Supplementary materials for

Impacts of climate change, weather extremes and alternative strategies in managed forests

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S1. A brief description of the sub-models included in the 3PG-Heureka model

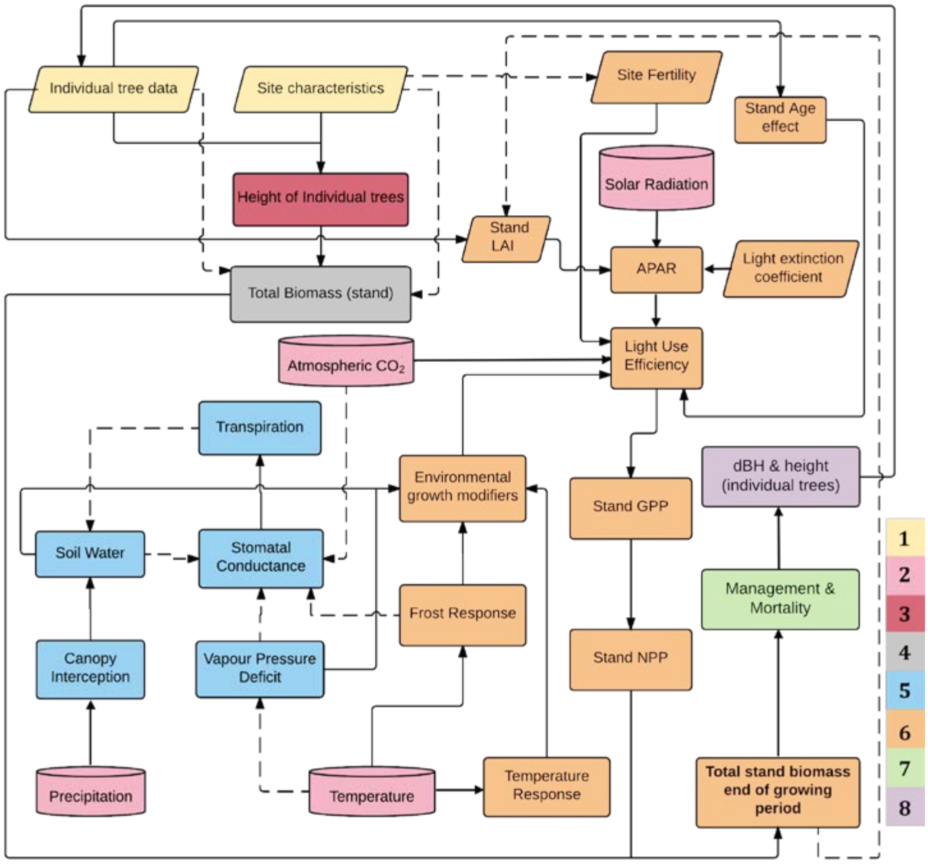

Figure S1. Schematic representation of the 3PG-Heureka model. The colours show the different model components and sub-models: (1) Initial stand and site input data, (2) Climate data, (3) Sub-model for estimating individual tree height at the start of the simulation, (4) Sub-model for estimating individual tree biomass, (5) Soil-water balance sub-model, (6) Biomass production sub-model, (7) Sub-model for estimating mortality and the impact of management activities in a plot. (8) Sub-model for estimating five-year increment of DBH and height of individual trees. Solid lines indicate direct relationship and dotted lines indicates indirect relationship.

The 3PG-Heureka model has seven major sub-models: (i) a sub-model for estimating the heights of individual trees at the start of the simulation; (ii) an individual tree biomass sub-model; (iii) a forest management sub-model; (iv) a mortality sub-model; (v) a soil-water balance sub-model; (vi) a biomass production sub-model and (vii) a sub-model for estimating five-year increment of DBH and height of individual trees (Figure S1). The first five sub-models were taken from Heureka-Regwise and the latter two were taken from 3-PG. The calculations of the 3PG-Heureka model are initially performed at stand level and then the stand level growth is re-distributed to individual trees based on their diameter (Figure S1).

S1.1. Sub-model for estimating heights of individual trees at the start of the simulation

The individual tree height sub-model is an empirical model based on data for sample trees in the 1973-1977 National Forest Inventory (NFI) plots (Söderberg 1992). Separate functions were developed for pine (*Pinus spp.*) in northern, central, and southern Sweden; for spruce (*Picea spp.*) and birch - both Downy birch (*Betula pubescens* Ehrh.) and Silver birch (*Betula pendula* Roth) will be referred as birch hereafter - in northern and southern Sweden; for European beech (*Fagus sylvatica* L.) and oak (*Quercus spp.*) in southern Sweden; and for other broadleaved species in northern and southern Sweden. The input variables of this sub-model are the diameter at Breast Height (dBH), tree age, basal area, latitude, altitude, dBH of the largest tree in the NFI plot, proportion of pine and spruce in the NFI plot, and distance from the coast (Söderberg 1992).

S1.2. Individual tree biomass sub-model

The individual tree biomass sub-model is an empirical model based on NFI data for sample trees. It incorporates several different functions. For mature trees (dBH>10cm), the total biomass of the aboveground components is calculated using Marklund’s function (Marklund 1988) while the belowground biomass is computed with the functions of Petersson and Ståhl (2006). The biomass of young trees (dBH≤ 10cm) is calculated using the functions of

Claesson (2001), which also compute the biomass of individual trees' foliage. The foliage biomass of mature Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) trees was calculated using Marklund's function (Marklund 1988), and for mature birch tree the biomass of foliage was calculated using a function developed in Finland (Repola 2008). The foliage biomass of young trees was calculated using Claesson's function (2001).

S1.3. Soil water balance sub-model

Table S1. Constant values (tex_1 and tex_2) used in the soil water modifier (SW_{mod}) calculation. The values are based on soil texture (Landsberg & Sands 2010).

Soil texture	tex_1	tex_2
Rock	0.7	9
Gravel	0.7	9
Coarse sand	0.7	9
Medium sand	0.6	7
Fine sand	0.6	7
Coarse silt	0.6	7
Fine silt	0.5	5
Clay	0.4	3

The soil water modifier (SW_{mod}) is a function of moisture ratio (M_{ratio}) and soil texture (Equation S1). The M_{ratio} or soil water balance is a function of the difference between the total monthly transpiration and total monthly precipitation (Equation S2). Total monthly transpiration was calculated using the Penman-Monteith equation, whose input variables include the fraction of incoming solar radiation incident on the canopy, the atmospheric boundary layer conductance, the density of water, and the VPD (Equation S3). The fraction of solar radiation incident on the canopy is a function of the LAI, light extinction coefficient and total incoming solar radiation (Equation S4). The stomatal conductance (Equation S5) was calculated from the VPD, maximum stomatal conductance and the CO_2 modifier of stomatal conductance (Landsberg & Waring 1997; Almeida et al. 2009; Landsberg & Sands 2010).

$$SW_{mod} = \frac{1}{\left[1 + \left(\frac{(1-M_{ratio})}{tex_1}\right)\right]^{tex_2}} \tag{S1}$$

$$M_{ratio} = \frac{[CSW + (ppt - T)]}{ASW} \tag{S2}$$

$$T = \frac{145R_n + (b * \rho * S * VPD)}{145 + \gamma(1 + (\frac{b}{cond}))} \tag{S3}$$

$$R_n = \left[\frac{(1-m-n)}{(1-m)}\right]\left[1 - e^{-k*LAI}\right] R \tag{S4}$$

$$cond = cond_{max}\left[CO_{2mod_2} * e^{-2.5(VPD)}\right] \tag{S5}$$

Where SW_{mod}= Soil water modifier; tex_1 and tex_2 are constant values based on soil texture (Table S1); M_{ratio}=Moisture ratio (Soil water balance), CSW=Current Soil Water (mm), ASW=Avaialble Soil Water (mm), T=total monthly transpiration (mm), VPD=Vapour Pressure Deficit (kPa), R=Incoming solar radiation (Million Joules m^{-2} day^{-1}), R_n=fraction of R incident on canopy, m=scattered fraction of R, n=transmitted fraction of R, k=light extinction coefficient, LAI=Leaf Area Index, , b=atmospheric boundary layer conductance, ρρ=density of water (kg m^{-3}), s=Specific heat of dry air (Joules kg^{-1} K^{-1}), γ=psychrometric constant, *Cond* =stomatal conductance (m s^{-1}), $Cond_{max}$=maximum stomatal conductance (m s^{-1}), CO_{2mod2}=CO_2 modifier affecting stomatal conductance.

S1.4. Biomass production sub-model

The Absorbed Photosynthetically Active Radiation (APAR) value for foliage was calculated using Beer's law (Equation S6) on the basis of the total incoming solar radiation, Leaf area Index (LAI), extinction coefficient of light, and fractional canopy cover (*fcc*) of the forest stand (Sands 2004). The fractional canopy cover was calculated by assuming that canopy cover increases linearly with stand age until full coverage is attained (Equation S7; Landsberg & Sands 2010). Stands were assumed to reach full canopy cover (fcc= 1) at a stand basal area of 20 m^2 ha^{-1}. The stand LAI was calculated from the biomass of foliage and the stand Specific Leaf Area (SLA; Equation S8; Subramanian 2016). The stand SLA is highest at the beginning of stand development and decreases with stand age (Bond-Lamberty et al. 2002; Weiskittel et al. 2008). The SLA also varies according to the position of the foliage in the canopy (Weiskittel et al. 2008). The SLA of Scots pine and Norway spruce trees of the same age varied with size characteristics such as height and diameter (Hager & Sterba 1985; Xiao et al. 2006). Therefore, using the tree size (mean height) as a predictor for the SLA makes it possible to explain the variation of the SLA with both stand age and canopy position (Subramanian 2016). The SLA was assumed to be constant for young stands (mean height< 8m) and old stands (mean height >20 m). For middle-aged stands (mean stand height 8m-20m), the SLA was assumed to decrease with increasing stand height (Table S2).

The Light Use Efficiency (LUE) of a forest stand is a function of its APAR and the environmental constraints on tree growth imposed by the Vapor Pressure Deficit (VPD; Pérez et al. 1994), soil water content, site productivity, stand age, atmospheric CO_2

concentration (Almeida et al. 2009), temperature response, frost response, and the canopy quantum efficiency (Landsberg & Sands 2010). These environmental constraints were implemented as growth modifiers in the LUE function (Equation S9). Details of the computation of these dimensionless environmental growth modifiers have been presented previously (Landsberg & Waring 1997; Sands & Landsberg 2002; Landsberg et al. 2005; Almeida et al. 2009; Landsberg & Sands 2010). The age modifier function was modified to better suit boreal tree species (Equation S10). The LUE calculations were performed using the lower of the VPD-modifier and the soil water-modifier because stomata close at higher VPD values (corresponding to lower values of the VPD-modifier), limiting the transpiration rate. Under such conditions, the soil water-modifier is not a limiting factor (Landsberg & Waring 1997). Similarly, when the soil water deficit is high (corresponding to lower values of the soil water modifier), the canopy conductance is strongly dependent on the soil water content. In this case, the soil water content will be the limiting factor rather than the canopy conductance (Landsberg & Waring 1997). The monthly Gross Primary Production (GPP tons ha^{-1}) was calculated from the APAR, LUE and number of days in the month (Equation S11). The biomass accumulated in a forest stand per month, which is otherwise known as the Net Primary Production (NPP tons ha^{-1}), is calculated by scaling the computed GPP value (Equation S12). These equations collectively comprise the biomass production sub-model:

$$APAR = 1 - \left[e^{\frac{-k*LAI}{fcc}} \right] fcc * R \quad \text{(S6)}$$

$$fcc_y = 0.05 * age - 0.05 \quad \text{(S7)}$$

$$LAI = 0.1 * SLA * bm_L \tag{S8}$$

$$LAU = 24(Q * F_{mod} * a_{mod} * Fr_{mod} * T_{mod} * CO_{2mod_1} * min(VPD_{mod}, SW_{mod})) \tag{S9}$$

$$a_{mod} = \frac{1}{1 + \left[\frac{\left(\frac{age}{age_{max}}\right)^{0.55}}{age_{Rel}}\right]^{n_{age}}} \tag{S10}$$

$$GPP = APAR * LUE * n_{days} \tag{S11}$$

$$NPP = GPP * 0.47 \tag{S12}$$

where APAR=Absorbed Photosynthetically Active Radiation, k=extinction coefficient of light, LAI =Leaf Area Index, R=Total incoming solar radiation (Million Joules m^{-2} day^{-1}), fcc=fractional canopy cover, fcc_y=fractional canopy cover for young stands (stand basal area less than 20 m^2 ha^{-1}). For stands with basal area more than 20 m^2 ha^{-1} fcc=1, SLA= Specific Leaf Area (m^2 kg^{-1}), bm_L=biomass of foliage (tons ha^{-1}), LUE=Light Use Efficiency,

VPD_{mod}=VPD modifier, SW_{mod}= Soil water modifier, F_{mod}=Frost modifier, Fr_{mod}=site

productivity modifier, T_{mod}=Temperature modifier, CO_{2mod1}=CO_2 modifier on LUE, Q= Canopy quantum efficiency, a_{mod}=stand age modifier, age =stand age (years), age_{max}= stand longevity (years), age_{Rel}=relative age of stand when a_{mod} is 0.5, n_{age}=strength of the response curve, GPP =Gross Primary Productivity (tons ha^{-1}), n_{days}=Number of days, NPP=Net Primary Production (tons ha^{-1}) and 0.47= respiratory constant for the stand.

Table S2. Specific Leaf Area (SLA; $m^2 kg^{-1}$) of various tree species. H_{mean}= mean height of the stand (dm).

Tree species	**SLA ($m^2 kg^{-1}$)**		
	$H_{mean} < 80$	$200 < H_{mean} < 80$	$H_{mean} > 200$
Scots pine	4.5	$-0.0067 H_{mean}+5.0333$	3.7
Norway spruce	5	$-0.01 H_{mean} +5.8$	3.8
Birch	13	$-0.01 H_{mean} +13.8$	11.8

S1.5 Management and Mortality submodel

The distribution of thinning in a sample plot is based on the proportion of the total basal area attributable to different species and size classes within the plot (Elfving & Nyström 2010). Tree mortality was modeled using a two-step approach. In the first step, the average mortality for each stand was estimated; in the second, the estimated mortality was distributed across individual trees (Fridman & Ståhl 2001). Average mortality was modeled with a logistic function whose independent variables include the basal area of larger trees, soil moisture, vegetation type and thinning history. The probability of mortality for individual trees was modeled using the tree-species specific logistic functions developed by Fridman and Ståhl (2001). The independent variables of these functions include the basal area, individual tree diameter, thinning history and mean diameter.

S2. Projected changes in the climatic variables in the study area

The average monthly values of selected climate variables such as daily maximum temperature (t_{max}, K), and daily minimum temperature (t_{min}, K) and total monthly values of precipitation (ppt, mm), frost days ($n_{frostdays}$), solar radiation (R, Wm^{-2}) and the number of vegetation days per month (n_{vdays}) predicted by each GCM were computed over 11 year periods at the beginning of simulation period (2010 – 2020), in the middle of the simulation period (2050 – 2060) and during the end of the simulation period (2090 – 2100) (Figure S2 - S7). n_{vdays} was the number of days in a month when the average temperature ≥ 5 °C. The atmospheric CO_2 concentrations for the future climate scenarios (RCP4.5 and RCP8.5) and the historic climate scenario were plotted as functions of the time in years from the start of the simulation for the entire simulated period (Figure S8).

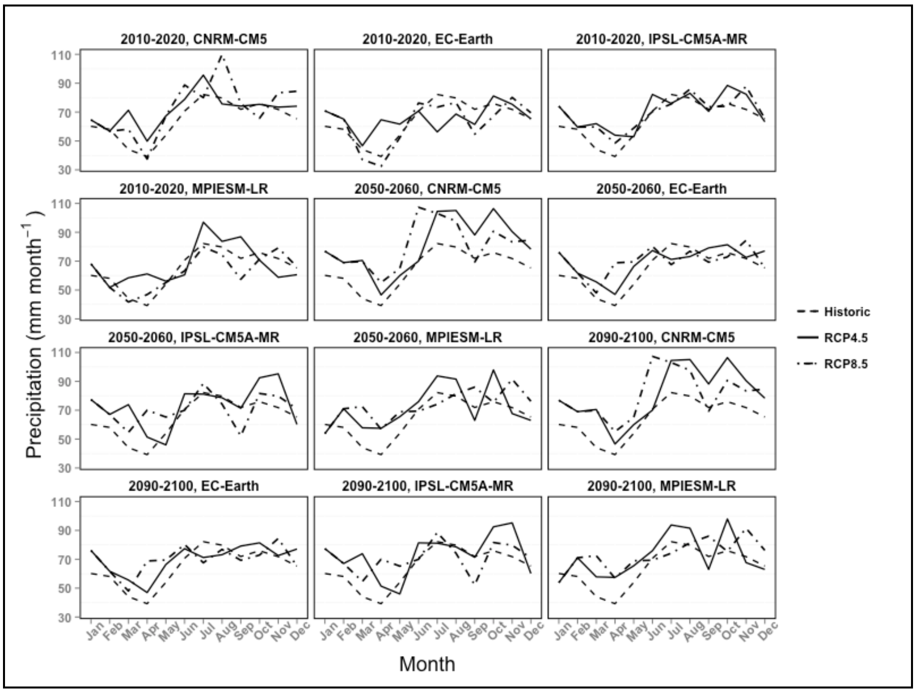

Figure S2. The 11-year averages of the total monthly precipitation (mm month^{-1}) predicted by the General Circulation Models (GCMs) CNRM-CM5, EC-Earth, IPSL-CM5A-MR and MPIESM-LR under two future climate scenarios (RCP4.5 and RCP8.5) during the early (2010-2020), middle (2050-2060), and final (2090-2100) phases of the simulation period. The 22-year average total monthly precipitation based on historic climate data (1989-2010) is also shown.

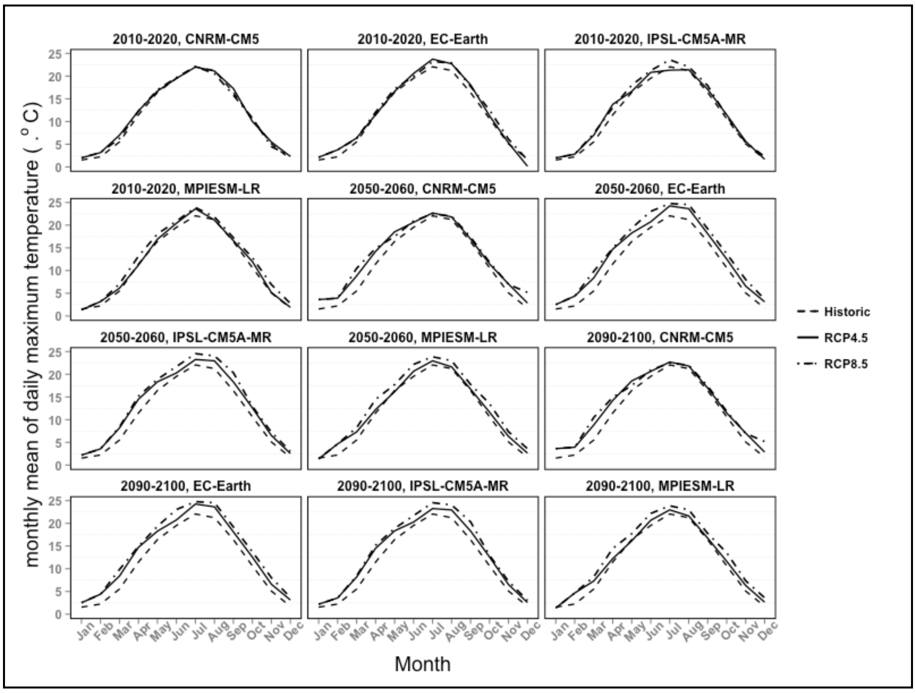

Figure S3. The 11-year averages of the monthly mean daily maximum temperature (°C) predicted by the General Circulation Models (GCMs) CNRM-CM5, EC-Earth, IPSL-CM5A-MR and MPIESM-LR under two future climate scenarios (RCP4.5 and RCP8.5) during the early (2010-2020), middle (2050-2060), and final (2090-2100) phases of the simulation period. The 22-year average of the monthly mean daily maximum temperature based on historic climate data (1989-2010) is also shown.

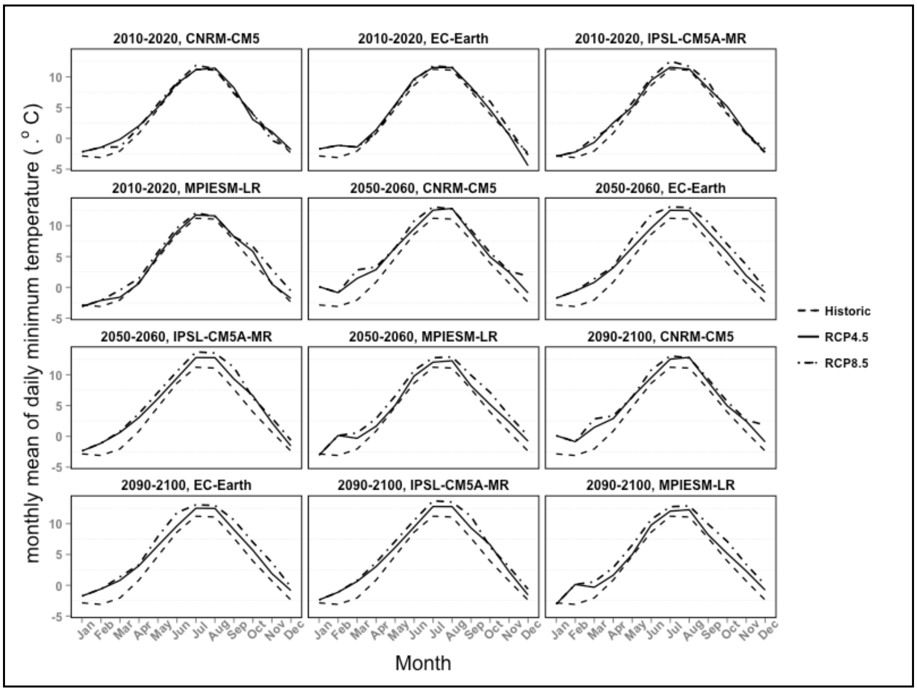

Figure S4. The 11-year averages of the monthly mean daily minimum temperature (°C) predicted by the General Circulation Models (GCMs) CNRM-CM5, EC-Earth, IPSL-CM5A-MR and MPIESM-LR under two future climate scenarios (RCP4.5 and RCP8.5) during the early (2010-2020), middle (2050-2060), and final (2090-2100) phases of the simulation period. The 22-year average of the monthly mean daily minimum temperature based on historic climate data (1989-2010) is also shown.

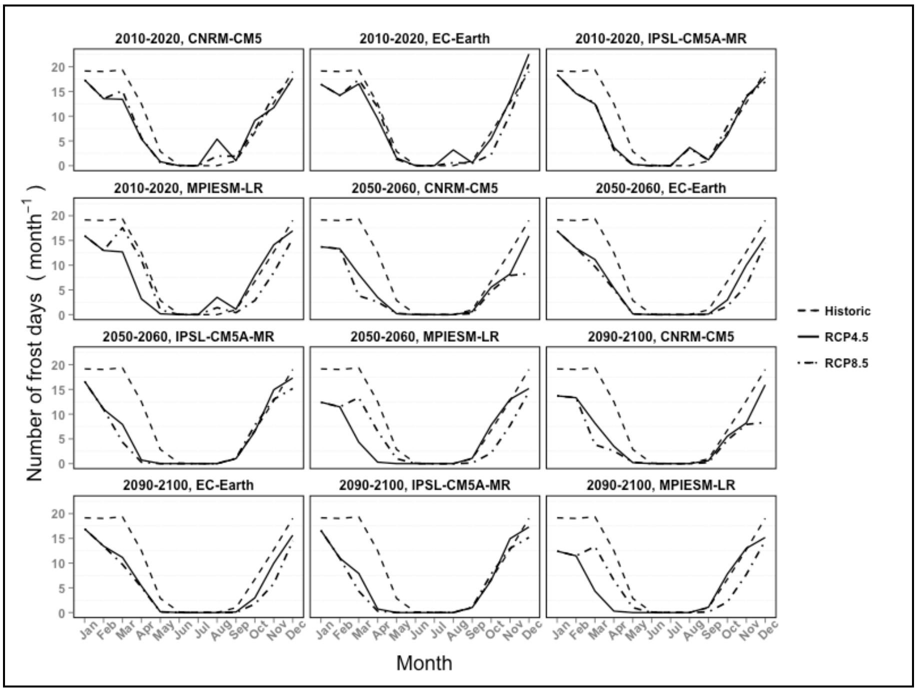

Figure S5. The 11-year average value of total number of frost days per month (month^{-1}) predicted by the General Circulation Models (GCMs) CNRM-CM5, EC-Earth, IPSL-CM5A-MR and MPIESM-LR under two future climate scenarios (RCP4.5 and RCP8.5) during the early (2010-2020), middle (2050-2060), and final (2090-2100) phases of the simulation period. The 22-year average of the total number of frost days per month based on historic climate data (1989-2010) is also shown.

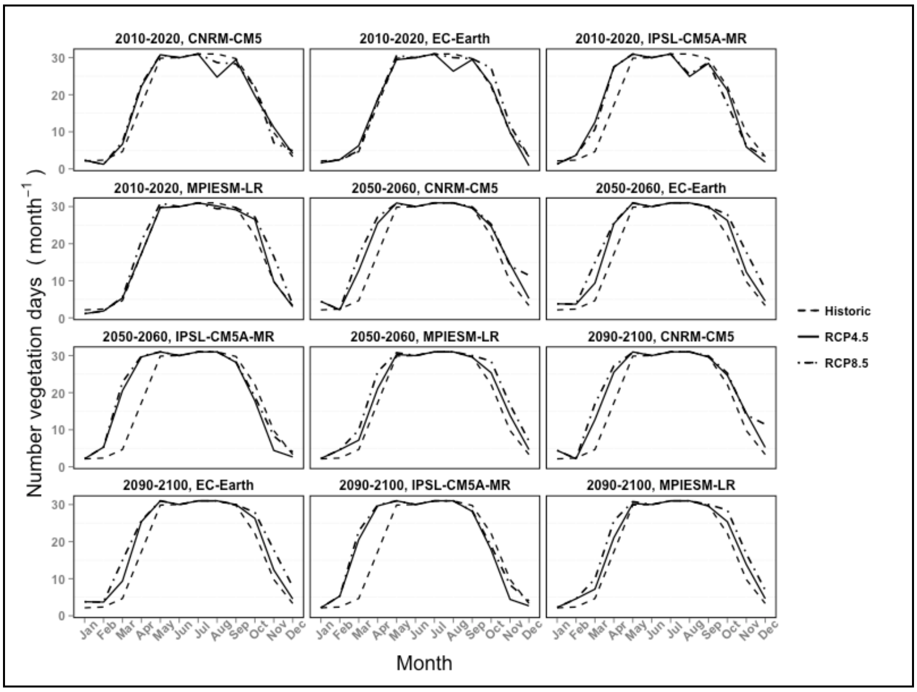

Figure S6. The 11-year average of the total number of vegetation days per month (month^{-1}) predicted by the General Circulation Models (GCMs) CNRM-CM5, EC-Earth, IPSL-CM5A-MR and MPIESM-LR under two future climate scenarios (RCP4.5 and RCP8.5) during the early (2010-2020), middle (2050-2060), and final (2090-2100) phases of the simulation period. The 22-year average of the total number of vegetation days per month (month^{-1}) based on historic climate data (1989-2010) is also shown.

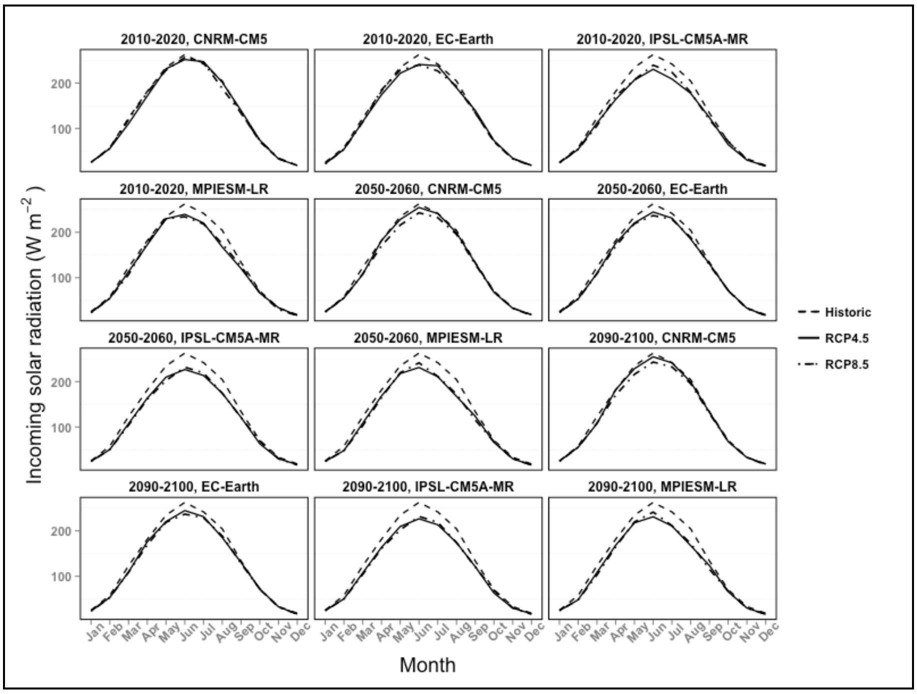

Figure S7. The 11-year average total incoming solar radiation (W m^{-2}) per month predicted by the General Circulation Models (GCMs) CNRM-CM5, EC-Earth, IPSL-CM5A-MR and MPIESM-LR under two future climate scenarios (RCP4.5 and RCP8.5) during the early (2010-2020), middle (2050-2060), and final (2090-2100) phases of the simulation period. The 22-year average of the total incoming solar radiation (W m^{-2}) per month based on historic climate data (1989-2010) is also shown.

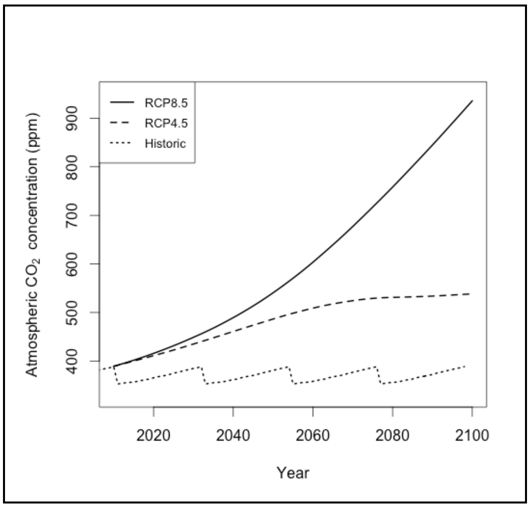

Figure S8. Atmospheric CO_2 concentrations (ppm) for the future climate scenarios (RCP4.5 and RCP8.5) and the historic climate scenario over the complete simulation period.

S3. Calculation of whole tree biomass and foliage biomass of individual trees in 3PG-Heureka model

The biomass of individual trees (g $tree^{-1}$) were estimated using the individual tree biomass sub-model. Separate functions were available for calculating the biomass of mature trees (dBH>10cm) and young trees (dBH≤10cm). For mature Scots pine and Norway spruce trees, the biomass of the whole tree was estimated directly using Marklund's function, which depends on the dBH, d_5, tree age, and site co-ordinates (Marklund 1988). For mature birch trees the biomasses of tree components such as the stem (including the bark), foliage (including the branches) and stump (including the roots) were estimated separately.

The biomass of aboveground components (stem including bark and foliage including branches) was computed with Marklund's function (1988). In addition, the biomass of stumps including roots was computed for mature birch trees (Petersson & Ståhl 2006). The whole tree biomass of individual birch trees was then calculated by summing the computed biomasses of their separate components (Equation S13). Biomass values for other broadleaf tree species were computed using the birch biomass functions.

$$bm = bm_s + bm_f + bm_r \qquad \text{(S13)}$$

where bm =whole tree biomass (g $tree^{-1}$), bm_s= biomass of stem including bark (g $tree^{-1}$), bm_f=biomass of foliage including branches (g $tree^{-1}$) and bm_r=biomass of stump including roots (g $tree^{-1}$).

The biomass of the aboveground components (stem including bark and foliage including branches) of individual young trees (dBH≤10cm) was calculated using Claesson's function (2001); the biomass of below ground components (stump including roots) was calculated separately (Petersson & Ståhl 2006). The whole tree biomass of young trees was then computed by combining the computed biomasses of the individual components (Equation S13). Suitable functions for young trees were only available for Norway spruce, Scots pine and birch trees; the biomass of young broadleaved trees belonging to other species was computed using the birch functions.

In addition to the whole tree biomass, the biomass of foliage (g tree^{-1}) was also calculated for all of the individual tree species (Figure 2). For mature Norway spruce and Scots pine trees (dBH>10cm), the foliage biomass was calculated using Marklund's function (Marklund 1988). The foliage biomass of mature birch trees was calculated using biomass functions developed in Finland (Repola 2008). Foliage biomass values for all young trees (dBH≤10cm) were calculated using Claesson's biomass function (2001).

S4. Estimation of stand level foliage biomass from stand level whole tree biomass

The stand level foliage biomass was estimated from the stand level whole tree biomass (tons ha^{-1}) and stand age using a linear regression function (Equation S14; Table S3). Ideally, this variable should be updated monthly with the NPP. However, doing this would make the model very computationally expensive when performing landscape-level simulations covering long periods of time. Therefore the foliage biomass was only updated on a yearly basis in the simulations (Figure 2). Species-specific functions were used for Norway spruce, Scots pine and birch trees, and the birch functions were used for all other broadleaved trees. Previous study on phenology of birch clones has shown that the bud burst occurs by the beginning of April (111th day) and leaf shedding occurs by the end of September (281st day) in Sweden (Stener 1996). Therefore in this study the growing season was assumed to start from April and lasts until end of September for the whole simulation period. The calculations were performed using data for the permanent sample plots from the NFI 2008 – 2012 dataset. To minimize error when updating foliage biomass and LAI values on the basis of calculated whole tree biomass values, the LAI pattern was established at the start of each simulated year (LAI_{start}) from the whole tree biomass at the start of the simulated year (Equation S14). Then at the end of each year the LAI pattern is again calculated (LAI_{end}) using the updated whole tree biomass data (Equation S14). The change in the LAI over that year (LAI_{dev}) was then computed by subtracting LAI_{start} from LAI_{end}, and LAI_{dev} was added to the stand's initial LAI (Equation S8). This updated LAI was then used in the biomass sub-model when performing the simulation for the next year.

$$bm_L = a + b(bm_{total}) + c(age) \tag{S14}$$

where bm_L=foliage biomass (tons ha^{-1}), bm_{total}=stand level whole tree biomass (tons ha^{-1}) and age= mean age of the stand (years).

The LAI is a key input factor for the 3PG-Heureka model. It was calculated from the stand level foliage biomass (tons ha^{-1}), but because the current version of 3PG-Heureka does not include an allocation function, it was not possible to update the foliage biomass in 3PG-Heureka simulations. To circumvent this problem, the stand level foliage biomass was estimated from the whole tree biomass (tons ha^{-1}) and the stand age using an empirical function. The error component arising from estimating the foliage biomass from the whole tree biomass on a monthly basis will be much larger than would be the case for a model simulating NPP with the same foliage biomass and LAI for a whole year. This is because the former approach represents a fairly rough approximation; it would have been better if tree height or site productivity could be included in the foliage biomass function because the foliage biomass of a tree of a given age depends on the site productivity and the tree's height.

Table S3. Input variables for calculating the stand foliage biomass (tons ha^{-1}) for Scots pine, Norway spruce and birch from the whole tree biomass of the stand (bm_{total}; tons ha^{-1}) using the hybrid model.

Coefficient	**Scots Pine**		**Norway Spruce**		**Birch**	
	Value	SE	Value	SE	Value	SE
Intercept	6.9537048	0.37955	24.0104805	0.7356246	0.004822	0.01617
bm_{total}	0.0403258	0.000066	0.1183384	0.0004613	0.009546	0.00006064
age	-0.0939934	0.005268	-0.5997185	0.0166292	0.0003225	0.0003005

S5. Calculation of stand level basal area from stand level whole tree biomass

Table S4. Input variables for calculating the stand level basal area (m^2 ha^{-1}) for Scots pine, Norway spruce and birch from the stand level whole tree biomass (bm_{total}; tons ha^{-1}), stand density (N; ha^{-1}) and mean stand age (age; years).

Coefficient	**Scots Pine**		**Norway Spruce**		**Birch**	
	Value	***SE***	***Value***	***SE***	***Value***	***SE***
Intercept	-0.94979	0.043028	-1.56201	0.053868	-1.67678	0.071865
$ln(bm_{total})$	0.933516	0.003777	0.887078	0.004851	0.886645	0.005437
ln(N)	0.085461	0.004771	0.130195	0.007296	0.123355	0.008436
ln(age)	-0.196493	0.008681	-0.158299	0.010268	-0.085962	0.015278

A linear function for estimating the stand level basal area from the stand biomass was developed using data for the permanent NFI sample plots from the NFI 2008 – 2012 dataset (Equation S15; Table S4). This function enables to transfer data between 3-PG model and Heureka model in the hybrid model 3PG-Heureka. The input variables of this function include (in addition to the stand biomass) the stand density and stand mean age. Separate functions were developed for Scots pine, Norway spruce and birch stands, and the birch function was used for all other broadleaved species.

$$ln(BA) = a + b[ln(bm_{total})] + c[ln(N)] + d[ln(age)] \qquad \text{(S15)}$$

where BA=stand level basal area (m^2 ha^{-1}), bm_{total}=stand level whole tree biomass (tons ha^{-1}), N= stand density (ha^{-1}) and age= mean age of the stand (years).

S6. Parameterization of the site productivity modifier

Table S5. The different ground vegetation types and the corresponding scaled index values (S_{veg}) used when computing site productivity function (Elfving & Nyström 2010)

Type of ground vegetation	Scaled index value (S_{veg})
Poor shrubs	-5
High sedge (*Carex spp)*	-3
Low sedge	-3
Crowberry	-3
Lichen (dominating)	-1
Lingonberry	-0.5
Lichen (not dominating)	-0.5
Bilberry	0
Horsetail grass (*Equisetum spp*)	1
Thinleaved grass	1.5
Rich herbs with Lingonberry	2
Low herbs with lingonberry	2
Rich herbs with shrubs	2.5
Low herbs with bilberry	2.5
Broadleaved grass	2.5
Low herbs without shrub	3
No field vegetation	3
Rich herbs without shrub	4

The site productivity modifier (Fr_{mod}) was estimated based on the site's ground vegetation type, which is known to be an indicator of site fertility (Hagglund & Lundmark 1977). Scaled index factors reflecting site fertility were assigned to each ground vegetation type (Table S5), ranging from -5 (low fertility) to 4 (high fertility; Elfving & Nyström 2010). These scaled vegetation type index values (S_{veg}) were used in the site productivity modifier function. The initial stand and site characteristics used for model parameterization were obtained from the NFI 2008 - 2012 dataset. The Heureka-Regwise model was used to simulate the evolution of stand-level whole tree biomass in all 657 permanent sample plots in Kronoberg county over the 22-year period between 1989 and 2010; this was taken as the baseline simulation. Then, the stand level whole tree biomass for the same time period and NFI plots was simulated using the 3PG-Heureka hybrid model in conjunction with historic climate data (1989 – 2010). Mean whole tree biomass values were computed for each ground vegetation type index value, after which the percentage residual of the whole tree biomass was calculated and plotted against the vegetation type index. Simulations with the 3PG-Heureka model were performed with different values of the coefficient for the site productivity modifier function until the model's output was sufficiently similar to that of the Heureka-Regwise model. Once the variation in the residual plot had been minimized in this way, the coefficients of the Fr_{mod} function were fixed (Figure S2). Thus the site productivity was computed using a polynomial function of the vegetation type index (Equation S16; Table S6).

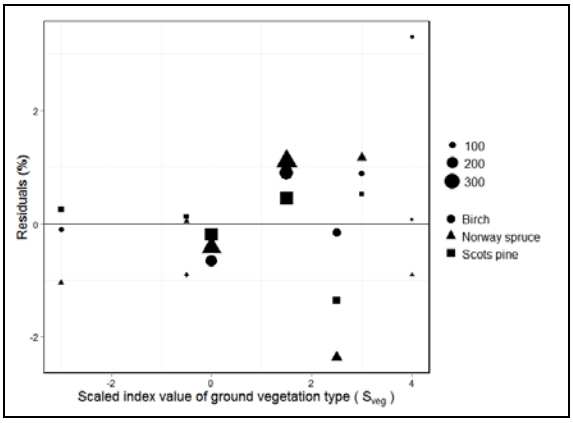

Figure S9. Residuals in the mean whole tree biomass (tons ha^{-1}) values predicted for Scots pine, Norway spruce and birch with the 3PG-Heureka hybrid model relative to the baseline Heureka-Regwise model. The residual values are plotted against the scaled ground vegetation type index (S_{veg}); the number of observations for each value of S_{veg} is indicated by the size of the dots.

$$Fr_{mod} = a + bx + cx^2 \qquad \text{(S16)}$$

where Fr_{mod}= site productivity modifier parameter and x= scaled ground vegetation type index value (S_{veg}; Table S5).

Table S6. Coefficients used in the calculation of the site productivity modifier function.

Coefficient	Scots pine	Norway spruce	Birch
a	0.38	0.53	0.37
b	0.036	0.0528	0.0013
c	0.0013	0.0032	0.004

The residuals (%) in the predicted mean whole tree biomass (tons ha^{-1}) for the 3PG-Heureka hybrid model relative to the baseline scenario simulated using the Heureka-Regwise model was plotted as a function of the scaled ground vegetation type index (S_{veg}). The residuals of the mean whole tree biomass (tons ha^{-1}) varied appreciably with both the vegetation type index and the tree type (Figure S2). Most of the stands had scaled ground vegetation type index values (S_{veg}) of 0-3 (Table S5). The 3PG-Heureka model slightly underestimated the whole tree biomass of all the tree species at intermediately fertile sites (S_{veg}= 1.5) and fertile sites (S_{veg}= 3), and moderately overestimated the whole tree biomass of Scots pine and birch at intermediately fertile sites (S_{veg} = 0). In addition it moderately overestimated the whole tree biomass of Norway spruce in less fertile sites (S_{veg}= 0) and highly fertile sites (S_{veg} = 4). The whole tree biomass of Norway spruce and Scots pine at fertile sites (S_{veg} = 2.5) was strongly overestimated, while that of birch trees at highly fertile sites (S_{veg} = 4) was strongly underestimated. However, the dataset included very few low fertile (S_{veg}=-3) and high fertile sites (S_{veg} = 4).

In the 3-PG model, site productivity is accounted for using a linear function of the site fertility index. The growth modifier is a decimal number varying from 0 (low productivity) to 1 (high productivity), and its value was estimated when the model was being parameterized using field data. This approach works well for a stand level model such as 3-PG. However, linear site fertility functions are less suitable for landscape level models such as 3PG-Heureka because of the high variability of the stand and site conditions in the input datasets that must be used in the parameterization of such models.

The productivity of a forest stand can be estimated from the type of ground vegetation present on the forest floor (Hagglund & Lundmark 1977). The NFI dataset used in the hybrid model's development included information on sites of widely varying productivity (very low to very high), soil moisture (dry to wet), and stand age (0 to 180 years). It should be noted that while the ground vegetation type is a useful indicator of site productivity, fertility depends on a number of physicochemical factors such as the soil moisture and texture, the thickness of the humus layer, the soil depth, and soil drainage (Hagglund & Lundmark 1977). However, for the sake of simplicity, a single function based on the ground vegetation type was developed to account for variation in site productivity for individual tree species. While this approach may be less accurate than one that accounts for other site variables, it eliminates the need for detailed calculations that could have made it difficult to calibrate the site productivity function and incorporate it into the model. Moreover this approach also reduces the risk of model over-parameterization.

S7. Evaluation of the 3PG-Heureka hybrid model

The predictive capacity of the 3PG-Heureka model was evaluated by comparing the predicted values of age-dependent stand variables from 3PG-Heureka simulations to the output of baseline simulations performed with the Heureka-Regwise model. The age-dependent stand variables considered for this purpose were the basal area (m^2 ha^{-1}), basal area weighed stand height (m), stand density (ha^{-1}) and standing volume (m^3 ha^{-1}) for the time period 1989 – 2010. The deviation of the 3PG-Heureka model's predictions for these variables from the predictions of the baseline simulation was computed, expressed as residual percentage, and plotted as a function of the stand age class to analyze the hybrid model's predictive capacity and behavior. Negative error values for a given stand variable indicate that the 3PG-Heureka model overestimates that variable relative to the baseline simulation, and positive error values indicate that the hybrid model underestimates the corresponding stand variable.

The 3PG-Heureka model's predictions for stand variables such as the mean whole tree biomass (tons ha^{-1}), mean stand basal area (m^2 ha^{-1}), mean basal area weighed height (m) and mean stand density (ha^{-1}) were compared to those predicted in the baseline Heureka-Regwise simulation by plotting the residuals (%) for each such variable as functions of the stand age class (Figure S3). There were 9 age classes in total, each spanning a range of 20 years, with the oldest stands in the dataset being around 180 years old. Most of the simulated stands were in the 21-40, 41-60 and 61-80 age classes.

The 3PG-Heureka model overestimated the mean whole tree biomass of young stands in the 0-20 years age class and underestimated the mean whole tree biomass for middle aged stands, i.e. those in the 41-60 age classes (Figure S3). The highest relative residual among the whole tree biomass values predicted by the 3PG-Heureka model occurred for Scots pine (-10.2%), Norway spruce (-19.8%) and birch (-6.3%) in the 0-20 age class. The average residual in the whole tree biomass predicted by the 3PG-Heureka model over the entire simulation period was -1.13% for Scots pine, -0.02% for Norway spruce and -0.67% for birch (Table S7). A similar distribution of residuals was observed for the mean stand basal area (Figure S3; Table S7). The mean basal area weighed height was estimated satisfactorily overall, with relative errors below 7.5% for all age classes (Figure S3).

However, the hybrid model underestimated the mean basal area weighed height of young stands (age class 0-20) and middle-aged stands (age class 41-60) for all tree species. No significant error was found in mean stand density predictions by the model (Figure S3).

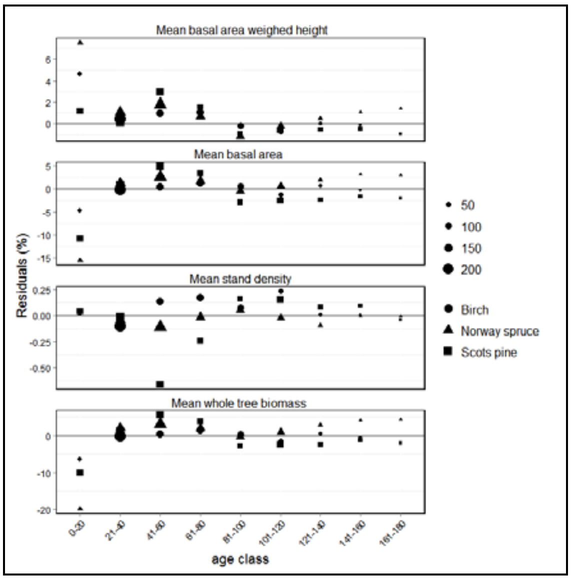

Figure S10. Comparison of the mean basal area weighed height (m), mean stand basal area (m^2 ha^{-1}), mean stand density (ha^{-1}) and mean whole tree biomass (tons ha^{-1}) for Scots pine, Norway spruce and birch as predicted by the 3PG-Heureka hybrid model and the baseline Heureka-Regwise model during the period 1989-2010. The residuals (%) were plotted against the age class. The number of observations in each age class is indicated by the size of the dots.

Table S7 Comparison of age-dependent stand variables such as whole tree biomass, mean stand basal area, mean stand density, mean basal area weighed height and mean standing volume predicted by 3PG-Heureka model and the baseline Heureka-Regwise simulation.

	Range of residuals (%)	**Average residual value for the whole simulation period (%)**
Mean whole tree biomass (tons ha^{-1})		
Scots pine	-10.1 – 5.6	-1.13
Norway spruce	-19.8 – 4.4	-0.02
Birch	-6.3 – 1.5	-0.67
Mean stand basal area (m^2 ha^{-1})		
Scots pine	-10.9 – 4.8	-1.52
Norway spruce	-15.7 – 3.2	-0.20
Birch	-4.2 – 1.3	-0.44
Mean stand density (ha^{-1})		

Scots pine	-0.7 – 0.2	-0.05
Norway spruce	-0.1 - 0.05	-0.02
Birch	-0.1 - 0.2	0.07
Mean basal area weighed height (m)		
Scots pine	-0.9 - 3.0	0.27
Norway spruce	-1.2 - 7.5	1.40
Birch	-0.7- 4.6	0.76

S8. Planting and Pre-Commercial thinning settings used in different management regimes.

S8.1 Business As Usual management regime (BAU)

In BAU regime Norway spruce was extensively regenerated in Kronoberg county (Table S10). Birch was considered as the secondary species and was naturally regenerated in stands dominated by Norway spruce or Scots pine. Five percent of all stands with low site index values were regenerated with Scots pine seedlings. Wet sites with sub-soil water depth less than 1 m are predominantly naturally regenerated by seed tree retention but in all other cases regeneration is achieved by planting. The planting density in such cases was dictated by the site index (Equation S17; Table S7). Genetically improved Norway spruce and Scots pine seedlings were used for planting. The choice of species for regeneration was based on the dominant species during the second generation. Scots Pine-dominated stands were regenerated with 95% Scots pine and 5% Birch, Norway spruce-dominated stands were regenerated with 95% Norway spruce and 5% Birch, and Birch dominated stands were regenerated exclusively with Birch seedlings. Scarification was performed one year after the last final felling and regeneration was performed within two years of the last final felling.

Pre-Commercial thinning (PCT) was done in all stands and the target stem density after PCT was determined by the site index (Equation 2). The maximum permissible stem density after PCT was set to 2800 ha^{-1}. PCT was allowed for stands with mean stand heights of 2 - 10 m. Regeneration species were prioritized during PCT as future crops; second priority was assigned to broadleaved species. Commercial thinning was allowed for stands with dominant heights of 8 - 25 m. Strip roads of width 4 m were established and the distance between adjacent strip roads was set to 22 m. The thinning grade was between 20 and 45%. In general, two thinnings were imposed for Norway spruce, Scots pine and Birch stands before final felling. Stands dominated by Norway spruce were thinned for biofuel extraction from the point that their mean stand height exceeded 15 m until they reached 60 years of age. A clear felling system was implemented for final felling in most of the stands. Under the seed tree retention system, a minimum basal area of 2 m^2 ha^{-1} was retained in the stand during final felling to serve as seed trees. Seed trees were removed within five years of final felling. Fertilization with 150 kg ha^{-1} Ammonium Nitrate was allowed if the site index was between 15-32 m, its proportion of conifers was above 70%, and its current annual increment was below 12 m^3 ha^{-1}. Fertilization was done once in 10 years.

$$pd = a(SI) + b \tag{S17}$$

$$st_{pct} = c + d(SI) \tag{S18}$$

where *pd* = planting density, st_{pct}= target stem density after pre-commercial thinning; a, b, c and d are constants and SI is the site index value (m). Values for a, b, c, and d are given in Table S8.

Table S8. Input parameters for estimating planting density and target stem density after Pre-Commercial thinning under the management regime Business as usual (BAU). Birch was the secondary species in conifer dominated stands and therefore naturally regenerated.

Coefficients	Scots pine	Norway spruce	Birch
a	85	65	
b	650	425	
c	600	400	1200
d	80	70	25

Table S9. Cost of various management activities implemented in 3PG-Heureka model. SEK= Swedish Kronor.

Mangement activity	Cost in SEK
Regeneration	2.5 seedling^{-1}
Soil preparation	1000 ha^{-1}
Pre-Commercial thinning	2500 ha^{-1}
Fertilization	1250 ha^{-1}
Thinning	99 m^{-3}
Final felling	89 m^{-3}

Fixed costs were used to calculate the cost of various management activities for the whole simulation period in BAU regime (Table S9). For calculation of economic returns from the landscape the timber prices were obtained from forest owners association Mellanskog (Mellanskog 2016). Timber prices from the year 2013 were used in this study. The price for sawn timber was ranging from 300 - 700 SEK m^{-3} and 300 - 625 SEK m^{-3} respectively for Scots pine and Norway spruce. The price varied according to the quality and diameter of the timber. There were four and two quality classes for Scots pine and Norway spruce respectively; and 13 diameter classes for all the timbers. Price for pulpwood was 250, 265 and 310 SEK ton^{-1} respectively for Scots pine, Norway spruce and birch. Harvest residues were sold at a price of 380 SEK ton^{-1}.

S8.2 Promoting Alternative tree Species regime

In the PAS scenario, all the dry sites and a majority of the sites with low site index values (SI < T26) were regenerated with Scots pine seedlings after final felling of the existing stands (Table S10), while moist and fertile sites (SI > T26) were regenerated equally with Scots pine and Norway spruce seedlings. Wet sites with depth of sub-soil water table < 1 m were regenerated by natural regeneration while all other sites were regenerated by planting. The planting density was determined by the site index (Equation S17).

Table S10. Regeneration settings used in the 3PG-Heureka model. The values indicate the percentage of NFI plots regenerated with that particular species. SI= Site Index (dominant height of the stand at an age of 100 years). The letter in the site index indicates the site index species (T= Scots pine) and the number shows the height the stand attains at an age of 100 years. BAU= Business as usual scenario and PAS= Promoting alternative species scenario. The regeneration settings used in the management regimes Business as usual + Storm (BAU+Storm) and Shorter rotation length (SR) were similar to those for the BAU scenario.

	Dry sites		**SI (<T22)**		**SI (T22-T26)**		**SI (>T26)**		**Moist sites**	
	BAU	*PAS*	*BAU*	*PAS*	*BAU*	*PAS*	*BAU*	*PAS*	*BAU*	*PAS*
Scots pine	0	100	5	95	5	95	1	50	0	50
Norway spruce	96	0	94	5	94	5	98	50	100	50
Birch	4	0	1	0	1	0	1	0	0	0

S8.3 The shorter rotation length scenario

In this scenario the final felled stands were regenerated by planting genetically improved seedlings, and the seedling density was based on the site index (Equation

S17). Pre-Commercial thinning (PCT) was performed in all stands and the target stem density after PCT was determined by the site index (Equation S18). The PCT in this scenario was more intense than under the other simulated management regimes: the maximum stem density after PCT was set to 1500 stems ha^{-1} and PCT was allowed for stands with mean heights of 2-10 m. Commercial thinning was not performed, so clear felling was performed at an earlier stage.

S9. Estimation of storm damage in 3PG-Heureka model

The calculation of damage caused by storm events was based on its wind load. The concept of wind load was used to distribute the damage caused by storm events to different NFI plots in the landscape based on direction of the storm and maximum wind speed (Lagergren et al. 2012). The yearly wind load was calculated for Kronoberg county from maximum recorded wind speed during each storm event (Lagergren et al. 2012). In this study same wind load was used for all the NFI plots during a storm event.

Apart from wind load the storm-felled volume also depends on the state of the forest at the time of the storm (Lagergren et al. 2012; Eriksson et al. 2015). The state of the forest landscape depends on its exposure index (EI), height index (HI), root stability index (RSI), frozen soil index (FSI) of each NFI plots; height index (*hi*) and allometric relationship index (*ai*) of tree individuals within a NFI plot (Lagergren et al. 2012). The EI depends on forest fragmentation and average patch size of stands. HI depends on average basal area weighed height of a NFI plot and average basal area weighed height for the whole landscape (Lagergren et al. 2012). RSI was calculated from the difference in fine root biomass before and after thinning and the time since last thinning activity in each NFI plots (Lagergren et al. 2012). *hi* was calculated from the average basal area weighed height of the NFI plot and height of individual trees within plot. The *ai* was calculated using height (*h*), dBH (*d*) of individual trees and a specific coefficient value for each tree species (Equation S19; Lagergren et al. 2012). If $h < 5$ m or $d \leq 12$ cm for a particular tree individual in a plot then that particular tree withstand the storm (Lagergren et al. 2012). The total storm sensitivity index of a NFI plot (SI) was calculated (Equation S20). The proportion of storm-felled trees in a NFI plot (P_p) after each storm event was calculated from SI, wind load and FSI (Equation S21; Lagergren et al. 2012). The total storm-felled volume in a NFI plot was calculated from P_p.

$$ai_{pi} = \left[\frac{(h_{pi} - 5)}{(d_{pi} - 12)}\right] k_{pi} \tag{S19}$$

$$SI_p = EI_p * HI_p * RSI_p * hi_{pi} * ai_{pi} \tag{S20}$$

$$P_p = SI_p * FSI_p * WL \tag{S21}$$

Where $_p$= index value for NFI plot, $_i$= index value for tree individuals within a NFI plot *p*, *ai*= allometric index of tree individual in NFI plot, h= height of individual trees, d=dBH of individual trees, *k*= coefficient value for each tree species (k= 0.85, 1.7 and 0.17 for pine spruce and broadleaves respectively), SI= Storm sensitivity index of individual trees in a NFI plot, EI= exposure index of NFI plot, HI=Height index of NFI plot, RSI= Root stability index of NFI plot, *hi*= height index of individual trees within a NFI plot, P_p= Proportion of storm-felled trees in a NFI plot after each storm event, WL= yearly wind load and FSI_p= frozen soil index of NFI plot, FSI_p= 1 if the soil was not frozen during storm event.

For each storm, the wind load factor was tuned so that the model predicted the amount of storm-felled volume as had been recorded. For Kronoberg, this resulted in nine storms with different wind-load factors for the period 1948-2013. The storm during year 55 was the strongest (wind load =2.58) and that during year number 10 was the weakest (wind load= 0.04). If the storm felling in a stand exceeded 35% after a storm event, that stand was final felled. If the extent of storm felling was below 35%, only the storm-felled proportion was extracted during thinning. Around 8% of the storm-felled trees were left in the stand as deadwood. The storm-felled volume in future storms depended partly on the wind-load calculated from historic storms and partly from the forest-state at the time when future storms occurred.

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