Supplementary Information

Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity

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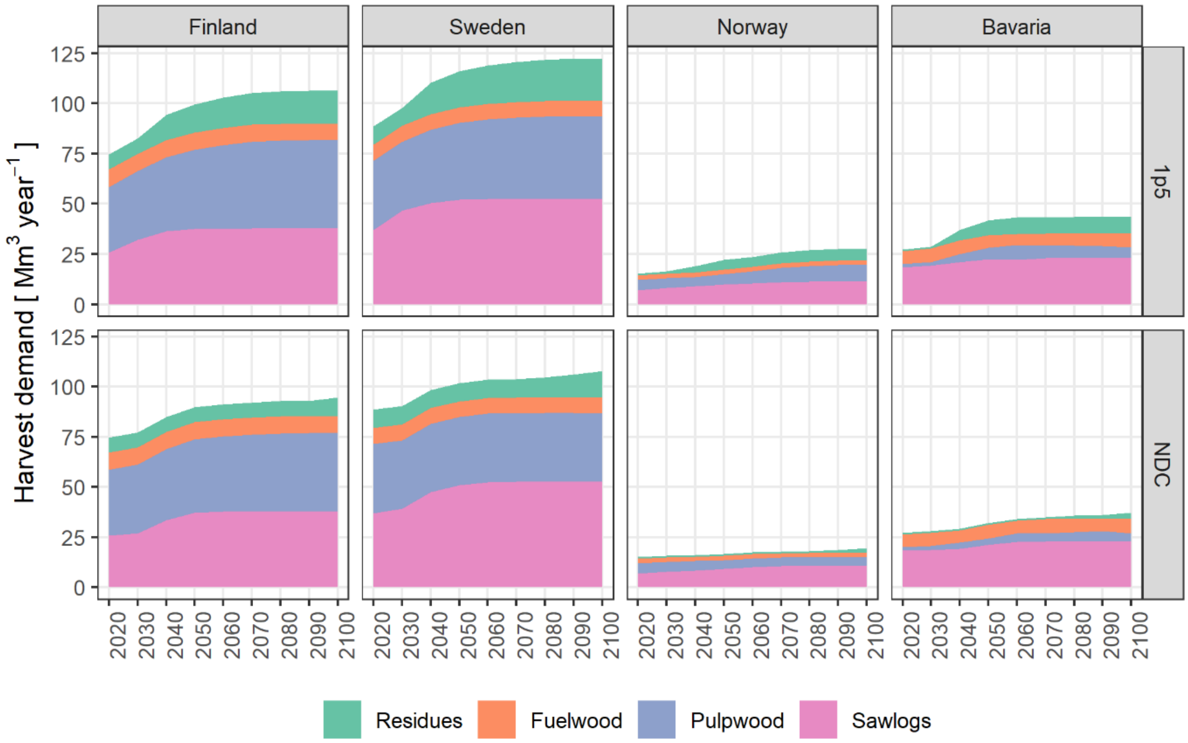
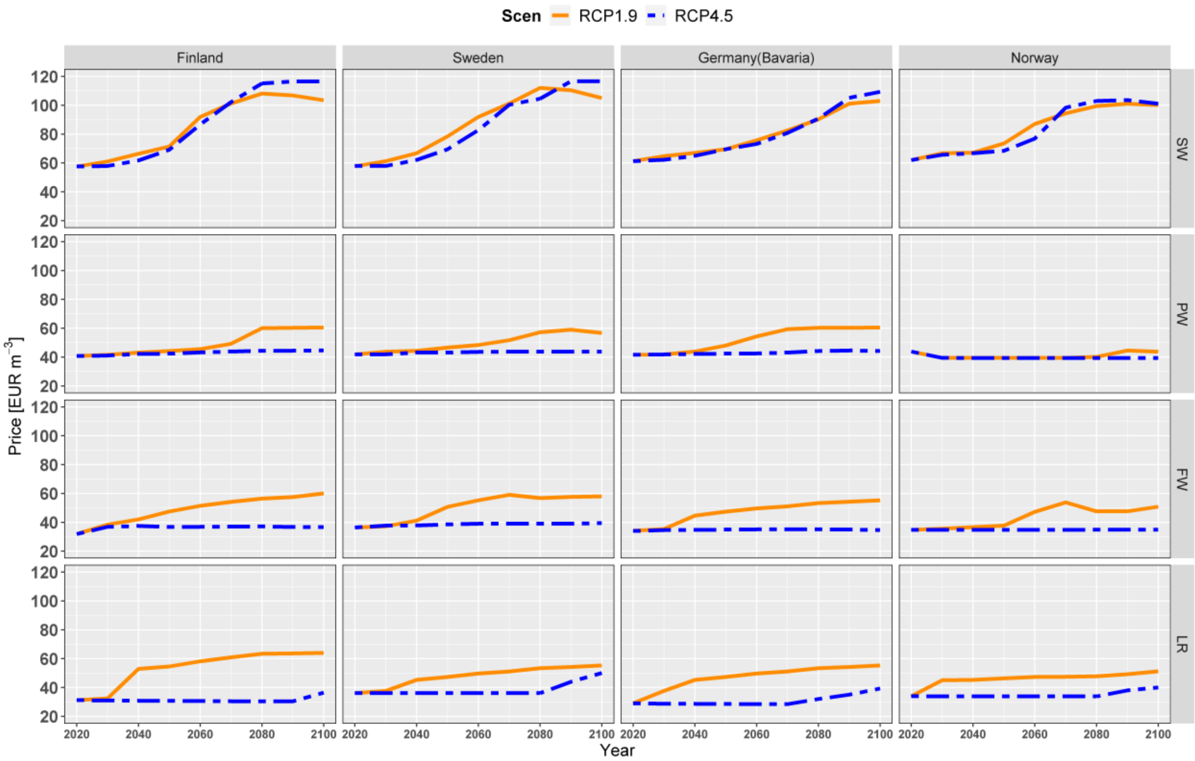
Supplementary Fig. 1: harvest demands representing EU climate change mitigation targets and related timber prices.

Expected future harvest demands (projected by GLOBIOM) representing the two EU climate change mitigation targets: 1.5℃ scenario (1p5), Nationally Determined Contribution (NDC) (**Supplementary Note 5**). Values of the four timber assortments are presented under bark, except for fuelwood (over bark). Demands were projected from 2010 to 2100 in ten-year time steps.

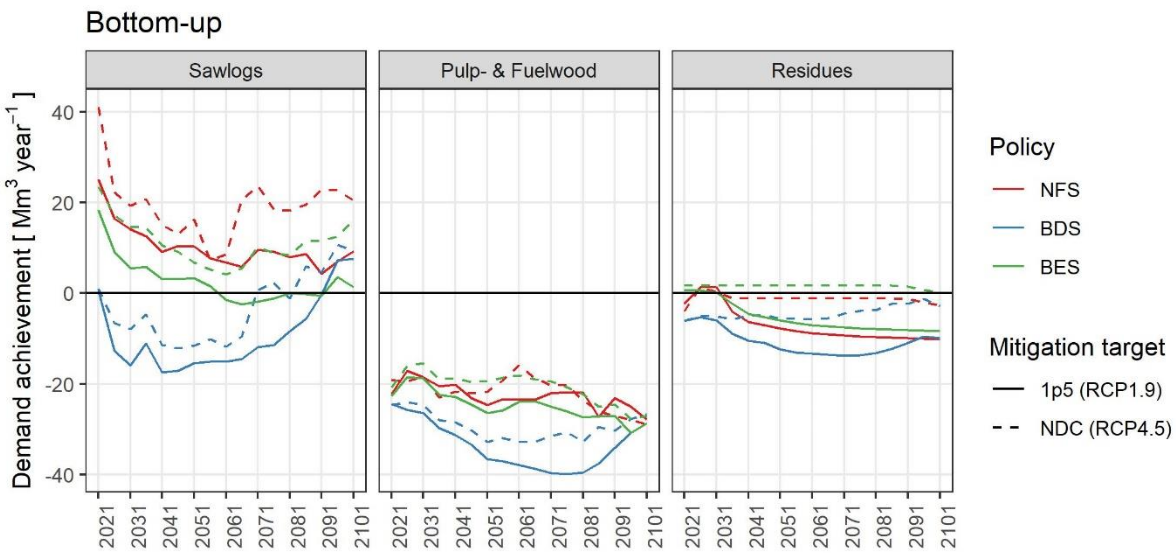


Expected future wood assortment prices at the industry gate in the four study regions according to the GLOBIOM scenario results (1.5℃ scenario = RC1.9, Nationally Determined Contribution = RCP4.5), with SW= sawlogs, PW= pulpwood, FW = fuelwood, LR = logging residues. Prices of sawlogs show almost a similar development under both scenarios assuming an increase to the end of the considered planning horizon. Prices for pulpwood, fuelwood, and logging residues develop more stable under the NDC scenario, which follows the climate trajectory of RCP4.5. Under the more ambitious 1p5 scenario, prices show an increase offering a higher income for forestry, also due to increased harvests under this scenario (see figure above).



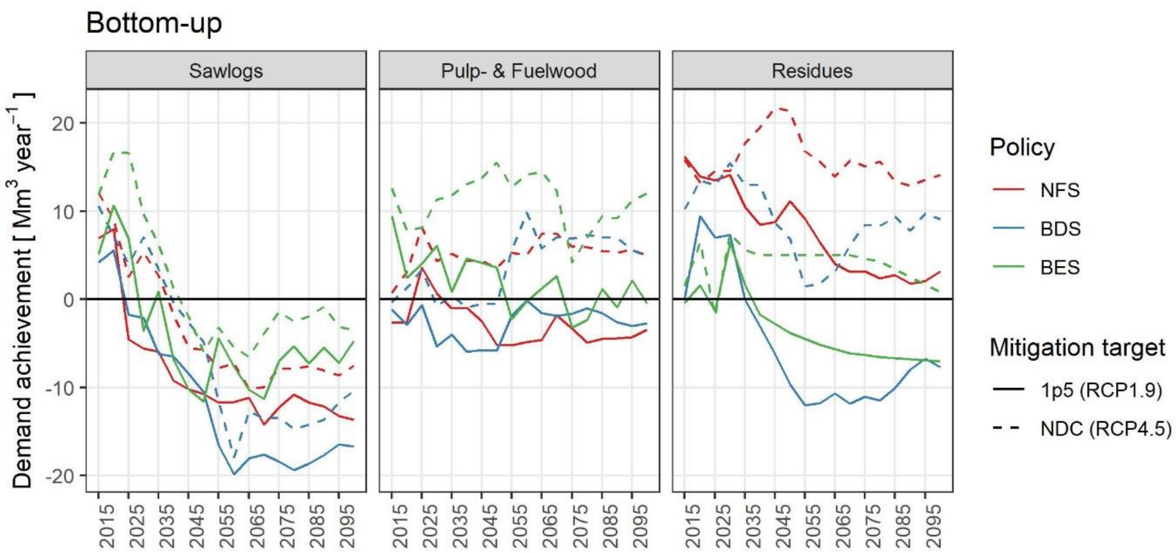
Supplementary Fig. 2: Optimization results under **bottom-up** approach in **Finland**

a) Optimal forest management under bottom-up optimization **prioritizing national policy demands for FESB**. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests under the three policy scenarios for the different assortment classes. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5°C scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



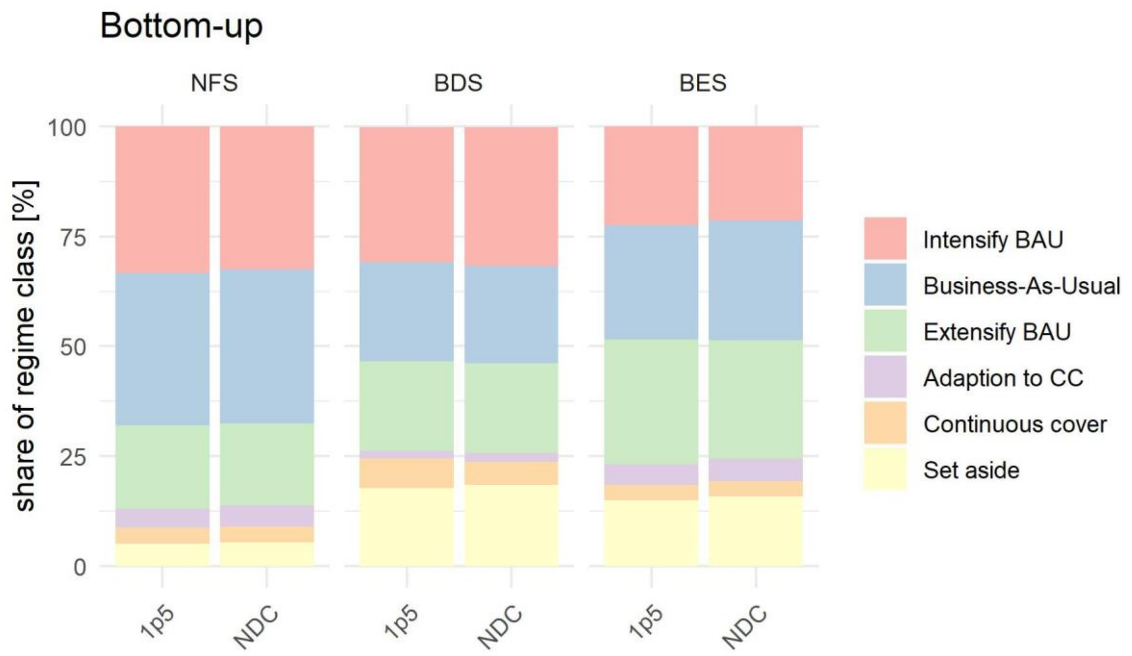
Supplementary Fig. 3: Optimization results under **bottom-up** approach in **Sweden**

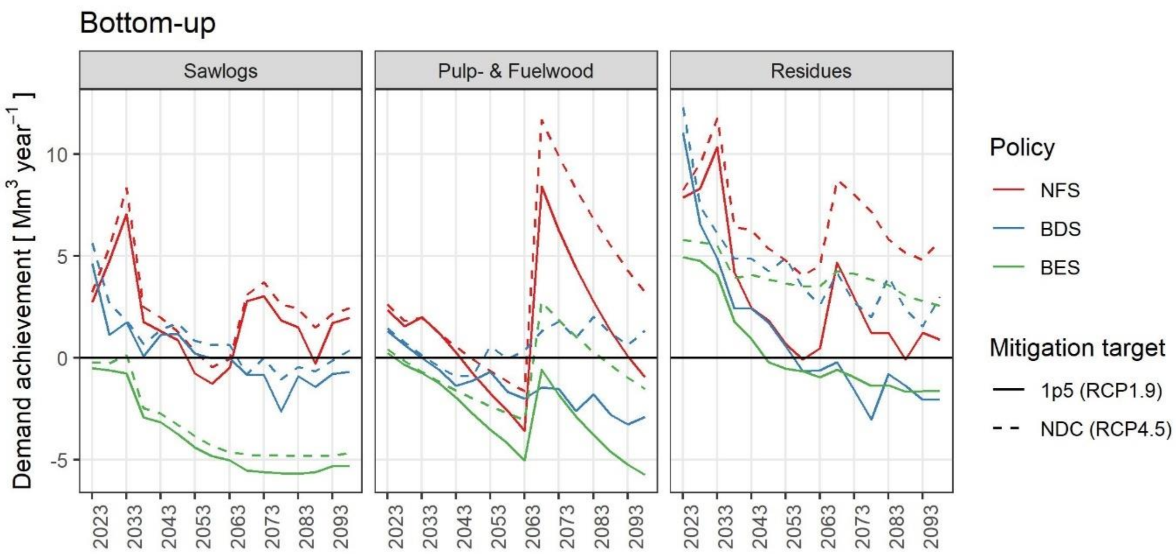
a) Optimal forest management under bottom-up optimization **prioritizing national policy demands for FESB**. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests for the different assortment classes under the three policy scenarios. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5°C scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



Supplementary Fig. 4: Optimization results under **bottom-up** approach in **Norway**

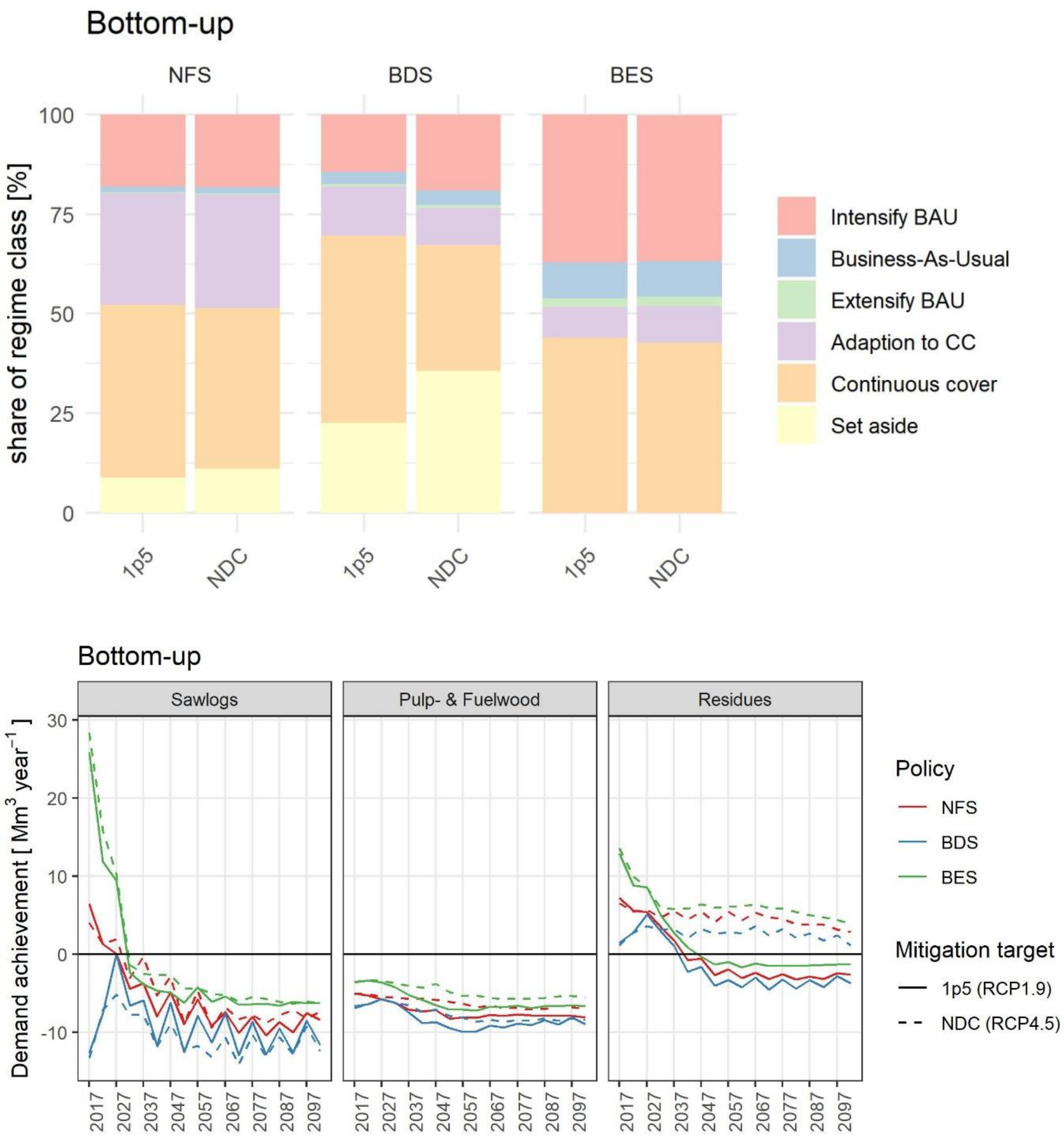
a) Optimal forest management under bottom-up optimization **prioritizing national policy demands for FESB**. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests for the different assortment classes under the three policy scenarios. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5°C scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).





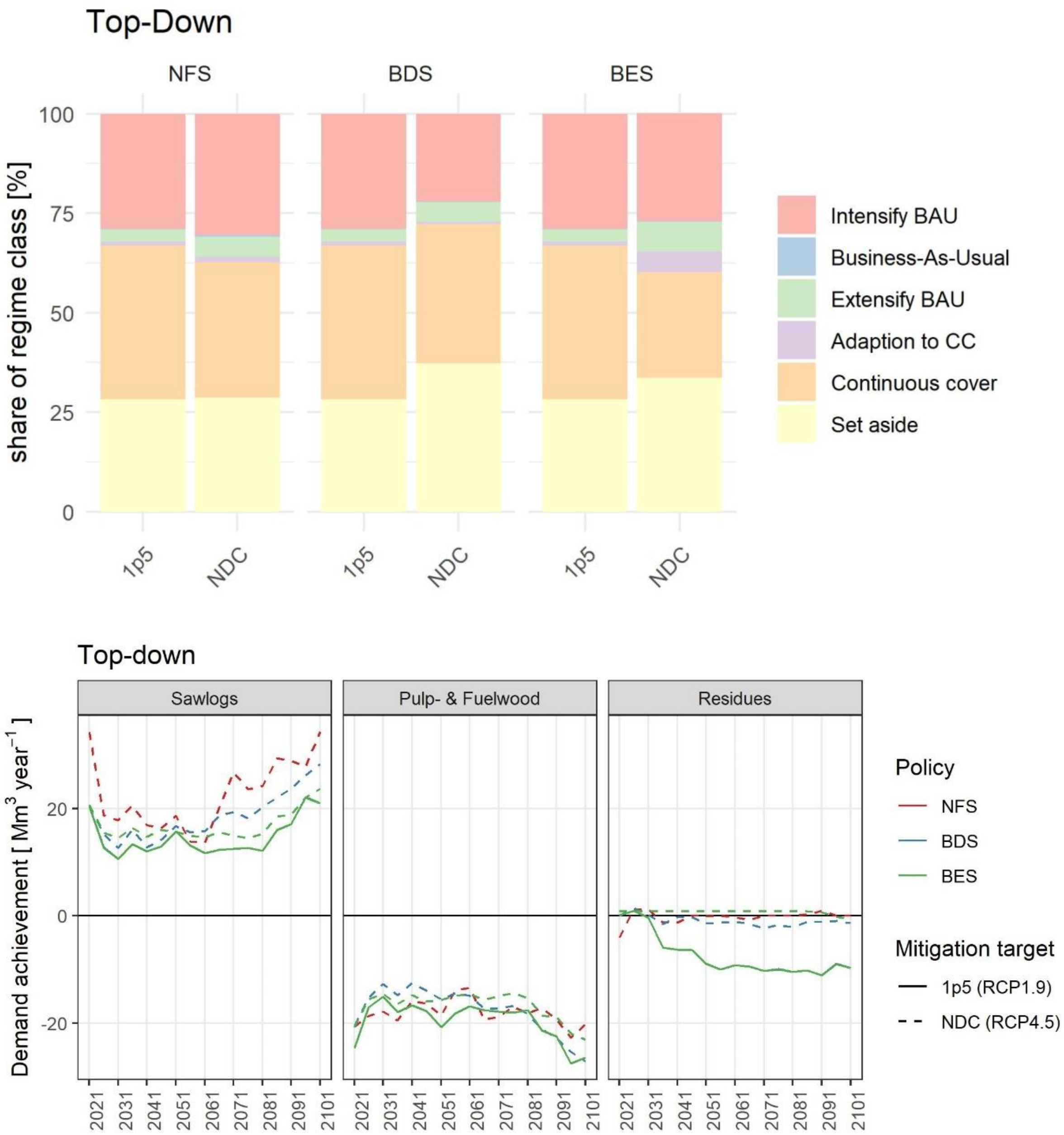
Supplementary Fig. 5: Optimization results under **bottom-up** approach in **Germany (Bavaria)**

a) Optimal forest management under bottom-up optimization **prioritizing national policy demands for FESB**. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests for the different assortment classes under the three policy scenarios. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5°C scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



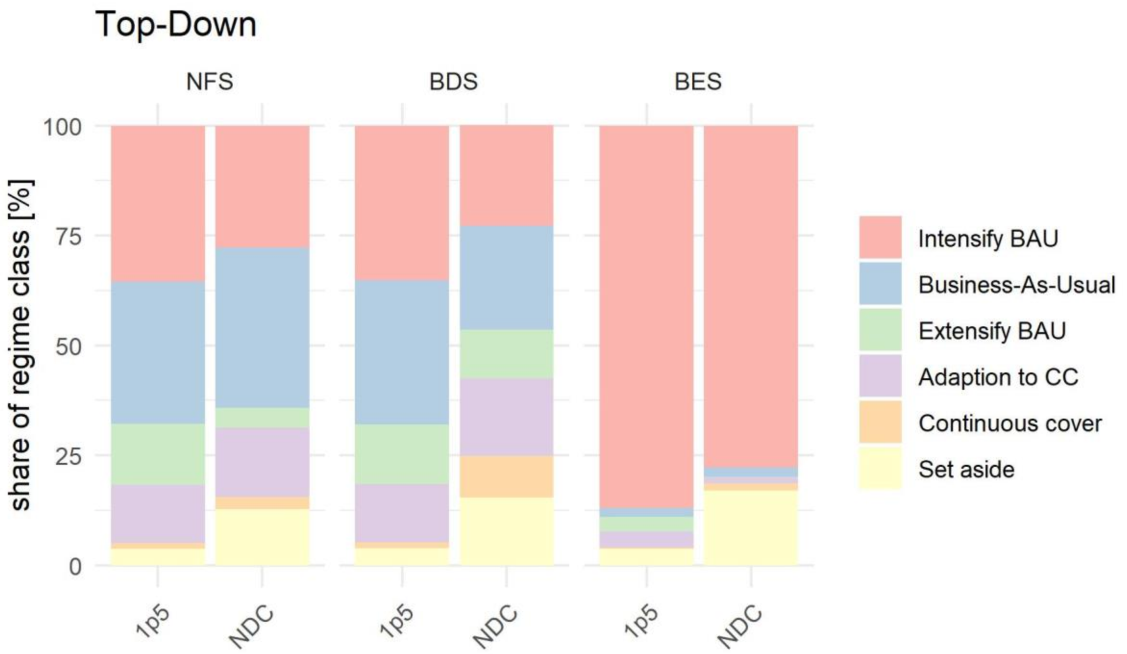
Supplementary Fig. 6: Optimization results under **top-down** approach in **Finland**

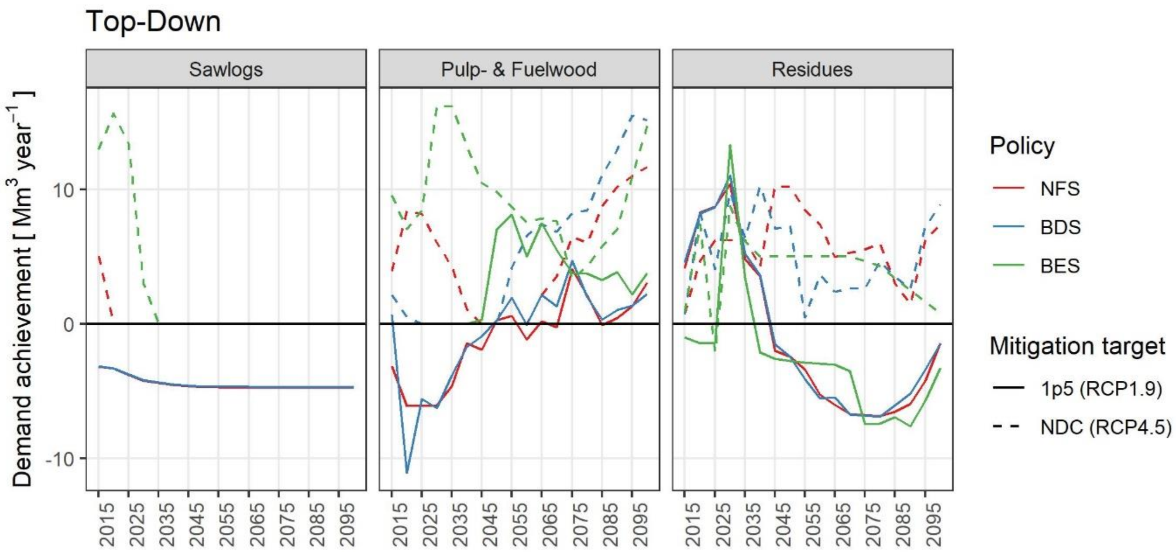
a) Optimal forest management under top-down optimization **prioritizing timber demands for EU climate change mitigation targets** over national policy demands for FESB. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests for the different assortment classes under the three policy scenarios (lines for 1p5 overlap). The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5℃ scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



Supplementary Fig. 7: Optimization results under **top-down** approach in **Sweden**

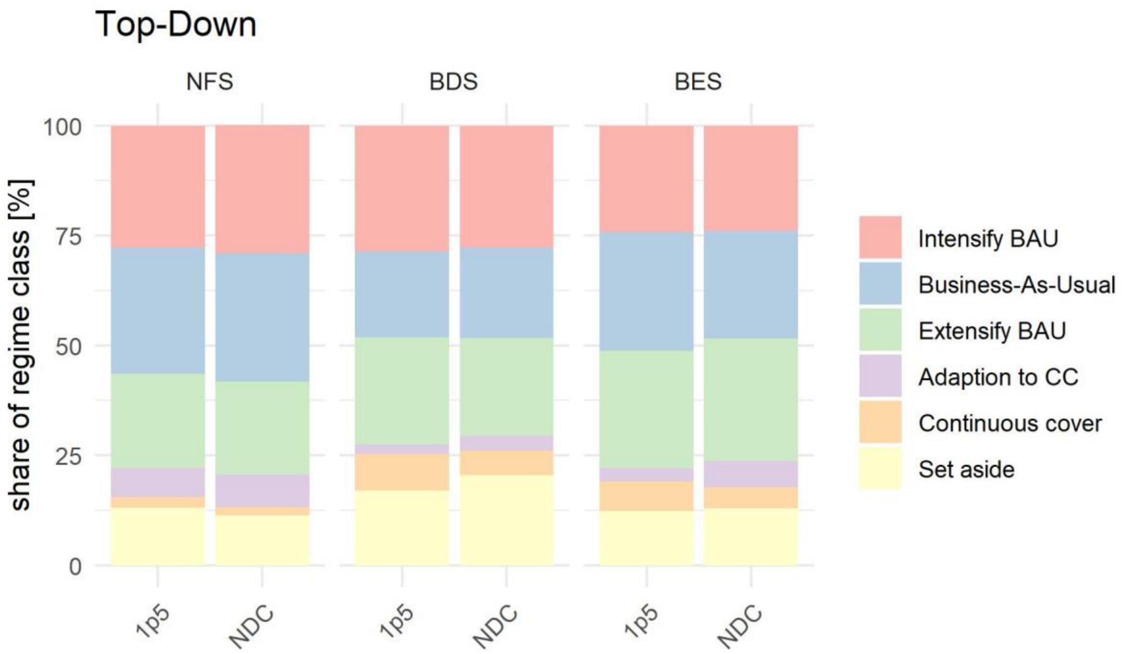
a) Optimal forest management under top-down optimization **prioritizing timber demands for EU climate change mitigation targets** over national policy demands for FESB. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests for the different assortment classes under the three policy scenarios (lines for Sawlogs overlap). The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5℃ scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).

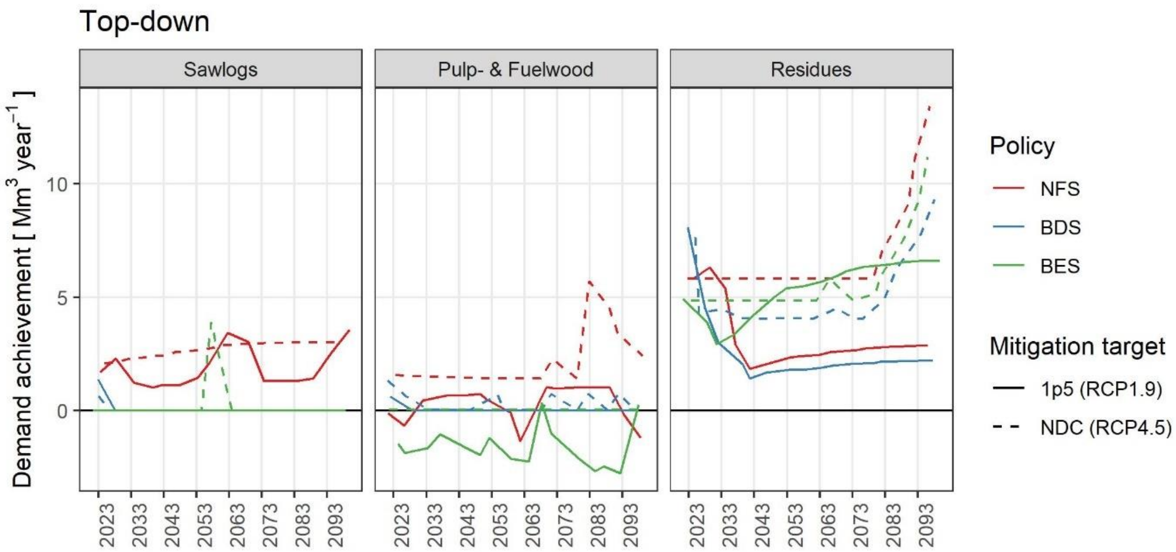




Supplementary Fig. 8: Optimization results under **top-down** approach in **Norway**

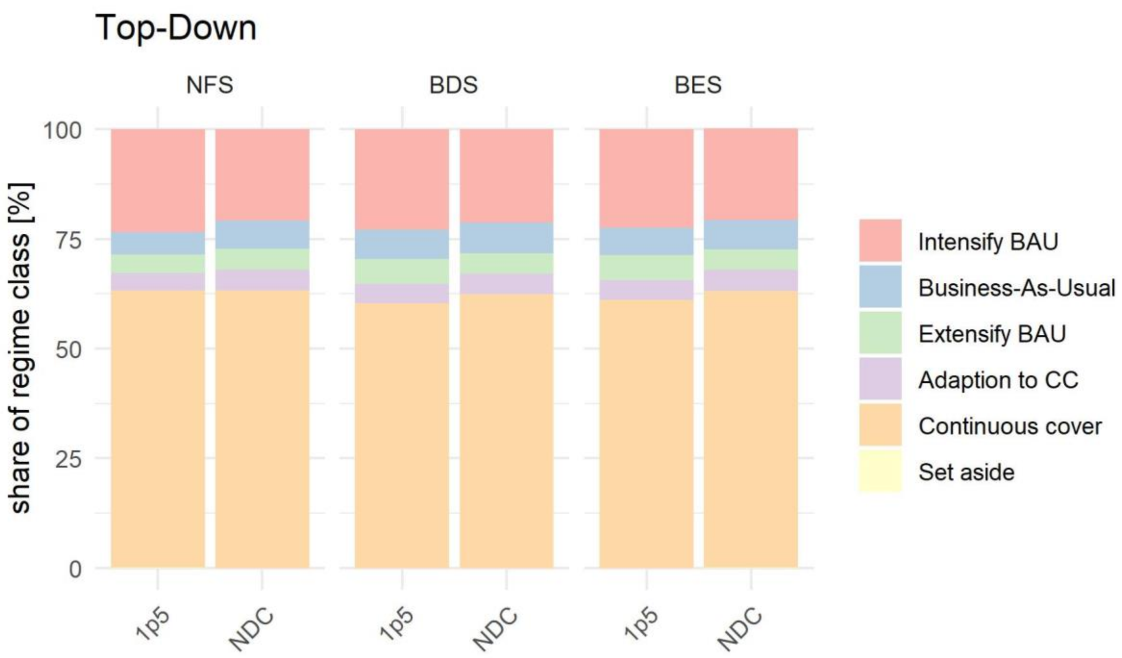
a) Optimal forest management under top-down optimization **prioritizing timber demands for EU climate change mitigation targets** over national policy demands for FESB. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests for the different assortment classes under the three policy scenarios. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5°C scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).

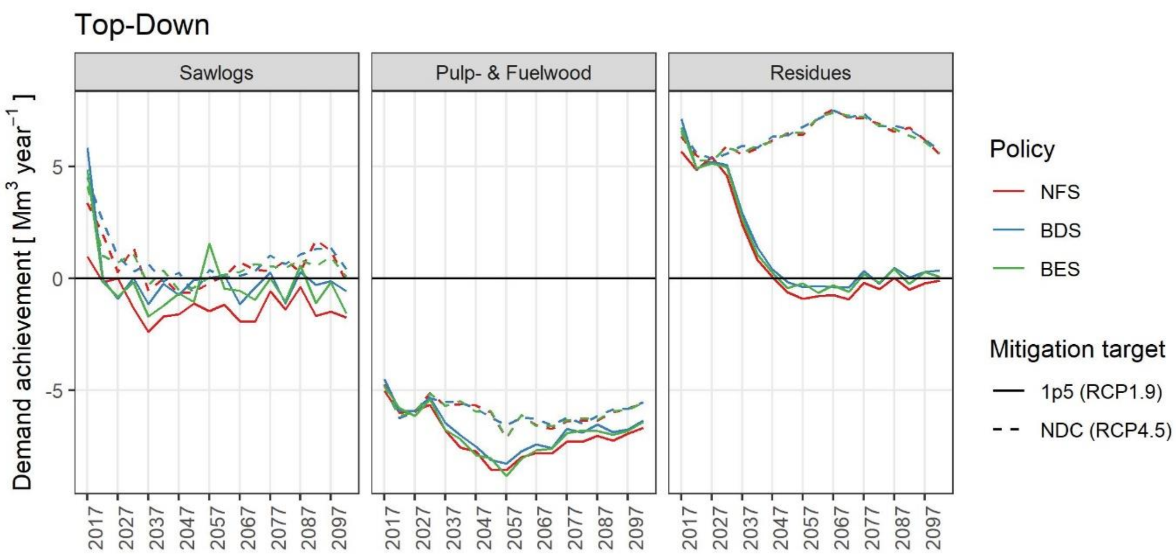




Supplementary Fig. 9: Optimization results under **top-down** approach in **Germany (Bavaria)**

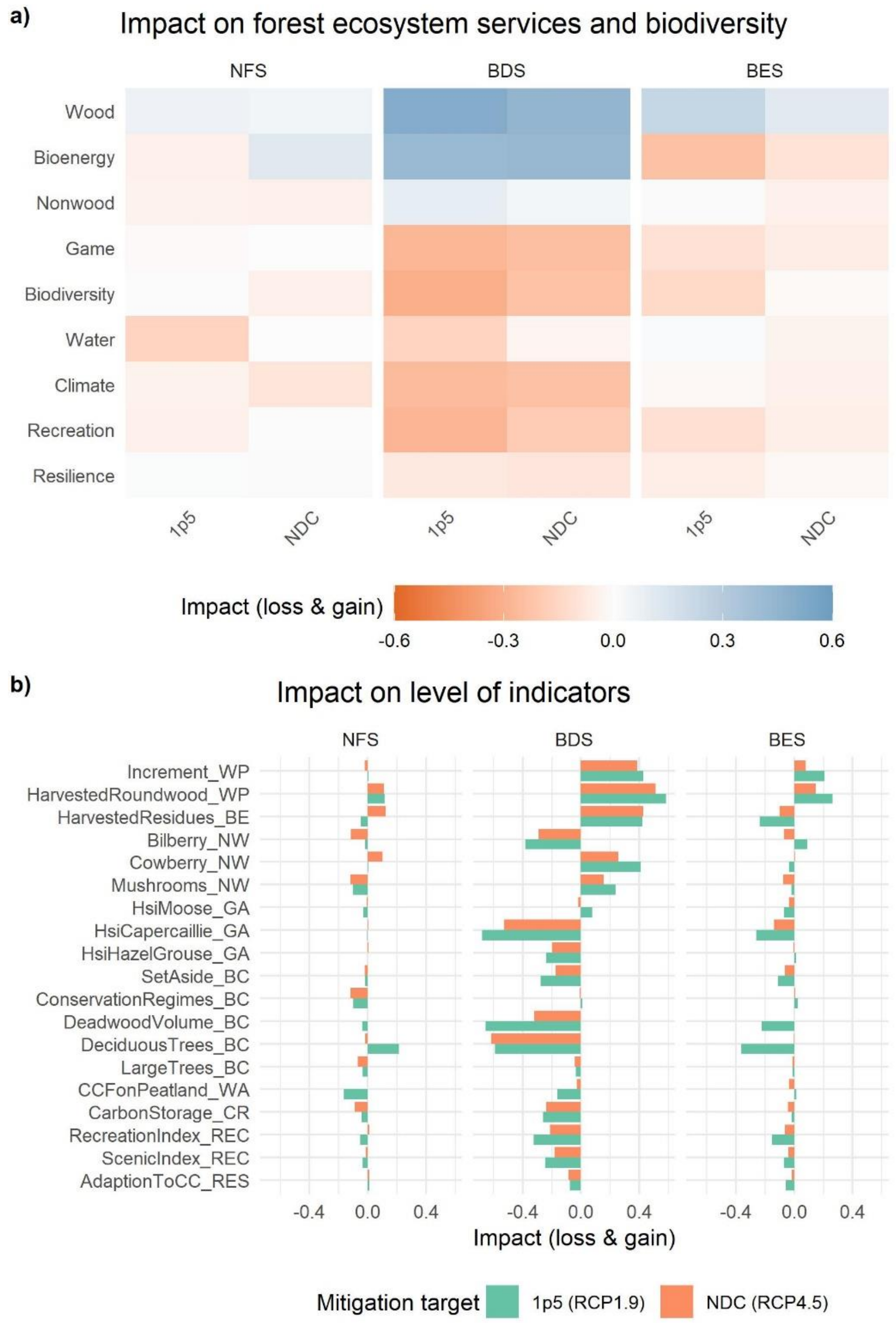
a) Optimal forest management under top-down optimization **prioritizing timber demands for EU climate change mitigation targets** over national policy demands for FESB. **b)** Timely difference between timber demands for EU climate change mitigation targets and simulated harvests for the different assortment classes under the three policy scenarios. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5°C scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).





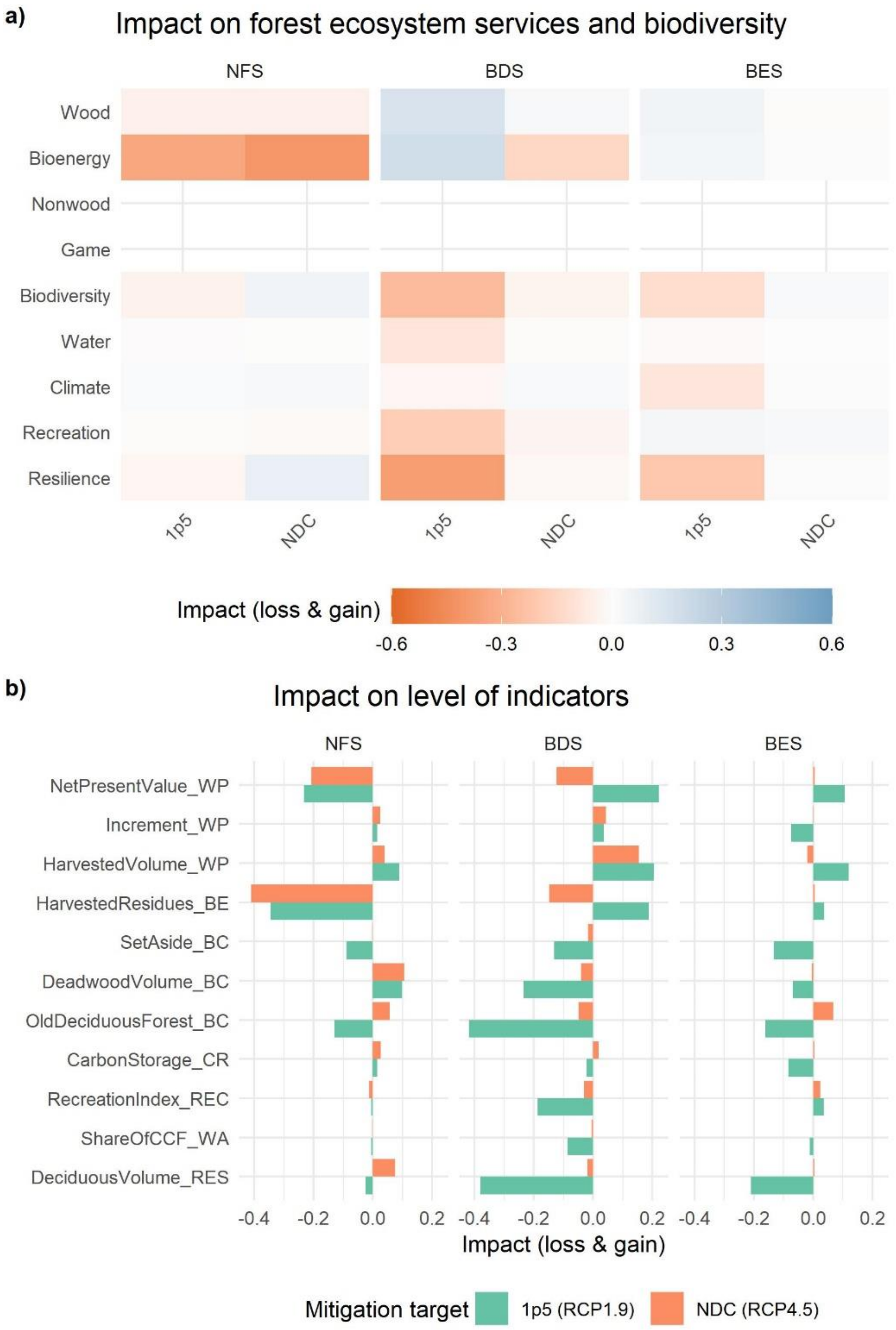
Supplementary Fig. 10: Top-down effect on ecosystem services in Finland

a) Impact on the FESB provided under national policies when aiming for EU climate change mitigation targets (blue – FESB gain, red – loss). Presented are the differences (top-down minus bottom-up) in normalized indicator values averaged by FESB if represented by more than one indicator. **b)** Differences in normalized values for each indicator with the abbreviation indicating the FESB class: WP = wood production, BE = bioenergy, NW = nonwood, GA = game, BC = biodiversity conservation, WA = water protection, CR = climate regulation, REC = recreation and RES = resilience (see **Supplementary Table 1**).



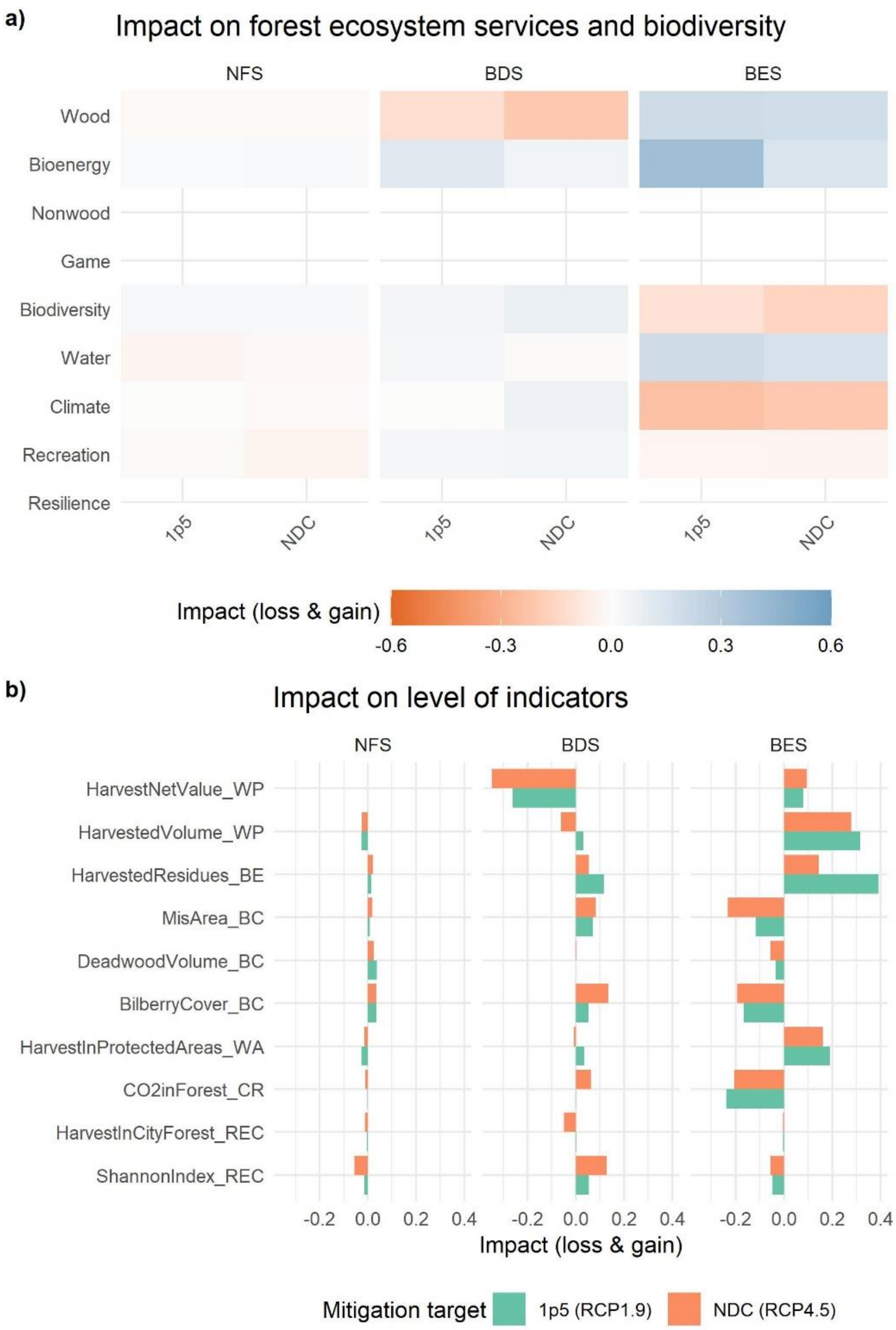
Supplementary Fig. 11: Top-down effect on ecosystem services in **Sweden**

a) Impact on the FESB provided under national policies when aiming for EU climate change mitigation targets (blue – FESB gain, red – loss). Presented are the differences (top-down minus bottom-up) in normalized indicator values averaged by FESB if represented by more than one indicator. **b)** Differences in normalized values for each indicator with the abbreviation indicating the FESB class: WP = wood production, BE = bioenergy, BC = biodiversity conservation, WA = water protection, CR = climate regulation, REC = recreation and RES = Resilience (see **Supplementary Table 2**).



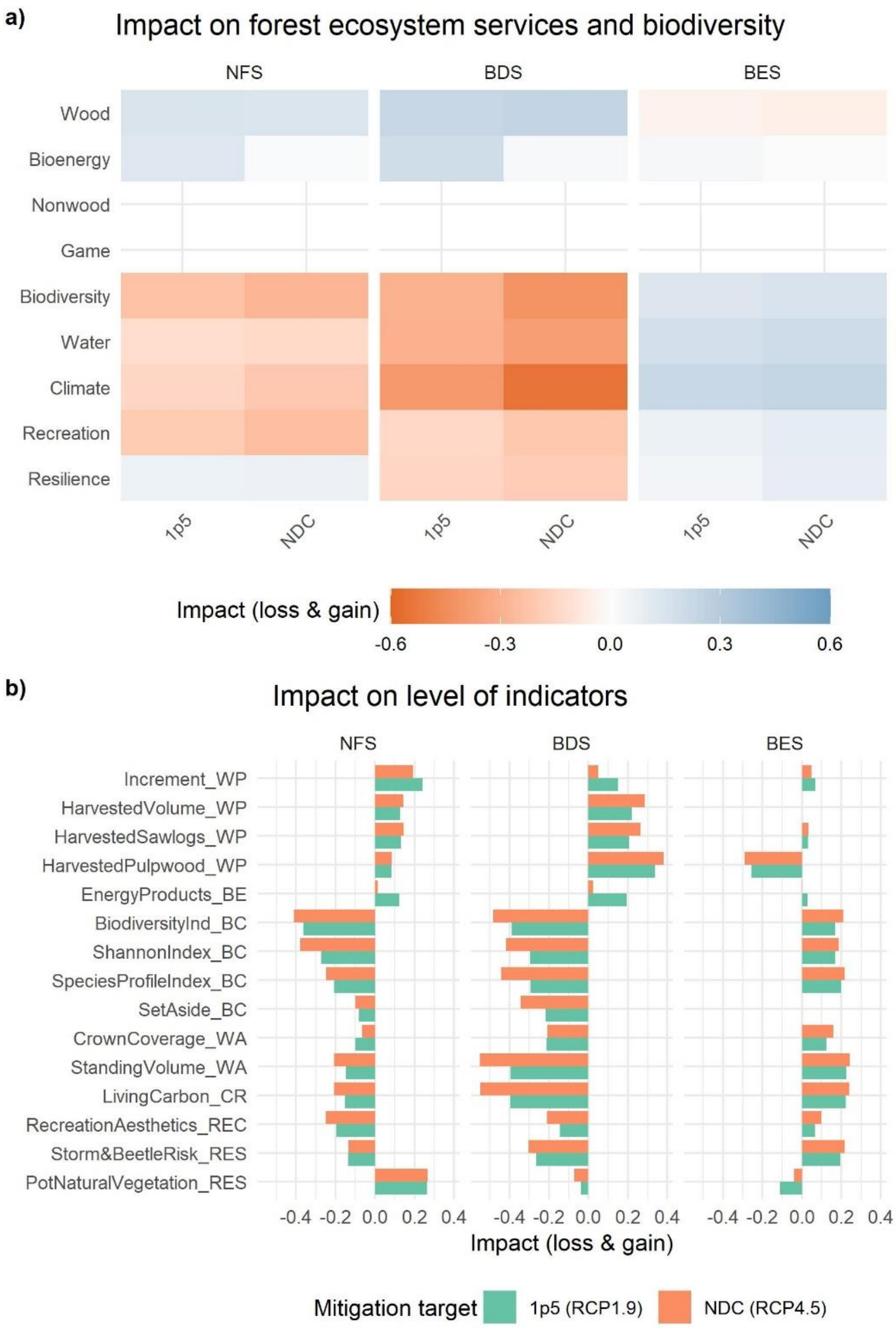
Supplementary Fig. 12: Top-down effect on ecosystem services in Norway

a) Impact on the FESB provided under national policies when aiming for EU climate change mitigation targets (blue – FESB gain, red – loss). Presented are the differences (top-down minus bottom-up) in normalized indicator values averaged by FESB if represented by more than one indicator. **b)** Differences in normalized values for each indicator with the abbreviation indicating the FESB class: WP = wood production, BE = bioenergy, BC = biodiversity conservation, WA = water protection, CR = climate regulation and REC = recreation (see **Supplementary Table 3**). Forest ecosystem was set as system boundary. Thus, carbon storage in wood products were not considered.



Supplementary Fig. 13: Top-down effect on ecosystem services in **Germany (Bavaria)**

a) Impact on the FESB provided under national policies when aiming for EU climate change mitigation targets (blue – FESB gain, red – loss). Presented are the differences (top-down minus bottom-up) in normalized indicator values averaged by FESB if represented by more than one indicator. **b)** Differences in normalized values for each indicator with the abbreviation indicating the FESB class: WP = wood production, BE = bioenergy, BC = biodiversity conservation, WA = water protection, CR = climate regulation, REC = recreation and RES = resilience (see **Supplementary Table 4**). The Forest ecosystem was set as system boundary. Thus, carbon storage in wood products were not considered.



Supplementary Note 1: National policy scenarios and indicators

The policy scenarios representing forest ecosystem services and biodiversity (FESB) demands were based on national level policy documents of each study region representing: the national forest strategy (NFS), the biodiversity strategy (BDS) and the bioeconomy strategy (BES). For each policy document, the stated FESB targets were categorized and assessed following the policy analysis framework of Primmer et al. (2021). First, the documents were mapped along nine FESB classes: wood, bioenergy, non-wood products, game, water protection, climate regulation, resilience, recreation and biodiversity conservation. Six of these classes were represented among all national policy documents (see Figure 5 main text). Second, the stated demand was evaluated for the addressed FESB in each policy. Finally, the outcomes of the policy analyses were used to define multi-objective optimization problems separately for each policy scenario. Therefore, the stated demands for FESB were related to our simulated FESB indicators by individual objective functions (e.g., Blattert et al. (2022)).

How each study region has translated their national policy documents into an optimization problem and linked it to the simulated FESB indicators is presented in **Supplementary Table 1 – Table 4**. The main narrative behind national policy scenarios representing FESB demand is next described.

In Finland, the number and detail of FESB addressed among the policies varied strongly. The NFS recognized the multifunctional use of forest ecosystem addressing all FESB with clear numerical targets for wood production, bioenergy and biodiversity, but overall being still strongly centered around the value chain of wood and bioenergy. The BDS aimed at urgently undertaking effective actions to halt biodiversity loss and reach a favorable status by 2050. The Finnish BES followed the logic that the forest resources for bioeconomy should be mobilized, while biodiversity should be simultaneously safeguarded on the current level. Ecosystem services others than wood and biodiversity received little attention in the individual policies. Resilience and climate regulation were indirectly address by two contradictory mechanisms: forest area under protection (BDS), or sustainable use of timber resources (BES).

In Bavaria, the federal republic policy documents were analyzed to represent state level developments, however generally lacking quantitative objectives. Forest ecosystems have a long tradition of multifunctional use in Germany, which was explicitly reflected in the NFS addressing a wide variety of FESB. In contrast the BDS and BES focused more narrowly on the provision of specific FESB, i.e. biodiversity and wood production, respectively. In Bavaria, the provisioning ecosystem services beyond wood and bioenergy (e.g., berries, mushrooms, game) gain little focus, as they are not considered matters of forest policies.

In Norway, the policies were more specialized to specific FESB, and the detail in which these FESB were addressed also varied significantly between policies. The forest policy aimed at boosting the wood industry by increasing the production and extraction of wood-based materials, bioenergy and biofuels. In contrast, the BDS aimed to preserve and enhance biological diversity as well as integrate the protection against erosion and the recreational value into mainstream policies. Contrary to other countries, the BES highlighted the value of multifunctional use of forest ecosystems, recognizing the role of forests for climate regulation, wood-production, bioenergy, biodiversity, and recreation. However, similar to the other countries, the policies generally lack quantitative objectives.

In Sweden, dedicated documents fully corresponding to the focal policy strategies are not yet available, but partly developing. Instead, available public documents and reports were grouped to represent the three strategies. NFS was replaced by the developing National Forest Program with recommendations to increase wood growth, national forest use scenarios and main legislation. The BDS was replaced by the Swedish Environmental Objectives and the Swedish Achi Targets of the CBD and recognized the multifunctional use of forest ecosystems. Finally, BES was replaced by inputs from specific studies on how to increase wood growth and enduring future harvest levels, in combination with fulfilling conservation targets. The selection of documents was further based on consultation of stakeholder in the sector and represents more bottom-up understanding of the future development of the sector than the other study regions.

The three scenarios and background documents were:

Scenario – National forest strategy (NFS)

- Finland: National Forest Strategy 2025 (FMAF 2015, 2019)
- Germany: Forest Strategy 2020 (BMELV 2011)
- Norway: Verdier i vekst. Konkurransedyktig skog- og trenæring (NMAF 2016)
- Sweden: National forest program 2018, National Forest Impact Analysis - SKA 15 (SFA 2015), Swedish Forestry Act, The Swedish Environmental Code

Scenario – Biodiversity strategy (BDS)

- Finland: Saving Nature for People - National action plan for the conservation and sustainable use of biodiversity in Finland (FME 2012)
- Germany: National Strategy on Biological Diversity (BMU 2007)
- Norway: Natur for livet. Norsk handlingsplan for naturmangfold (MCE 2015)
- Sweden: CBD Aichi Target 11, Swedish Environmental Objectives

Scenario – Bioeconomy strategy (BES)

- Finland: Finnish Bioeconomy Strategy (FMME et al. 2014)
- Germany: National Bioeconomy Strategy (BMBF and BMEL 2020)
- Norway: SKOG22 Nasjonal Strategi for Skog- og Trenaeringen (INNRC 2015)
- Sweden: National Forest Impact Analysis - SKA 15 (SFA 2015), Forest management with new possibilities - Report 24 (SFA 2019), Possibilities for intensive growth of forest (MINT) (Larsson et al. 2009), CBD Aichi Target 11

Supplementary Table 1: Optimization scenarios of **Finland**

Optimization scenarios of Finland describing the applied indicators and optimization rules to address the forest ecosystem service demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize objective. The corresponding equations types (Eq.) for the individual objective functions are explained in **Supplementary Note 6**.

Ecosystem services & biodiversity	Indicator (unit)	National forest strategy			Biodiversity strategy			Bioeconomy strategy		
		Objective / Constraint	Eq.	step	Objective / Constraint	Eq.	step	Objective / Constraint		step
Wood production	Increment (m^3 ha^{-1} yr^{-1})	Target 2025: ≥ 115 Mm^3; target 2050: ≥ 125 Mm^3	**S1**	**1**						
	Harvested roundwood (m^3 ha^{-1})	Target 2025: ≥ 80 Mm^3	**S1**	**1**	Maximize (even flow)	**S5a**	**1**	Maximum even flow	**S5a**	**2**
Bioenergy	Harvested residues (m^3 ha^{-1})	Target 2025: ≥ 6.5 Mm^3	**S1**	**1**				Maximum even flow	**S5a**	**2**
Nonwood	Bilberry (kg ha^{-1}) *(Miina et al. 2009)*	No decline, maximize further	**S2**	**3**						
	Cowberry (kg ha^{-1}) *(Turtiainen et al. 2013)*	No decline, maximize further	**S2**	**3**						
	Mushrooms (kg ha^{-1}) *(Tahvanainen et al. 2016)*	No decline, maximize further	**S2**	**3**						
Game	HSI moose (-) *(Kurttila et al. 2002)*	Maximize	**S5c**	**4**	Maximize	**S5c**	**1**			
	HSI capercaillie (-) *(Mönkkönen et al. 2014)*	Maximize	**S5c**	**4**	Maximize	**S5c**	**1**			
	HSI hazel grouse (-) *(Mönkkönen et al. 2014)*	Maximize	**S5c**	**4**	Maximize	**S5c**	**1**			
Biodiversity	Share of regime SA (%)				Target of 17%	**S3a**	**1**			
Conservation	Conservation regimes (-) [a)]	Target of ≥ 4.5 %	**S3a**	**2**	Target of 4.5%	**S3a**	**1**			
	Deadwood (m^3 ha^{-1})	Target 2025: avg. ≥ 8 $m^3 ha^{-1}$	**S1**	**2**	Target 2050: increase by 60%	**S6**	**1**	No decline & no target	**S6**	**1**
	Deciduous tree volume (%)	Maximize	**S5b**	**4**	Target 2050: increase by 10%	**S6**	**1**	No decline & no target	**S6**	**1**
	Large trees (DBH > 40cm) (n ha^{-1})	Maximize	**S5b**	**4**	Target 2050: increase by 10%	**S6**	**1**	No decline & no target	**S6**	**1**
Water protection	Regimes CCF/SA on peatland (%)	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**			
Climate regulation	CO_2 sink in forest (t CO_2 ha^{-1} yr^{-1}): including deadwood decomposition *(Mäkinen et al. 2006)* and soil, mineral *(Liski et al. 2005, Tuomi et al. 2009, Tuomi et al. 2011)* and peatland *(Ojanen et al. 2014)*	Target 2025: ≥ 27.88 $MtCO_2$ equivalent	**S1**	**2**						
Recreation	Recreation index (-) *(Pukkala et al. 1995)*	Maximize	**S5a**	**4**	Maximize	**S5a**	**1**	Maximize	**S5a**	**2**
	Scenic index (-) *(Pukkala et al. 1995)*	Maximize	**S5a**	**4**	Maximize	**S5a**	**1**	Maximize	**S5a**	**2**
Resilience	Share of regime ACC (%)	Maximize	**S3b**	**4**						

a) Conservation oriented regimes were represented by two CCF regimes with reduced thinning intensity (CCF_3, CCF_4), and an extensified BAU regime with retention tree (BAUwGTR, see **Supplementary Note 4** – Simulator and regimes of Finland)

Indicators of Finland

Wood production – The ecosystem service was measured by the simulated annual yearly increment (m^3 ha^{-1} yr^{-1}) and the periodically harvested timber volume (m^3 ha^{-1}).

Bioenergy – It assessed the harvested biomass (m^3 ha^{-1}), which summarises the combined volume of harvest residues, uplifted tree stumps and roots (only for spruce and pine stands under rotation forestry on fertile and medium fertile site types).

Nonwood – We assessed by the yield of bilberry, cowberry and marketable mushrooms, which are important non-timber products in the boreal forest (Wolfslehner et al. 2019, Miina et al. 2020). The yield (kg ha^{-1}) for Bilberry (*Vaccinium myrtillus L.*) (Miina et al. 2009) and cowberry (*Vaccinium vitis-idaea L.*) (Turtiainen et al. 2013) was predicted with models considering site and stand characteristics like basal area and the dominant tree species as independent variables. Marketed mushrooms yield (kg) was estimated using the models of (Tahvanainen et al. 2016).

Game –We selected three species to represent a wide range of important game animals in Finland: moose (*Alces alces*), western capercaillie (*Tetrao urogallus*), hazel grouse (*Bonasia bonasa*). The occurrence of moose was measured with a species-specific habitat suitability index (HSI) describing their winter-feeding habitats based on the forest stand characteristics (e.g., tree species, stand density and height of trees) (Kurttila et al. 2002). HSI models describing the stand characteristics for the occurrence of capercaillie and hazel grouse were taken from (Mönkkönen et al. 2014).

Biodiversity conservation – According to the red list of habitat types in Finland (Kontula and Raunio 2019), the reasons for forest habitat types becoming red-listed are reduction in deadwood, reduction in old-growth forests and individual old trees as well as changes in tree species composition by reducing the share of deciduous trees. Thus, we measured biodiversity by five separate variables: deadwood volume (m^3 ha^{-1}); percentage of deciduous trees; the number of large trees (diameter at breast height DBH > 40 cm); the share of stands managed by set aside (representing strict protected areas), as well as the share of stands managed with CCF (two regimes with reduced thinning intensity) and rotation forestry with green tree retention (representing conservation oriented management in commercial forests (see **Supplementary Note 4**, Simulator and regimes of Finland).

Water protection – We used the share of CCF on peatlands as a management option to decrease negative water quality impacts to lakes and streams (Nieminen et al. 2018), which are caused by intensive management options (clearfelling combined with ditching) (Nieminen et al. 2017, Marttila et al. 2020, Tolkkinen et al. 2020).

Climate regulation – We measured by the carbon sink (t CO_2 ha^{-1} yr^{-1}), which represents the change in carbon storage between two simulation time steps. Carbon storage was the sum of the total carbon held within standing timber, deadwood, and soil, converted in its corresponding CO_2 content. The carbon of standing timber and deadwood was evaluated as 50% of the dry biomass (see Eyvindson et al. (2021)). The carbon storage in wood products was not included since national policies mainly defined the forest landscape as system boundary when setting targets.

Recreation – The ecosystem service was calculated using two indices developed by (Pukkala et al. 1988, Pukkala et al. 1995), which estimates people's average opinion about the recreational value (recreation index) and beauty of forests (scenic index) of managed forest stands, assuming that their values increases with the age and size of trees, as well as increasing the shares of pines and birches.

Resilience – We quantified by the share of forest stands managed with the adaption regimes, applied in Southern and Central Finland on medium fertile sites (see **Supplementary Note 4**, Simulator and regimes of Finland). It is widely acknowledged that minimizing the future effects of climate induced disturbances require an increase of broadleaves in the forest stands and landscape (Venäläinen et al. 2020).

Supplementary Table 2: Optimization scenarios of **Sweden**

Optimization scenarios of Sweden describing the applied indicators and optimization rules to address the FESB demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize objective. The corresponding equations types (Eq.) for the individual objective functions are explained in **Supplementary Note 6**.

Ecosystem services & biodiversity	**Indicator (unit)**	**National forest strategy Objective / Constraint**	**Eq.**	**step**	**Biodiversity strategy Objective / Constraint**	**Eq.**	**step**	**Bioeconomy strategy Objective / Constraint**	**Eq.**	**step**
Wood production	Net Present Value (SEK)	Maximize	**S5a**	**2**	Maximize	**S5a**	**3**	Maximize	**S5a**	**6**
	Wood increment (m^3 ha^{-1} yr^{-1})				Maximize	**S5a**	**2**	Target 2050: 5.5 m^3 ha^{-1} yr^{-1}	**S1b**	**1**
	Average harvest volume (m^3 ha^{-1} yr^{-1})	Maximize (even-flow)	**S5a**	**2**	Maximize (even-flow)	**S5a**	**3**	Maximize (even-flow)	**S5a**	**4**
	Total harvest volume (m^3 yr^{-1})	Enabled constraint: Harvest ± 10% of increment	**S4b**	**1**				Target 2080: 120 Mm^3	**S1b**	**1**
Bioenergy	Harvested residues (m^3 yr^{-1})							Target 2030: 14 Mm^3	**S1a**	**2**
Nonwood a)										
Game a)										
Biodiversity Conservation	Share of regime SA (%)	12.8%	**S3a**	**1**	17%	**S3a**	**1**	17%	**S3a**	**3**
	Deadwood volume (m^3 ha^{-1})	No decrease	**S2**	**1**	Target 2050: increase by 60% on managed land	**S6a**	**1**	No decrease	**S2**	**5**
	Old, deciduous-rich forest area (ha)	No decrease	**S2**	**1**	Target 2050: increase by 60% on managed land	**S6a**	**1**	No decrease	**S2**	**5**
Climate regulation	Carbon in wood and soil (t CO_2 ha^{-1})	No decrease	**S2**	**1**	No decrease	**S2**	**1**	No decrease	**S2**	**5**
Recreation	Recreation index (-)	No decrease	**S2**	**1**	No decrease	**S2**	**1**	No decrease	**S2**	**5**
Water protection	Share of regime CCF (%)				10%	**S3a**	**1**			
Resilience	Deciduous volume (m^3 ha^{-1})	No decrease	**S2**	**1**	Target 2050: increase by 60% on managed land	**S6a**	**1**	No decrease	**S2**	**5**

a) No up-to-date indicator models were available for assessing the nonwood and game in Sweden at the time of this study.

Indicators of Sweden

Wood production – We used the net present value (NPV in SEK), wood increment ($m^3\ ha^{-1}\ yr^{-1}$), and the average ($m^3\ ha^{-1}\ yr^{-1}$) and total annual harvest ($m^3\ yr^{-1}$). The NPV is the discounted revenue minus the expenses for growing and extracting timber, calculated for the first year of the simulation. Wood increment is the net increase in biomass of the living trees. The average and total yearly harvest is the harvested forest biomass extracted and left in the forest.

Bioenergy – We used the harvested residues ($m^3\ yr^{-1}$) as an indicator for bioenergy. In Heureka branches, foliage, roots > 5mm, and tree tops can be extracted as residues depending on the management regime, e.g. stump harvesting is only allowed under *BAU_FocusBioenergy_StumpHarvest* (see **Supplementary Note 4,** Simulator and regimes of Sweden).

Biodiversity conservation – Biodiversity was measured by the share of set asides (%), deadwood volume ($m^3\ ha^{-1}$), and the area of old (>80 years) deciduous-rich (>30 %) forest. The set aside area is a good biodiversity metric, since a large share of the threatened and rare species in Nordic forests depend on unmanaged forest where only natural disturbances are taking place, which are typical of set asides. The dead wood volume and the area of old deciduous-rich forests are two of the official environmental quality objectives indicators used to measure the state of Swedish forests from the perspective of biodiversity (see Swedish EPA 2022[1]).

Water protection – For Sweden, we used the share of continuous cover forestry (% CCF) for the same reason as described in the case of Finland above, although CCF can be applied only where Norway spruce is the dominating species. Heureka does not allow CCF on forest land dominated by Scots pine. In Finland CCF is frequently applied on ditched mires dominated by pine, but mires are not managed in Sweden.

Climate regulation – We used the carbon stock in wood and soil (t $CO_2\ ha^{-1}$) as an indicator for the role of the forest in the global carbon balance. The indicator is the sum of the carbon stock in the soil, deadwood, and the living biomass above ground.

Recreation – The recreation index ranges between 0 and 1 and is calculated from forest stand variables changing through time in the projections (Lind 2007). The index increases with stand age, tree size diversity, deadwood volume, and share of deciduous trees, and decreases with the number of downed logs, harvest residues, number of stems, and soil damage.

Resilience – The volume deciduous trees ($m^3 ha^{-1}$) is a good measurement of resilience against natural disturbances in Nordic forests that are expected to increase with climate change (Venäläinen et al. 2020).

[1] Swedish EPA. 2022. Strukturer i skogslandskapet - Sveriges miljömål. Available from https://www.sverigesmiljomal.se/miljomalen/levande-skogar/strukturer-i-skogslandskapet/ (May 2022)

Supplementary Table 3: Optimization scenarios of **Norway**

Optimization scenarios of Norway describing the applied indicators and optimization rules to address the FESB demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize objective. The corresponding equations types (Eq.) for the individual objective functions are explained in **Supplementary Note 6**.

Ecosystem services & biodiversity	**Indicator (unit)**	**National forest strategy** Objective / Constraint	**Eq.**	**step**	**Biodiversity strategy** Objective / Constraint	**Eq.**	**step**	**Bioeconomy strategy** Objective / Constraint	**Eq,**	**step**
Wood production	Harvest net value (NOK)	Maximize	**5a**	**1**				Maximize	**5a**	**1**
	Harvested volume (Mm^3)				Maximize (even-flow)	**5a**	**1**			
Bioenergy	Harvested residues (Kt)	Maximize: plots with harvest costs < 150 NOK)	**S8**	**2**				Maximize: plots with harvest costs < 200 NOK)	**S8**	**2**
Nonwood [a]										
Game [b]										
Biodiversity Conservation	MIS [c] area (ha) *(Gjerde et al. 2007)*	No decline allowed	**2**	**3**	No decline allowed	**2**	**1**	No decline allowed	**2**	**3**
	Deadwood volume (Mm^3)				No decline allowed	**2**	**1**			
	Bilberry [d] cover (%)				No decline allowed	**2**	**1**			
	MIS [c] area (ha) *(Gjerde et al. 2007)*				Maximize	**5a**	**1**			
	Dead wood volume (Mm3)				Maximize	**5a**	**1**			
	Bilberry [d] cover (%) **[d]**				Maximize	**5a**	**1**			
Water protection	Harvest vol. in protect areas (Mm^3)				No increase allowed	**S7**	**1**			
Climate regulation	Natl. CO_2 in harvested wood product (Kt)	Maximize	**5c**	**2**				Maximize	**5c**	**2**
	Natl. CO_2 in forest (MKt): including CO_2 in living biomass, and mineral soils *(Liski et al. 2005)*							Maximize	**5d**	**2**
Recreation	Harvest vol. in city forest (Mm^3)				No decline allowed	**2**	**2**	No decline allowed	**2**	**3**
	Shannon index (-) *(Jost 2006)*				No decline allowed	**2**	**2**	No decline allowed	**2**	**3**
Resilience [a]										

a) No targets or objectives mentioned in national policies.

b) No indicator models were available for assessing the game in Norway at the time of this study.

c) MIS = Norwegian hot spot national inventory for biodiversity, the abundance of big and broadleaved trees.

d) Bilberry was allocated to biodiversity, since the Biodiversity strategy mentioned it more explicitly under this service.

Indicators of Norway

Wood production – We used two indicators: discounted harvest net income (NOK) and total amount of harvested volume commercial timber (m^3). Discounted harvest net income was calculated based on the revenues for harvested timber minus the cost of silvicultural operations and transportation. Timber prices and harvest costs were kept constant over the simulation horizon (Vennesland et al. 2013)

Bioenergy – We assessed bioenergy production by the amount of harvested energy wood, i.e. tops and branches, known in the Norwegian acronym as GROT and here labelled as harvested residues.

Biodiversity – Biodiversity conservation was assessed by MiS area, bilberry coverage, and deadwood volume. MiS (Miljøregistrering i skog in Norwegian) is a habitat inventory approach, called "Complementary Hotspot Inventory" (CHI). This habitat inventory approach is currently used in forestry planning in Norway and is based on identifying areas that are particularly important for red-listed species (Gjerde et al. 2007, Timonen et al. 2010). Therefore, the NFI plots were classified as MiS plot (1) or not (0) focusing on the abundance of big trees and broadleaved trees. Bilberries are the most common wild berries in Norway. The bilberry coverage (%) was calculated using a beta regression model fitted to the Norwegian NFI bilberry cover data, which predicts the bilberry coverage of the forest ground based on stand characteristics (stand age, vegetation type, and stand basal area). We also included volume of deadwood as an indicator since it is important for forest biodiversity conservation (Müller and Bütler 2010, Gao et al. 2015). The deadwood volume was estimated using a species and diameter class specific, climate adjusted decomposition function based on the mortality of stands from the NFI.

Water protection – We calculated the clear-cut area (ha) in steep terrain and in mountain forests, assuming that forest areas that were recently clear-felled are lacking a sufficient protection effect against erosion (Brang et al. 2006).

Climate regulation – We calculated the sum of the predicted amount of carbon stored in living trees, deadwood, and soil. To calculate the flow of carbon sink in living trees, the estimated biomass of individual trees was converted to its carbon equivalent using a factor of 0.5 (IPCC 2006). Soil carbon was estimated using the Yasso07 model (Liski et al. 2005). We also assessed the carbon storage in harvested wood products (HWP) considering two products, saw timber and wood-based panels with half-lives of 35 and 25 years, respectively. The current HWP pool is assumed to be zero. Thus, the carbon storage in HWP pool only increases at the beginning of the simulations, since there is no release of carbon from the current HWP pool (until 25 years from the first harvest).

Recreation – We measured the recreational aspects of forests by the Shannon index and proportion of City Forest. The Shannon index (Jost 2006) was used to calculate the tree species diversity for each NFI plot, assuming that a higher diversity is more attractive for people seeking recreation. City forest is defined as a 30 km buffer zone around cities with a population greater or equal to 40.000 inhabitants, which was based on the urban area layer from Statistics Norway.

Supplementary Table 4: Optimization scenarios of **Germany (Bavaria)**

Optimization scenarios of Germany describing the applied indicators and optimization rules to address the FESB demands of the three national policy scenarios; with step = order of optimization steps following the priority assigned to objectives, red = epsilon constraint, blue = maximize/minimize objective. The corresponding equations types (Eq.) for the individual objective functions are explained in **Supplementary Note 6**.

Ecosystem services & biodiversity	**Indicator (unit)**	**National forest strategy Objective / Constraint**	**Eq.**	**step**	**Biodiversity strategy Objective / Constraint**	**Eq.**	**step**	**Bioeconomy strategy Objective / Constraint**	**Eq.**	**step**
Wood production	Increment (m^3 ha^{-1} yr^{-1})	Maximize (even-flow)	**S5a**	**1**						
	Harvested volume (m^3 ha^{-1} yr^{-1})	Maximize (even-flow)	**S5a**	**1**						
	Sawlogs (m^3 ha^{-1} yr^{-1})							Maximize (even-flow)	**S5a**	**1**
	Pulpwood (m^3 ha^{-1} yr^{-1})							Maximize (even-flow)	**S5a**	**1**
Bioenergy	Energy products (m^3 ha^{-1} yr^{-1})	Maximize	**S5a**	**2**				Maximize	**S5a**	**1**
Nonwood [a)]										
Game [a)]										
Biodiversity	Biodiversity indicator (-) *(Biber et al. 2021)*	Maximize (change >0)	**S5c**	**1**	Maximize	**S5c**	**1**	Maximize	**S5a**	**3**
Conservation	Shannon index (-) *(Jost 2006)*	Maximize	**S5c**	**3**	Maximize	**S5c**	**1**			
	Species profile index (-) *(Pretzsch 2009)*	Maximize	**S5c**	**3**	Maximize	**S5c**	**1**			
	Share of regime SA (%)				Target of 5%	**S3a**	**1**			
Water protection	Crown coverage (m^2 ha^{-1})	Maximize	**S5a**	**1**				Maximize	**S5a**	**3**
	Standing volume (m^3)	Constant (change > 0)	**S2**	**1**						
Climate regulation	Total Carbon Balance (tC $year^{-1}$) *(Biber et al. 2021)*	Maximize	**S5a**	**3**				Maximize	**S5c**	**2**
	Relative Living Carbon (tC $year^{-1}$) *(Biber et al. 2021)*				Maximize target 2020 (+5%)	**S6a**	**1**			
Recreation	Recreation & aesthetics indicator (-) *(Biber et al. 2021)*	Maximize	**S5c**	**1**						
Resilience	Storm & bark beetle risk (-) *(Biber et al. 2021)*	Minimize	**S7**	**3**						
	potential natural vegetation (PNV) (-)				Minimize	**S7**	**1**			
Legal constraints	CCF on protected land	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**
	CCF on state forests	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**	Enabled constraint	**S4a**	**1**

a) No targets or objectives mentioned in national policies.

Indicators of Germany (Bavaria)

Wood production – We addressed by the indicators annual increment and harvested timber amount per simulation period. Both, harvested timber and bioenergy were calculated for individual tree dimensions based on the wood assortment program BDATPro (Kublin 2003).

Bioenergy – We used marginal assortments that are typically used for energy wood products (harvest residues and stumps).

Biodiversity conservation – We used the biodiversity fuzzy indicator from Biber et al. (2021). Additionally, it was also addressed based on tree species diversity, like the Shannon index of tree species (Jost 2006), and the species profile index developed by Pretzsch (2009). Further, the share of stands managed by set aside was considered representing strict protected areas.

Water protection – It was evaluated through forest stability indicators: the standing volume and the crown coverage.

Climate regulation – We addressed it through indicators of carbon storage on the one hand and avoidance of carbon emission on the other. We therefore applied a total carbon balance that accounts for carbon storages in standing volume and, in wood products, as well as the avoidance of CO_2 emission through substitutional use of construction wood instead of other construction materials (Biber et al. 2021).

Recreation – We used the “recreation & aesthetics” fuzzy indicator reported by Biber et al. (2021).

Resilience – We characterized resilience with the “storm & bark beetle risk” indicator from Biber et al. (2021) and by the potential natural vegetation (PNV). The latter was estimated as a distance metric between the species composition of the stand and the PNV defined by Bavarian Regional Office for the Environment. This metric was calculated as simple Euclidian distance between the ideal species proportion of the PNV composition and the simulated one. The species composition was simplified to match SILVA’s simulated tree species and species groups.

Supplementary Note 2: Forest situation and effects of scenarios

Supplementary Table 5: Current forest situation in the four study regions

We studied the four regions Finland, Sweden, Norway, and Germany (Bavaria), which represent two main forest ecosystems in Europe – boreal and temperate. The below comparison of the study regions is based on reported values of national forest statistics: Finland (Peltola et al. 2020), Germany (BMEL 2016), Norway (Statistics Norway 2021) and Sweden (Swedish Forest Agency 2022).

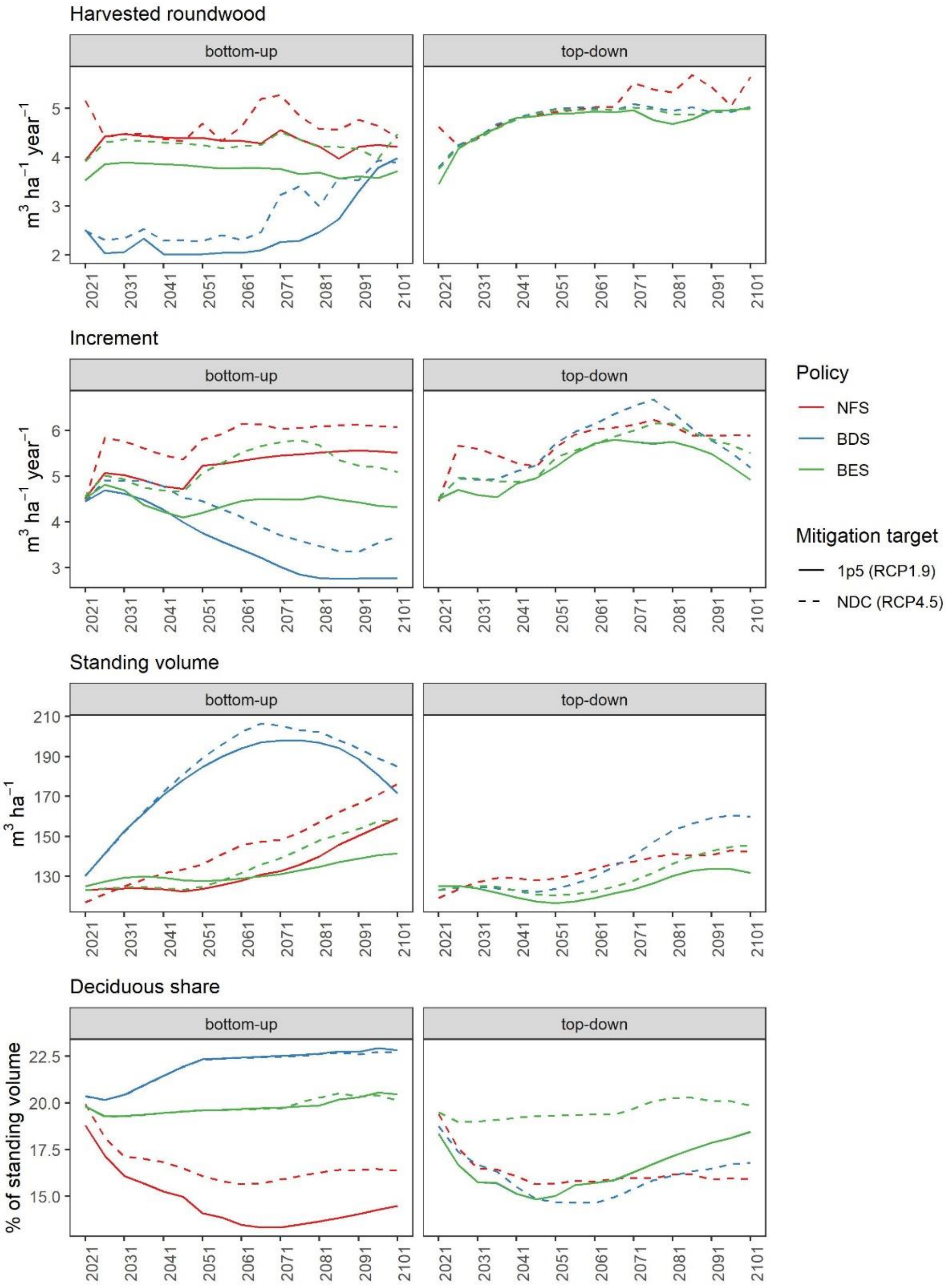
	Finland	**Germany (Bavaria)**	**Norway**	**Sweden**
Forest ecosystem	Boreal	Temperate	Boreal	Boreal
Forest area	26.3 Mha (86% of the land area), 20.2 Mha productive forest	2.6 Mha (31% of the land area)	14 Mha (37.5% of the land area), 8.3 Mha productive forest	28 Mha (69% of the land area), 23 Mha productive forest
Main tree species	50% Scots pine (*Pinus sylvestris*), 30% Norway spruce (*Picea abies*), 17% birch (*Betula pendula, B. pubescens*), remaining 3% other broadleaved trees	40.9 % Norway spruce (*Picea abies*) 16.8% Scots pine (*Pinus sylvestris*) and 13.6% European beech (*Fagus sylvatica)*	44% Norway spruce (*Picea abies*), 31% Scots pine (*Pinus sylvestris*), and 25% broadleaved (*Betula pendula, B. pubescens).*	41.9% Norway spruce (*Picea abies*), 38.4% Scot's pine (*Pinus sylvestris*), 12.0% birch (*Betula pendula, B. pubescens*), 6.2% other broadleaved trees and 1.4% exotic species
Total annual increment (productive forest)	105 Mm^3 * ($5.2\ m^3ha^{-1}yr^{-1}$)	29.7 Mm^3 ($11.9\ m^3ha^{-1}yr^{-1}$)	21.95 Mm^3 ($2.6\ m^3ha^{-1}yr^{-1}$) **	115 Mm^3 ($5.2\ m^3ha^{-1}yr^{-1}$)
Mean growing stock (productive forest)	119 m^3ha^{-1}	396 m^3ha^{-1}	105 m^3ha^{-1}	140 m^3ha^{-1}
Total roundwood harvest	73,3 Mm^3 (in 2019)	22.3 Mm^3 (in2012)	12.7Mm^3 (in 2019)	88 Mm^3 (in 2018)
Typical management practice	Rotation forestry with clear-felling and artificial regeneration	Rotation forestry with clear-felling and shelterwood cut (23%), continuous cover forestry (77%, incl. Plenterwald)	Rotation forestry with clear-felling and artificial regeneration	Rotation forestry with clear-felling and artificial regeneration

* Mean increment per hectare multiplied by productive forest area.

** Total annual increment divided by productive forest area.

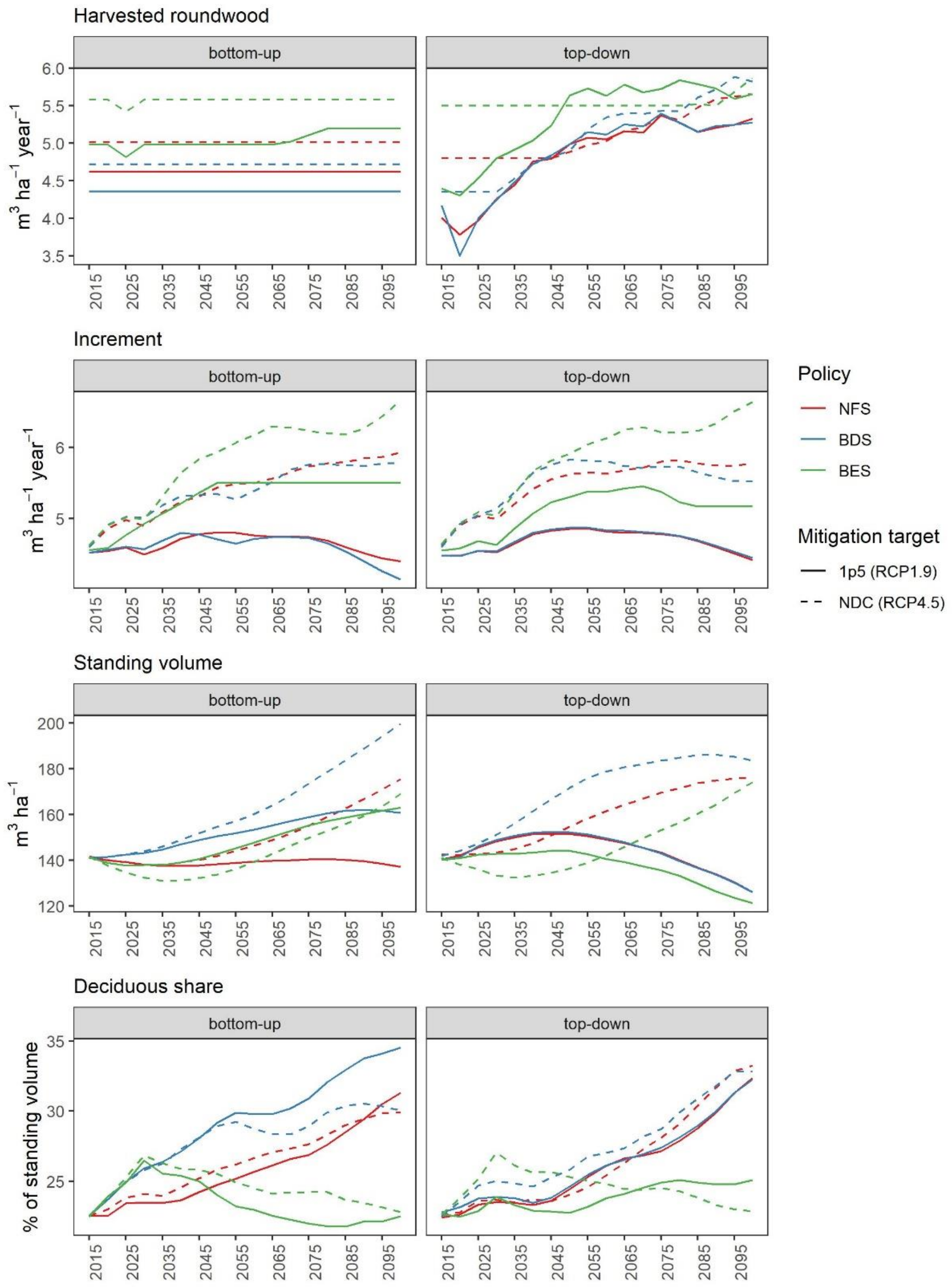
Supplementary Figure 14: Scenario effects on main forest characteristics in **Finland**

Effects of the optimal forest management under bottom-up and top-down optimization scenarios on main forest characteristics (productive forest), including average values of: annual harvested roundwood, annual increment, standing volume of living trees, and share of deciduous trees. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5℃ scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



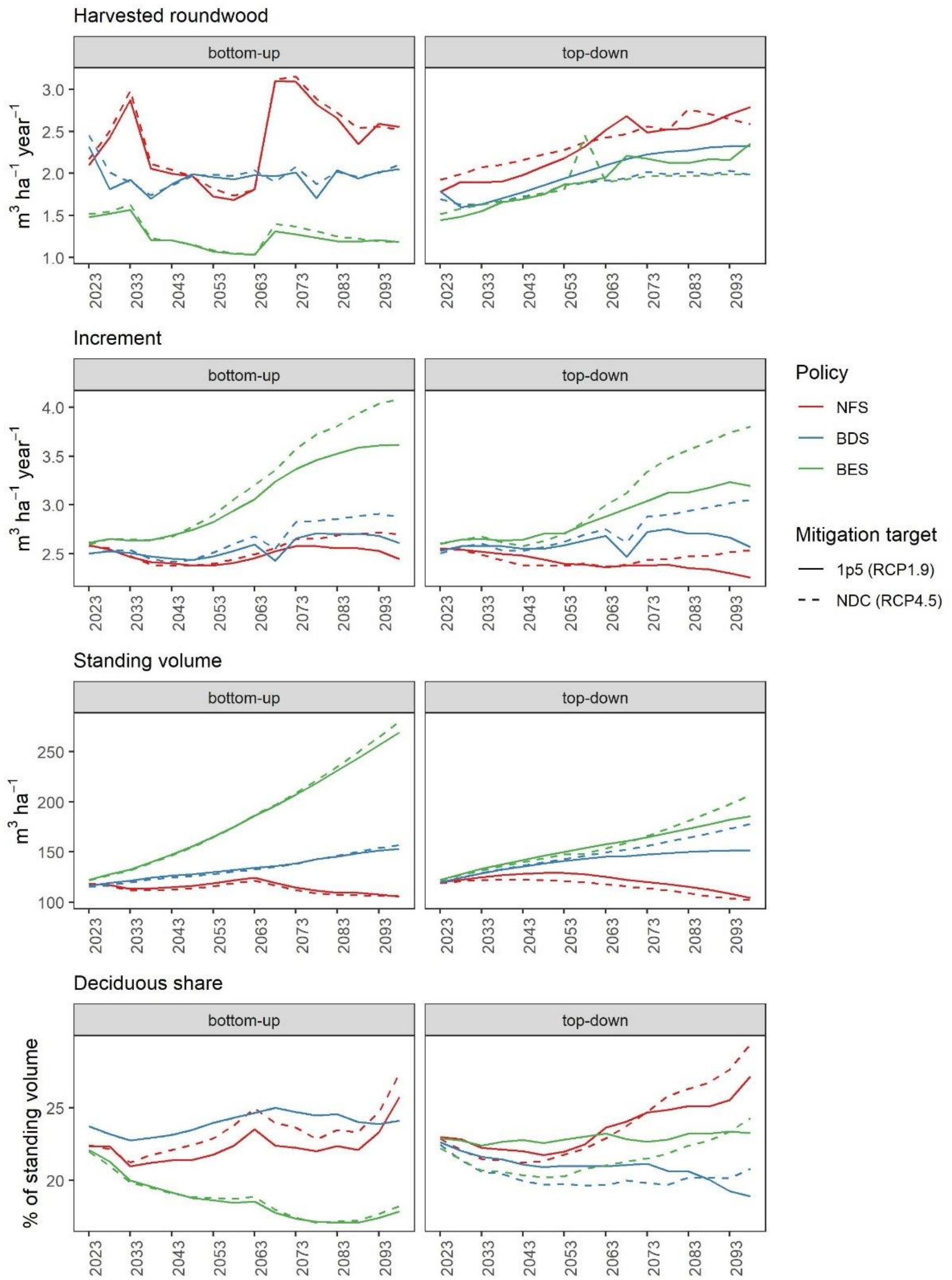
Supplementary Figure 15: Scenario effects on main forest characteristics in **Sweden**

Effects of the optimal forest management under bottom-up and top-down optimization scenarios on main forest characteristics (productive forest), including average values of: annual harvested roundwood, annual increment, standing volume of living trees, and share of deciduous trees. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5℃ scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



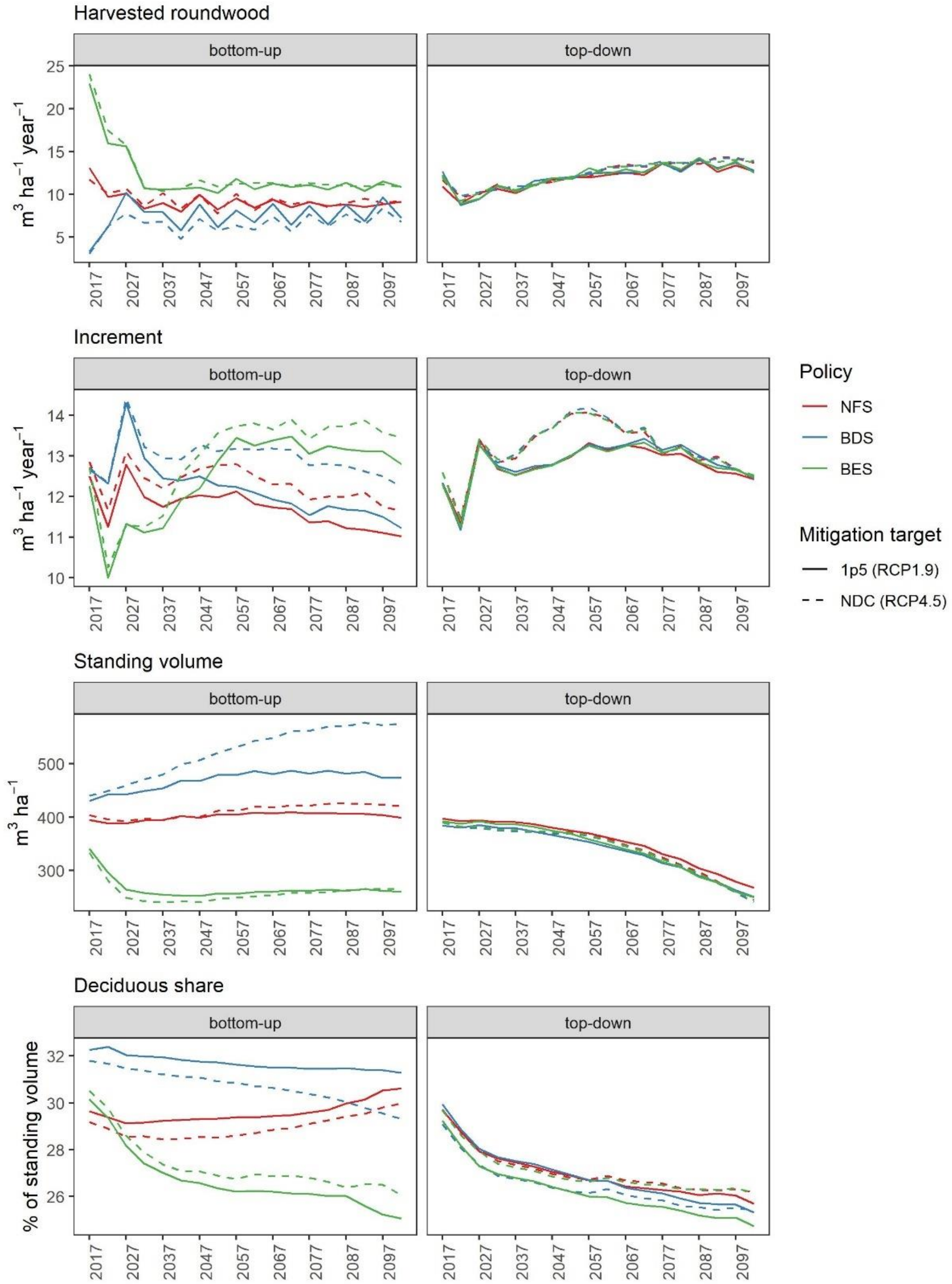
Supplementary Figure 16: Scenario effects on main forest characteristics in Norway

Effects of the optimal forest management under bottom-up and top-down optimization scenarios on main forest characteristics (productive forest), including average values of: annual harvested roundwood, annual increment, standing volume of living trees, and share of deciduous trees. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5℃ scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



Supplementary Figure 17: Scenario effects on main forest characteristics in **Germany**

Effects of the optimal forest management under bottom-up and top-down optimization scenarios on main forest characteristics (productive forest), including average values of: annual harvested roundwood, annual increment, standing volume of living trees, and share of deciduous trees. The three national policy scenarios represent: NFS = national forest strategy, BDS = biodiversity strategy, BES = bioeconomy strategy (BES) (**Supplementary Note 1**). The two mitigation targets are: 1.5℃ scenario (1p5), and Nationally Determined Contribution (NDC) (**Supplementary Note 5**).



Supplementary Note 3: Forest input data

Input data **Finland**

The data used to define the initial forest state represents a sub-sample of the public data from the Finnish Forest Centre (www.metsaan.fi) from 2016, which provides detailed forest stand information of private forest land. This data was complemented by the Multi-source National Forest Inventory from 2015, which provides information on the whole forest land in raster format (http://kartta.luke.fi/index-en.html) (Mäkisara et al. 2019). Both data sets were sampled along the regional and temporal systematic clusters following the design of the 11th Finnish National Forest Inventory (NFI). The NFI sampling design distinguished between four regions:

- Lapland and North Lapland (the design from Lapland was extended to North Lapland)
- Southern North Finland
- Central Finland
- Southernmost Finland.

See http://www.metla.fi/ohjelma/vmi/vmi11-otanta-en.htm for more information about the NFI design. In total 56221 forest plots were selected over whole of Finland.

Input data **Germany (Bavaria)**

Data from the latest German NFI (2012) was used to define the initial forest state for the simulations, with a total of 7456 NFI plots situated in Bavaria. The NFI applies a permanent four-by-four-kilometer sampling grid (locally even denser) over the entire country, where each grid point is represented by a cluster of four inventory plots (BMEL 2016). The NFI data are publicly available upon request (https://bwi.info/).

Input data **Norway**

Data from the last Norwegian NFI (2015-2019) was used to define the initial state of the simulations. The Norwegian NFI is based in a five-year cycle, so that each plot is resampled every 5th year with 1/5 of all NFI plots visited annually. The NFI plots are 250 m2 in size and were established at each intersection of a 3x3 km grid across the major forested areas of the country. In total 9371 plots were selected over whole Norway. The NNFI divides Norway into 4 strata:

- Lowland (below coniferous limit) except Finmark (94%)
- Mountain areas (above conif. Limit) except Finnmark (3.75)
- Lowland in Finnmark (1.6%)
- Mountain areas in Finnmark (0.4%)

For a more detailed description of the sampling design see Breidenbach et al. (2020) or https://www.ssb.no/en/jord-skog-jakt-og-fiskeri/skogbruk/statistikk/landsskogtakseringen.

Input data Sweden

The initial state is based on data from the Swedish NFI (2008-2012) plots, which are distributed over the country in a systematic cluster design comprising of squared tracts. Two thirds of the tracts are permanent and revisited every fifth year and one third are temporary and only visited once. Each tract contains circular plots with a radius of 7 or 10 meters placed alongside the borders of the tract, where the border length varies between 300 and 800 meters. Plot and tract sizes differ depending on where in the country it is located and if it is a temporary or permanent plot (Fridman et al. 2014). In total 29 892 plots were used, representing the productive forest area of Sweden. Forestry is only allowed on productive forest land in Sweden, i.e., forest land with a potential yield capacity of 1 $m^3ha^{-1}year^{-1}$.

Supplementary Note 4: Forest dynamic and management simulations

Simulator and regimes of **Finland - SIMO**

Forest simulations were performed with the open source forest simulator SIMO (Rasinmäki et al. 2009) for the case study of Finland. SIMO simulates individual tree growth, mortality and regeneration for even-aged (Hynynen et al. 2002) and uneven-aged boreal forests (Pukkala et al. 2013). Climate variables driving stand growth and soil dynamics (mean and amplitude of temperature, CO_2 concentration, precipitation) were based on Lehtonen et al. (2016), and the climate data of the Canadian Earth system model CanESM (von Salzen et al. 2013). The impacts of climate on tree growth are introduced into the calculation of volume growth and further allocated between diameter and height growth, based on the models of Matala et al. (2006). Simulations were conducted with high performance computational resources provided by CSC – IT Center for Science LTD (cPouta, https://research.csc.fi).

For each NFI plot, forest management was simulated in five-year periods over 100 years. The basic concepts of the six management regime classes are described in **Supplementary Table 6** and are based on the work of Eyvindson et al. (2018). The maximum number of management regimes simulated by stand was 29 depending on the initial stand characteristics (i.e., dominant height, basal area, site type, and age). 24 regimes were modifications of even-aged rotation forestry, which is the business-as-usual regime (BAU). The implementation of BAU followed the "best practices guide" for managing forests in Finland (Äijälä et al. 2014). Four regimes represented a continuous cover forestry management and one regime represents setting aside, where no management takes place. (**Supplementary Table 7**).

Supplementary Table 6: Basic concepts of the six regime classes simulated in Finland.

Management class	**Description**
Business-as-usual (BAU)	Even-aged rotation forestry, according to Finnish recommendations (Äijälä et al. 2014); rotation length between 70-90 years; final felling is determined by site type, dominant stand height, and age; 5 retention trees ha^{-1}; replanting after final felling; 1-3 thinnings during rotation
Intensified BAU (I-BAU)	Modifications of BAU, regimes with shortened rotation length (-5 to -20 year); regimes with shortened rotation and additional fertilization (300kg N ha^{-1}) at basal area (BA) threshold of 14-20 m^2 ha^{-1} (Kukkola and Saramäki 1983, Pukkala 2017)
Extensified BAU (E-BAU)	Modifications of BAU, with either postponed final fellings (5, 15, 30 years) or with retention trees left after final felling (30 trees ha^{-1} or 30 m^3 ha^{-1})
Continuous Cover Forestry (CCF)	Large trees are periodically removed (thinning from above) down to BA threshold (16 - 22 m^2 ha^{-1} depending on site fertility); four different predefined BA thresholds; natural regeneration of stands
Adaption to climate change (ACC)	Modification of BAU, aims to increase resilience against climate change on the most prone medium fertile sites (Herb rich heath, Mesic heath) in Southern and Central Finland; replanted with broadleaves trees (*Betula pendula*) after final felling
Set aside (SA)	No management activities, only tree growth, mortality and natural regeneration are simulated

Supplementary Table 7: Summary table of the simulated management regimes for Finland and their allocation to the six management classes.

Management class	**Management regime**	
	Abbreviation	**Description**
Set aside (SA)	*SA*	No management, only growth and mortality
Business-as-usual (BAU)	*BAU*	Rotation forestry, no thinnigs prior clearfelling
	BAU w thin	Rotation forestry, with thinnings prior clearfelling
	BAU w/o thin	Rotation forestry, no thinnings prior or after clearfelling
Extensified BAU (E-BAU)	*BAU w GTR*	= *BAU*, with 30 retention trees or 30m^2 per ha left
	BAU w thin GTR	= *BAU w thin*, with 30 retention trees or 30m^2 per ha left
	BAU + 5	= *BAU*, with 5 year extended rotation age
	BAU + 15	= *BAU*, with 15 years extended rotation age
	BAU +30	= *BAU*, with 30 years extended rotation age
	BAU w thin +5	= *BAU w thin*, with 5 year extended rotation age
	BAU w thin +15	= *BAU w thin*, with 15 years extended rotation age
	BAU w thin +30	= *BAU w thin*, with 30 years extended rotation age
Intensified BAU (I-BAU)	*BAU -5,*	= *BAU*, with 5 years shorter rotation age
	BAU w thin -5	= *BAU w thin*, with 5 years shorter rotation age
	BAU w/o thin -20	= *BAU w/o thin*, with 20 years shorter rotation age
	BAU F	= *BAU*, with fertilization
	BAU w thin F	= *BAU w thin*, with fertilization
	BAU -5 F	= *BAU -5*, with fertilization
	BAU w thin -5 F	= *BAU w thin -5*, with fertilization
	BAU w/o thin -20 F	= *BAU w/o thin -20*, with fertilization
Adaptation to climate Change (ACC)	*BAU w thin B*	= *BAU w thin*, with increased broadleave planting
	BAU w thin GTR B	= *BAU w thin GTR*, with increased broadleave planting
	BAU w thin +5 B	= *BAU w thin +5*, with increased broadleave planting
	BAU w thin +15 B	= *BAU w thin +15*, with increased broadleave planting
	BAU w thin +30 B	= *BAU w thin +30*, with increased broadleave planting
Continuous Cover Forestry (CCF)	*CCF 1*	Thinning from above, basal area threshold -3 m^2/ha
	CCF 2	Thinning from above, basal area threshold +/-0 m^2/ha
	CCF 3	Thinning from above, basal area threshold + 3 m^2/ha
	CCF 4	Thinning from above, basal area threshold + 6 m^2/ha

Simulator and regimes of Germany (Bavaria) – SILVA

Forest management and dynamics were simulated using the forest simulator SILVA (Pretzsch et al. 2002, Pretzsch 2009). SILVA is a single-tree-based model that is distance-dependent (tree positions matter) and age-independent. Through that spatial explicitness, SILVA simulates the development of even-aged or uneven-aged mixed and monospecific forests under a broad range of silvicultural concepts. SILVA estimates potential height growth based on site quality, which is estimated from soil moisture and nutrient stage, length of the vegetation period and by a set of further climatic variables. The climatic driving forces are temperature, precipitation, temperature amplitude, and the atmospheric concentrations of CO_2 and NO_x. The climate variables, except the latter two, were computed from HADGEM2-ES GCM model (Jones et al. 2011), and were retrieved from Inter-Sectoral Impact Model Intercomparison Project (https://esg.pik-potsdam.de/search/isimip/).

In total, 15 management regimes were simulated in five-year periods over 100 years that can be grouped into six management classes. These classes represent the most relevant silvicultural practices (**Supplementary Table 8**): i) the business-as-usual classes (BAU), ii) intensified BAU, and iii) extensified BAU generally apply traditional silvicultural practices with thinning from below and final clearfelling. These three classes however differ in their degree of forest productivity stimulation. iv) The continuous cover forestry (CCF) regimes commonly aim at creating and maintaining a stable size class distribution with emphasis on steady wood provision. Regimes within this lass have thus been tailored to suit intervention frequency and intensity as typical for small private forest managers, who consider forestry rather as an additional source of income. v) To account for the state forestry's aim of establishing climate resilient forests, a further regime was simulated that aims at continuous cover with high structure and species diversity (adaptation to climate change). vi) The class of set aside (SA) strictly inhibits any intervention.

Supplementary Table 8: Summary table of the simulated management regimes for Germany and their allocation to the six management classes (S = stands dominated by spruce, B = stands dominated by beech, and P = stands dominated by pine).

Management classes	**Management focus**	**Abbreviation**	**Harvesting top height [m]**			**Description**
			S	**B**	**P**	
Business-as-usual (BAU)	Wood production clearfelling	BAU_0	30	30	30	Standard BAU
		BAU_0_p1				Initially mature stands not harvested before year 5
		BAU_0_p2				Initially mature stands not harvested before year 10
Extensified BAU (E-BAU)	Wood production with harvest delay	Extensified BAU	33	33	33	Lower intensity, later harvest
Intensified BAU (I-BAU)	Intensification of wood production	BAU_RR	25	30	25	Short rotation
		BAU_RR_p1				Initially mature stands not harvested before year 5
		BAU_RR_p2				Initially mature stands not harvested before year 10
		BAU_FS	33	30	30	Promote foreign species
Continues Cover Forestry (CCF)	Regular harvest structure mixture	CCF_P1	38	33	33	Standard CCF
		CCF_P2	38	33	33	Buffer temporal variation of supply
		CCF_P3	12	12	12	Thereby keep more straight and simple, harvest coniferous stand
		CCF_P3_p1				Initially mature stands not harvested before year 5
		CCF_P3_p2				Initially mature stands not harvested before year 10
Adaptation to Climate Change (ACC)	Multifunctionality	Adaptation to Climate Change	32	25	28	Promote diversity, stability, continuity, converts to broadleaved dominated stands
Set aside (SA)	Set aside	SA	-	-	-	No thinning, no harvest

Simulator and regimes of Norway – SiTree

Forest dynamics and management for Norway have been simulated using the open source simulator SiTree (Antón-Fernández and Astrup 2022), with imputation models (1 nearest neighbor) to estimate individual tree growth, mortality, and ingrowth. The imputation models used here were fitted to the Norwegian NFI. Forest inventory data from the last five-year cycles (2015 – 2019) were used as input data in the SiTree platform. The effect of climate change was included by modifying the site index of the plots using empirical Norwegian climate data (Antón-Fernández et al. 2016). The climatic variables needed to run the climate-sensitive site index functions were obtained from the Norwegian Meteorological Institute (MET). The climatic data for the RCP 4.5 scenario were originated from a combination of ten regional climate model simulations from the EURO-CORDEX archive (Wong et al. 2016), which were downscaled to a 1 × 1 km grid and bias corrected.

For each NFI plot, forest management was simulated in five-year periods over 100 years. The total number of management regimes simulated by stand was up to 99, depending on the initial stand characteristics. The regimes can be allocated into the six common defined regimes classes (**Supplementary Table 9**), of which four classes allow for a shift in the timing of the initial harvests in plots that were already in the mature age (to avoid a harvest peak in the first period). The shift allowed the already mature stands to be harvested at any time during the simulation for the regime class business-as-usual (BAU), as well as for the extensified (E-BAU) and intensified (I-BAU) subcategories of the class. For continuous cover forestry (CCF) the displacement was performed along 3 periods, since in CCF harvest activities are simulated every 15 years.

Supplementary Table 9: Summary table of the simulated management regimes for Norway and their allocation to the six management classes.

Management class	**Management regime**	
	Abbreviation	**Description**
Set aside (SA)	*SA*	Protection forest
Business-as-usual (BAU)	*BAU + 5* *BAU + 10* *BAU + 15* *….* *BAU + 90*	Even-aged management (thinning, clearfelling, planting)
Extensified BAU (E-BAU)	*E-BAU + 5* *E-BAU + 10* *E-BAU + 15* *….* *E-BAU + 90*	Extensive even-aged management – longer rotation age (rotation increase to 140% of rotation age)
Intensified BAU (I-BAU)	*I-BAU + 5* *I-BAU + 10* *I-BAU + 15* *….* *I-BAU + 90*	Intensive even-aged management (planting, higher density, fertilization, thinnings, clearfelling)
	I-short-BAU + 5 *I-short-BAU + 10* *I-short-BAU + 15* *….* *I-short-BAU + 90*	Intensive even-aged management -shorter rotation age (rotation decrease to 80% of rotation age)
Continues Cover Forestry (CCF)	*CCF + 5* *CCF + 10* *CCF + 15*	Continuous cover forestry with harvest every 15 years (take out the 15-year growth)
Adaptation to climate Change (ACC)	*ACC + 5* *ACC + 10* *ACC + 15* *….* *ACC + 90*	Multispecies even-aged management (regeneration with a mixture of species of spruce / pine / birch)

Simulator and regimes of Sweden – Heureka

The forest projections for the management regimes were simulated with the Heureka system (Wikström et al. 2011). The system projects individual tree development based on empirical growth models (Fahlvik et al. 2014), mortality models (Fridman and Ståhl 2001) and models for in-growth (Wikberg 2004). In addition to be able to simulate forest dynamics under climate change, the system has a built-in model modifying wood growth to the climate scenario RCP4.5, based on the process-based model BIOMASS (McMurtrie et al. 1990) adapted to Swedish conditions (e.g. Bergh et al. (2003)). To simulate the different management regimes, the Heureka application PlanWise was used, were many different alternatives (so called treatment schedules) are projected for each treatment unit (here NFI plot) with different timings of forest management actions (cleaning, thinning, clear-felling).

In Heureka, management regimes can be defined with relatively high level of detail (**Supplementary Table 10**). For each treatment unit and their assigned management regimes, several treatment schedules are generated in five-year periods over 100 years. Each treatment schedule covers the entire planning horizon and differs in the timing of management actions.

Supplementary Table 10: Summary table of the simulated management regimes for Sweden and their allocation to the six management classes. Regimes indicated with "*" were only used in the bioeconomy scenario (BES).

Management class	**Management regime**	
	Abbreviation	**Description**
Set aside (SA)	Unmanaged	Set aside; The forest grows from the initial state, no timber extraction
Business-as-usual (BAU)	BAU	Even-aged forestry; Biofuel extraction at final felling on dry and mesic soils, retaining 10 trees and 3 high stumps/ha at final felling (retention). Max 30 years delay in final felling after reaching minimum final felling age (according to the Swedish Forestry Act). Regeneration: planting
Extensified BAU (E-BAU)	BAU – No thinning	Even-aged forestry with no thinnings; BAU with no thinnings.
	BAU_ProlongedRotation	Even-aged forestry with prolonged rotations; BAU with final felling only allowed from 30 years to 50 years after reaching minimum final felling age
Intensified BAU (I-BAU)	BAU_FocusBioenergy_StumpHarvest	Even-aged forestry with bioenergy focus and stump harvest; BAU with biofuel extraction including stump removal (pine and spruce) and no retaining trees
	BAU FocusBioenergy	Even-aged forestry with bioenergy focus; BAU with biofuel extraction at final felling in all stands except on wet soils, bioenergy thinning is allowed.
	Int_prod*	BAU allowing breeding of plant material, short rotations, no thinnings and fertilization
	Int_HybridExotic*	BAU allowing planting hybrid/exotic-like species and managed accordingly (including no thinnings and short rotations)
	Int_Contorta*	BAU allowing planting Contorta and following adapted management (including shorter rotations and adapted thinnings)
Adaptation to climate change (ACC)	Even-aged forestry promoting broadleaves	BAU that aims at increasing the proportion of broadleaves in the landscape by increasing the share of retained broadleaves in cleaning and thinning operations, and allowing for longer rotation periods. Natural regeneration (seed trees).
Continuous Cover Forestry (CCF)	CCF	Reoccurring selection fellings, minimum 10 years in-between 2 fellings. Only possible in spruce dominated stands. Natural regeneration.

Supplementary Note 5: GLOBIOM timber demand scenarios

National timber demands scenarios were computed by the **IIASA Global Biosphere Management Model (GLOBIOM)** (Havlík et al. 2011, Havlík et al. 2014). GLOBIOM is a global land use model that spatially-explicitly covers the agricultural, forest, and bio-energy sectors. The model is solved recursively for 10-year periods and endogenously maximizes the societal economic surplus according to a series of policy constraints and future societal demands for commodities (Havlík et al. 2011, Havlík et al. 2014). The supply side of the model is based on detailed grid-cell information while the demand side and trade are based on national resolution for Europe and a coarser resolution outside the EU.

In this study, we use a version of the model called **GLOBIOM-forest**, where the representation of the agricultural sector is simplified, but where forestry, the forest industry and the forest bio-energy sectors are modelled in detail(Lauri et al. 2021). The forest biomass within GLOBIOM is represented by spatially explicit harvest potentials based on data from the Global Forest Model (G4M) (Kindermann et al. 2008, Gusti and Kindermann 2011). The model endogenously optimizes spatial distribution of forest types and management intensities according to scenarios specific timber demands and a series of forest resources constraints (e.g., protected forest areas). The **forest biomass supply** is represented by spatially explicit harvest potentials, which are based on increment data from the Global Forest Model (G4M) (Kindermann et al. 2008, Gusti and Kindermann 2011). When calculating the harvest potentials, spatially explicit harvest and transportation costs were taken into account (Di Fulvio et al. 2016), and forest management type specific land-use change costs. Land-use change costs were based on historical land-use change patterns and control the transition between different forest and management types.

GLOBIOM includes three **forest types** (primary forests, secondary forests, managed forests) **and** four **management types** (no management, low intensity, multifunctional, high intensity). Protected forests are forest areas where no management for wood supply is allowed. Primary forests are forested land that has not been used historically for production. Managed forests are forested land that is currently actively used for production while secondary forests are abandoned managed forests. Management types differ in the proportion of the increment that can be harvested. In high intensity management, the full increment can be harvested while in multifunctional and low intensity management, only a portion of the increment can be harvested (see Lauri et al. (2021)). For this assessment, the allocation procedure has been improved to accommodate additional and recently available data sources, including: current mapping of forest management types such as Global Forest Resources Assessment (FAO 2020b), World Database on Protected Areas (WDPA 2020) and Nature Map Explorer (IIASA 2020a). Inclusion of such data sources allowed to enhance the spatialization of protected forests according to two classes: 1) “statutory protected” forests excluded from wood harvest and represented by “no-management”; 2) forests with “management restrictions” for biodiversity protection that were set under the “low intensity” management type and where no transition to any other management type was allowed (**Supplementary Table 13**).

Modelling of future **national timber demands** in GLOBIOM are based on solving the model under its economic optimization. The GLOBIOM forest sector equations, modelling framework and assumptions are described in:

- https://github.com/iiasa/GLOBIOM_forest

- https://github.com/iiasa/GLOBIOM_forest/blob/main/GLOBIOM_forest_documentation.pdf

National bioeconomy growth and its impact on wood demands projection is taken into account for each country according to demands for wood products included in the GLOBIOM model. Future demands for final wood products are modelled according to GDP and population growth for each country under SSPs scenarios according to the IIASA SSP-RCP database (https://tntcat.iiasa.ac.at/SspDb). Income elasticities linking demands and economic growth are specific at level of wood products categories and countries income grouping. In addition, projections of wood demands for industrial energy production (bioenergy demands) under each RCP are obtained from the MESSAGE energy model (https://tntcat.iiasa.ac.at/RcpDb) at the level of global regions and downscaled to European countries according to their current production statistics (IEA). The downscaling of future RCPs bioenergy demands to each country is driven by the spatial explicit supply and trade competitiveness. For each country, the GLOBIOM model provides a solution as a market equilibrium at each 10 years-time steps by maximizing the social welfare for forest sector (sum of produced and consumer surplus), given future national wood demands and spatial explicit supply amount and costs (including wood trade costs between the countries/regions in the model), under a series of socio-environmental constraints. This solution of the model at each time step provides the “GLOBIOM timber demand” used in the paper for each region and forest assortment which is therefore aligned to the RCPs climate mitigation demand from bioenergy.

Final products demands are based on the constant elasticity inverse demand functions, which are parametrized by reference volumes, reference prices and elasticity coefficients. Reference volumes are based on the FAOSTAT in 2000-2020 (FAO 2020a). After 2020, the reference volumes are shifted over time by the GDP and population growth. The development of GDP and population is based on the SSP-RCP scenario data (IIASA 2020b). The elasticity parameters of demand functions are based on econometric estimates from Buongiorno et al. (2003), Buongiorno (2015) and Morland et al. (2018). Income-elasticities vary in the range between 0 to 1 depending on the product category, and they differentiate by low-, middle and high-income regions. Newsprint and printing and writing papers are assumed to have 0 income elasticity for all regions based on information technology development, which will decrease the demand for these paper grades in the future (Latta et al. 2016). Population elasticity is always 1. Price-elasticities vary in the range -0.1 to -0.5 depending on the product category. The detail on elasticities per product category can be found at: https://github.com/iiasa/GLOBIOM_forest/blob/main/GLOBIOM_forest_documentation.pdf

Traditional fuelwood demand is assumed to be constant or has negative income-elasticity depending on the version of the model. This can be justified by historical development, which has been relatively stable during the last 70 years (FAO 2020a). Modern industrial bioenergy (energy-wood) demand is exogenous to GLOBIOM and derived by coupling the model through look-up tables with the MESSAGE model, that provides demand levels associated to the mitigation demand under each SSP-RCP scenario (IIASA 2020b).

Circular economy is included in the GLOBIOM scenarios for each country according to its representation of recycled wood in the modeling framework (see the documentation above), and as described in detail in Lauri et al. (2021). Representation of recycled biomass in GLOBIOM-forest: Recycled biomass can be used to substitute virgin fibers in wood-based products production. The model includes three recycled products: wood, paper and pulp. Recycled wood is recovered from mechanical forest industry products, which are re-used as a raw material in fiberboard production or burned for energy. Recycled paper is recovered by paper and paperboard, which is re-used for recycled pulp production. Recycled pulp is used as a raw material in paper and paperboard production.

The **supply of recycled paper** is based on FAOSTAT statistics in 2000-2020 (FAO 2020a). After 2020, recycled paper supply is endogenous, and it is determined by the paper and paperboard consumption and recycled paper collection rates. The maximum recycled paper collection rate is assumed to be 80% based on observed maximum national collection rates (CEPI 2019). The **supply of recycled pulp** depends on the supply of recycled paper and the recycled pulp yield from recycled paper. Recycled pulp yields from recycled papers depend on the filler content of recycled papers and the ageing effect of recycled biomass (Levlin et al. 2010, van Ewijk et al. 2017). The average recycled pulp yield with the ageing effect is about 90%. Connecting this to filler content of different paper grades (packaging materials 0%, newsprint 10% and printing and writing papers 20%) gives recycled pulp yield of 70-90% depending on the paper grade. Other papers are assumed to have zero yields, since they include mainly sanitary papers, which are usually not recycled. Connecting the recycled pulp yields to the maximum collection rates and the consumption shares of different paper grades implies that the maximum technical share of recycled pulp varies from 60 % (current consumption shares) to 65 % (the consumption share of packaging materials increase from 50 to 70%) at the global level. The supply of recycled wood is based on the mechanical forest industry products' final consumption and recycled wood collection rates. The maximum recycled wood collection rate is assumed to be 50% based on expert opinion. Further details can be found in: https://github.com/iiasa/GLOBIOM_forest/blob/main/GLOBIOM_forest_documentation.pdf.

The products **recycling efficiency considered in the model is assumed to increase over time towards their respective theoretical maximum**. This recycled biomass can be used to substitute virgin fibers in wood-based products production. Therefore, the model includes indirectly some technological progress, by considering improvements in biomass use efficiency.

International trade is modelled by using bilateral trade flows. Historical bilateral trade volumes are based on BACI trade data for 2000–2020 (Gaulier and Zignago 2010). After 2020, trade volumes evolve according to trade dynamics, which depend on constant elasticity trade-cost functions that are parametrized by historical trade volumes and transport costs. Transport costs are estimated from the difference between world import and export values similar to Buongiorno et al. (2003). The share of transport costs in the value of the product is higher for raw materials such as roundwood, woodchips and recycled paper than for forest industry final products. Trade elasticity is assumed to be 0.5 for feedstocks and 3 for final products (for all products and Regions). Pellets trade-elasticity is assumed to be 0.1. Reference trade costs are based on Buongiorno et al. (2003) and they vary in the range 20 to 80 \$/m3 depending on the product. Reference trade costs stay constant over time, and they are same for all regions. If there is no trade in the previous period, then it is assumed that trade costs are linearly increasing function of the periodic trade quantity (similar land-use change cost functions). Reference prices are based on the world export prices and transport costs. The reference price for exporting regions is the world export price and for importing regions the world export price plus transport costs similar to Buongiorno et al. (2003). The world export price vary in the range 50 to 1000 \$/m^3. Preference prices are assumed to stay constant over time. An alternative option would be to shift reference prices over time by using previous period prices, as in Buongiorno et al. (2003), but this might cause artificial price fluctuations in the model.

GLOBIOM Scenario definitions

Two scenarios were developed to reflect future climate change mitigation ambition of the EU27. Each scenario was developed utilizing the SSP2 (Socio-Economic Pathway "Middle of the Road" (IIASA 2020b)) assumptions for global socio-economic developments (e.g., GDP and population growth) and bio-energy demand according to the RCP projections as estimated by the MESSAGE energy system model (Fricko et al. 2017). The two scenarios considered are (see below for more details):

- **NDC scenario:** The scenario accounted for the targets as set out in the 2016 Nationally Determined Contribution (NDC) by the European Commission and included a 40% reduction of GHG emissions by 2030 as compared to 1990 levels (translated into the RCP4.5).
- **1.5°C scenario:** The scenario assumed that the EU overall achieves net zero GHG emission by 2050 and further accounted for the Paris Agreement's temperature objectives of pursuing efforts to limit to 1.5°C temperature change (translated into RCP1.9).

The scenarios are built on top of each other and accumulate the efforts needed to reach each specific target. For each scenario, projected timber demands for material and bioenergy uses until 2100 were specified at the national (for Finland, Sweden, Norway) and NUTS2 level (Bavaria) for the five harvested products considered by GLOBIOM: sawlogs, pulpwood, other industrial roundwood, fuelwood, and logging residues. Demands were projected from 2010 to 2100 in ten-year steps.

National forest ecosystem and management models do not distinguish between detailed products of pulpwood, fuelwood and other industrial roundwood. Those are jointly covered by the simulated marketable product assortment pulpwood (except Sweden). Thus, the five products of GLOBIOM were grouped into three product demands of: sawlogs, pulpwood, fuelwood, and residues. These demands were then matched in the optimizations with the indicators of marketable product assortments arising under the simulated harvests (**Supplementary Table 11**). Therefore, demands were further linear interpolated among ten-year time steps to match them with the simulation intervals of national forest simulators (**Supplementary Table 12**).

Supplementary Table 11: Matching of the GLOBIOM product demands with indicators for marketable assortments arising under the simulated harvests.

<table>
<tr><th colspan="2">GLOBIOM demands</th><th colspan="4">Simulated indicators for marketable product assortments</th></tr>
<tr><th>By products</th><th>Grouped products</th><th>Finland, SIMO</th><th>Norway, SiTree</th><th>Germany, SILVA</th><th>Sweden, Heureka</th></tr>
<tr><td>Sawlog u.B.</td><td>Sawlogs</td><td>Sawlog u.B.</td><td>Sawlog u.B.</td><td>Sawlog u.B.</td><td>Sawlog u.B.</td></tr>
<tr><td>Pulpwood u.B.</td><td rowspan="3">Pulp- & fuelwood
=
Pulp u.B. +
Fuelwood / bark factor*+
Other industrial roundwood u.B.</td><td rowspan="3">Pulpwood u.B.</td><td rowspan="3">Pulpwood u.B.</td><td rowspan="3">Pulpwood u.B</td><td rowspan="3">Pulpwood u.B +
Fuelwood u.B.</td></tr>
<tr><td>Fuelwood o.B.</td></tr>
<tr><td>Other industrial roundwood u.B</td></tr>
</table>

Forest residues	**Forest residues**	Biomass	Biomass	Harvesting residues, stumps	Harvesting residues, stumps

* Bark factor = 1.136 for all countries

Supplementary Table 12: Time horizon and interval of GLOBIOM demands and simulated harvests. GLOBIOM demands were linear interpolated among two-time steps (e.g. 2010-2020) to match them with the simulation intervals of forest ecosystem models.

	GLOBIOM demand	**Simulated time horizon & interval**			
		Finland, SIMO	**Norway, SiTree**	**Germany, SILVA**	**Sweden, Heureka**
Time horizon (year)	2010-2100	2016-2101	2018-2103	2012-2102	2010-2110
Interval (years)	10	5	5	5	5

Nationally Determined Contribution (NDC) scenario

This scenario included the 2030 target for the EU as communicated in the Nationally Determined Contribution (NDC) documentation submitted by the EU to the UNFCCC. The scenario as such included a 40% reduction of greenhouse gas emissions by 2030 (from 1990 levels), a 27% share for renewable energy, and a 27% increase in energy efficiency.

This scenario built to a large extent on the achievement of the energy and climate 2030 targets as adopted by the EU leaders on October 2014, further refined on May 2018 with the agreement on the Effort Sharing Regulation and enhanced on June 2018 with the agreement on the recast of Renewable Energy Directive and the revised Energy Efficiency Directive. The scenario thereby built on the 2020 climate and energy package and incorporates several major recently agreed pieces of legislation, as well as recent Commission proposals:

- The revised EU ETS Directive (Directive (EU) 2018/410) which entered into force on 8 April 2018;
- The LULUCF Regulation (Regulation (EU) 2018/841) which entered into force on 9 July 2018;
- The Effort Sharing Regulation (Regulation (EU) 2018/842) which entered into force on 9 July 2018;
- The Energy Performance of Buildings Directive (Directive (EU) 2018/844) which entered into force on 9 July 2018, according to which new buildings are assumed to be nearly zero-energy buildings as of 2020;
- The Commission proposal for the recast of the Renewable Energy Directive. In its agreed version by the European Parliament and the Council on June 14th, 2018 it features a 32% overall RES EU target;
- The Commission proposal for the revision of the Energy Efficiency Directive. In its agreed version by the European Parliament and the Council on June 20th, 2018 it features 32.5% overall Primary Energy Consumption and Final Energy Consumption target (compared to 2007 Baseline), as well as a continuation of Art 7 of EED post-2020 without a sunset clause;
- The Commission proposal for the revision of the Eurovignette Directive;
- The Commission proposal for the revision of Combined Transport Directive;
- The Commission proposal for the revision of Clean Vehicles Directive;
- Regulation on electronic freight transport information;
- The Commission proposal for new CO2 standards for LDVs and HDVs.

It should be noted that it was assumed that the recent EU LULUCF Regulation[2] is included in the EU target but the harvest level for the individual member states and its forest reference level (FRL) estimates was not constrained, as stated in the countries NFAP's (National Forestry Accounting Plan). The reason, the FRL is only for accounting and it is not sure yet how member states will implement policies to influence the forest harvest levels as defined in the countries final FRL.

The scenario does not include any target after 2030 as this was neither included in the original EU NDC specifications. Thus, no long-term policy targets (i.e., 2040, 2050, 2100) were included and accounted for in this scenario as set by individual EU member states. Furthermore, it should be

[2] Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU.

noted that these scenarios do not account for the Agriculture, Forestry and Other land use (AFOLU) specific targets and accounting rules put forward in the EU 'Fit for 55' proposal (EC 2021), such as the target of the AFOLU sector to become climate neutral by 2035.

1.5°C scenario

The overall aim of this scenario was that the EU and the countries commit and actively contribute to the Paris Agreement's temperature objectives of pursuing efforts to limit the global rise in temperature to 1.5℃ by the end of the century (year 2100).

This scenario built up on the NDC scenario for reaching policy targets of 2030 (see section above) At the EU level, it is compatible with the European Commission's proposal for a climate-neutral Europe by 2050[3]. The scenario thus assumed that EU overall would achieve net-zero greenhouse gas emissions by 2050. It should be noted that net-zero greenhouse gas emissions were here interpreted as the reduction of all greenhouse gases to net zero. However, greenhouse gas emissions neutrality does not imply full decarbonization, as the remaining emissions of CO_2 in the transport, industry and building sectors, and of non-CO_2 greenhouse gases, mostly in agriculture, may be compensated by negative emissions from LULUCF sink (mainly forests) and through the use of Biomass for Energy production coupled with Carbon Capture and Storage (BECCS). At the national level, it was intended to include policies as legislated and currently proposed for the period of 2030 to 2050 (e.g. legislation that Sweden would reach net-zero emissions by the year 2045).

Biodiversity restrictions

In the three scenarios, a common biodiversity limitation to the use of forest areas was included in the projection of wood demands. This restriction was based on the continuation of the former EU biodiversity strategy[4], which was the most up-to date strategy at the time of generating those scenarios.

In this respect, areas designed in 2020 as statutory protected, according to national laws, were excluded from wood supply under the GLOBIOM scenarios (**Supplementary Table 13**). In addition, areas where wood harvesting was restricted to a certain threshold, were designed to be managed in the future with low intensity.

[3] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM/2018/773 final

[4] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. Our life insurance, our natural capital: an EU biodiversity strategy to 2020. COM(2011) 0244 final

Supplementary Table 13: Statutory protected forest areas excluding timber harvest and areas with restriction on timber harvest included in GLOBIOM timber demand projections.

Country	Statutory protected forests (no harvest)[1]		Forests with restrictions on timber harvest[2]		Source
	(% national forest land area)	NFI categories included	(% national forest land area)	NFI categories included	
Finland	7.1	1.A. Nature reserves and sites reserved for nature conservation. 1.B. Other statutory protected areas, no felling. 1.C. Fixed-term protection areas on privately owned land 2.A. Special biodiversity sites in commercial forests, no forestry measures	2.8	1.B. Other statutory protected areas, cautious felling possible. 2.B. Biodiversity sites in commercial forests, restricted forestry use 3. Forests supporting conservation of nature values, other special sites, restricted forestry use	LUKE, 2019[5]
Bavaria	4,9	Wood use not permitted or not expected	1.7	Allowed to harvest 1/3 of volume; Allowed to harvest 2/3 of standing volume	BWI, 2012[6]
Norway[3]	4.8	Natural reserves	8.0	Allowed to harvest 70% of the volume; Allowed to harvest 85% of the volume.	provided by partner NIBIO (2020)
Sweden	8.7	Formally protected areas	-		Skogsstyrelsen, 2019[7]

1) Areas designed as statutory protected, according to national laws, totally excluded from wood supply; 2) areas where wood harvesting is restricted for biodiversity to a certain threshold, designed to be managed in future with a low intensity.

[5] https://statdb.luke.fi/PXWeb/pxweb/en/LUKE/?rxid=4f4e4db2-27ac-47ae-b5bc-0282615cfb47, 2019 values (Oct. 2021)
[6] https://bwi.info/start.aspx (Oct. 2021)
[7] Skogsstyrelsen, Statistical Database of Forestryhttps://www.skogsstyrelsen.se, 2019 values (Oct. 2021)

Supplementary Note 6: Multi-objective optimization

The elaborated policy scenarios and their demands for FESB (**Supplementary Note 1**) and timber demands for climate mitigation targets (**Supplementary Note 5**) were represented by basically 11 different types of objective functions and constraints (**Supplementary Equation S1 – S11**), each addressing a simulated FESB indicator. Depending on the scenario definitions, those individual functions and constraints were combined to a logically consistent multi-objective optimization problem. See **Supplementary Note 1** for the scenario definition, the indicators used and the allocation of the equation types to the different scenarios. The notations of below equations are:

$f_n(x)$ the objective function addressing a FESB indicator

$f_{n,0}$ the objective function addressing a FESB indicator in starting year t_0

P_{target} the target value for an objective function (FESB indicator)

x_{kj} the decision for stand k to conduct management regime j

c_{kjt} the indicator value from stand k according management regime j at the simulation period t (in total 5-year steps over 100years); values of c_{kjt} were normalized in the way that the ideal point becomes *1* and the nadir point becomes *0* by using a pay-off table

K the total number of stands

J_k the set of all management regimes for stand j

$J_{LandType}$ the smaller set of management regimes on certain land type (e.g. peat, state forest)

T the total number of simulated periods (t) under consideration. Each forest simulator projected the indicator development in 5-year steps over 100 years.

$Y_{\geq target\ year}$ the set of years equal to and greater than a target year t

a_j the area of a stand under management j

u positive and negative deviations allowed for a specific target.

Supplementary Equation 1: a) Reach a stated indicator level P_{target} until a target year t and maintain indicator levels for all years afterward; ***b)*** optionally, there is a linear increase required from the current levels to the target level on target year.

a) $f(x) \leq \sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt} - P_{target}\ ,\ \forall\ t \in Y_{\geq target\ year}$

b) $f(x) \leq \sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt} - \left(\frac{target\ year - t}{target\ year - t_0} f_0 + \frac{t - t_0}{target\ year - t_0} P_{target}\right)\ ,\ \forall\ t \in T \setminus Y_{\geq target\ year}$

Supplementary Equation 2*:* avoid a decrease in indicator level compared to the current state ($t = t_0$) and aim to maximise it further (relative values, maximise the minimum).

$$f(x) \leq \frac{\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt}}{\sum_{k \in K} \sum_{j=1}^{J_k} x_{kj} c_{kjt_0}}, \forall\ t \in T$$

Supplementary Equation 3: a) target a certain percentage share P_{target} of a management regime from the start of the planning horizon or ***b)*** maximize it without a target.

a) $f(x) \leq \frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}}{\#K} - P_{target}\ ,\forall\ t \in T$

b) $f(x) \leq \frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}}{\#K},\forall\ t \in T$

Supplementary Equation 4: enabled constraint that **a)** restricts management regimes on specific land types (e.g. peatland, state forest) to a smaller set of allowed regimes, and **b)** makes sure the aggregated value of an indicator is u *%* larger/lower than the aggregated value of another indicator.

a) $if\ k = LandType,\ j\ \in J_{LandType}$

b)

$$\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt} \geq (1-u)\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}^{*}\ ,\forall t \in T$$

$$\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt} \leq (1+u)\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}^{*}\ ,\forall t \in T$$

$c_{kjt}^{*} \setminus c_{kjt}$

Supplementary Equation 5: maximize an ecosystem service indicator, with different planning horizons: ***a)*** minimum value over years that leads to the even-flow solution, ***b)*** last year value, ***c)*** average value over years, and ***d)*** for the sum over years.

a) $f(x) = min_{t\in T}\left(\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)$

b) $f(x) = \sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kj\#T}$

c) $f(x) = \sum_{t\in T}\frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}}{\#T}$

d) $f(x) = \sum_{t\in T}\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}$

Supplementary Equation 6: a) increase the indicator by a certain percentage (P_{target}) until a target year in comparison to the initial situation, ***b)*** optionally, there is a linear increase required from the current levels to the target level on target year.

a) $f(x) \leq \frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}}{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt_0}} - P_{target}\ ,\forall t \in Y_{\geq target\ year}$

b) $f(x) \leq \frac{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}}{\sum_{k\in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt_0}} - \left(\frac{target\ year - t}{target\ year - t_0}f_0 + \frac{t - t_0}{target\ year - t_0}P_{target}\right)\ ,\forall t \in T \setminus Y_{\geq target\ year}$

Supplementary Equation 7: minimize an ecosystem service indicator (maximum value over years).

$$f(x) = max_{t \in T}\left(\sum_{k \in K}\sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)$$

Supplementary Equation S8: maximize an ecosystem service indicator (minimum value over years) in **a subgroup** of plots (e.g., maximize harvests of stands with harvest costs < 150/200 Norwegian krone).

$$f(x) = min_{t \in T}\left(\sum_{k \in K}\sum_{j=1}^{J_k} x_{kj}c^{*}_{kjt}\right)$$

$$c^{*}_{kjt} = c_{kjt} \ if \ c^{*}_{kjt} < 150/200 \ NOK\ , \qquad and \ zero \ otherwise$$

Targeting the GLOBIOM timber demands (P_{target}), and considering an assortment transfer to meet the demands was represented by the following equation.

Supplementary Equation S9: minimize the maximum difference between possible harvest and targeted timber demands: **a)** where harvests can still exceed demands, and **b)** with aiming for "exact" matching of demands as a constraint. The combination of assortments for demand matching (transfer of higher class assortment to lower classes) classes can be defined by the decision maker

a) $f(x) = max_{t \in T}\left(max\left(\sum_{j=1}^{J_k} x_{kj}c_{kjt} - P_{target,t}\right),\ max\left(P_{target,t} - \sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)\right)$

b) $f(x) = max_{t \in T}\left(max\left(\sum_{j=1}^{J_k} x_{kj}c_{kjt} - P_{target,t}\right),\ max\left(P_{target,t} - \sum_{j=1}^{J_k} x_{kj}c_{kjt}\right)\right) = 0$

Supplementary Equation S10: All objective functions are subject to the ***area constraint*** that each stand needs to be completely assigned to some management regime j:

$$\sum_{j=1}^{J_k} x_{kj} = a_j\ , \forall\ k \in K$$

Supplementary Equation S11: All functions are subject to an augmentation term that makes the optimization efficient, i.e. forcing secondarily the other objective function(s) within the multi-objective problem to be optimal:

$$\rho \sum_{t \in T} \sum_{k \in K} \sum_{j=1}^{J_k} x_{kj}c_{kjt}$$

Supplementary Equation S12: The individual objective functions were optimized by formulation of unique multi-objective optimization problems, each representing one optimization scenario (Miettinen 1999a):

$$\min_{x}\ \{f_1(x), \ldots,\ f_n(x)\}$$

$$subject\ to\ \ x \in S$$

Here $f_n(x)$ denotes the individual objective functions, x the vector of management regimes that are to be chosen in the optimization, and S is the feasible set of management regimes determined by a set of constraints.

Each objective function can be interpreted as setting targets for the relevant demands (FESB indicators, timber demands for climate mitigation). Technically this was done by implementing two approaches: 1) so-called achievement scalarizing function (ASF) of Wierzbicki (1986), which can be seen as “soft targets” or so-called reference points that are aimed to be achieved, but that will be relaxed if targets cannot be reached; 2) so called epsilon constraint method (Miettinen 1999b), which can be interpreted as set strict maximal (or minimal) levels for minimization (or maximization) objectives. Solving the multi-objective optimization problem resulted from combining the two methods.

Supplementary Equation S13: The first component of the objective is an ASF function to be optimized (Hartikainen et al. 2016), incorporating the ε-constraint method:

$$s^{asf}: f(Q) \times R^{\tau} \to R,$$

$$\left(z, z^{ref}\right) \mapsto max_{i \in \tau}\left(z_i - z_i^{ref}\right)/\left(z_i^{ideal} - z_i^{nadir}\right)$$

$$+\rho \sum_{i \in \tau} z_i/\left(z_i^{ideal} - z_i^{nadir}\right)$$

subject to:

$$f_l(x) \leq \varepsilon_l \ \forall \ l \in \tau$$

$$x \in S$$

where τ is the set of objectives assigned to the ASF function, with *f(Q)* being the feasible objective set, i.e. the set of all objective vectors that can be obtained from feasible solutions, and the elements of it being the objective vectors z. The reference points $z^{ref} \in R^{\tau}$ are provided as the aspiration levels, which are the desired values of objective functions that should be achieved. The objective vector z is in the image space of the feasible set, with z^{ideal} being the ideal vector of the problem (maximum values of objectives) and z^{nadir} being the nadir vector (minimum of individual objective) within the set of Pareto optimal solutions. The summation term at the end is a so-called augmentation term guaranteeing that the solutions are indeed Pareto optimal and not just weakly Pareto optimal, with ρ denoting an arbitrary small positive constant, e.g., the machine epsilon.

The overall complexity of multi-functional optimization scenarios required using a lexicographic approach (Miettinen 1999c) to balance among different demands and solve the optimization problem. Therefore, optimizations were done groupwise in sequential steps. The objective functions are numbered according to the order of optimization steps (**see Supplementary Table 1 – Table 4**), i.e., $g_1(x)$ is the first function(s) group by the priority of policy demands, second is the objective $g_r(x)$, and finally $g_{\#G}(x)$.

Supplementary Equation S14: The optimization consists in solving the problem according to its lexicographic ordering.

$Lex(\min x) = g_1(x), g_r(x), g_{\#G}(x), r \in \{2, \dots, \#G - 1\}$

The optimal solution of the lexicographic optimization problem is the solution of the last problem in the sequence $g_{\#G}(x)$. The optimization framework comes with a graphical user interface. This allowed setting flexibly and iteratively (sequential optimization steps) both options for the objective functions: soft reference points and hard upper/lower targets as epsilon constraints.

The new developed multi-objective optimization framework was implemented in python and defines the common optimization rules. Each country applied the same python class, which was called in study regions specific Jupyter notebooks. Within the notebooks, the optimization problems were tailored to represent the specific national scenarios. For demonstration, we uploaded the Jupyter notebook for Finland on an online repository together with a sample dataset. (https://github.com/maeehart/MultiForestDemonstration)

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