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Quantifying climate change effects on future forest biomass availability using yield tables improved by mechanistic scaling

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Abstract

Forests and wood products play a major role in climate change mitigation strategies and the transition from a fossil-based economy to a circular bioeconomy. Accurate estimates of future forest productivity are crucial to predict the carbon sequestration and wood provision potential of forests. Since long, forest managers have used empirical yield tables as a cost-effective and reliable way to predict forest growth. However, recent climate change-induced growth shifts raised doubts about the long-term validity of these yield tables. In this study, we propose a methodology to improve available yield tables of 11 tree species in the Netherlands and Flanders, Belgium. The methodology uses scaling functions derived from climate-sensitive process-based modelling (PBM) that reflect state-of-the-art projections of future growth trends. Combining PBM and stand information from the empirical yield tables for the region of Flanders, we found that for the period 1987 – 2016 stand productivity has on average increased by 13% compared to 1961 – 1990. Furthermore, simulations indicate that this positive growth trend is most likely to persist in the coming decades, for all considered species, climate or site conditions. Nonetheless, results showed that local site variability is equally important to consider as the in- or exclusion of the CO_2 fertilization effect or different climate projections, when assessing the magnitude of forests' response to climate change.

Our projections suggest that incorporating these climate change-related productivity changes lead to a 7% increase in standing stock and a 22% increase in sustainably potentially harvestable woody biomass by 2050. The proposed methodology and resulting estimates of climate-sensitive projections of future woody biomass stocks will facilitate the further incorporation of forests and their products in global and regional strategies for the transition to a climate-smart circular bioeconomy.

Keywords:

Climate change, forest production, process-based modelling, bioeconomy, sustainable resource management, transfer function

1 INTRODUCTION

Ambitious reduction of greenhouse gas (GHG)-emissions is necessary to limit global warming to 2°C by 2050, in compliance with the Paris Agreement (United Nations, 2015; Rogelj et al., 2016; Roe et al., 2019). The forestry sector plays a vital role in the resulting climate change mitigation strategies (Nabuurs et al., 2017; Rockström et al., 2017; Verkerk et al., 2020). The sector can increase carbon sequestration through afforestation, increasing standing stock in existing forests (Bastin et al., 2019) and carbon storage in long-living wood products (Churkina et al., 2020). Moreover, wood products contribute to reducing industrial carbon emissions by replacing more GHG-intensive products, i.e. the so-called substitution effect (Brunet-Navarro et al., 2021). Finding a balance between the use of wood products, to benefit from the substitution effect, and the carbon sequestration potential of forests is crucial for effective climate change mitigation (Schulze et al., 2020). In that regard, accurate regional monitoring and prediction of biomass availability are necessary to ensure that wood does not exceed forest growth. Current projections of future forest biomass availability and growth are based on empirical growth tables, extrapolation of observed growth trends from national forest inventories, or process-based models (PBMs) (Barreiro et al., 2016; Law et al., 2018; Verkerk et al., 2019). Although these methods can give a good indication of either current biomass availability or future growth trends, they fail to make accurate projections on future biomass availability under changing environmental conditions (Pretzsch et al., 2014).

Empirical growth tables are derived from statistical correlations between measurements of tree species-specific growth and site conditions. While this leads to accurate growth predictions under the observed conditions, they lose accuracy when extrapolated to different environments (Fontes et al., 2010; Pretzsch et al., 2014). PBMs can better meet this challenge by describing the underlying mechanisms of forest growth. They are therefore often used to evaluate the effect of changing environmental conditions on forest growth. However, these models require a large amount of information for initialization and parametrization. Furthermore, they often lack accuracy due to simplifications made to restrict their complexity or to limited knowledge of the processes involved (Fontes et al., 2010; Adams et al., 2013). Therefore, PBMs have been extensively used to predict *relative* future growth trends, but are rarely used to quantify *absolute* future biomass availability (Reyer et al., 2014).

Recent studies show the benefits of combining empirical growth tables and PBMs into hybrid models. These hybrid models intend to exploit the strengths of the empirical models; i.e. predictive ability and parsimony in the calibration data; and the PBMs, i.e. sensitivity to changing environmental conditions, in a unified hybrid modelling approach (Fontes et al., 2010). Examples of such a hybrid model approaches are the combination of the empirical model EFISCEN (Schelhaas et al. 2007) with different PBMs to account for stemwood volume changes Nabuurs et al. (2002) or the more recent study using the PBM 4C (Lasch-Born et al., 2020) by Schelhaas et al. (2015), which illustrated the benefits of this hybrid approach to evaluate future biomass stocks and different management strategies in Europe. Our study builds further on this methodology by considering a larger set of site conditions, tree species and climate projections to evaluate the effect of climate change on stand mean annual increment, rather than net primary production (NPP) changes, which is particularly relevant for wood availability studies. Similar to the methodology of Matala et al. (2005), we define transfer functions (further referred to as scaling functions), based on growth changes departing from growth in the past, as simulated with a PBM, and incorporate them in existing empirical yield tables, to make the latter climate-sensitive. Furthermore, we consider regional differences in forest growth changes, based on variability in climatic and soil conditions using a case study for the region of Flanders (Belgium). By accounting for these local differences, we address the scale discrepancy between climate change studies, which are often global or regional, and climate change mitigation policy implementation, which is often performed on more local scales. The specific objectives of this study were to (i) evaluate the effect of regional differences in soil and climate on forest growth responses under climate change, (ii) develop a methodology to make climate-sensitive, spatially explicit predictions of future forest biomass growth by scaling existing yield tables with trend information supplied by process-based modelling, and (iii) illustrate the effect of climate change-induced growth changes on future biomass availability in Flanders.

2 MATERIALS AND METHODS

The overall methodological framework to predict future available biomass is shown in Figure 1. Based on stand characteristics derived from empirical growth tables, we defined a set of hypothetical forest stands on varying soil conditions whereby the latter are derived from the Aardewerk soil inventory (Van Orshoven et al., 1988). We used the process-based forest growth model 4C (Lasch-Born et al., 2020) to simulate growth changes of these stands over four different periods corresponding to (i) the historical period (1961 – 1990) - when the bulk of the measurements underpinning the yield tables were executed, (ii) current climatic conditions (1987 – 2016), (iii) expected near-future conditions (2041 – 2070), and (iv) expected climatic conditions in the far-future (2071 – 2100). Next, we used the relative growth change between the historical climate compared to the current and future climatic conditions to define scaling factors. The resulting *scaling factors* were combined into a time-dependent *scaling functions* and used to adjust the empirical growth tables, making them climate-sensitive. The updated growth tables were then integrated into the decision support system Sim4Tree , which was developed to support forest management in Flanders (Dalemans et al., 2015).

2.1 Forest growth models

2.1.1 The model 4C

The process-based forest growth model 4C (‘FORESEE’ –FORESt Ecosystems in a changing Environment) (Lasch-Born et al., 2020) describes tree growth processes based on physiological modelling, long-term growth observations and eco-physiological experiments. 4C simulates tree and stand development of forest structure, leaf area, carbon and water balance of homogeneous cohorts, representing trees of the same species, similar age and structure. Photosynthesis is simulated mechanistically as a function of environmental factors (temperature, water, nitrogen, global radiation and CO_2) using the model of Haxeltine & Prentice (1996) under the assumption of abundant water and nutrient supplies. Reduction factors on optimal photosynthesis levels account for growth reductions due to temperature, water or nutrient deficiencies. Temperature affects photosynthesis, respiration, length of the growing period, phenology and the water and nutrient balance through its effects on evapotranspiration and mineralization. Precipitation effects are mostly limited to the soil water balance, which is represented by a multi-layer bucket model. Nitrogen limitations affect the light-use efficiency through a nitrogen balance depending on species-specific daily nitrogen demand in combination with nitrogen availability, affected by deposition, soil temperature, humidity and pH. Finally, elevated CO_2 levels affect productivity positively by increasing the light-use efficiency and water-use efficiency by reducing the stomatal conductance and potential transpiration water demand. The effect of elevated CO_2 levels can be switched on or off by assuming varying or constant CO_2 concentrations in time, independent of other climate variables. A detailed description of the model can be found in Lasch-Born et al. (2020). The model requires daily meteorological data, initial stand data and chemical and physical soil characteristics for each soil horizon. 4C has been used and validated to evaluate forest growth responses to climate in Finland (Mäkelä et al., 2000), Belgium (Kint et al., 2009), Germany (Lasch-Born et al., 2015), Europe (Reyer et al., 2014; Schelhaas et al., 2015) and Russia (Suckow et al., 2016).

2.1.2 Empirical growth tables

The empirical growth tables of Jansen & Oosterbaan (2018) developed for the Netherlands are also commonly used in the neighbouring temperate lowland region of Flanders (13,625 km²; 11% forested). These tables give the evolution of height, diameter at breast height, stem number, standing and growing biomass for homogeneous even-aged monoculture stands in five-year time steps for different management regimes and site indices. For the construction of these tables, growth curves were drawn using statistical correlations based on growth observations from permanent sampling and experimental plots from 1920 until 2010, although most measurements occurred between 1950 and 2000. Separate growth tables were developed for each of the most prominent tree species in Flanders and the Netherlands.

2.2 Model initialization

2.2.1 Stand data

The effect of climate change on forest growth was simulated over 30 years (from 30-year to 60-year-old) for virtual mono-species stands (*see Appendix A 2*) of the most prominent forest tree species in Flanders, i.e. inland oak (*Quercus robur* and *Quercus petraea),* red oak (*Quercus rubra)*, common beech (*Fagus sylvatica*), birch (*Betula spp.*), poplar (*Populus spp.*), ash (*Fraxinus excelsior*), black alder (*Alnus glutinosa*), sycamore maple (*Acer pseudoplatanus*), Scots pine (*Pinus sylvestris*), Corsican pine (*Pinus nigra* subsp. *salzmannii* var. *corsicana*), douglas fir (*Pseudotsuga menziesii*), Japanese larch (*Larix kaempferi*) and Norway spruce (*Picea abies*) (Storms & Muys, in press). These virtual stands were initialized using stand characteristics (diameter at breast height, height and basal area) and management (thinning) in line with the empirical growth tables developed for the Netherlands for each site index, resulting in a total of 109 forest stands (Jansen & Oosterbaan, 2018). Species present in the yield tables, but not parametrized in 4C were approximated by their most resembling parametrized species within 4C, as suggested in the 4C initialization manual.

2.2.2 Climate data

We divided Flanders into seven different climatic zones to accurately represent the effect of varying climatic conditions on forest growth in Flanders whilst minimizing the total number of simulations necessary. The environmental zones were derived using a dynamic time warping clustering technique to aggregate the observations from 1961 until 2016, derived from the gridded observational database of the Royal Meteorological Institute of Belgium (5 km x 5 km) (Giorgino, 2009; Sardà-Espinosa, 2017; RMI, 2018; see SI 1). The daily historical climate data were split into two parts, a baseline period from 1961 until 1990 – corresponding to the period in which the bulk of measurements underpinning the empirical growth tables were acquired – and a period from 1987 until 2016 – reflecting the recent growth conditions. CO_2 concentrations were derived from the Mauna Loa series (Tans, 2016).

Future climate was considered for the representative concentration pathways (RCP) 4.5 and 8.5. These projections were made for both the near- and far-future, i.e., 2041 – 2070 and 2071 – 2100 respectively. We simulated forest growth under five different Earth System Models (ESM) and two Global Circulation Models (GCM) from the coupled model intercomparison project (CMIP5) to account for the uncertainty within the RCP scenarios (Table 1, Taylor et al., 2012). The climate model projections were bias-corrected using the quantile perturbation method for precipitation changes (Willems & Vrac, 2011;

Ntegeka et al., 2014). Temperature, radiation, wind speed and sunshine duration data were adjusted using the delta change method (Gleick, 1986). Moreover, additional forest growth simulations keeping a constant CO_2 concentration of 340 ppm, corresponding with CO_2 concentrations during the observations of the empirical yield tables, were executed to evaluate the effect of CO_2 fertilization for four of the most prominent tree species in Flanders i.e. *F. sylvatica*, *Populus spp.*, *P. sylvestris* and *Quercus spp.*

2.2.3 Soil data

Flanders' polygon-based morphogenetical soil map (cartographic scale 1:20.000) was converted to a one-hectare grid by assigning to each pixel of the grid the mapped soil type overlapping with the pixel's centre. For each pixel, sequence, depth and thickness of the soil horizons and their textural characteristics (sand content, silt content and clay content) were derived from the Aardewerk-STAT database (Van Orshoven et al., 1991) in line with Ottoy et al. (2015). For the matching process (see Appendix A 3), only forest soil profiles were considered. As a result, the 1,362,500 pixels were matched with 302 different horizon sequences. We decided to update Aardewerk‘s chemical properties using the ForSite database as the measurements contained in the Aardewerk database were conducted in the 1947 – 1974 period and were unlikely to reflect current chemical properties (De Vos, 2009). The ForSite database is a more recent, but less extensive soil database containing information on chemical properties, i.e. pH, nitrogen content and carbon content. Physical properties like granulometry are less variable in time and could, therefore, still benefit from the more extensive Aardewerk database.

2.3 Scaling factors

We defined scaling factors as the relative change in forest growth between two different environmental conditions. To simulate the effect of climate change on forest growth, we used the forest growth model 4C and assumed persistent CO_2 fertilization effects on light-use efficiency and stomatal conductance. We combined the climate zones information and soil profiles to create 2114 (7 x 302) virtual environments reflecting the range of different conditions within Flanders. Forest growth was simulated for the baseline (1961 – 1990), recent (1987 – 2016), near-future (2041 – 2070) and far-future (2071 – 2100) periods, resulting in 59,192 simulations for each of the 109 forest stands. We assumed thinning operations of the same intensity as described in the yield tables. Disturbance effects were excluded as the predominant disturbance in Flanders, i.e. windthrow, floods and diseases, would be better addressed on larger scales through landscape models rather than one-hectare stand development with a gap model.

Climate change effects on forest productivity were derived using *scaling factors* (SFs) based on the mean annual increment (MAI) of the forest stand over a 30-year period. We used an annual metric such as MAI over cumulative metrics such as standing volume, height or DBH to minimize the effect of cumulative errors occurring in the mechanistic model. SFs were calculated by dividing the MAI of a stand under the current or future period by the MAI of the same stand with the same soil conditions under the historical baseline period. A scaling factor larger than one implies faster growth than captured by the base yield table, while a scaling factor smaller than one implies slower growth.

$$SF_{stand,soil,considered\ period} = \frac{MAI_{stand,soil,considered\ period}}{MAI_{stand,soil,baseline\ period}}$$

2.4 Scaling functions and climate-sensitive growth tables

Based on the resulting four SFs over the historical and current climate conditions and near- and far-future projections, we derived third-degree polynomial *scaling functions*, which can be used to estimate non-linear growth changes over the entire time period (1975 – 2085). The empirically derived growth tables were adjusted using the applicable scaling functions to make them climate-sensitive in terms of the relative growth change over time. Growth changes were translated to the empirical growth tables by allowing the forest to progress faster or slower through its regular growth curve (see Box 1). With the implementation of scaling functions, timing of management interventions in the growth curves had to be adjusted. Management interventions continued to occur every five years, but these five years corresponded with a progression differing from five years in age in the forest stand according the empirical yield tables (e.g. every six years in the yield tables with a scaling factor of 1.2, see Box 1). Therefore, the yield tables had to be recomputed for each stand on every soil condition for every initial age.

***Box 1**: Example of a hypothetical change in stand growth through the use of mechanistically derived scaling functions applied to empirical yield tables.*

By definition, the scaling factor for the historical period equals one. In this hypothetical example, the scaling factors equal 1.16, 1.55 and 1.57 for the current period, near- and far-future, respectively. Using these four scaling factors, a third-degree polynomial is derived, the *scaling function (SF(t)*) *(Fig. B1 a)*, describing how scaling factors evolve over time.

$$SF(t) = a + b * t + c * t^2 + d * t^3$$

With t, the year in which a scaling factor needs to be calculated and a, b, c and d species- and site-specific coefficients (Appendix A 4). The derived scaling function is used in combination with the empirical yield tables to describe stand growth. For this illustration, we describe the growth of a 20-year old forest stand, thinned every five years, with an initial stand volume of 131 $m^3.ha^{-1}$ from 2020 to 2080 in five year time steps. To avoid confusion between progression in terms of age of the forest stand in the empirical yield table and the progression of the forest stand age through time, we redefine the age of forest stands in the empirical yield tables as *Relative Volumetric Age (RVA)*. In a scenario without climate change, the stand volume would increase to 331.0 $m^3.ha^{-1}$ and a total of 360.0 $m^3.ha^{-1}$ would be harvested over these 60 years (Fig. B1 d points 2). When considering climate change through scaling functions, by 2080 the standing volume increases to 363.6 $m^3.ha^{-1}$ with a cumulative harvest of 478.2 $m^3.ha^{-1}$ (Fig. B1 e points 2). This change was achieved by allowing the stand to progress faster through its growth curve or RVA using the scaling function (Fig. B1 b and c). After the first time step in 2025, the scaling factor equals 1.34, meaning the stand grows 34% faster or the stand progresses seven (≈ 5 * 1.34) years in its RVA in a 5-year period. In 2025, the stand volume and cumulative harvest under climate change is thus derived from the RVA of 27 (triangles 1 in Fig. B1 b, c and e), instead of the RVA of 25 when no climate change is considered (squares 1 in Fig. B1 b, c and d). In 2030, the scaling factor equals 1.38, resulting in another RVA increase of about seven years in a five year period meaning that the stand reflects the characteristics of a 34-year old stand (27 + 7) instead of a 30-year old stand. Repeating this process in 5-year steps until 2080 leads to a stand reflecting an RVA of 111 years (triangles 2 in Fig. B1 b, c and e) when climate change is considered instead of an RVA of 80 years (squares 2 in Fig. B1 b, c and d) when climate change is omitted.

2.5 Validation climate-sensitive growth tables

The updated climate-sensitive growth tables were evaluated against observations from the regional forest inventory (RFI) of Flanders (Govaere & Leyman, 2020). The RFI consists of a 1-km by 0.5-km grid over Flanders of permanent forest sampling plots, measured in 1997 – 1999 (RFI I) and between 2009 – 2018 (RFI II). Only homogeneous, even-aged coupled plots (measured in both RFI I and RFI II) dominated by species for which growth tables exist in Flanders and the Netherlands were retained (N = 228). Model evaluation was performed on dominant height growth, i.e. the mean height of the 100 thickest trees, as management is not included in the RFI and height is less sensitive to management than diameter growth and standing stocks. The effect of scaling factors in growth tables was assessed by comparing the model bias of the growth tables of Jansen & Oosterbaan (2018) with the climate-sensitive growth tables. The significance of the bias change was evaluated using a paired t-test after verifying variance distributions using an F-test.

2.6 Case study: Future biomass availability in Flanders

Future biomass availability over the period 2020 to 2050 in Flanders was simulated using the Sim4Tree tool. The Sim4Tree simulation tool is part of the Sim4Tree decision support system and models forest growth in a particular territory in a spatially explicit way (Dalemans et al., 2015). The model describes the initial forest condition as one-hectare homogeneous stands and allocates species and stand characteristics based on the regional forest inventory of Flanders. Forest growth is simulated in 5-year time intervals using empirical yield tables developed for the Netherlands (Jansen & Oosterbaan, 2018). For this simulation study, we assumed recent forest management trends by applying the stand-still principle and prioritizing native deciduous species for regeneration (Appendix A 5). The species allocation to a specific regenerating pixel happens at random in Sim4Tree, meaning exact replications are impossible. Besides management, the simulation was expanded with a business as usual land use change scenario, created by Engelen et al. (2011). This scenario spatially defines the expected afforestation (13,312 ha) and deforestation (620 ha) between 2015 and 2050 based on a socio-economic development scenario, and was rescaled to fit the 5-year time interval of Sim4Tree (Appendix A 5). Furthermore, the empirical yield tables were updated with the above-described procedure using scaling functions.

3 RESULTS

3.1 Influence of climate change on stand growth

According to the simulation with the 4C model, forest stands grew, on average, 13% (0.47% yr^{-1}) faster[1] between 1987 – 2016 than in the historical growth period (1961 – 1990) (see appendix A 5, Table A5 1, Table A5 2). This positive growth trend is projected to continue in the near- and far-future with pronounced growth increases for both RCP 4.5 (34.0% and 43.7%, respectively) and RCP 8.5 (44.1% and 61.0%, respectively). However, the annual growth increase is levelling off for RCP 4.5 from 0.47% yr^{-1} for current conditions to 0.32% yr^{-1} for the near-future to 0.24% yr^{-1} for the far-future. For RCP 8.5, annual growth increases level off slower from 0.45% yr^{-1} for the near-future to 0.37% yr^{-1} for the far-future.

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[1] Annual growth rate changes were calculated as a compounded annual growth rate assuming the middle of each climatic period as a start or end year

Fast-growing deciduous species, i.e. *B. pendula, A. glutinosa*, *P. tremula,* show the most pronounced and most variable growth increases. Coniferous species and slower-growing deciduous species show a milder and more uniform response to the changing environmental conditions. Overall, species show a more pronounced and variable response to RCP 8.5 than RCP 4.5 (Fig. 2).

3.2 Effect of carbon fertilization on stand growth

Persistent CO_2 effects positively influenced predicted forest growth for both RCP 4.5 and RCP 8.5. Without CO_2 fertilization, stand growth responses to climate change remained positive and were most pronounced for RCP 8.5. However, for *Quercus spp.* annual growth changes became negative (-0.15% yr^{-1}) for RCP 8.5 for the period 2071 – 2100, when no CO_2 fertilization was considered (Table 2). Also, for *P. tremula* and *F. sylvatica,* annual growth changes decreased over time for both RCP 4.5 and RCP 8.5. However, they remained positive compared to historical conditions, at a minimum of 0.21% yr^{-1} for *P. tremula* and 0.13% yr^{-1} for *F. sylvatica*. Only *P. sylvestris* increased or maintained its annual growth trend from the near- to far-future when no CO_2 fertilization was considered for RCP 4.5 (from 0.20% yr^{-1} to 0.26% yr^{-1}) and RCP 8.5 (from 0.31% yr^{-1} to 0.29% yr^{-1}). Markedly, when CO_2 fertilization is not included, both near- and far-future annual growth rate changes are lower than the modelled current annual growth changes for all species under both RCP 4.5 and RCP 8.5. The relative difference between the scenarios in- and excluding CO_2 fertilization was most predominant for the deciduous tree species, particularly for the slow-growing deciduous species (i.e. *Quercus spp.* and *F sylvatica*). On average, species growth increase under climate change was reduced by 36% when no CO_2 fertilization was assumed for both the near- and far-future under RCP 4.5

compared to 40% for the near- and 49% for the far-future under RCP 8.5. Under current environmental conditions, the exclusion of CO_2 fertilization diminished the predicted growth increase by 26%.

3.3 Regional differences in growth changes per species

Although the spatial pattern of growth changes varied between species a general gradient from strong growth changes to mild growth changes stretching from west to east is prevalent for most species. This is corresponding with a gradient from relative strong to mild precipitation increases, with the exception of *Quercus spp.* for the far-future in RCP 8.5 (Fig. 3).

3.4 Validation of climate-sensitive growth tables

Stands from the RFI grew on average 0.31 $m.yr^{-1}$ over an average period of 15 years. Our validation set consisted predominantly of *P. sylvestris* (55 %), *P. nigra* (22%), *Quercus spp.* (8%) and *Populus spp.* (6%). Over this entire population, climate-sensitive growth tables predicted growth in Flanders significantly better ($p < 0.01$) than the growth tables of 2018. Including climate sensitivity in the growth tables led to an average bias reduction of 0.45 m, decreasing the underestimation of dominant height growth from 1.30 m to 0.86 m.

3.5 Effect of climate change on future biomass production estimates

A total of 39.1 Mm^3 or 1.3 $Mm^3.yr^{-1}$ (8.0 $m^3.ha^{-1}.yr^{-1}$) of biomass could be harvested between 2020 and 2050 under historical climate conditions and a business-as-usual forest management in Flanders. By applying scaling factors, this potential harvest is expected to increase to 46.0 Mm^3 (9.4 $m^3.ha^{-1}.yr^{-1}$) for RCP 4.5 and 47.7 Mm^3 (9.8 $m^3.ha^-$

^{1}.yr^{-1}) for RCP 8.5. Standing stocks decrease from 35.7 Mm^{3} (219.4 m^{3}.ha^{-1}) in 2020 to 31.7 Mm^{3} (194.8 m^{3}.ha^{-1}) by 2050 without climate change, with a sharp initial decline (-11%) from 2020 to 2030. When considering climate change-induced productivity changes, standing stocks also decline between 2020 and 2030 but can partially recover by 2050, with slightly decreased standing stocks of 34.7 (213.3 m^{3}.ha^{-1}) and 35.6 Mm^{3} (218.8 m^{3}.ha^{-1}) for RCP 4.5 and RCP 8.5. This means that between 2020 and 2050, a total of 35.1 Mm^{3} (7.2 m^{3}.ha^{-1}.yr^{-1}), 45 Mm^{3} (9.2 m^{3}.ha^{-1}.yr^{-1}) and 47.6 Mm^{3} (9.8 m^{3}.ha^{-1}.yr^{-1}) of woody biomass is produced in the Flemish forest landscape under historical, RCP 4.5 and RCP 8.5 climatic conditions, respectively (Table 3). Thus, considering climate change-induced productivity changes in regional production estimates leads to an expected additional 230.000 m^{3} (+ 17%) or 280.667 m^{3} (+ 22%) of woody biomass becoming potentially available annually under RCP 4.5 and RCP 8.5, respectively. Furthermore, when including productivity changes, this biomass becomes available without threatening the existing standing stocks in the Flemish forests.

4 DISCUSSION

4.1 Influence of climate change on species growth

The state of the art process-based modelling using 4C indicates that climate change is likely to positively affect forest productivity for all considered species and under all occurring site conditions. This is in agreement with other simulation studies (Reyer et al., 2014; Louis de Wergifosse et al., 2022) and empirical observations (Pretzsch et al. 2014). Current climate conditions (1987 – 2016) already lead to a modelled increase in MAI of up to 16.3% compared to the baseline conditions for 1961 – 1990. This increase in forest productivity backs the empirical evidence showing overall increases of up to 30% in current conditions compared to 1960, bringing the empirical yield tables' validity into question (Pretzsch et al., 2014). Our simulated growth increase falls on the lower side of the ranges observed by Pretzsch *et al.* (2014), which might partially be attributed to the exclusion of the changing nitrogen deposition in our simulations, which increased until the mid-1980s all over Europe. Although they have played an important role for forest productivity in the past (De Vries et al., 2006; Schulte-Uebbing & de Vries, 2018), their future role is debated and magnitude uncertain (Churkina et al., 2007; Reay et al., 2008; van der Graaf et al., 2021).

Although nitrogen is generally seen as a limiting factor, evidence suggests that an excess of nitrogen can also negatively influence forest productivity by decreasing pH and altering foliar nutrient concentrations (Etzold et al., 2020). This adverse effect of nitrogen on forest productivity was also observed in Flemish beech forests, with a tipping point of positive to negative effects of atmospherically deposited nitrogen around 20 kg N ha^{-1}.yr^{-1} (Kint et al., 2012; Aertsen et al., 2014). It is in strong contrast with the 11.4% growth increase that we simulated for beech. However, our simulated productivity increases correspond with other empirical studies observing positive trends (Dittmar et al., 2003; Bontemps et al., 2010; Charru et al., 2010), which are projected to continue in the near- and far-future (Sabaté et al., 2002; Prislan et al., 2019). The overall positive effect of climate change on beech should, however, be interpreted with care. Sousa-Silva et al. (2018) found that drought triggered vitality decreases in beech and oak. In more water-limited regions and in dry years, beech trees also showed growth decreases, which are attributed to (i) higher respirative carbon losses, (ii) higher atmospheric water demand, and (iii) increased fruit production (Zimmermann et al., 2015). Although these adverse effects of droughts are to some extent present in the simulation (Appendix A 8), they are softened by considering a 30-year period, giving beech sufficient time to recover from these drought events (van der Werf et al., 2007) and benefit from a dominant effect of increased CO_2 concentrations and lengthening of the temperature based growing period. This dominant effect of CO_2 fertilization and prolonged vegetation period leading to increased stand production despite increases in transpiration deficit was also found, and discussed in further extent, by de Wergifosse et al. (2022).

The positive effect of increased CO_2 concentrations has also been used to explain growth increases in *Populus spp.*, where growth increases in aboveground biomass of up to 29% have been recorded under elevated CO_2 concentrations, even after canopy closure (Norby et al., 2005). The higher productivity increases in our study – 44.2% for RCP 4.5 and 63.4% for RCP 8.5 – can partially be explained by the higher CO_2 concentrations considered in our simulations (up to 936 ppm) than in most Free Air CO_2 Enrichment experiments (around 550 ppm) and the lengthening of the growing season. Furthermore, they remain in the same order of magnitude as observed growth increases in other CO_2 enrichment experiments for *Populus spp.* (Calfapietra et al., 2010).

Other broadleaved species, such as *Quercus spp.,* have experienced reduced growth in drier years (Perkins et al., 2018). However, overall positive effects of up to 123% have been simulated and are projected to persist under elevated CO_2 concentrations and temperature as long as water does not become a limiting factor (Kint et al., 2012; Nölte et al., 2020). de Wergifosse et al. (2020) reached more moderate NPP increases for oak and beech of up to 34% for RCP 8.5 for their simulation experiment in the Walloon region of Belgium.

P. sylvestris, an important needle-leaved species in Flanders, shows moderate to large productivity increases in the near-future under climate change for both RCP 4.5 (33.9%) and RCP 8.5 (45.5%). The simulated productivity increase in *P. sylvestris* is in contradiction with the findings of Vallet & Perot (2018), who observed a minor decrease in growth, but are supported by Vila et al. (2008). Rehfeldt et al. (2002) already noted the site-dependent reaction of *P. sylvestris* on climate change stating that positive growth changes are expected as long as precipitation is expected to increase. Sabaté et al. (2002) found increases of up to 130% in NPP but also observed decrease in allocation to stem biomass. This emphasizes the importance of considering the volume changes or NPP changes to investigate the effect of climate change on wood production and carbon sequestration, respectively.

4.2 The effects and limitations of assumptions underlying the simulations

We consider persistent CO_2 fertilization effects affecting photosynthesis, stomatal conductance and water-use efficiency as defined by Haxeltine and Prentice (1996). However, this persistent effect of CO_2 under climate change is still debated, and not all effects of CO_2 on future forest growth are accounted for in the 4C model (Reyer et al., 2014, 2015). Moreover, Wang et al. (2020) were able to identify a declining effect of CO_2 fertilization with nutrient and water limitations becoming more dominant. However, overall growth trends remained positive regardless of the in- or exclusion of the CO_2 fertilization effect (Table 2). In contrast, a similar study in the southern part of Belgium found more moderate growth changes when considering CO_2 fertilization and found no significant change in growth when CO_2 fertilization effects were excluded (de Wergifosse et al., 2020). The discrepancy between this and our simulation study can probably be partially explained by (i) the different soil conditions, (ii) the wetter climatic conditions in the southern part of Belgium, (iii) the consideration of four sites rather than the 302 sites considered in this study and (iv) the difference in the reference period (1975 – 2005 compared to 1961 – 1990 for this study).

Annual growth change trends varied depending on the assumption of the CO_2 fertilization effect, further emphasizing the importance of acknowledging this uncertainty in future modelling studies. However, the uncertainty related to CO_2 effects was smaller than the divergent results of the different climate models considered (results not shown). Reyer *et al.* (2014) stress the importance of taking into account different climate scenarios, acknowledging this uncertainty, as their effect is larger than the consideration of different CO_2 emission scenarios.

We found a predominantly positive effect of climate change on forest productivity despite more frequent, more prolonged, severe and hotter drought episodes expected for the near-future (Allen et al., 2015; Spinoni et al., 2020). This overall positive effect was found in other studies considering a more extended period and is likely related to (i) longer growing periods, (ii) higher temperatures and (iii) improved photosynthetic and water-use efficiency due to elevated CO_2 concentrations (Sabaté et al., 2002; Reyer et al., 2014; Nölte et al., 2020). In our simulations, drought effectively led to growth decreases in dry years and the year(s) following the dry year. But these negative growth trends in dry years were overruled by positive growth trends in the, more common, drought-free years, considering a 30-year period (Appendix A 8). It is important to note that the 4C model only considered direct growth reductions due to drought, neglecting drought-induced tree mortality and the interaction of drought with other disturbances such as increased susceptibility to pests and diseases (Seidl et al., 2017). Furthermore, other disturbances such as windthrow and nutrient imbalances, i.e. phosphorus - likely to become limiting in the future (Jonard et al., 2015; Talkner et al., 2015; Bergkemper et al., 2016; Krishna & Mohan, 2017) - or nitrogen deposition, were not considered in this study.

4.3 Regional differences in growth changes per species

Abiotic stand conditions have a significant effect on forest stands' response to climate change. Although overall trends remained positive under all site conditions, the extent of this productivity change varied largely between sites (standard deviations of up to 15%, Table A5 1, Fig. 3). This site effect on forest response during climate change had already been measured in empirical studies (Jump et al., 2006; Aertsen et al., 2014; Latte et al., 2015), but is rarely accounted for when discussing the future effects of climate change on forest productivity. Forest responses thus do not only vary considerably on a north-south (Rehfeldt et al., 2002; Perkins et al., 2018), altitudinal (Dittmar et al., 2003; Jump et al., 2006; Vila et al., 2008) or precipitation gradient (Zimmermann et al., 2015; Vallet & Perot, 2018), which are typically considered in European-scale studies (Reyer et al., 2014), but also vary locally depending on local soil and climate conditions. Our results indicate that relative growth changes in Flanders span the same order of magnitude in variation as studies evaluating relative growth changes on a European scale or the in- or exclusion of the CO_2 fertilization effect (Reyer, 2015, Table 2 & Fig. 3).

Aertsen et al. (2014) found that good site conditions buffer negative impacts of climate change on growth. Our results indicate that the same is true for positive impacts. This buffering effect of good site conditions on positive responses to climate change is partially attributed to the requirement of more significant absolute increases to reach the same amount of relative growth increase. Also, after an initial growth increase, factors unaffected by climate change may become limiting, negating the positive effects of periods of increased growth, increased precipitation and CO_2 fertilization (Norby et al., 2010).

Although forest stand responses differ in magnitude between species, spatial patterns are similar for most species considered (Fig. 3). The west-east pattern is related to the climate zones and is more visible for RCP 4.5 than RCP 8.5. This higher visibility of the climatic gradient is likely attributed to the dominant effect of CO_2 fertilization in RCP 8.5 over other climatic factors. Apart from this east-west gradient, a large variety exists between nearby sites, which can only be attributed to differences in the soil's granulometrical, hydrological and chemical properties. This effect of variation on forest productivity response to climate change is often neglected in studies estimating growth changes on a regional (Sabaté et al., 2002) or European scale (Reyer et al., 2014; Schelhaas et al., 2015). However, this local variation becomes essential when aiming for actual growth projections for economic analysis or regional policy advice. We acknowledge the uncertainty related to soil conditions and soil processes within the 4C mechanistic forest growth model. Nevertheless, we argue that addressing this uncertainty is as important as addressing the uncertainty related to carbon fertilization, CO_2 emission scenario or climate projections, as discussed in Reyer et al. (2014). Even when empirical measurements indicate limited or no variability in forest productivity response to climate change, these variations are likely to become apparent in future climatic conditions (Fig. 3).

4.4 Incorporation of mechanistically modelled growth trends in empirical yield tables

To support forestry's involvement in developing new industries facilitating the transition to a circular bio-economy accurate projections of current and future biomass availability are necessary (Leskinen et al., 2018; Schulze et al., 2020). The positive growth trends experienced (Pretzsch et al., 2014) and projected bring the validity of empirical models in current and future conditions into question. This issue can be omitted by combining process-based models with empirical models (Nabuurs et al., 2002; Schelhaas et al., 2015).

Although integrating growth changes in yield tables rather than applying them to NFI data for forest growth projections suffers the drawback that forest stands need to be characterised by stand characteristics available in yield tables, while yield table management no longer exists in Europe (Schelhaas et al., 2018). Nonetheless, empirical yield tables are still widely used by forest managers. Thus, making PBMs results available in a format familiar to forest managers contributes to bridging the gap between academic research to forest management (Sousa-Silva et al., 2016). Furthermore, yield tables are still widely used in simulation and decision support systems (Dalemans et al., 2015), allowing this methodology to serve as a blueprint for future research on making DSS climate-sensitive.

Even though our validation is executed on a short time frame, 10 to 20 years, our climate-sensitive growth tables already indicate a significant improvement compared to existing growth tables. As climate conditions continue to deviate from those experienced in the past this improvement is expected to become more pronounced. Hence, the proposed methodology is not only useful for predicting growth changes due to climate change but can also be used to regularly update existing growth tables at a minimal cost. As more regions include PBM predictions into growth tables, validation of this methodology per species should become possible. However, due to the study area's limited size and stand heterogeneity, such a validation was currently impossible, limiting us to a regional scale assessment.

4.5 Effect of climate change on future biomass production estimates

For the region of Flanders in Belgium, the accounting for climate change-induced growth changes led to an increase of additional potential harvested woody biomass of 230,000 to 280,667 m^3 per year (1.4 – 1.7 $m^3.ha^{-1}.yr^{-1}$). These potential woody biomass availabilities should not be interpreted as predictions towards actual biomass availability as this is dependent on factors beyond growth, i.e. owners' willingness to harvest (Blennow et al., 2014; Hengeveld et al., 2015), distance to roads or industry (Di Fulvio et al., 2016), wood prices and policy trends (Verkerk et al., 2019). Knowledge about such increases in future potential and actual biomass availability is crucial for evaluating the feasibility and regional strategies to defossilize the economy by 2050 along the policy lines of the European Green Deal, in which woody biomass will be a crucial renewable carbon or energy source.

For example, Tschulkow et al. (2020) concluded that a minimum intake of 190,000 – 234,000 tonnes of virgin woody biomass is necessary before a lignin-first biorefinery – a new technology showing potential for defossilizing the petrochemical industry (Liao et al., 2020) – could become profitable with woody biomass sourced exclusively in Flanders. In- or excluding climate change-induced accelerated growth could make or break the feasibility analysis of these studies as an additional biomass harvest of 190 kilotonnes in Flanders is not possible without threatening existing markets or biodiversity goals.

Despite the improvement in predicting future growth trends, some uncertainties regarding the future woody biomass potential of the Flemish forest landscape are not addressed in this study, and our results should be interpreted with care. Forest disturbances are an important driver of current and future forest ecosystem functioning and can significantly affect actual biomass harvest (Seidl et al., 2014). In Flanders, wind disturbance is the most important natural disturbance under the current climatic conditions. Although wind damage can have significant ecological, social and economic impacts, it rarely makes woody biomass completely unusable, but rather reduces the number of applications because of losses in wood quality (Gardiner et al., 2010). Nonetheless, increased harvesting costs and decreased wood prices potentially lead to decreases in harvested volume. However, for high-value, low-quality industries like the biochemical industry, this could increase biomass availability in the short term. Hence new industries with high feedstock flexibility could reduce the adverse effects of these disturbances in the overall wood value chain (Tschulkow et al., 2020). Other disturbances, i.e. pathogens, insects, drought and fire, are likely to increase with changing temperature and water availability in the future and vary strongly on a regional scale (Seidl et al., 2017). Future studies addressing the effect of climate change on forest functioning should address the interaction between different disturbances to shine light on the effect these disturbances will have on future available biomass in Flanders.

Also, management plays an important role in future biomass potential, as shown by the increased harvesting rates between 2020 – 2030, caused by species conversion and the felling of old forest stands when applying the Sim4Tree rotation times (Table 3). Recent trends in Flemish forest management hint at a more nature-oriented mindset, reducing management interventions and decreasing biomass availability. However, assessing the effect of management interventions was beyond the scope of this study but should be included in future studies focusing on regional woody biomass projections, as was done by Nabuurs et al. (2002) and Schelhaas et al. (2015). Particularly different species conversion strategies and rotation times should be considered. Additionally, we currently considered a single land-use change, based on a business-as-usual scenario, while several land-use change maps have been created for Flanders, each based on a different socio-economic scenario with a distinct focus point (e.g. nature oriented). Further inclusion of these different results would also improve the robustness of future biomass production estimates (Engelen et al., 2011). Finally, Sim4Tree assumes homogeneous, even-aged forest stands while the Flemish forests become increasingly more heterogeneous regarding species composition and age distribution (Storms & Muys, in press; Govaere, 2020).

5 CONCLUSION

Through mechanistic modelling, our study found that stand growth in Flanders has, on average, increased by 13% under current (1987 – 2016) environmental conditions compared to historical (1961 – 1990) conditions. This positive growth change is likely to continue when considering persistent CO_2 fertilization effects, especially under RCP 8.5 where CO_2 concentrations keep increasing until 2100. Fast-growing deciduous species benefit more from climate change than slow-growing deciduous species or coniferous species in general. Apart from differences in individual species responses to climate change, local variation in site conditions also affects the response, leading to variations within species in an equal order of magnitude as the in- or exclusion of the CO_2 fertilization effect. However, this local variation is often neglected in current biomass projection studies.

Moreover, our study developed a new approach for improving the flexibility of empirical yield tables by combining them with scaling factors resulting from state-of-the-art mechanistic modelling. By incorporating climate-induced growth changes, quantified by the forest growth model 4C, in empirical yield tables, we created climate-sensitive biomass projections in a format familiar to forest managers and decision support systems. Incorporating the scaled yield tables in the Sim4Tree DSS showed that climate change is likely to positively influence future potential harvestable biomass in Flanders. More specifically an increase of 17% for RCP 4.5 and 22% for RCP 8.5 is expected, without compromising current forest standing stocks. This 22% increase in sustainably harvestable biomass is of the same order of magnitude as the additional biomass estimates necessary in feasibility analysis for the bioeconomy, showcasing that the proposed improvement in regional future biomass projections by accounting for climate change-induced growth changes and its local variation could make or break future feasibility of investments in wood-based industries like biorefineries. Further progress can be made by (i) combining the proposed approach with a more extensive set of land-use and management scenarios, and by (ii) evaluating the impact of natural disturbances on future biomass harvest and standing stocks.

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8 Tables

Table 1: Average temperature (T) and relative precipitation (P) changes over the seven climate zones of the downscaled and bias-corrected climate projections compared to the observed baseline period 1961 - 1990 (see Table S1 2 and Table S1 3 for the difference between the different climate zones).

		2041 - 2070		**2071 - 2100**	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
	Change T (°C)				
GCM	CNRM-CM5	+ 2.49	+ 3.53	+ 3.46	+ 5.18
	INMCM4.0	+ 1.79	+ 2.59	+ 2.28	+ 3.62
ESM	GFDL-ESM2G	+ 1.83	+ 2.79	+ 2.36	+ 3.96
	GFDL-ESM2M	+ 1.91	+ 2.61	+ 2.5	+ 3.65
	MIROC-ESM	+ 3.32	+ 4.9	+ 4.84	+ 7.47
	IPSL-CM5A-LR	+ 2.96	+ 4.68	+ 4.24	+ 7.05
	BNU-ESM	+ 2.95	NA	+ 4.22	NA
	Change P (%)				
GCM	CNRM-CM5	+ 13.84	+ 21.11	+ 20.09	+ 32.53
	INMCM4.0	- 5.88	- 4.9	- 12.2	- 10.43
ESM	GFDL-ESM2G	+ 5.37	+ 2.96	+ 6.18	+ 1.25
	GFDL-ESM2M	+ 9.01	+ 9.81	+ 12.05	+ 13.07
	MIROC-ESM	+ 24.39	+ 28.64	+ 37.89	+ 45.73
	IPSL-CM5A-LR	+ 8.69	+ 3.28	+ 11.48	+ 3.03
	BNU-ESM	+ 8.3	NA	+ 11.26	NA

Table 2: Average growth increase (%) compared to the baseline period, with and without persistent CO_2 fertilization effects for different species for the forest of Flanders shown for the current period (1987 – 2016), near-future (2041 – 2070) and far-future (2071 – 2100) for RCP 4.5 and RCP 8.5.

Species	**1987 - 2016**		**2041 – 2070**				**2071 – 2100**			
			RCP 4.5		**RCP 8.5**		**RCP 4.5**		**RCP 8.5**	
	CO_2	$\cancel{CO_2}$	CO_2	$\cancel{CO_2}$	CO_2	$\cancel{CO_2}$	CO_2	$\cancel{CO_2}$	CO_2	$\cancel{CO_2}$
P. tremula	15.2	11.6	41.2	26.6	54.3	32.7	54.0	34.7	79.9	42.1
P. sylvestris	11.7	10.7	34.4	23.3	46.8	30.6	47.4	32.4	70.9	42.5
Quercus spp.	11.3	8.1	30.1	18.4	37.4	20.6	37.4	22.4	43.2	15.8
F. sylvatica	13.5	9.2	31.3	19.7	39.2	22.7	39.3	24.5	55.4	27.4

Table 3: Cumulative harvest (Mm^3) and standing stock ($m^3.ha^{-1}$) estimates of woody biomass for Flanders when considering no scaling, the scaling functions for RCP 4.5 and the scaling functions for RCP 8.5

	Standing stock ($m^3.ha^{-1}$)				**Cumulative harvest (Mm^3)**		
	2020	2030	2040	2050	2030	2040	2050
No scaling function	219.4	194.8	201.6	194.8	14.2	25.4	39.1
RCP 4.5	219.4	201.0	213.9	213.3	16.8	30.2	46.0
RCP 8.5	219.4	201.6	216.3	218.8	16.9	31.1	47.7

10 Figures

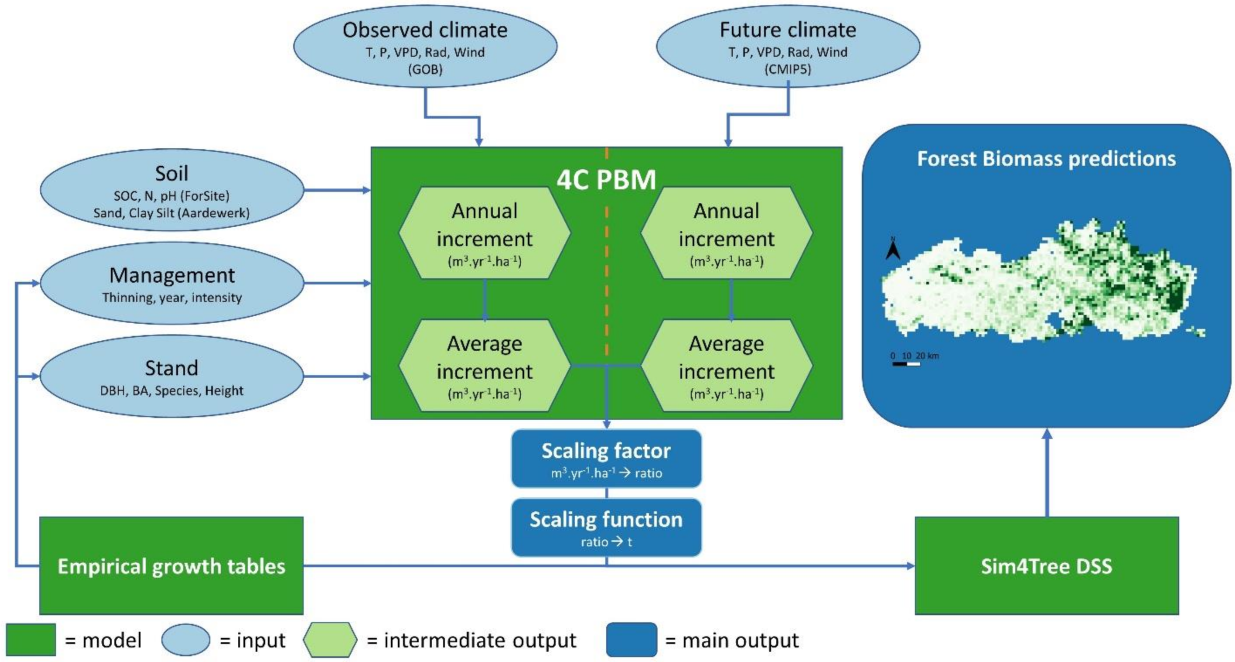

Figure 1: Schematic overview of the modelling approach used to scale empirical yield tables for future climatic conditions. DBH = diameter at breast height, BA = basal area, SOC = soil organic carbon, N = nitrogen content, ForSite = Forest site and soil database of Flanders, T = temperature, P = precipitation, VPD = vapour pressure deficit, Rad = radiation, GOB = gridded observational database and CMIP5 = coupled model intercomparison project 5.

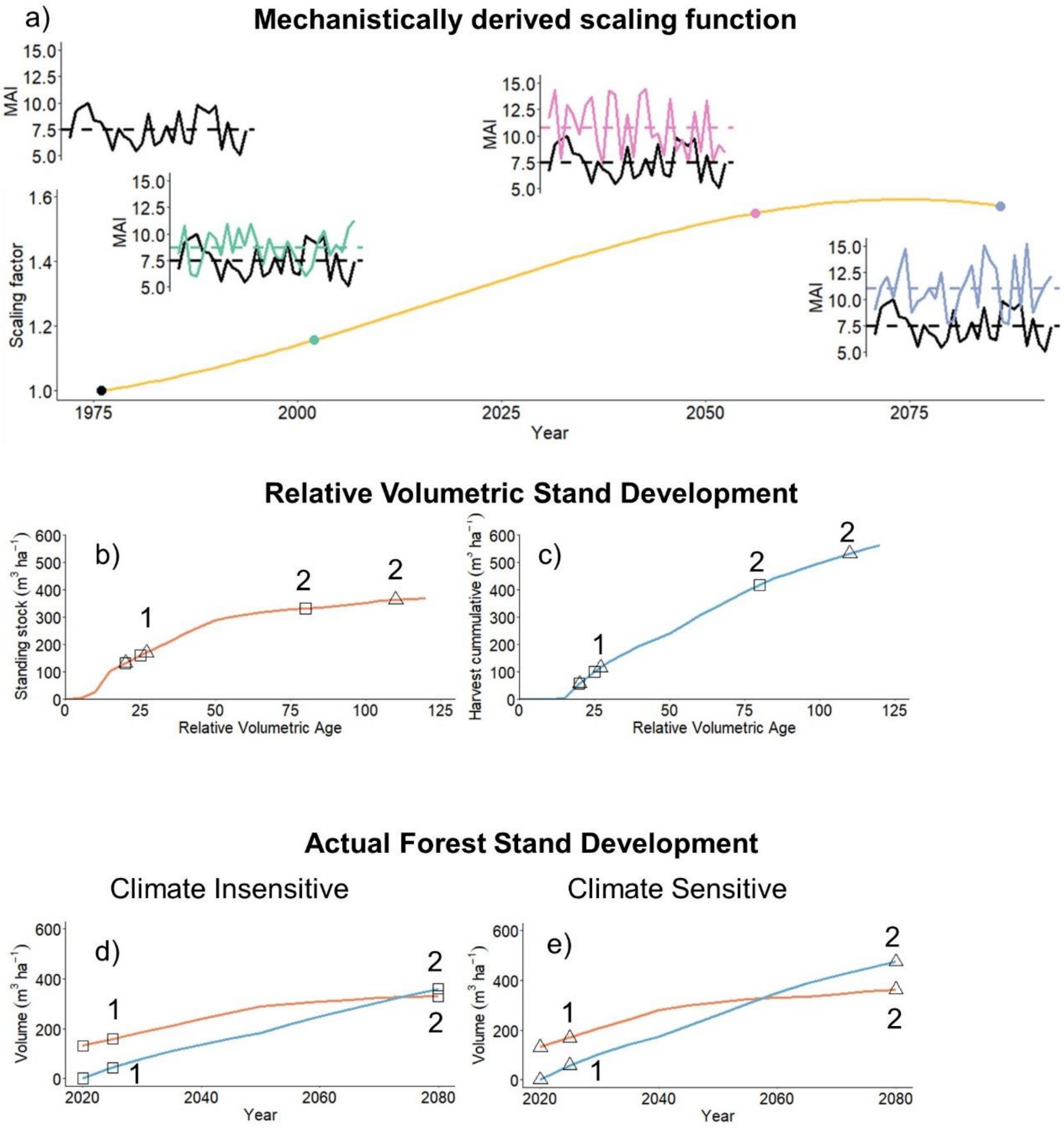

Figure B 1: (a) Tree species and site condition specific scaling function describing the evolution of the scaling factor through time, derived from the mean annual increment under historical conditions (black), current conditions (green), conditions in the near future (pink) and far future (purple); (b) Standing stock evolution of the considered forest stand used to derive stand development without climate change (squares) and with climate change (triangles) in d and e; (c) Cumulative harvest of the stand for the relative volumetric age; (d) Standing stock (orange) and cumulative harvest (blue) evolution for the stand after five years (squares 1) and 80 years (squares 2) without climate change; (e) and with climate change after five years (triangles 1) and 80 years (triangles 2).

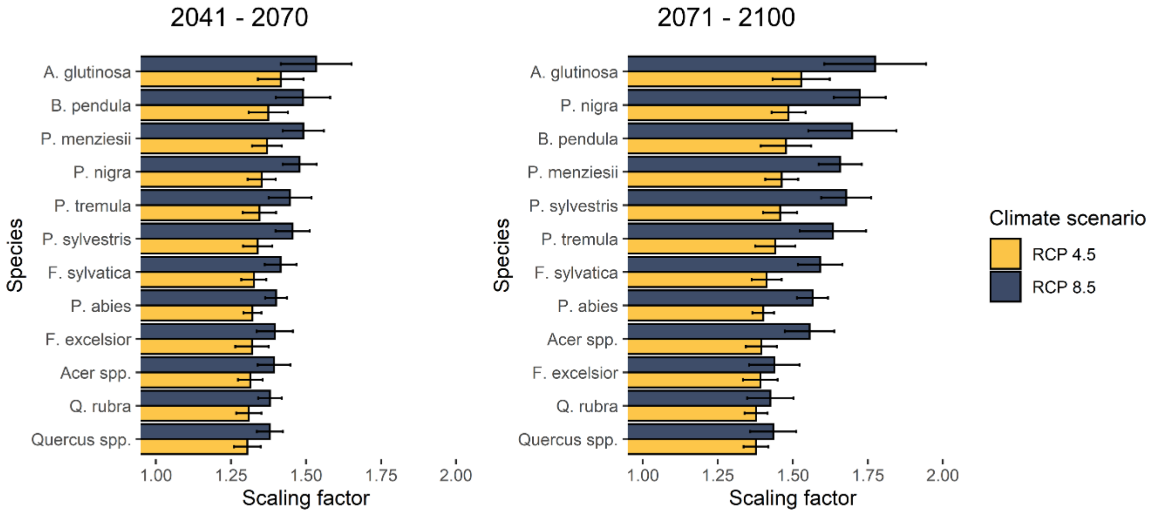

Figure 2: The average scaling factor with standard deviations for the region of Flanders for the near- (left) and far-future (right) shown for RCP4.5 (yellow) and RCP 8.5 (blue).

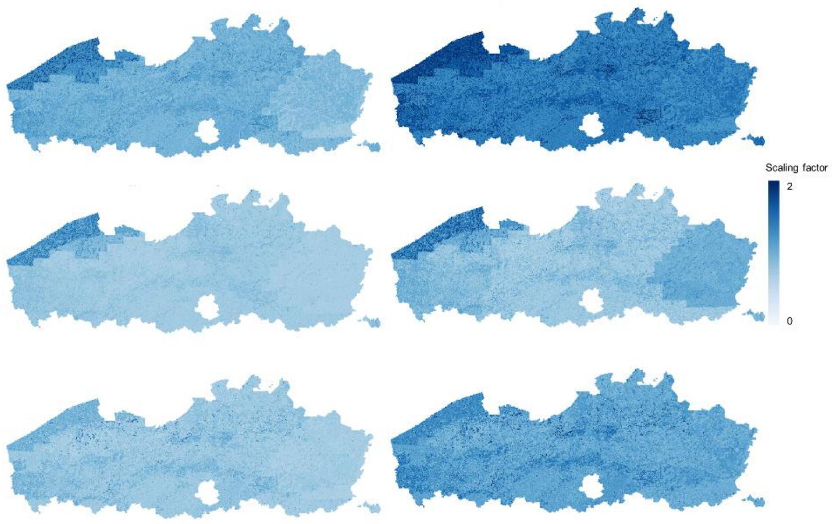

Figure 3: Spatial distribution of the scaling factors for the far-future (2071 – 2100) for P. sylvestris (top), Quercus. spp, (middle) and F. sylvatica (bottom) for RCP 4.5 (left) and RCP 8.5 (right).