European Journal of Forest Research (2019) 138:287–297
https://doi.org/10.1007/s10342-019-01168-4

ORIGINAL PAPER

Water limitation can negate the effect of higher temperatures on forest carbon sequestration

Salim Belyazid[1] · **Zanchi Giuliana**[2]

Received: 13 September 2018 / Revised: 26 December 2018 / Accepted: 16 January 2019 / Published online: 25 January 2019

Abstract

Climate change will bring about a consistent increase in temperatures. Annual precipitation rates are also expected to increase in boreal countries, but the seasonal distribution will be uneven, and several areas in the boreal zone will experience wetter winters and drier summers. This study uses the dynamic forest ecosystem model ForSAFE to estimate the combined effect of changes in temperature and precipitation on forest carbon stocks in Sweden. The model is used to simulate carbon stock changes in 544 productive forest sites from the Swedish National Forest Inventory. Forest carbon stocks under two alternative climate scenarios are compared to stocks under a hypothetical scenario of no climate change (baseline). Results show that lower water availability in the future can cause a significant reduction in tree carbon compared to a baseline scenario, particularly expressed in the southern and eastern parts of Sweden. In contrast, the north-western parts will experience an increase in tree carbon stocks. Results show also that summer precipitation is a better predictor of tree carbon reduction than annual precipitation. Finally, the change in soil carbon stock is less conspicuous than in tree carbon stock, showing no significant change in the north and a relatively small but consistent decline in the south. The study indicates that the prospect of higher water deficit caused by climate change cannot be ignored in future forest management planning.

Keywords Forest carbon stock · Water deficiency · Climate change · Dynamic modelling · ForSAFE · Sweden

Introduction

Climate change strongly affects the water cycle and can alter the magnitude and seasonality of precipitation (IPCC 2001). Boreal forests are expected to be particularly sensitive to climate change due to the rate of change projected at higher latitudes (Gauthier et al. 2015). A decrease in productivity and drought-induced mortality are among the main potential threats to boreal forests caused by future drier conditions (Gauthier et al. 2015; Price et al. 2013). In some areas, boreal and hemi-boreal forests are already experiencing water stress, including drought-induced tree mortality (Allen et al. 2010; Michaelian et al. 2010; Peng et al. 2011; Soja et al. 2007). Rapid changes of climate and trends towards drier conditions increase the risk of forest decline due to water stress in the boreal zone (Price et al. 2013; Wang et al. 2014). In Sweden, some studies show that water availability already limits forest growth in the southern part of the country (Bergh et al. 1999, 2005; van Leeuwen et al. 2000). In 2016–2018, groundwater levels were lower as compared to historical levels in several parts of Sweden, during the growing season. The situation was particularly alarming in southern Sweden where groundwater levels were critically low (below the 15th percentile) for more extended periods (SGU 2018). Moreover, future climate scenarios highlight that southern Sweden could experience drier summers (Ministry of Environment 2014), therefore increasing the risk of lower water availability during the growing season.

Boreal forests are important global carbon stocks and sinks (Bradshaw and Warkentin 2015) and can substantially contribute to climate change mitigation by storing carbon and by providing biomass for the production of renewable

---

Communicated by Agustín Merino.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10342-019-01168-4) contains supplementary material, which is available to authorized users.

✉ Salim Belyazid
salim.belyazid@natgeo.su.se

[1] Department of Physical Geography, Stockholm University, Svante Arrhenius väg 8, 114 18 Stockholm, Sweden

[2] Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden

energy and materials (Canadell and Raupach 2008; Lundmark et al. 2014). Sweden has set ambitious targets to increase the production of bioenergy and renewable products from forests while preserving forest carbon stocks to achieve climate change mitigation goals (SOU 2016: 47 2016; Swedish Government 2017). However, to guarantee a long-term balance between forest production and carbon sequestration, it is necessary to account for environmental changes that can affect forest ecosystem processes, such as climate change. In evaluating the potential contribution of Swedish forests to climate mitigation goals, climate change effects were often disregarded (Cintas et al. 2017; Lundmark et al. 2015). A study by Poudel et al. (2011) included the effect of temperature increase on future forest production in Sweden suggesting a positive effect of climate change on forest production. However, this study excluded the effect of changes in precipitation, which was shown to play a significant role in future forest growth in Finland where water deficiency could reduce the growth of pine and spruce by 6–7% compared to non-water-limited forests (Kellomäki et al. 2018). The combined effect of temperature and precipitation changes and the consequences of reduced water availability on forests' growth and carbon stocks in Sweden is yet to be investigated.

This study aims to simulate the effects of temperature changes combined with precipitation changes on tree and soil carbon stocks in Swedish forests by the end of this century. For this purpose, we will test the two following hypotheses:

1. Water deficiency has the potential to cancel out the positive effect of temperature increase on tree growth.
2. Litterfall and decomposition will react similar to changes in temperature and precipitation, making the overall response of soil carbon inconclusive.

The study is based on the simulation of future forest growth with the dynamic ecosystem model ForSAFE and climate change assumptions based on two global climate models (ECHAM5, CCSM3) for the period 2010–2100.

Materials and methods

ForSAFE

ForSAFE is a mechanistic model of the dynamics of forest ecosystems. The model is a mechanical aggregation of interacting, but mutually independent processes that constitute the building blocks of the model. Each independent process—chemical, physical or physiological—is based on empirical dependencies on environmental drivers (Belyazid et al. 2006; Wallman et al. 2005). The model was designed for the purpose of simulating the dynamic responses of forest ecosystems to environmental changes. ForSAFE combines the process algorithms of four established models: the tree growth model PnET (Aber and Federer 1992), the soil chemistry model SAFE (Alveteg 1998), the decomposition model Decomp (Wallman et al. 2006; Walse et al. 1998) and the hydrology model PULSE (Lindström and Gardelin 1992). Merging these components brings together the three basic material and energy cycles in a single integrated model: the biological cycle representing the processes involved in tree growth; the biochemical cycle including uptake, litter decomposition and soil nutrient and hydrological dynamics; and the geochemical cycle including atmospheric deposition and weathering processes (Fig. 1).

Input data

The ForSAFE model requires input data on deposition, climate, soil properties, tree species and forest management practices. Data sources used in this study are summarized in Table 1.

The model was applied to 544 productive forest sites in Sweden included in the Swedish National Forest Inventory.

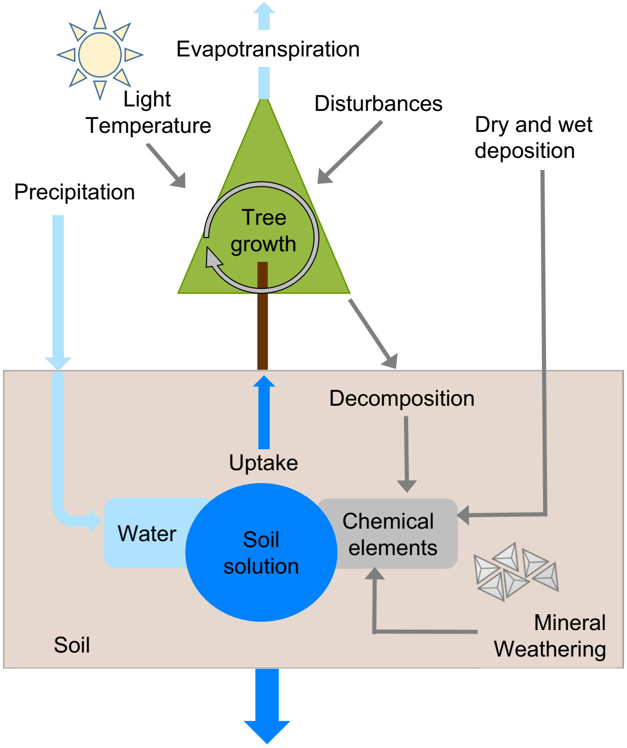

Fig. 1 Illustration of the ForSAFE model—the potential tree growth is driven by temperature and solar radiation. This potential growth is constrained by water and nutrient availability. Nutrient availability is determined by decomposition, deposition and mineral weathering. Tree growth is further affected by disturbances, such as forest management and storms

Table 1 Summary of the input data to ForSAFE

Input data	Source
Climate	
Precipitation and temperature	Historical records from the Swedish Meteorological Institute (SMHI) and the two future projections using the ECHAM5-r3 and CCSM models following the A2 storyline of emissions (David Rayner, personal communication)
PAR	Global radiation from the NCEP/NCAR reanalysis converted into photosynthetically active radiation using SMHI's STRÅNG model
Deposition	
SO_4^{2-}, NO_3^-, NH_4^+	EMEP model (Simpson et al. 2012), historically according to the emission scenarios from Schöpp et al. (2003) and the future projections following the emissions scenario of the current legislation of the revised Gothenburg protocol of the Long Range Transboundary Air Pollution Convention (LRTAP)
Cl^-, Na^+, Ca^{2+}, K^+, Mg^{2+}	MATCH model (Persson et al. 1996), held constant over the simulation period
Soil	
Texture and mineralogy	Raw data from the Research Infrastructure National Forest Inventory (RINFI) of Sweden (Hägglund 1985). Soil mineralogy was estimated with the UPPSALA model based on soil total elemental analysis from the RINFI (Alveteg 2004)
Vegetation	
Tree species	Norway spruce, Scots pine
Management	Based on recommendations by the Swedish Forest Agency

The database describing soil properties at the studied sites was originally compiled by Warfvinge and Sverdrup (1995) and Alveteg (2004).

Climate

Monthly averages of the historical temperature and precipitation data for the period 1961–2010 were interpolated from the Swedish Meteorological Institute's station data for that period. Monthly averages of photosynthetically active radiation for the same period were converted from global radiation from the NCEP/NCAR reanalysis by calibrating with SMHI's STRÅNG model.

Temperature and precipitation trends from historical data were used to extend the climate series in the past back to 1900.

Future climate scenarios in 2010–2100 include:

- A baseline scenario (BAS), which projects steady temperatures and precipitation until 2100 by repeating the values of climate variables from 1981 to 2010 in the future.
- Two climate change scenarios derived from two global climate models (GCMs), namely the Max Plank Institute's ECHAM5 and the National Center for Atmospheric Research's CCSM3. Both models simulated future climate changes under the SRES A2 emissions storyline. The GCM data were calibrated so that the monthly means and variances matched the observations from 1961 to 2008 period (David Ryner, personal communication). Both GCMs predict a clear increase in winter and summer temperatures (Fig. 2). While the predicted increase in winter temperatures is geographically comparable, ECHAM gives a generally higher increase in summer temperatures, with a more pronounced increase in the south and the north-east. Both models predict an increase in winter precipitation, but differ markedly on summer precipitation. With the exception of a few east-coastal sites, CCSM gives a clear distinction between a wetter north and a drier south. ECHAM predicts drier summers overall except in the western half of central and northern Sweden and the very north-east.

Atmospheric deposition

The atmospheric deposition of nitrogen (N, reduced and oxidized) and sulphur (S) is derived from the EMEP model (Simpson et al. 2012) by associating each site with its corresponding cell on the EMEP grid. The historical N and S depositions were based on the emission trends described in Schöpp et al. (2003). The atmospheric deposition of calcium, magnesium, potassium, sodium and chloride were derived from the MATCH model (Langner et al. 1996) and Lövblad et al. (1992). The atmospheric deposition of base cations and chloride are held constant throughout the simulation period.

Soil data

In ForSAFE, the soil profile is represented as a column divided in discrete soil layers with homogeneous properties. The soil properties used as input data include information on texture, bulk density, base saturation, cation exchange

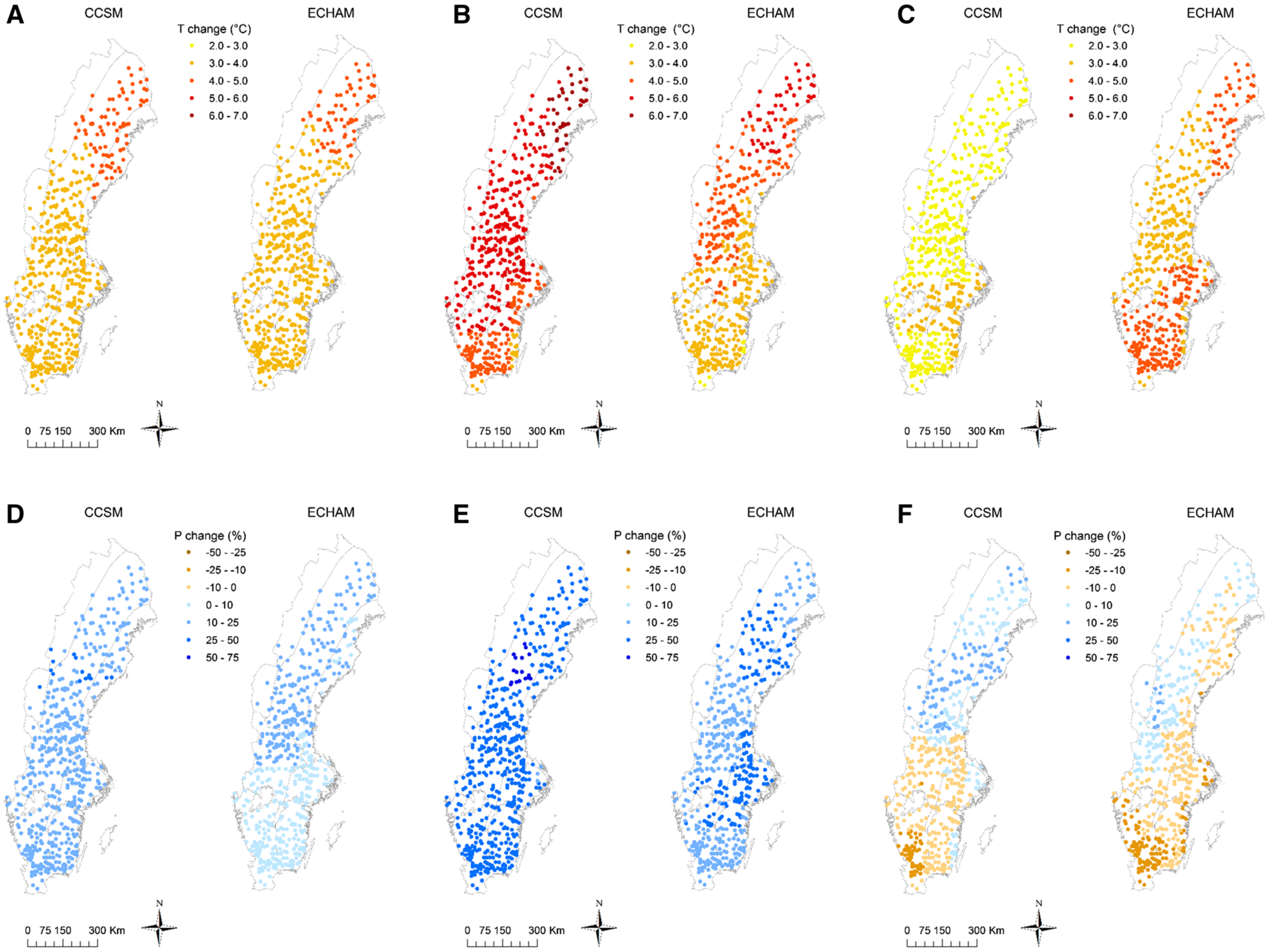

Fig. 2 Maps illustrating the change of temperature (T) and precipitation (P) under two climate change scenarios (CCSM, ECHAM) as compared to a future that does not include climate changes (BAS). The difference is an average value in 2070–2100 for each climate variable. CCSM: difference between CCSM and BAS scenarios; ECHAM: difference between ECHAM and BAS scenarios; **a** change of mean yearly temperature (°C); **b** change of mean winter temperature (°C); **c** change of mean summer temperature (°C); **d** change of annual precipitation (%); **e** change of winter precipitation (%); **f** change of summer precipitation (%)

capacity, hydraulic properties (field saturation, field capacity and wilting point) and mineralogy composition for each soil layer.

The soil database was originally compiled by Alveteg (2004) based on Swedish National Forest Inventory (SNFI) data (Hägglund 1985). The availability of soil base saturation (BS) in a subset of the SNFI dictated the selection of sites included in this study. Observed base saturation is necessary to back calculate the initial base saturation at the starting year of the simulations. The initial base saturation is found by iteratively and adaptively selecting starting values so that the simulated BS levels match the observed values on the observation years (Belyazid et al. 2006).

Vegetation

The 544 forest sites included in this study are managed forests dominated by Scots pine and/or Norway spruce. Parametrization data to the model include vegetation parameters that regulate photosynthesis, tree phenology, tree water use, nutrient allocation in the biomass and mortality rates. More detailed information on the vegetation parameters are reported in the Electronic Supplementary Material, Table S1.

Forest management

In ForSAFE, the modelled forest growth at each site is affected by the length of the rotation period and the amount and intensity of the thinnings. The forest management scenarios applied in this study were based on the current recommendations for spruce and pine forests in Sweden which vary according to the tree species, geographical location (north or south of Sweden) and the productivity of the site (Jacobson et al. 2008). The rotation length was further corrected based on information on the stand age data from the Swedish National Forest Inventory (Zanchi and Belyazid 2019). The number and the age of thinnings were based on the indications provided for spruce and pine in the management tables (*gallringsmall*) developed by the Swedish Forest Agency. To validate model results, we compared the modelled tree biomass against calculated values of tree biomass based on National Forest Inventory data on tree diameter. Measured data on tree diameter were converted to tree biomass based on the functions by Marklund (1988) for Scots pine and Norway Spruce. The calculated tree biomass was compared to the modelled biomass at the year of measurement for each simulated site and aggregated over seven climatic regions (Naturvårdsverket 2016). The comparison showed that the modelled tree biomass was generally in good agreement with the estimated biomass based on SNFI data (Fig. 3).

Data analysis

The ForSAFE model is applied to analyse the effects of climate change on future water deficiency and carbon stocks in Swedish forests. For this purpose, we simulated the development of indicators for water deficiency and carbon stocks in trees and topsoil under the baseline climate scenario and two climate change scenarios. The effects of climate change are evaluated as a per cent difference between the indicator value (X) under the climate scenario (CC) and the baseline scenario (BAS):

$$\Delta X(\%) = \frac{X_{\mathrm{CC}} - X_{\mathrm{BAS}}}{X_{\mathrm{BAS}}} \times 100 \qquad (1)$$

As a first step, we simulated the relative evapotranspiration at the 544 sites in 1900–2100 under the baseline and climate change scenarios. Relative evapotranspiration (RET) is the per cent ratio between actual (AET) and potential evapotranspiration (PET). A value less than 100% indicates that water availability is less than water demand which indicates drought stress. Therefore, RET can be used to assess tree water deficiency (WD):

$$\mathrm{WD}(\%) = 100 - \mathrm{RET}(\%) = \left(1 - \frac{\mathrm{AET}}{\mathrm{PET}}\right) \times 100 \qquad (2)$$

A WD value of 0 indicates no water deficiency, while a value towards 100% means complete lack of water for plant uptake (i.e. water content below wilting point).

As a second step, we simulated the carbon content in tree biomass (TreeC) and topsoil (SOC) over the period 1900–2100 under the baseline and climate change scenarios to evaluate the effects of climate change on forest carbon stocks (see Eq. 1). Finally, we analysed the relations between carbon stock changes and changes of temperature, precipitation and relative evapotranspiration to understand which variables better explain the changes of TreeC and SOC in the future. The analysis on the summer period refers to the months June, July and August, while the winter period includes the months December, January and February.

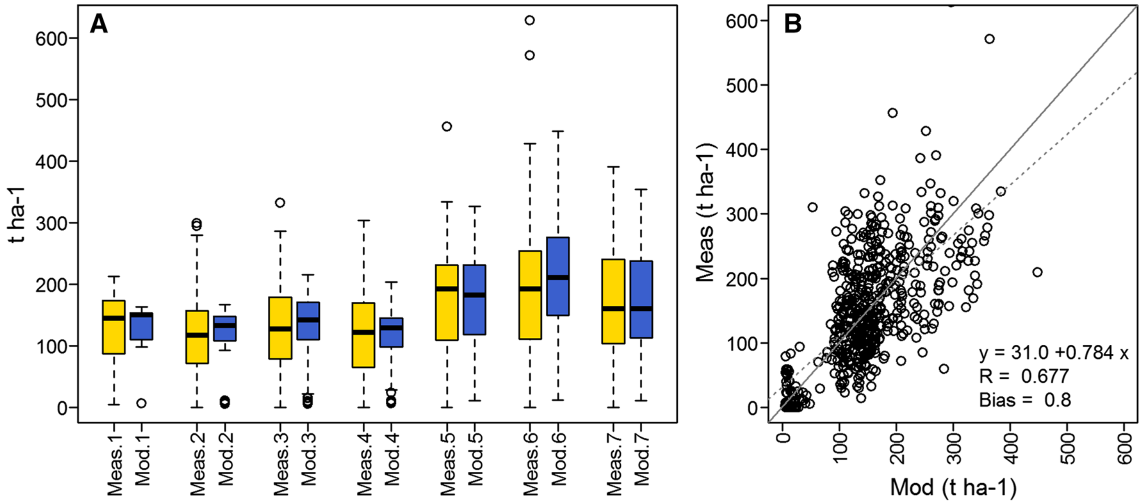

Fig. 3 Modelled tree biomass as compared to the estimated one based on SNFI data. **a** Comparison at the regional level (Meas: estimated tree biomass based on SNFI data; Mod: modelled tree biomass; 1–7: climate regions from northern to southern Sweden). **b** One-to-one comparison between measure-based (Meas) and modelled tree biomass (Mod)

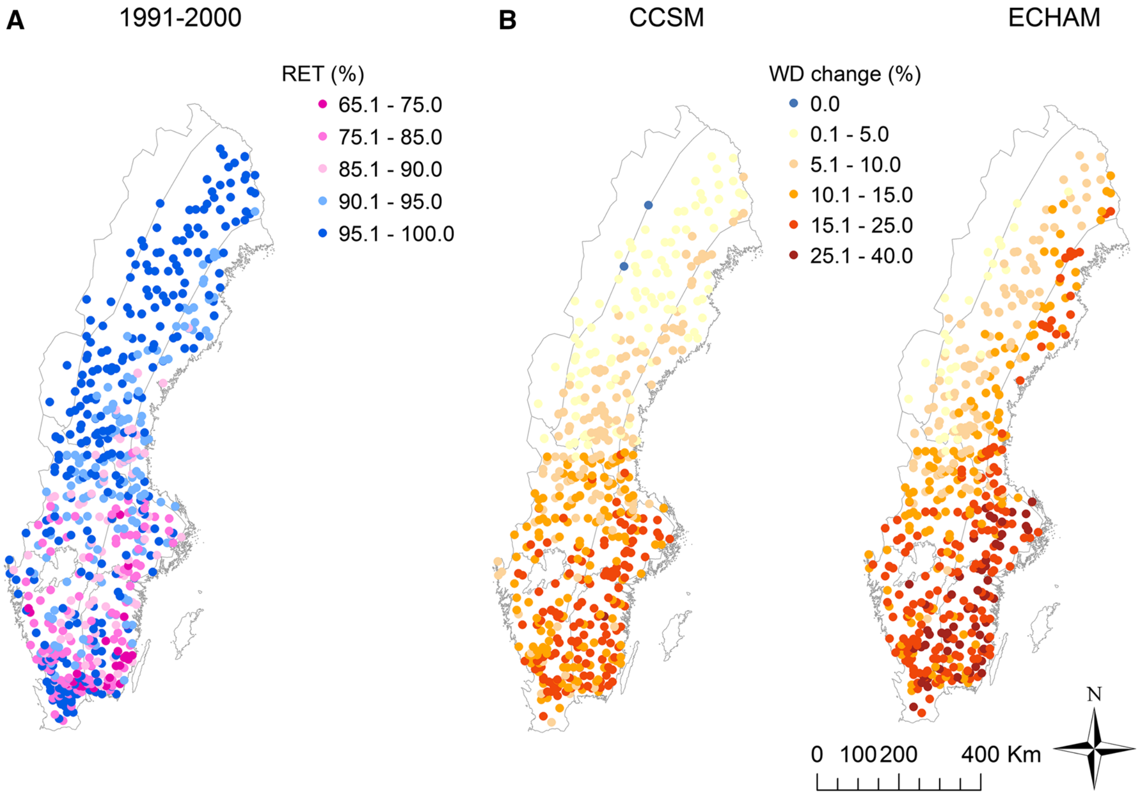

Fig. 4 Simulated water deficiency in Swedish forests. **a** Mean relative evapotranspiration (RET) in 1991–2000; **b** mean change of water deficiency (WD, %) in 2071–2100 under the two climate change scenario (ECHAM, CCSM) as compared to the baseline climate scenario

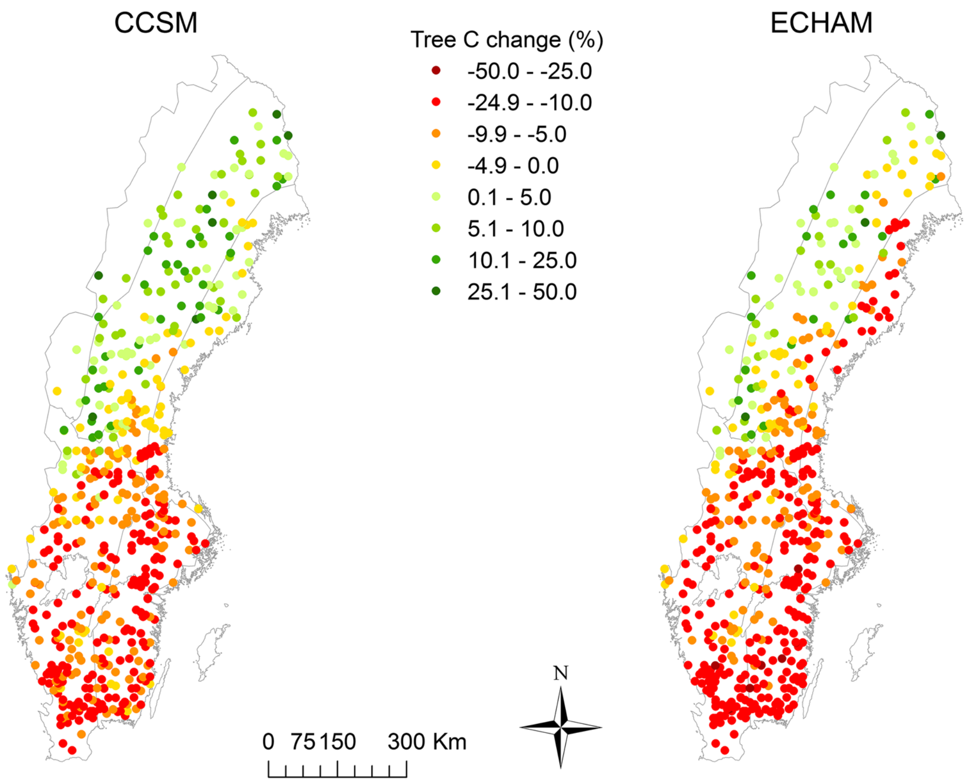

Fig. 5 Changes of tree carbon stock produced by climate change as compared to a future without climate change. The effects of two different climate change scenarios are presented (CCSM, ECHAM)

Results

Water deficiency

Model results on the relative evapotranspiration (RET) for the period 1991–2000 show that in some areas in Sweden, forest growth is already today constrained by water availability (Fig. 4a). Coniferous forests are currently most water-limited in the south-east of Sweden. Water deficiency is also higher closer to the coastal regions compared to the inland regions. In northern Sweden, forest growth is not constrained by water availability, since the actual evapotranspiration is equal to the potential evapotranspiration. The results are in agreement with previous results presented in van Leeuwen et al. (2000) on the ratio between actual and relative transpiration in European forests, showing similar trends and range of variations. In addition, few experimental studies confirm that forest growth of Norway spruce is constrained by water availability in southern Sweden (Bergh et al. 1999, 2005).

The simulation of future tree water deficiency (WD) under the baseline and climate change scenarios at the 544 forest sites projects that existing water limitation patterns will be exacerbated by climate change as compared to the baseline (Fig. 4b). WD will become even more severe in central and southern regions and in the coastal areas. These changes are a combination of increased temperature affecting transpiration through increasing the vapour pressure difference and changes of summer precipitation affecting water inputs during the growing season. The Swedish forest areas that will be most water-limited correspond to the areas where higher temperatures will be combined with lower summer precipitation. According to the CCSM climate model, this will cover the southern half of Sweden, while according to ECHAM, this may stretch along the coast to northern Sweden (Fig. 4b).

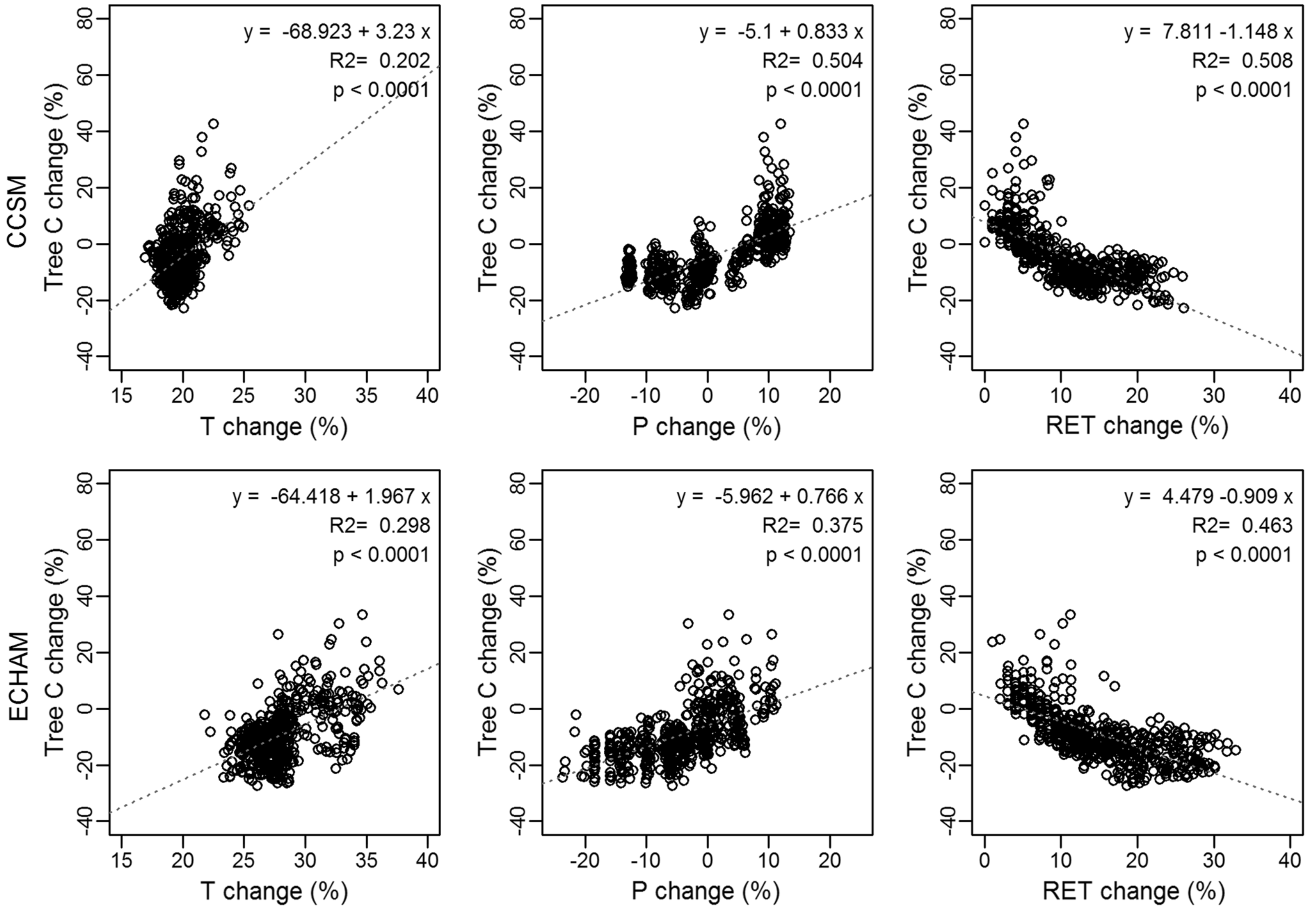

Fig. 6 Linear regressions between changes in tree carbon stock (Tree C change) and change of summer temperature (T change), summer precipitation (P change) and summer relative evapotranspiration (RET change). The changes correspond to the per cent difference between the variable under the climate scenario (CCSM, ECHAM) and under the baseline climate

Tree carbon

The future tree carbon stock under a changed climate is projected to be higher than under a baseline climate in the northern regions, but lower in southern regions (Fig. 5). Using the ECHAM model, projection of climate extends the reduction in tree carbon also to north-eastern coast. When comparing the geographical pattern of the tree C stock changes to the maps illustrating future climate changes, the pattern reflects the future changes in water deficiency illustrated in the previous section. When comparing to future climate changes, there is a clear link between changes of tree C stock and changes of summer precipitation (Fig. 6). Although annual precipitation is expected to increase under climate change (see Fig. 2), both climate models indicate a decrease in summer precipitation. It is this decline in water availability during the growing season that drives the decline in tree carbon. The link with summer precipitation shows that future tree carbon stocks will be most significantly affected by climate during the growing season. An analysis of the linear regression between changes in tree carbon stock and summer temperature, summer precipitation and relative evapotranspiration show that all the relationships are significant. The change of relative transpiration and of summer precipitation are better predictors for the tree carbon stock change than summer temperature, as indicated by the higher R^2 values.

Soil carbon

The overall response of soil organic carbon (SOC) to climate change (Fig. 7) is less pronounced than that of tree carbon shown above. Geographically, SOC is expected to decrease in the southern part of Sweden, with less clear differences between the two climate scenarios. In the northern half of Sweden, SOC is not expected to change significantly, despite the marked change in tree carbon.

The change in SOC is significantly and positively related to temperature and precipitation increases, and significantly negatively related to the change in ERT (Fig. 8). SOC relates more strongly to changes in temperature than changes in precipitation and RET (given by the higher slope value), although the spread of the former regression is wider (given by the lower R^2 values). Positive change in summer precipitation drives a more expressed increase in SOC, than a decline in precipitation drives a corresponding decline in SOC.

Discussion and conclusions

The results are able to verify the first hypothesis of the study that lower summer precipitation has the potential to override the positive effect of higher temperatures on forest growth. While higher temperatures are expected to promote growth

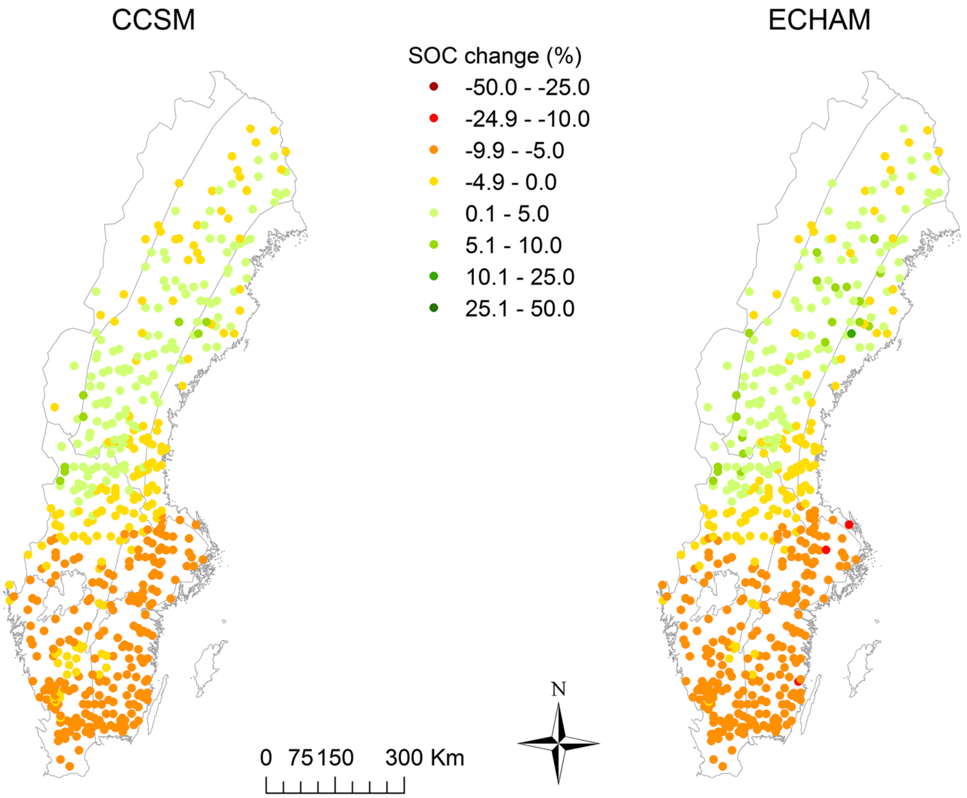

Fig. 7 The change in soil organic carbon (SOC) in a future with climate change according to two climate models (CCSM and ECHAM) as compared to a hypothetical future without climate change

in the north and north-western parts of Sweden, lower water availability in the south may drive a net reduction in tree carbon stocks compared to a hypothetical baseline without climate change.

The second hypothesis, the effect of climate change on soil carbon will be inconclusive, could not be verified by the study. Instead, the results show a similar pattern to tree carbon, with a possible increase in the north and a decrease in the south in response to climate change. The change in soil carbon is, nevertheless, less expressed than the change in tree carbon.

The simulations show that water deficiency is already today a limiting factor to growth in many parts of Sweden and more severe in the south-eastern part of the country. This is one of only a few studies to address water stress in Swedish forests (Bergh et al. 1999; van Leeuwen et al. 2000) and the first to analyse the possible effects on forest growth on a national scale.

The simulated lower water availability during the growing season is expected to become more severe in the future, restricting and even demoting forest growth. While this effect of lower water availability on forest growth is not confirmed by other investigations specific to Sweden, it is in line with other regional studies (Gustafson et al. 2017; Reichstein et al. 2007; von Buttlar et al. 2018). The negative effect of the simulated climate change scenarios on ecosystem productivity is more expressed in the southern Sweden where elevated temperatures coincide with lower summer precipitation, as is corroborated by the findings by von Buttlar et al. (2018). These results can be considered conservative given that the model only simulates changes in photosynthesis and respiration; droughts combined with high temperatures can additionally lead to forest dieback (Allen et al. 2010; Michaelian et al. 2010; Price et al. 2013) and more frequent and severe disturbances such as pests and fires (Astrup et al. 2018; Brecka et al. 2018; Jönsson et al. 2007), further exacerbating the effect of future climate on forest productivity.

The simulations also indicate that using annual projections of precipitation to forecast forest growth may be misleading, given that annual precipitation is expected to increase all over the country. In contrast, it is more relevant to focus on summer precipitation which more closely affects forest growth. According to our results, higher

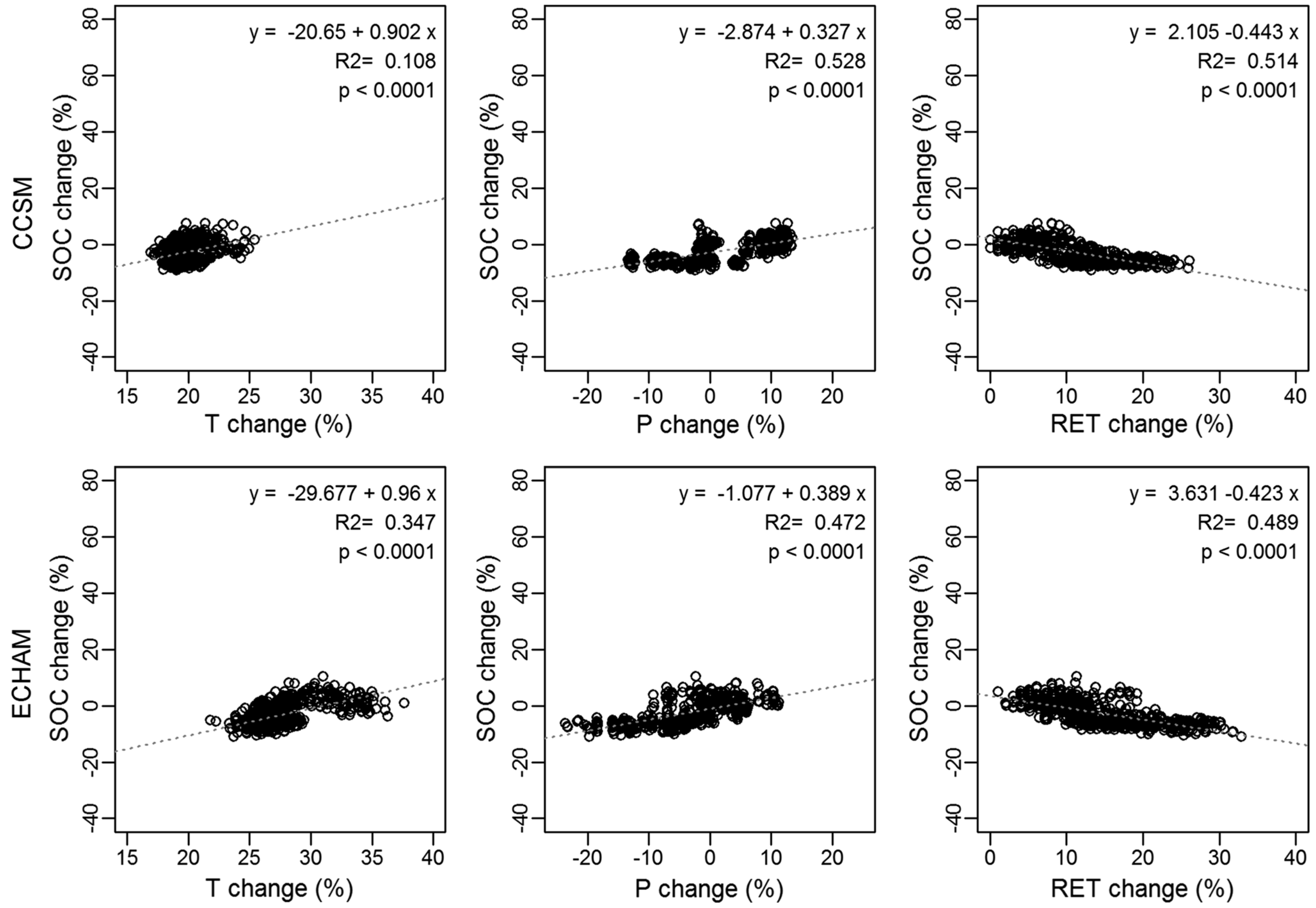

Fig. 8 Linear regressions between changes in soil organic carbon (SOC) and change in summer temperature (T change), summer precipitation (P change) and summer relative evapotranspiration (RET change) given by two climate scenarios (CCSM and ECHAM)

water deficiency during the growing season is likely to become a reality in all of Sweden, more so in the south and east, but even in the rest of the country. This creates new challenges that Sweden's current forestry model is not well adapted to deal with. At the same time, yearly precipitation levels are expected to increase because of a significant increase in winter precipitation, having implications on the water-regulating function of forests. Combined with increased temperatures, higher winter precipitation may have substantial implications on the hydrological fluxes even on a landscape level. Forestry can, however, be effective in adapting to and mitigating these changes through the choice of alternative forest management regimes (Aussenac and Granier 1988; Kubin et al. 2017; Roche et al. 2018) or different tree species (Ellison et al. 2017). It remains urgent to explore the economic and technical feasibility of these measures to select appropriate management strategies in a timely manner.

Ecosystem productivity, expressed as tree carbon and soil carbon stocks, is likely to be constrained by climate change in the simulated future. This further stresses the need to review forestry practices that have traditionally been put forward to stimulate forest growth but implicitly assumed no risk of water limitation. The choice of tree species, soil preparation techniques (such as scarification and clearing of ditches) and the prospect of increasing productivity through fertilization all need to be reviewed in light of the possibility of water scarcity.

The results of this study challenge the prospect of maintaining the current levels of high forest productivity in Sweden, and points to a limited possibility of increased forest productivity with current management practices. The expectation of using forest products and services as a cornerstone in Sweden's effort to reach climate neutrality cannot ignore the plausible possibility that climate change may constrain the supply of those services.

Acknowledgements The authors would like to thank Formas for the financial support granted under the projects QWARTS and ForWater and the Swedish Energy Agency.

Funding Funding was provided by the Swedish Research Council (Formas) (projet numbers 2011–01691 and 2010–89) and by the Swedish Energy Agency (Energimyndigheten).

References

Aber JD, Federer CA (1992) A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. Oecologia 92:463–474. https://doi.org/10.1007/bf00317837

Allen CD et al (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Alveteg M (1998) Dynamics of forest soil chemistry. Lund University, Lund

Alveteg M (2004) Projecting regional patterns of future soil chemistry status in Swedish forests using safe. In: Wieder RK, Novák M, Vile MA (eds) Biogeochemical investigations of terrestrial, freshwater, and wetland ecosystems across the globe. Springer, Dordrecht, pp 49–59. https://doi.org/10.1007/978-94-007-0952-2_4

Astrup R, Bernier PY, Genet H, Lutz DA, Bright RM (2018) A sensible climate solution for the boreal forest. Nat Clim Change 8:11–12. https://doi.org/10.1038/s41558-017-0043-3

Aussenac G, Granier A (1988) Effects of thinning on water stress and growth in Douglas-fir. Can J For Res 18:100–105. https://doi.org/10.1139/x88-015

Belyazid S, Westling O, Sverdrup H (2006) Modelling changes in forest soil chemistry at 16 Swedish coniferous forest sites following deposition reduction. Environ Pollut 144:596–609. https://doi.org/10.1016/j.envpol.2006.01.018

Bergh J, Linder S, Lundmark T, Elfving B (1999) The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. For Ecol Manag 119:51–62. https://doi.org/10.1016/S0378-1127(98)00509-X

Bergh J, Linder S, Bergström J (2005) Potential production of Norway spruce in Sweden. For Ecol Manag 204:1–10. https://doi.org/10.1016/j.foreco.2004.07.075

Bradshaw CJA, Warkentin IG (2015) Global estimates of boreal forest carbon stocks and flux. Global Planet Change 128:24–30. https://doi.org/10.1016/j.gloplacha.2015.02.004

Brecka AFJ, Shahi C, Chen HYH (2018) Climate change impacts on boreal forest timber supply. For Policy Econ 92:11–21. https://doi.org/10.1016/j.forpol.2018.03.010

Canadell JG, Raupach MR (2008) Managing forests for climate change mitigation. Science 320:1456–1457. https://doi.org/10.1126/science.1155458

Cintas O et al (2017) The potential role of forest management in Swedish scenarios towards climate neutrality by mid century. For Ecol Manag 383:73–84. https://doi.org/10.1016/j.foreco.2016.07.015

Ellison D et al (2017) Trees, forests and water: cool insights for a hot world. Global Environ Change 43:51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002

Gauthier S, Bernier P, Kuuluvainen T, Shvidenko AZ, Schepaschenko DG (2015) Boreal forest health and global change. Science 349:819–822. https://doi.org/10.1126/science.aaa9092

Gustafson EJ, Miranda BR, De Bruijn AMG, Sturtevant BR, Kubiske ME (2017) Do rising temperatures always increase forest productivity? Interacting effects of temperature, precipitation, cloudiness and soil texture on tree species growth and competition. Environ Model Softw 97:171–183. https://doi.org/10.1016/j.envsoft.2017.08.001

Hägglund B (1985) En ny svensk riksskogstaxering (A new Swedish National Forest Survey). Swedish University of Agricultural Sciences, Report 37. Uppsala, Sweden (In Swedish with English summary)

IPCC (2001) Chapter 4—hydrology and water resources. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Climate change 2001: impacts, adaptation and vulnerability, Contribution of Working Group II to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 191–234

Jacobson S, Sikström U, Nyström K, Övergaard B (2008) INGVAR—thinning schedules and forest management planning tool. (In Swedish with English Summary). SkogForsk, Uppsala

Jönsson AM, Harding S, Bärring L, Ravn HP (2007) Impact of climate change on the population dynamics of Ips typographus in southern Sweden. Agric For Meteorol 146:70–81. https://doi.org/10.1016/j.agrformet.2007.05.006

Kellomäki S, Strandman H, Heinonen T, Asikainen A, Venäläinen A, Peltola H (2018) Temporal and spatial change in diameter growth of Boreal Scots Pine, Norway Spruce, and Birch under Recent-Generation (CMIP5) global climate model projections for the 21st century. Forests 9:118

Kubin E, Křeček J, Palán L (2017) Effects of forest practices on water resources recharge in the boreal. Clim Environ Process 4:509–522. https://doi.org/10.1007/s40710-017-0249-4

Langner J, Persson C, Robertson L, Ullerstig A (1996) Air pollution assessment study using the MATCH Modelling System. Application to sulphur and nitrogen compounds over Sweden 1994. Swedish Meteorological and Hydrological Institute, Report no. 69, Norrköping

Lindström G, Gardelin M (1992) Chapter 3.1: hydrological modelling—model structure. In: Modelling groundwater response to acidification vol 5. SMHI, Reports Hydrology, Norrköping

Lövblad G, Andersen B, Joffre S, Pedersen U, Hovmand M, Reissell A (1992) Mapping deposition of sulphur, nitrogen and base cations in the Nordic countries. Swedish Environmental Research Institute. Report B 1055, Stockholm

Lundmark T et al (2014) Potential roles of Swedish forestry in the context of climate change mitigation forests 5. https://doi.org/10.3390/f5040557

Lundmark R, Athanassiadis D, Wetterlund E (2015) Supply assessment of forest biomass—a bottom-up approach for Sweden. Biomass Bioenergy 75:213–226. https://doi.org/10.1016/j.biombioe.2015.02.022

Marklund LG (1988) Biomassafunktioner för tall, gran och björk i Sverige vol Rapport 45. Sveriges lantbruksuniversitet, Institutionen för skogstaxering

Michaelian M, Hogg Edward H, Hall Ronald J, Arsenault E (2010) Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Global Change Biol 17:2084–2094. https://doi.org/10.1111/j.1365-2486.2010.02357.x

Ministry of Environment (2014) Sweden's sixth national report on climate change (in Swedish) vol Ds 2014:11. Swedish Ministry of Environment and Energy, Stockholm

Naturvårdsverket (2016) Climate change and the environmental objectives—CLEO (in Swedish), vol 6705. Bromma, Sweden

Peng C, Ma Z, Lei X, Zhu Q, Chen H, Wang W, Liu S, Li W, Fang X, Zhou X (2011) A drought-induced pervasive increase in tree mortality across Canada's boreal forests. Nat Clim Change 1:467–471

Persson C, Langner J, Robertson L (1996) Air pollution assessment studies for Sweden based on the match model and air pollution measurements. In: Gryning S-E, Schiermeier FA (eds) Air pollution modeling and its application XI. Springer, Boston, pp 127–134. https://doi.org/10.1007/978-1-4615-5841-5_15

Poudel BC, Sathre R, Gustavsson L, Bergh J, Lundström A, Hyvönen R (2011) Effects of climate change on biomass production and substitution in north-central Sweden. Biomass Bioenergy 35:4340–4355. https://doi.org/10.1016/j.biombioe.2011.08.005

Price DT et al (2013) Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environ Rev 21:322–365. https://doi.org/10.1139/er-2013-0042

Reichstein M et al (2007) Determinants of terrestrial ecosystem carbon balance inferred from European eddy covariance flux sites. Geophys Res Lett. https://doi.org/10.1029/2006gl027880

Roche JW, Goulden ML, Bales RC (2018) Estimating evapotranspiration change due to forest treatment and fire at the basin scale in the Sierra Nevada, California. Ecohydrology. https://doi.org/10.1002/eco.1978

Schöpp W, Posch M, Mylona S, Johansson M (2003) Long-term development of acid deposition (1880–2030) in sensitive freshwater regions in Europe. Hydrol Earth Syst Sci 7:436–446. https://doi.org/10.5194/hess-7-436-2003

SGU (2018) Grundvattennivåns avvikelse historiskt. https://www.sgu.se/grundvatten/grundvattennivaer/slider/. 07-11-2018

Simpson D et al (2012) The EMEP MSC-W chemical transport model—technical description. Atmos Chem Phys 12:7825–7865. https://doi.org/10.5194/acp-12-7825-2012

Soja AJ et al (2007) Climate-induced boreal forest change: predictions versus current observations. Global Planet Change 56:274–296. https://doi.org/10.1016/j.gloplacha.2006.07.028

SOU 2016: 47 (2016) A climate and air conservation strategy for Sweden (in Swedish). Stockholm, Sweden. https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2016/06/en-klimat–och-luftvardsstrategi-for-sverige/

Swedish Government (2017) Environmental objectives—with a view to the future (in Swedish), Skr. 2017/18:265. https://data.riksdagen.se/fil/EDA7C87D-9121-4D0D-A03E-DC33C06E745A. Accessed 24 Jan 2019

van Leeuwen EP, Hendriks KCMA, Klap JM, de Vries W, de Jong E, Erisman JW (2000) Effects of environmental stress on forest crown condition in Europe. Part II: estimation of stress induced by meteorology and air pollutants. Water Air Soil Pollut 119:335–362. https://doi.org/10.1023/A:1005182226292

von Buttlar J et al (2018) Impacts of droughts and extreme-temperature events on gross primary production and ecosystem respiration: a systematic assessment across ecosystems and climate zones. Biogeosciences 15:1293–1318. https://doi.org/10.5194/bg-15-1293-2018

Wallman P, Svensson MGE, Sverdrup H, Belyazid S (2005) ForSAFE—an integrated process-oriented forest model for long-term sustainability assessments. For Ecol Manag 207:19–36. https://doi.org/10.1016/j.foreco.2004.10.016

Wallman P, Belyazid S, Svensson MGE, Sverdrup H (2006) DECOMP—a semi-mechanistic model of litter decomposition. Environ Model Softw 21:33–44. https://doi.org/10.1016/j.envsoft.2004.09.026

Walse C, Berg B, Sverdrup H (1998) Review and synthesis of experimental data on organic matter decomposition with respect to the effect of temperature, moisture, and acidity. Environ Rev 6:25–40. https://doi.org/10.1139/a98-001

Wang Y, Hogg EH, Price DT, Edwards J, Williamson T (2014) Past and projected future changes in moisture conditions in the Canadian boreal forest. For Chron 90:678–691. https://doi.org/10.5558/tfc2014-134

Warfvinge P, Sverdrup H (1995) Critical loads of acidity to Swedish forest soils, vol 5. Lund University, Lund

Zanchi G, Belyazid S (2019) Swedish forests are greyer than prescribed. (manuscript in preparation)