in parenthesis represents the proportion for Norway spruce

The effects of climate change to forest dynamics and damage risks were not directly taken into account in future forecasts of forests. The increased growth rate could have been predicted using existing models for growth response to increased temperature and CO_2 content in the atmosphere (e.g. Matala et al 2005). However, currently there are no reliable generalizable models for assessing

the negative effects of increased mortality and damage risk on forest growth and structure. The average growth rate in the simulations equals to that observed in 11th Finnish National Forest Inventory (2009 – 2013). Thus, it already includes the observed effect of climate change on forest growth rate by that time.

However, forest management strategies of three scenarios differed: a) with respect to mitigation and adaptation to climate change, b) in taking into account the changes in operational environment, and c) emphasizing holistic sustainability in forest management. In forest management, adaptation and mitigation measures were widely applied especially in COMB scenario.

Sweden

Three different scenarios were simulated, two with varying use of genetically improved forest reproductive material (FRM) and one where broadleaves were favored:

1. business as usual: BAU
2. increased use of FRM: PROD
3. as PROD combined with increased proportion of broadleaves: COMB

All other management was according to business as usual, except for COMB where broadleaves were favored in cleaning and thinning. Harvest intensity was set 80% of the net growth on wood production land throughout the simulation period of 100 years in all scenarios. When planting was applied after harvest, about 50% was planted with Norway spruce and about 50% with Scots pine.

The use of improved FRM can be controlled by *i*) setting the proportion of planting of the total regenerated area, *ii*) setting the proportion of improved FRM of the total planted area, and by *iii*) setting the expected breeding effect as increased growth (%). In BAU, *i* was set to 75%, *ii* was set to 87% for Norway spruce and 100% for Scots pine, and *iii* was set to 13% Norway spruce and 16% for Scots pine. In PROD, i was set to 100%, *ii* increased from 87% to 92% for Norway spruce during 20 years, and *iii* increased successively from 13% to 21% during the first 20 years for Norway spruce and from 16% to 22% for Scots pine. After 20 years *iii* remained constant for the rest of the simulation period.

5 Highlighted results of scenario simulation

Finland

Cutting removals and growing stock volumes

Cutting removals were highest in PROD scenario, as expected (Fig. 5). They were at high level especially during the first two decades due to the aim at maximizing net present value of cutting incomes. In COMB emphasizing carbon sequestration, removals were at lower level compared with two other scenarios, mainly due to the longer rotation periods.

From the current year (2021) to year 2100 the average annual roundwood removal was 5.8 m^3 ha^{-1} for BAU, Business-as-Usual scenario, which is similar to the realized annual average roundwood removal in the region between years 2015-2018 realized. Average cutting levels were the highest for PROD scenario, 6.1 m^3 ha^{-1}, and lowest for COMB 5.1 m^3 ha^{-1}.

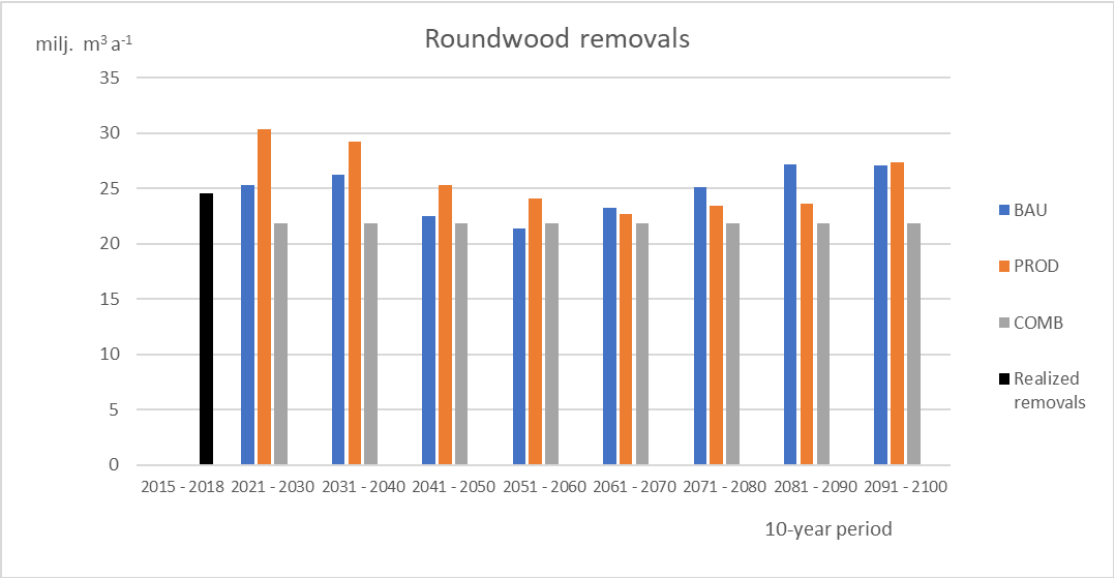


Figure 5. **Estimated *annual volumes of roundwood removals between 2021 and 2100 in three management scenarios***. The realized mean annual removals between 2015 – 2018 presented by a black bar.

The differences in cutting levels of scenarios affected notably the development of growing stock volumes (Fig. 6). The COMB scenario was distinctive – from 2021 to 2100 the growing stock increased almost 70%. At the year 2100 the difference of growing stock between BAU and COMB scenario was over ca. 380 million m^3 which accounts for about 50% of the growing stock of BAU at the particular year. However, in all scenarios the growing stock increased during the 100-yr time horizon indicating sustained yield forestry.

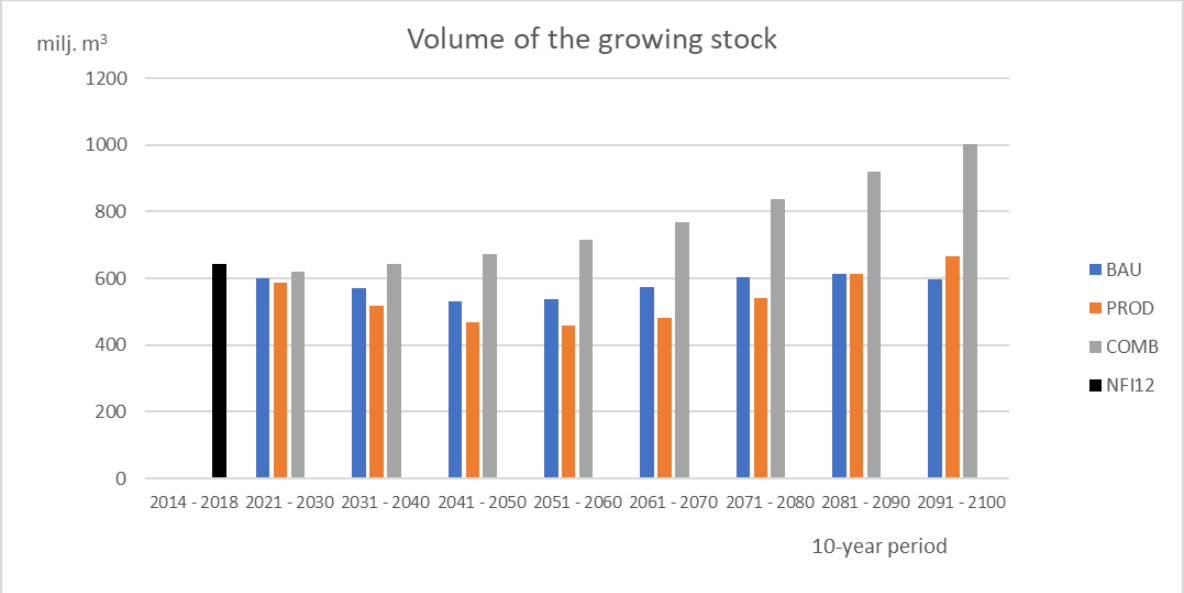


Figure 6. ***Estimated growing stock between 2021-2100 by 10-yr intervals in three management scenarios***. Average growing stock between 2014 and 2018 according to the 12th National Forest Inventory presented by a black bar.

Carbon sequestration

With respect to carbon balance (incl. stocking and soil) both BAU and PROD scenario turned out to be carbon sources between 2021-2030 (Figure 7). This is due to vigorous cuttings at the beginning

of simulation period – those cuttings could not be either postponed or avoided due to the existing structure of forests and constraints of the scenarios. However, after 2030 all scenarios turned to be carbon sinks so that distinctively the biggest average sink was produced by COMB scenario (Figure 3).

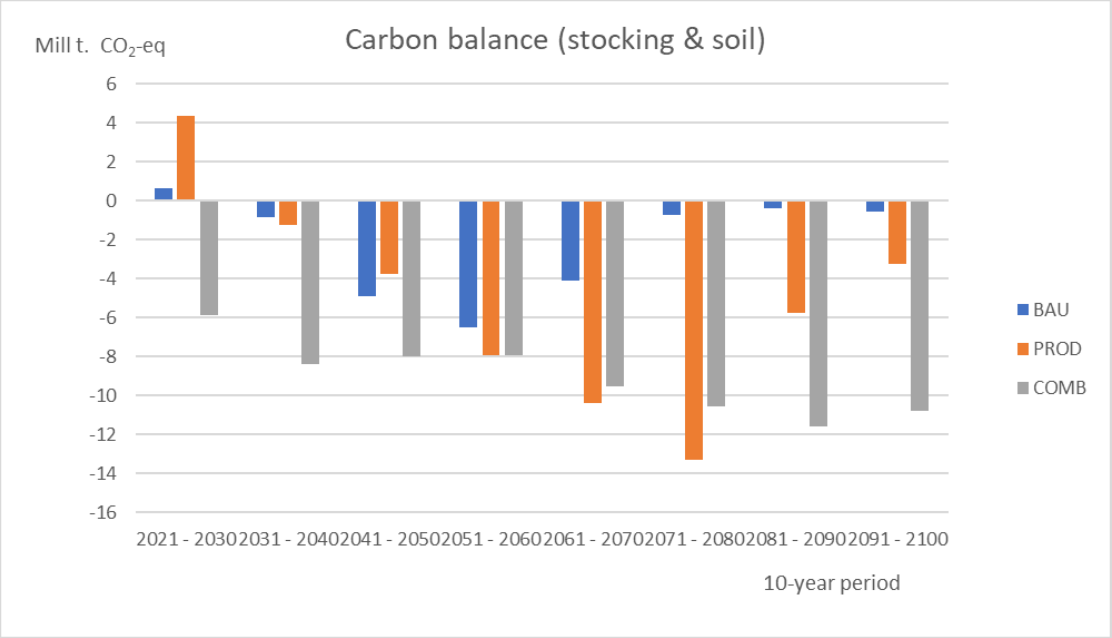


Figure 7. ***Estimated carbon balance associated with BAU, PROD and COMB scenarios, million tons of CO_2-eq***.

Profitability

The best performer in monetary terms (expressed as net present value, NPV) was PROD scenario with all interest rates, 2%, 3% and 4% (Figure 8). For instance, with 3% interest rate PROD scenario outperformed COMB scenario by app. 1 626 €ha^{-1} corresponding a 26% increase to COMB (Figure 4). COMB scenario resulted in 12 % lower NPV of incomes than BAU scenario. It can be seen as a cost of reconciling multiple goals in forest management more than in BAU management.

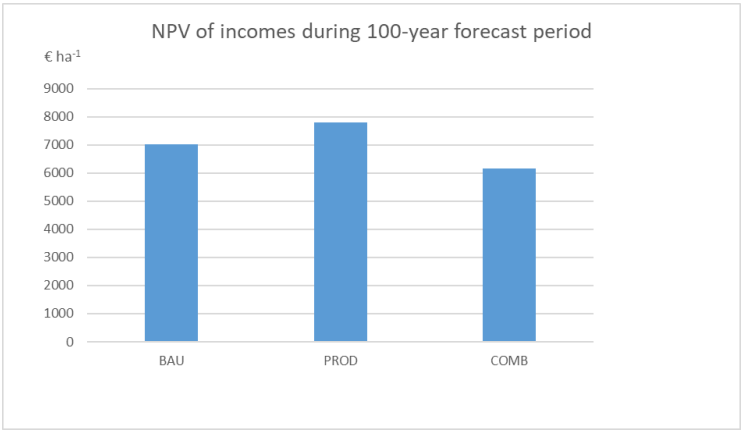


Figure 8. ***Net present value (NPV) with 3%, € ha^{-1}according to three management scenarios***.

Sweden

All results concern wood production land, i.e. productive forests available for wood supply, which means that set-aside areas are excluded.

Growth, cutting removals and growing stock volumes

After 50 years the annual growth was about 3 % higher in PROD and 4 % lower in COMB compared to BAU, and after 100 years corresponding figures were about 4 and 6 %. Since the harvest intensity were the same in all scenarios, the harvest followed the same pattern (Figure 9, 10).

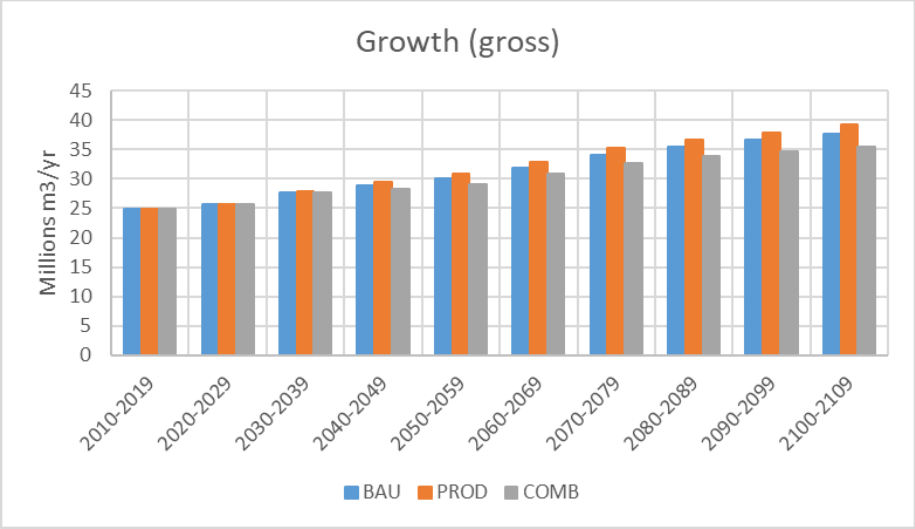


Figure 9. Average annual growth during ten-year periods for the different scenarios, includes stemvolume+bark for all trees h>1.3 m.

Differences in growth and harvest between the scenarios did not appear until 20-30 years. In the actual area, the average growth corresponds to 1.3 m^3/ha/yr during the first 20 years after stand establishment and increases to about 7 m^3/ha/yr between 20-40 years (where it remains until a stand age of about 80 years and thereafter the growth decreases). At the same time, less than 1% of the area is harvested and regenerated each year, meaning that it takes several years until the effect from a silvicultural measure that is limited to regeneration after harvest will be noticeable at this scale.

In COMB, the proportion of broadleaves increased from 16 % in 2010 up to 35-40 % after about 50 years and onwards, whereas in the other scenarios the proportion increased up to about 27 % after 50 years and thereafter it decreased down to 20 %. A majority of the broadleaves was birch which is known to have slower growth at late developmental stages compared to the conifers, and since the broadleaves were naturally regenerated there were no breeding effect.

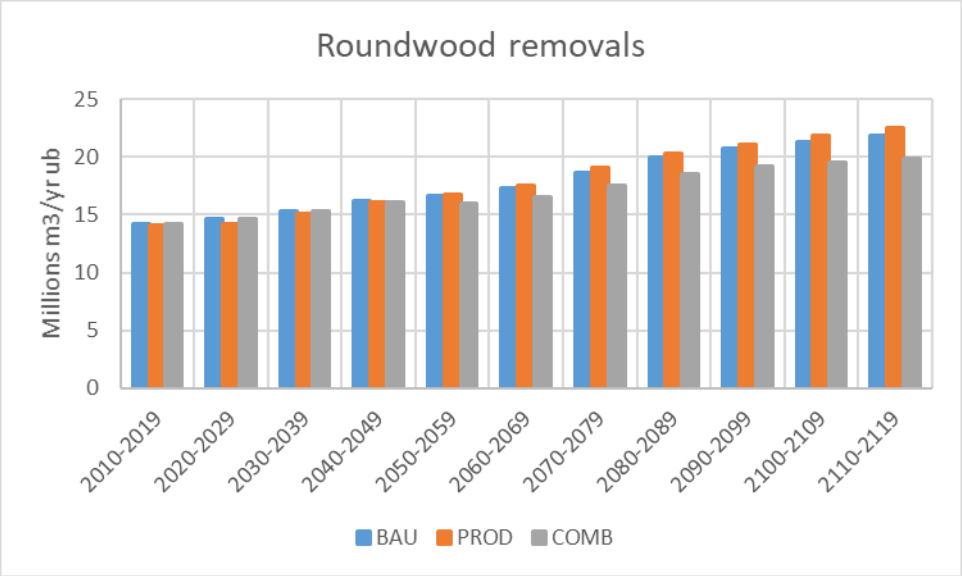


Figure 10. ***Roundwood removals in the different scenarios, including fuelwood, pulpwood and saw logs***, bark is excluded.

The standing volume increased in all scenarios. After 50 years, the standing volume was about 3 % higher in PROD and compared to BAU and COMB, and after 100 years corresponding figure was about 5 % whereas the volume in COMB was 2 % lower (Figure 11). This is also in line of what could be expected. The fact that less than 100% of the net growth (growth minus mortality) was harvested should of course result in an increase of the standing volume. The difference between net growth and harvest is equal to difference in standing volume and given that the harvested percentage of the net growth is kept constant (80% in this case), the difference between growth and harvest in absolute numbers becomes larger as the growth increases.

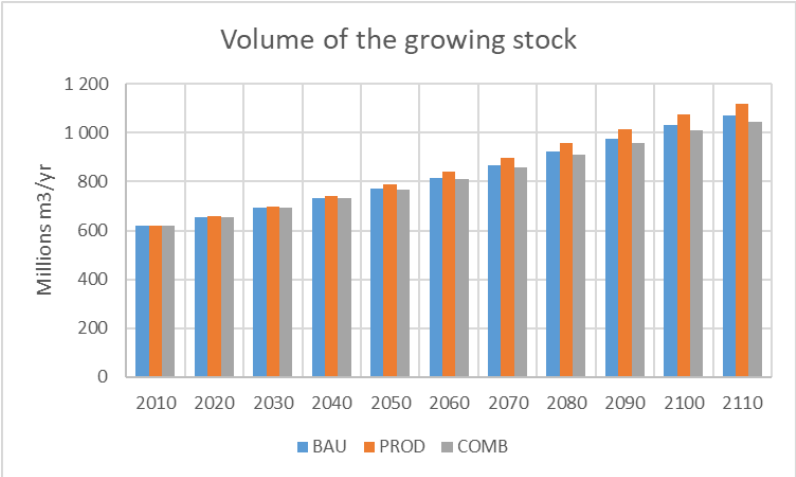


Figure 11. ***Standing volume in the different scenarios.***

Carbon sequestration

Emissions of greenhouse gases from the carbon pool living tree biomass were negative in all scenarios, meaning that the carbon pools were increasing or sinks (Figure 12). Harvest and mortality were lower than the growth leading to an increase of the standing volume as well as total biomass.

The pool of living tree biomass was a larger sink in scenario PROD compared to BAU due to the same reason as for standing volume. Compared to BAU, the larger difference between growth and

harvest plus mortality in PROD resulted in a higher accumulated carbon sequestration corresponding to 13 Mton CO_2 after 50 years, and 29 Mton after 100 years. Standing volume for BAU increased more rapidly than for COMB (Figure 11) but the CO_2-emissions indicate the opposite, at least up to 2080. Obviously, the total biomass of the trees increased more rapid than the volume in COMB, which is explained by the higher proportion of broadleaves. Birch is dominating among the broadleaves and the wood density of birch is about 20% higher than for the conifers.

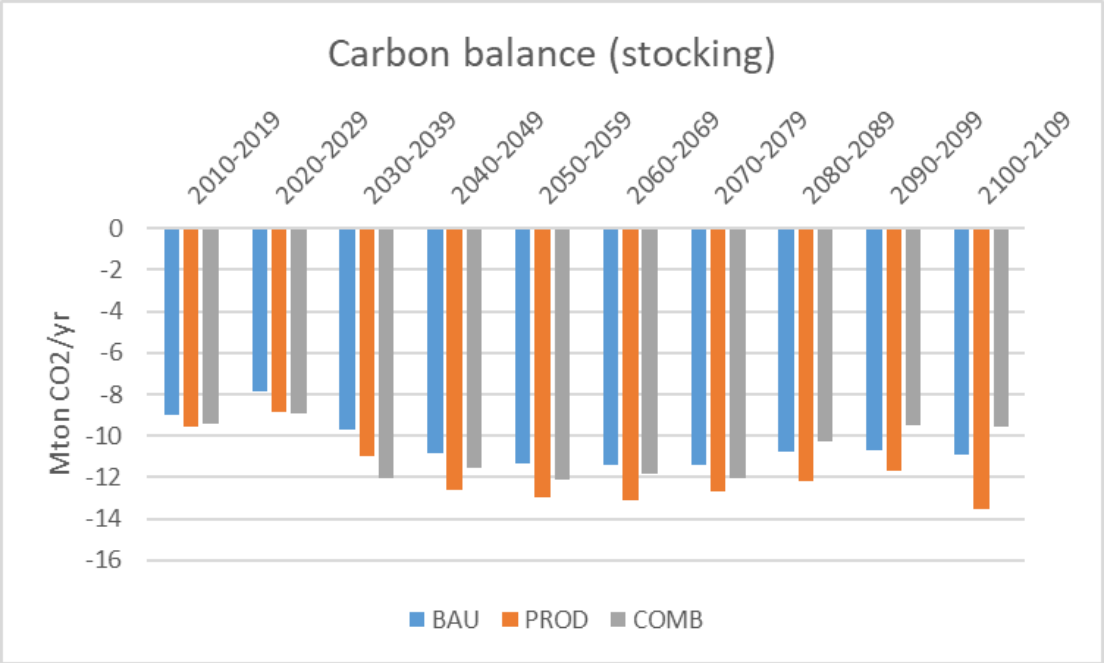


Figure 12. ***CO_2-emissions derived from stock changes in living tree biomass***, millions of tonnes CO_2 per year.

Carbon assimilation in the soil was about the same in all scenarios during the first decades and thereafter the assimilation was higher for PROD and lower for COMB than for BAU (Figure 13). Compared to BAU, the higher growth in PROD resulted in a higher litter fall and thereby a higher accumulated carbon sequestration corresponding to 1 Mton CO_2 after 50 years, and 6 Mton after 100 years. Corresponding values for COMB was -4 and -7 Mton.

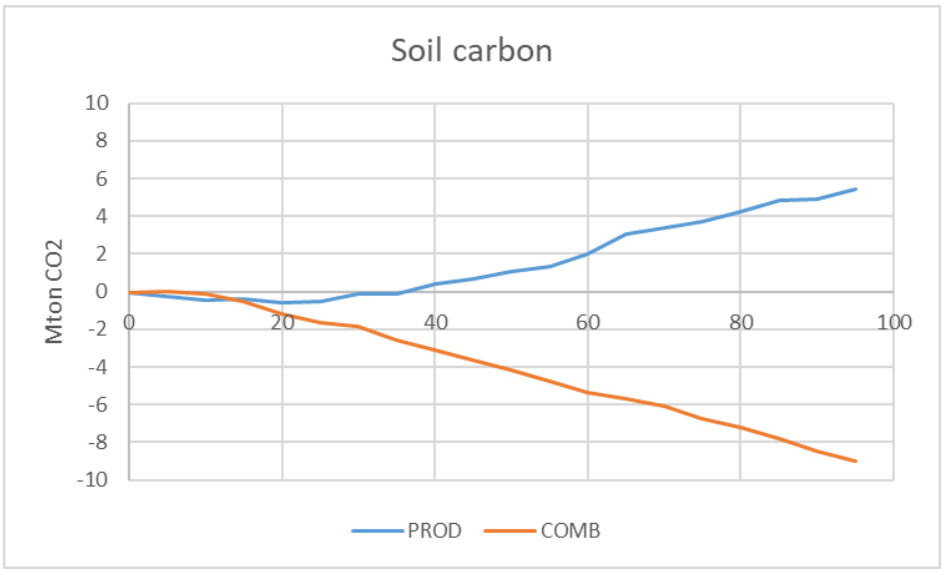


Figure 13. ***Differences in accumulated CO_2-sequestration*** between BAU (=0), PROD and COMB.

It must be noted that the results might have been slightly different if other pools included in the national greenhouse gas reporting, such as products (Harvested Wood Products (HWP)) and dead wood, would have been included but in this study these pools were considered as constant over time. One could for instance expect that the HWP-pool should increase faster in PROD due to the higher harvest level.

Profitability

The net present value varied slightly between the scenarios (Figure 14). Income from harvest and expenses for silvicultural measures where similar in all scenarios during the first decades. Thereafter the income from harvests was lower in scenario COMB than in the other two due to a lower harvested volume and a lower fraction of saw logs. Beside the slower growth for the broadleaves, resulting in lower harvest, the larger fraction of broadleaves in scenario COMB resulted in a larger fraction of pulpwood at the expense of saw logs.

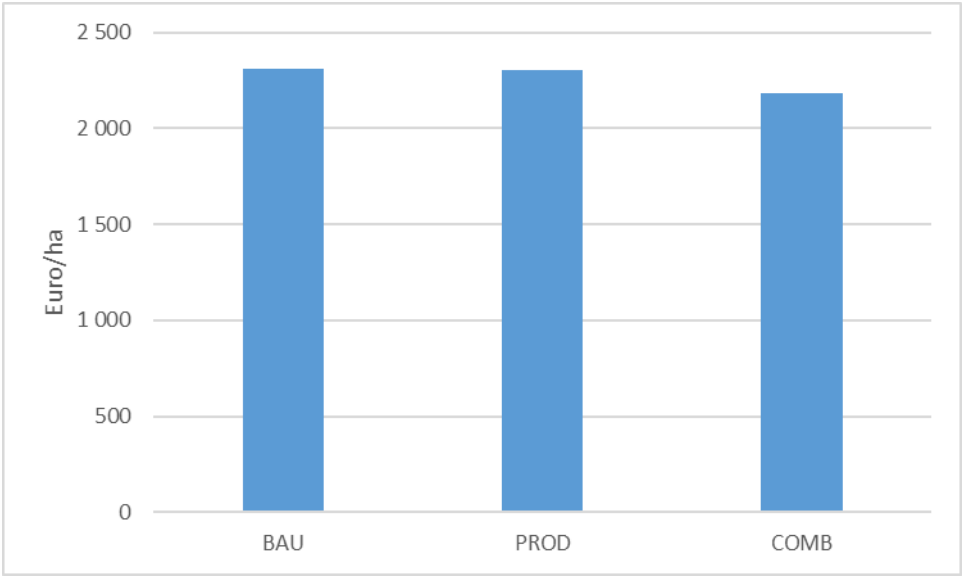


Figure 14. ***Net present value (Euro/ha), calculated with an interest rate of 3 %.***

6 Discussion

6.1 Approach

This Layman's report focuses on benefits, costs and risks related use of improved FRM in the Nordic countries. The aim was to address the long-term impacts of deployment of improved reproductive material. The changing climate has been widely identified to be highly important driver of change in forests. Thus, an emphasis has been in assessing the role of improved FRM and forest management to maintain and improve health, resilience and productivity of Nordic forests under climate change.

For the first time, alternative deployment strategies of improved FRM and management strategies were jointly assessed and reported for large forest regions of Nordic countries. The results provide up-to-date scientific basis for forest policy decision-making and deployment and management strategies at regional and national levels.

6.2 Country-specific differences

The principles of the analysis and constructed scenarios were similar in both countries. However, there were some differences between Sweden and Finland in analysis methods and the forest management assumptions. In the analyses, prevailing country-specific scenario analysis tools were applied as such without any methodological modifications or harmonization. Differences in the simulation frameworks affect the results in several ways.

It is well known that harvesting levels have a major effect on the development and structure of the growing stock in forests. In Swedish scenarios, harvest intensity was set to 80% of the net growth, and length of rotation period was restricted in all scenarios. In Finnish harvesting levels and rotation lengths were not strictly controlled, and they varied between scenarios. Therefore, the general effects and ranking of different management scenarios on were similar, but the magnitude and temporal effects of management scenarios on cutting removals, volume increment and carbon sequestration of the growing stock, as well as profitability varied between the countries.

In overall the stocking (m^3/ha) is at a lower level in Sweden than in Finland. This is due to differences in the historical background of silviculture as well as average site fertility. The Swedish region has large forest areas at high altitudes bordering the tree line in the Scandinavian mountain-range while the Finnish region is mainly low altitude forests, with higher temperature sums and a longer vegetation period, as wells more fertile sites. This also leads to differences between the countries in growth rates, stocking, harvestable volumes and profitability.

The most distinctive difference between Sweden and Finland is the profitability associated with the scenarios. In brief the net present values are notably higher in Finland compared to Sweden. Reasons for this discrepancy are many, but the two main reasons are likely a lower level of timber prices in Sweden and the lower growth due to lower productivity forests in the Swedish region.

6.3 Implications for the tree breeding and forest management

In general, we conclude that an increased use of improved FRM may give the forest managers not only improved wood-production and economy but also a tool to handle the trade-offs with biodiversity and other important ecosystem services. Finally, the use of improved reproductive material together with tailored site-and species-specific silviculture seems to be a feasible way to promote the vitality and resilience of production forests under changing environment.

Despite some differences in analysis results between countries However, some of the most important results are similar between the two countries. We conclude that an increased use of

seedlings from the tree breeding programmes has the possibility to increase long-term wood-production and wood-removals as well as the economic performance of forestry, as demonstrated in the PROD-scenarios in both countries.

In the COMB scenarios in both countries, we demonstrate an alternative option to reap the benefits of tree breeding. The increased growth from the improved conifer seedlings gives us the opportunity to increase the share of broadleaved tree species in coniferous dominated production forests, and prolong rotations without losing much of the wood-production or profitability in relation to a business-as-usual management. The relative loss in the net present value of cutting incomes when shifting from BAU to COMB scenario was ca 10% for both countries.

The increased share of broadleaves and prolonged rotations are effective measures to improve the resilience, biodiversity and output of a range of ecosystem services from the forest. In our simulations we have assumed that the increase in broadleaves comes from naturally regenerated broadleaves, mainly birches. We have not assumed planting of improved birch seedlings, which could be an option to further improve the wood-production in the future. In the long term, the benefits from improved vitality and strengthened resilience of production forests under changing climate are likely to prove much more valuable than predicted loss of profitability.

7 Collaboration and dissemination

This report is a deliverable of Task 5.3 in WP5. However, from the beginning of the work, cooperation within the B4EST project between other work packages, as well as collaboration with stakeholders beyond B4EST has been an indispensable part of the implementation of the work. In the beginning, an extensive stakeholder and actors survey (DL 5.1 of WP5) provided a valuable information about societal and industrial demands and expectations for FRM of the forest-based bio-economy. They have been taken into account in the construction of the scenarios. The collaboration within B4EST has been active with WP1 referring the effects of climate change on the study regions in Sweden and Finland. The deployment strategies of FRM as well as tailored silvicultural management regimes applied in scenarios were the result of cooperation between WP5 and WP4.

Collaboration with national stakeholders in Sweden and Finland took place first in the form of stakeholder survey bay Task5.1 of WP5. Then it continued in collaboration in constructing the scenarios. We discussed with stakeholder groups about the contents and feasibility of proposed scenarios in national stakeholder events. After completing the analyses, preliminary results were presented and discussed with local stakeholder groups, such as Advisory Board of Tree Breeding for Finland. In the future (after B4EST), dissemination at national levels will be continued in the form of participation in the stakeholder events and preparing national police brief based on the B4EST results.

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