

RESEARCH ARTICLE

Current and future drought vulnerability for three dominant boreal tree species

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Abstract

Climate change is projected to increase the frequency and severity of droughts, possibly causing sudden and elevated tree mortality. Better understanding and predictions of boreal forest responses to climate change are needed to efficiently adapt forest management. We used tree-ring width chronologies from the Swedish National Forest Inventory, sampled between 2010 and 2018, and a random forest machine-learning algorithm to identify the tree, stand, and site variables that determine drought damage risk, and to predict their future spatial-temporal evolution. The dataset consisted of 16,455 cores of Norway spruce, Scots pine, and birch trees from all over Sweden. The risk of drought damage was calculated as the probability of growth anomaly occurrence caused by past drought events during 1960–2010. We used the block cross-validation method to compute model predictions for drought damage risk under current climate and climate predicted for 2040–2070 under the RCP.2.6, RCP.4.5, and RCP.8.5 emission scenarios. We found local climatic variables to be the most important predictors, although stand competition also affects drought damage risk. Norway spruce is currently the most susceptible species to drought in southern Sweden. This species currently faces high vulnerability in 28% of the country and future increases in spring temperatures would greatly increase this area to almost half of the total area of Sweden. Warmer annual temperatures will also increase the current forested area where birch suffers from drought, especially in northern and central Sweden. In contrast, for Scots pine, drought damage coincided with cold winter and early-spring temperatures. Consequently, the current area with high drought damage risk would decrease in a future warmer climate for Scots pine. We suggest active selection of tree species, promoting the right species mixtures and thinning to reduce tree competition as promising strategies for adapting boreal forests to future droughts.

KEYWORDS

birch, climate change adaptation, drought risk, machine learning, Norway spruce, random forest, Scots pine, tree-ring data

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1 | INTRODUCTION

Increasing global temperatures with higher atmospheric evaporative demand are leading to more frequent and severe droughts with a critical impact on human and environmental systems (Hammond et al., 2022; Vicente-Serrano et al., 2022). Intense and recurrent droughts have resulted in tree-crown defoliation (Moreno-Fernández et al., 2022), shifts from carbon sinks to sources (Anderegg et al., 2015; Kannenberg et al., 2020), and growth decline and/or mortality of trees across all forest types (DeSoto et al., 2020; Senf et al., 2020). As a consequence, changes in community structure and species distributions are ongoing (Brodribb et al., 2020). The frequency and severity of droughts are projected to increase in the future (Balting et al., 2021; Rakovec et al., 2022), leading to a shift in community diversity due to the projected high mortality of some species (Gazol & Camarero, 2022; Hartmann et al., 2022). Forests worldwide are becoming more vulnerable to sequential or multiple droughts (Anderegg et al., 2020; Moravec et al., 2021), and boreal forests are predicted to be especially susceptible to global change (Anderegg et al., 2022; Hammond et al., 2022).

Boreal forests, such as those in Scandinavia, are an essential part of the climate system that controls and stores greenhouse gases on Earth (IPCC, 2019). Climatic changes toward longer and warmer growing seasons may increase timber production in boreal forests (Bergh et al., 2010). However, recent observations show decreasing annual volume growth in northern European forests, possibly due to higher evaporative demand (Fridman et al., 2022; Mäkinen et al., 2022). Thus, the productivity increment could partly be offset by more frequent summer droughts. Like most of Europe, Sweden has recently suffered unusual summer heatwaves, for example in 2003 and 2018, causing very low tree growth (Buras et al., 2020; Moravec et al., 2021) and leading to recently identified mortality hotspots (Neumann et al., 2017). In this situation, droughts can be a predisposing factor increasing the vulnerability of the forests to other abiotic and biotic damages (Forzieri et al., 2021) such as fire (Ou, 2017), timber cracks (Rosner et al., 2018), and bark beetle attacks (Jönsson & Lagergren, 2018).

Of the countries in Europe, Sweden is one of the most forested and most economically reliant on the forest industry (Coyette & Schenk, 2019). Swedish forests will face altered growing conditions in the future, and how tree species will respond to these changes is still uncertain. Swedish forests are dominated by a few common Eurasian boreal tree species: Norway spruce (*Picea abies* L. Karst.), Scots pine (*Pinus sylvestris* L.), and birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.). Summer droughts strongly reduce growth for the both pine and spruce (Lévesque et al., 2014; Tremli et al., 2021; Zang et al., 2014). Fast dehydration and hydraulic collapse cause summer drought-induced mortality in adult Norway spruce (Arend et al., 2021). Accordingly, this species is regarded as more vulnerable to summer drought, while Scots pine is more susceptible to winter drought because it starts to produce tracheids earlier (Mäkinen et al., 2018). Birch is the most common broadleaf tree genus in northern Europe and mostly occupies relatively wet

soils. For this species, summer water shortage seems to be the main growth reduction driver while winter conditions have a secondary role (Matisons et al., 2022). Goude et al. (2022) predicted Scots pine growth to slow in south-eastern Sweden and increase in north-western Sweden in the future. Simultaneously, Norway spruce may suffer in the southern and eastern parts of the country (Goude et al., 2022).

In addition, other tree, stand, and site factors, which are not captured by climate data, might modify local soil conditions and microclimate, and hence, modulate tree drought responses (D'Orangeville et al., 2018; Steinkamp & Hickler, 2015). In this regard, competition could be even more relevant as a driver of growth compared to climate, and exacerbate drought effects (Sánchez-Salguero et al., 2015; Young et al., 2017). The identification of these factors may be key for developing new forest adaptation strategies to mitigate drought vulnerability risks.

Since it is urgent to adapt forest management to a warmer and drier future with more frequent droughts (Senf et al., 2020), improvement of both understanding and prediction of forest responses to climate change is needed (Hartmann et al., 2022). Accordingly, maps of forests' drought tolerance have proven to be a valuable tool for managers to mitigate the effects of climate change (Piedallu et al., 2022). National forest inventories (NFI) that perform systematic forest surveys across space and time along large environmental gradients are powerful tools to understand how climate controls forest growth at wide geographical scales, and may at the same time account for the effects of local abiotic and biotic interactions (Kulha et al., 2023). The Swedish NFI provides a dense network of plots with tree-ring data and information on forest characteristics (Fridman et al., 2014), useful for meaningful reconstructions and interpretations of regional-scale patterns of tree drought responses. Tree radial growth is more sensitive to climate extremes than other variables (Kannenberg et al., 2019; Moreno-Fernández et al., 2022) and can be used as an early-warning signal of mortality risk (Cailleret et al., 2017). Cailleret et al. (2019) found that abrupt decreases in annual growth are a robust early-warning signal of tree mortality. Therefore, growth anomalies and mortality are closely linked, as changes in growth rate can affect the health and resilience of trees, making them more susceptible to other environmental factors that can lead to tree death.

The objective of this study was to estimate drought vulnerability for the dominant boreal tree species listed above using the extensive tree-ring network, and stand and site information, from the Swedish NFI. The risk of drought damage was calculated based on the number of years with exceptionally low tree growth because of drought. We specifically aimed to know: (1) what were the most important predictors of forest drought vulnerability and (2) how the risk of drought damage will evolve in space and time due to climate change for the studied species. We expected that, although influenced by other intrinsic factors, local climate was the most significant predictor of the risk of drought damage. Regardless of the species, we would anticipate a marked rise in the probability of drought-related damage in the future.

2 | MATERIALS AND METHODS

2.1 | Tree-ring, NFI, and climatic data

We used tree-ring data from Swedish NFI temporary plots, with cores that were taken between 2010 and 2018, for further analysis. Tree-ring cores were taken from one to three trees per plot which were mainly dominant or co-dominant (Fridman et al., 2014). The dataset consists of 6231, 8520, and 1704 cores for Norway spruce, Scots pine, and birch (*B. pendula* and *B. pubescens* were grouped together), respectively, evenly distributed along Sweden (Figures S1–S3). Tree-ring data are commonly used to calculate diameter growth, and also for detecting drought damage as described below. The Swedish NFI is based on square tracts, that is, clusters of circular permanent and temporary sample plots, with a side length of 300–1800 m. Tree and shrub characteristics are sampled using probability proportional to size (basal area) methods, so there are different circular subsample plots of different radii (1, 3.5, 7, and 20 m). More detailed information can be found in Fridman et al. (2014). Accordingly, the Swedish NFI provided detailed information about the state of forest resources at stand and tree level, as well as topography, soil, and local site conditions. We used information collected in the plot inventories at the same time as cores were taken (Table S1).

We obtained site-specific climate data from national meteorological services on a 4×4 km grid (re3data.org, 2022). Seasonal temperature was computed by averaging monthly values, and seasonal precipitation by summing monthly numbers. We also used a raster data layer with 2.5×2.5 km resolution for the different climate change scenarios from the Swedish Meteorological and Hydrological Institute forecast service (SMHI, 2022). The period 2041–2070 was used for average climate change scenarios in the near future, since at longer time horizon for emission scenarios would become more imprecise. Accordingly, the results are more helpful for supporting current forest management and decision-making processes. Data are open and free available in Zenodo public digital repository (Aldea & Dahlgren, 2023).

2.2 | Risk of drought damage

We defined a drought event as a year when a site's seasonal (autumn: October–December from the previous year; winter: January–March; spring: April–June; summer: July–September) or annual water balance was more than one standard deviation below the historical site mean. For that, the water balance of each period studied (seasonal or annual) was standardized based on the hydrological year. The water balance was calculated as the difference between monthly rainfall (seasonal or annual) and evapotranspiration calculated using the Thornthwaite equation (Thornthwaite, 1948). This computes the monthly potential evapotranspiration using monthly mean temperatures and site latitude (Vicente-Serrano et al., 2010).

We used the “dplR” R-package for the dendrochronological analysis (Bunn et al., 2021). The raw ring-width measurements were

converted to a standardized tree-ring width index by detrending with a 30-year cubic smoothing spline approach with a 50% frequency cutoff and pre-whitening process to remove the first residual autocorrelation. This method removes all but high-frequency variation in the series (Anderegg et al., 2015). Ring-width index series were discarded that failed to meet any of these three conditions: (1) a normal distribution, (2) a mean inter-series correlation above 0.4, and (3) an expressed population signal higher than 0.85 among the 30 series geographically closest to the target one. This process aimed to ensure a correct site-dating sequence and a common strength population signal. Afterward, we used the “zChron” pointer year detection method for each chronology (composed of 1–3 sampled trees per plot) to identify growth anomalies below -1.28 , that is, years when tree growth was lower than 90% of all observations from the entire chronology period (Jetschke et al., 2019). Then, we detected those anomalies which were in the time window common to all the chronologies (1960–2010) to allow comparison between species and sites. Finally, the probability of a growth anomaly for a tree species on a specific site due to drought, hereafter referred to as the “risk of drought damage,” was calculated as the proportion of years with negative anomalies which coincided with drought in the period common to all the chronologies. We also focused on climate–growth correlations for the tree species to clarify the relationship between climate and growth anomalies where necessary. For that reason, we performed a bootstrapped Pearson's correlation analysis with 1000 replicates and the same method in 25-year moving windows lagged by 1 year over the common period of 1960–2010.

2.3 | Statistical modeling and damage probability maps

We used a supervised machine-learning algorithm based on a random forest regression to predict the risk of drought damage for each species as a continuous outcome. The target or response variable for modeling propositions was calculated from the previously filtered chronologies with 1850, 2268, and 173 observations for Norway spruce, Scots pine, and birch, respectively (Figures S1–S3). Predictors were extracted from the climatic and NFI field data (Table S1). Those predictors were related to (1) climate (temperature and precipitation at different temporal scales and the Conrad–Pollak continentality index (CCI) (Conrad & Pollak, 1950) where low values indicate oceanic and high values continental climate), (2) stand (density, species-specific basal area, species proportion, and number of interventions), (3) tree (diameter, crown length, and social status), (4) topography (slope), and (5) site conditions (latitude, longitude, type of soil, and soil moisture). The random forest algorithm was combined with spatial cross-validation to increase outcome accuracy, since conventional random cross-validation techniques can lead to underestimation of prediction error and may result in inappropriate model selection (Valavi et al., 2019). Roberts et al. (2017) recommend this methodology to handle data with hierarchical and spatial dependence for selecting causal predictors and to predict beyond

the observed ranges of variables. This technique splits the area of the dataset into many spatial cells, or “blocks,” and then assigns all data into folds for cross-validation. There is no initial random shuffling of observations since the records are not independent. Consequently, we compared four different blocking strategies to evaluate the algorithm: random, systematic, checkerboard, and leave-one-out. Block size was chosen according to the level of spatial autocorrelation in the response and predictors according to geostatistical techniques, that is, semivariance plots (Figure S4). Then, the blocks were allocated to folds to determine training and testing sets. Finally, we contrasted the four different blocking strategies and the number of folds in cross-validation for each species' model and selected those with the highest R^2 and lowest root mean squared and mean absolute error (Tables S2–S4). We also checked the number of decision trees in the random forest algorithm; 100 was sufficient to observe a stable error (Figure S5). Once the final algorithm was chosen, the variable importance was computed according to the increment of mean squared error when permuting out of bag data. Next, partial dependence plots were calculated for the most important predictors by estimating the measure of change in the target variable (“yhat”) (Liaw & Wiener, 2002). Predictions for the total sample points were calculated from the final random-forest algorithm by each species to estimate the risk of drought damage for the current scenario based on recent climate data.

We also computed model simulations for the risk of drought damage in future climate scenarios based on three emissions scenarios known as “representative concentration pathways” (RCP) (Moss et al., 2010; van Vuuren et al., 2011):

1. RCP.2.6: Powerful climate policy leads emissions of greenhouse gases to decline rapidly, and radiative forcing reaches $2.6\text{W}/\text{m}^2$ in 2100, which is close to the ambitions of the Paris Agreement.
2. RCP.4.5: Strategies for reduced greenhouse gas emissions stabilize radiative forcing at $4.5\text{W}/\text{m}^2$ before 2100, described as an intermediate scenario close to the most probable situation.
3. RCP.8.5: Increasing greenhouse gas emissions push radiative forcing to $8.5\text{W}/\text{m}^2$ by 2100, resulting from a high-emission scenario caused by substantial new investments in fossil fuels and lack of global climate policy and governance.

Data from the rasterized climate scenarios (SMHI, 2022) were extracted for the locations of all sample sites (16,455 sites) by a map overlay operation (Hijmans, 2021). Since we aimed to predict beyond the range of historic climate variation, we used environmental blocks composed of model predictors to separate training and testing sets for more realistic error estimation (Valavi et al., 2019). Then, predictions from the random forest algorithm were calculated for all sample locations (Liaw & Wiener, 2002). Those values were then interpolated to regularly spaced grid cells (point to raster conversion) at a resolution offering the richest amount of information per unit area (Hijmans, 2021). This was based on the density/size ratio of the point cloud in the map where cell size was set to half the mean distance between nearest-neighbor points (Hengl, 2006). The

resulting grid resolutions for the final maps were $4\times 4\text{km}$, $3\times 3\text{km}$, and $7\times 7\text{km}$ for Norway spruce, Scots pine, and birch, respectively. Finally, the drought damage risk values were classified in five categories from very low to very high. Class intervals were defined by grouping for maximum homogeneity, that is, variance within groups was minimized, according to Fisher criteria (Fisher, 1958), considering all predicted values for the species and scenario for mapping (which ranged from 0% to 22%). Therefore, the drought damage risk classes were defined according to the probability of drought-induced growth anomalies as follows: very low: <6%, low: 6%–7.9%, medium: 8%–9.9%, high: 10%–11.9%, very high: >12%.

We used the “blockCV” (Valavi et al., 2019), “caret” (Kuhn, 2021), and “randomForest” (Liaw & Wiener, 2002) R packages for modeling analysis and the “raster” package for map algebra (Hijmans, 2021). All analyses were performed in R version 4.1.2. (R Development Core Team, 2023). R-code and the main model scripts are available in the Zenodo public digital repository (Aldea & Dahlgren, 2023).

3 | RESULTS

The predictive performance of the random forest algorithm for the risk of drought damage was good for all the studied species since the amount of variation explained by the regression (R^2) was higher than .83 with low root mean square and absolute errors (Tables S2–S4; Figure S6). The most important predictors in the algorithm consisted of 8, 13, and 6 variables for Norway spruce, Scots pine, and birch, respectively (Figure S7). Overall, the models' performance indicates that the predictions and maps could properly identify vulnerable forests for current and new climate scenarios.

3.1 | Drought damage risk for Norway spruce

The variables most associated with a high probability of drought damage for Norway spruce were climate related (Figure 1; Figure S7). Sites with a high mean spring temperature ($8\text{--}10^\circ\text{C}$), low accumulated precipitation from January to March (lower than 200mm), and an oceanic climate (negative values of CCI), which correspond to the southern part of Sweden, showed a higher risk of drought damage (Figure 1a–c). This risk also increased in pure, dense stands, and with tree size (Figure 1d–f). Therefore, climatic, stand, and tree factors all determine the risk of drought damage for Norway spruce in Sweden.

Currently, 34% of Sweden faces a medium risk of drought damage for Norway spruce, but the high-vulnerability area occupies 28% of the country and it will likely grow in the future (Figure 2). Both in southern and central Sweden, there are areas with high drought vulnerability. According to predicted values from the model, sites south of 60°N will be greatly affected by drought in the near future (Figure 2), increasing the high-probability damage area by 19% (Figure S8). Therefore, more than half of the country's area could be unsuitable in 2040–2070 for Norway spruce due to high drought vulnerability.

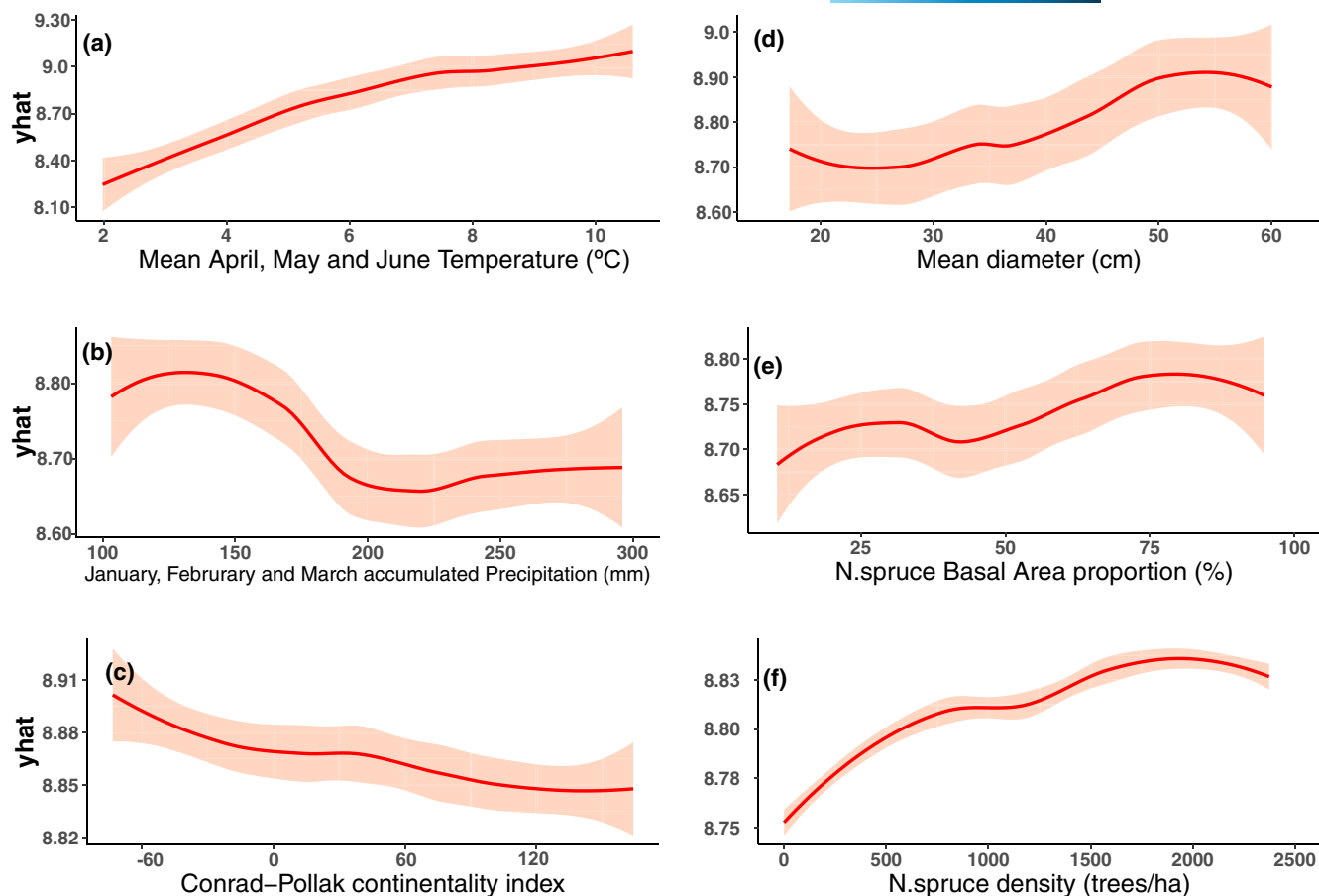


FIGURE 1 Partial dependence plots for the most important predictors of drought damage risk for Norway spruce: spring temperature (a), winter precipitation (b), CCI (c), mean tree diameter (d), basal area proportion of Norway spruce (e) and stand density (f). “y-hat” is the measure of change in the target variable. Low values of the Conrad–Pollak continentality index denote an oceanic climate.

3.2 | Drought damage risk for Scots pine

For Scots pine, climatic variables also strongly influence drought damage risk (Figure 3; Figure S7). Sites with cold temperatures (below 0°C) in March and April (such as north-western Sweden) showed a higher drought damage risk (Figure 3a). By comparing climate–growth responses, we found a positive relationship between Scots pine growth and late winter to early spring temperatures, which suggests that cold temperatures coincided with drought and tree-growth reduction (Figure 4). This pattern was observed across the country, although negative correlations were also occasionally detected (Figure 4a). We also detected a slight decreasing trend in the influence of late winter to early spring temperatures on Scots pine growth over the past few decades (Figure 4b). In addition, drier sites (400–600 mm of annual rainfall) and oceanic climates (negative values of CCI), that is, southern Sweden, were also susceptible to damage (Figure 3b,c). Furthermore, drought vulnerability decreased for trees with tall crowns (Figure 3d), which suggests that trees with reduced competition were less susceptible to drought. Similar to Norway spruce, drought damage risk increases with stem density, particularly when there are more than 1000 trees per hectare (Figure 3e). Drought vulnerability was higher in pure stands of Scots

pine compared to mixtures with Norway spruce, especially when the proportion of spruce was high (Figure 3f).

Currently, the risk of drought damage for Scots pine is high in the cold north-western part of Sweden (Figure 5). Future climate change scenarios show a general reduction of drought damage. Averaged across the three scenarios, the proportion of the area affected by high drought vulnerability will decrease from 26% to 14% (Figure S8).

3.3 | Drought damage risk for birch

Similar to Norway spruce and Scots pine, drought damage risk for birch strongly depends on climate (Figure 6; Figure S7). Warmer (mean annual temperature above 2.5°C) and oceanic/maritime sites (CCI values below 50), which correspond to southern Sweden, showed a higher risk (Figure 6a,b). Small diameter birch trees, where stand basal area is below 15 m²/ha and stem densities exceed 2000 trees/ha, which are characteristic of early stand development stages, showed high drought damage risk probability (Figure 6c–e). High stand basal area (30–40 m²/ha) in pure stands (Figure 6c), or mixed with Norway spruce (Figure 6f), that is, high competition,

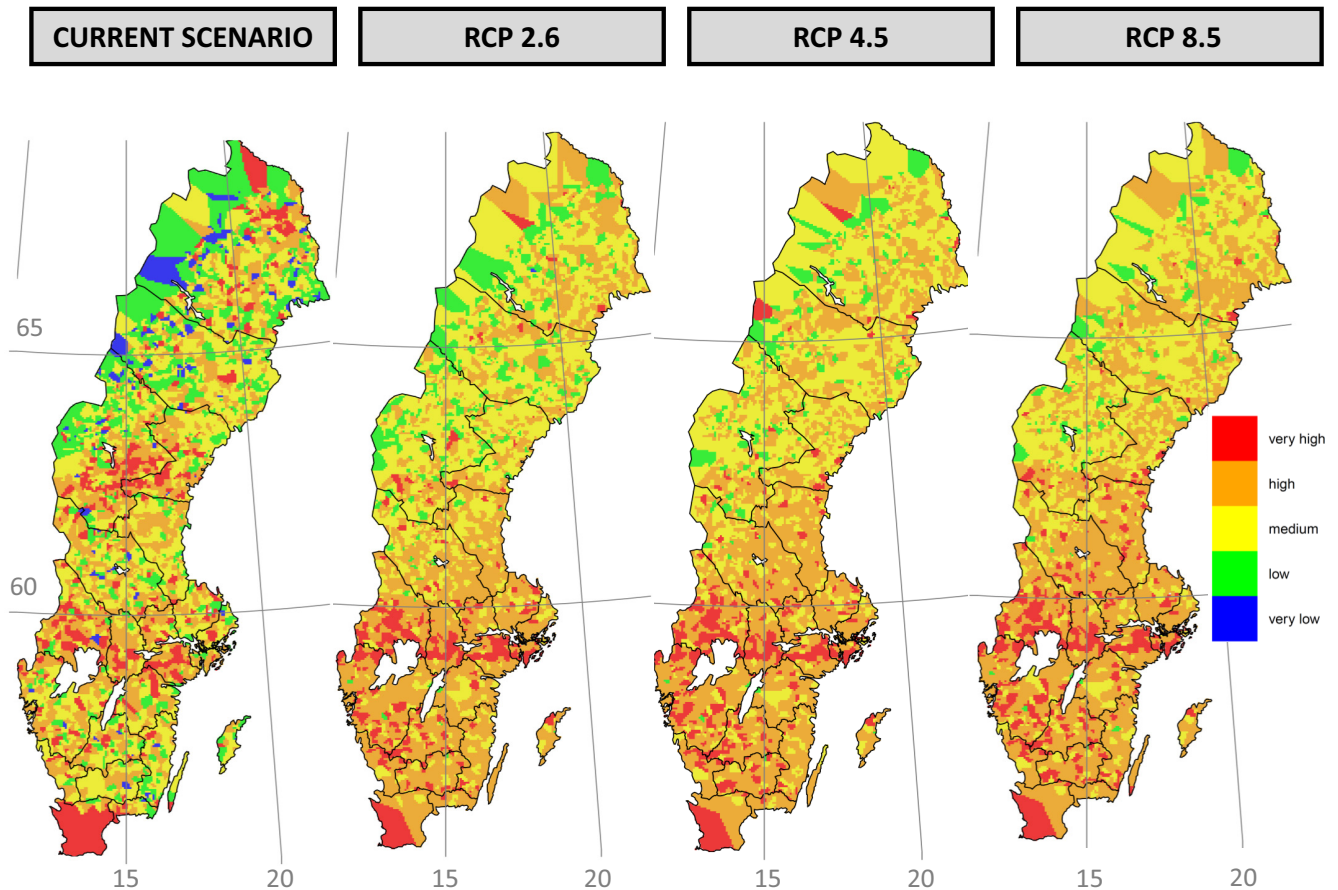


FIGURE 2 Maps of drought damage risk calculated for Norway spruce under current conditions and for three greenhouse gas emission scenarios (RCP) during 2041–2070. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

also increased drought damage risk. Thus, the drought vulnerability for birch in Sweden was associated with site climatic conditions, although stand and tree characteristics were also important contributing factors.

Currently, birch faces a medium or low drought vulnerability in 36% and 43% of Sweden, respectively (Figure 7). However, climate change would increase the high-risk area by 6% and decrease the low-risk class by 12% (Figure S8). This pattern could be slightly more accentuated in north and central Sweden where temperature increases will be greater.

4 | DISCUSSION

4.1 | Drought damage risk predictors and future forecasting

Site-specific climate was the most important predictor of drought damage risk for all tree species in this study. We observed that drought vulnerability of Norway spruce was largely explained by spring temperature and winter precipitation (Figure 1a,b). Sites with warm springs (mean temperature 8–10°C) and dry winters (<200 mm of precipitation) have a high evapotranspiration demand and might

reduce soil moisture during the growing period, inducing drought damage in this species. Vitasse et al. (2019) similarly found strong radial growth reduction in Norway spruce due to spring drought, but also a high sensitivity to summer drought (Trembl et al., 2021; Zang et al., 2014). Drought during both periods may induce mortality in adult trees (Arend et al., 2021).

High drought damage risk for Scots pine is associated with cold temperatures in late winter–early spring (mean March and April temperature below 0°C) and dry climates (400–600 mm of annual rainfall; Figure 3a,b). Scots pine growth has been associated both positively (Harvey et al., 2020) and negatively (Mäkinen et al., 2022) with winter temperatures in temperate and boreal forests. Our results are in line with Harvey et al. (2020), although we observed a slight decreasing influence of late-winter temperature on Scots pine growth (Figure 4b). This would suggest that cold winters coincided with drought and were related to low growth in the period studied (1960–2010), and it would explain why growth anomalies would become less likely in the future in line with our predictions (Figure 5). It is also possible that frost damage to needles was related to the growth anomalies induced by cold temperatures (Pederson et al., 2004). Conversely, warm late winters would speed up snow melt and soil thawing, extending the growing season and promoting tree growth (Appiah Mensah et al., 2023; Helama et al., 2013). We also occasionally

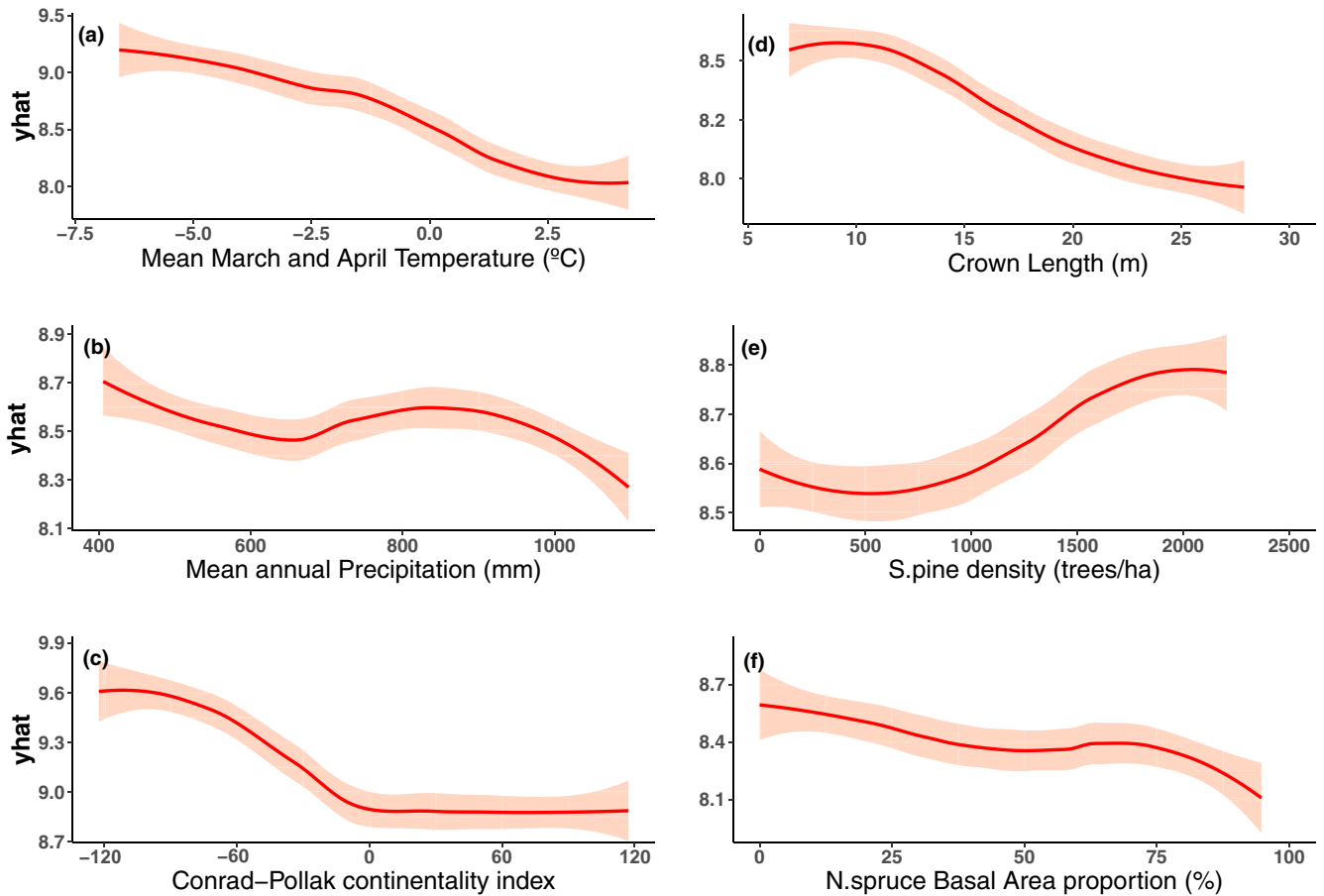
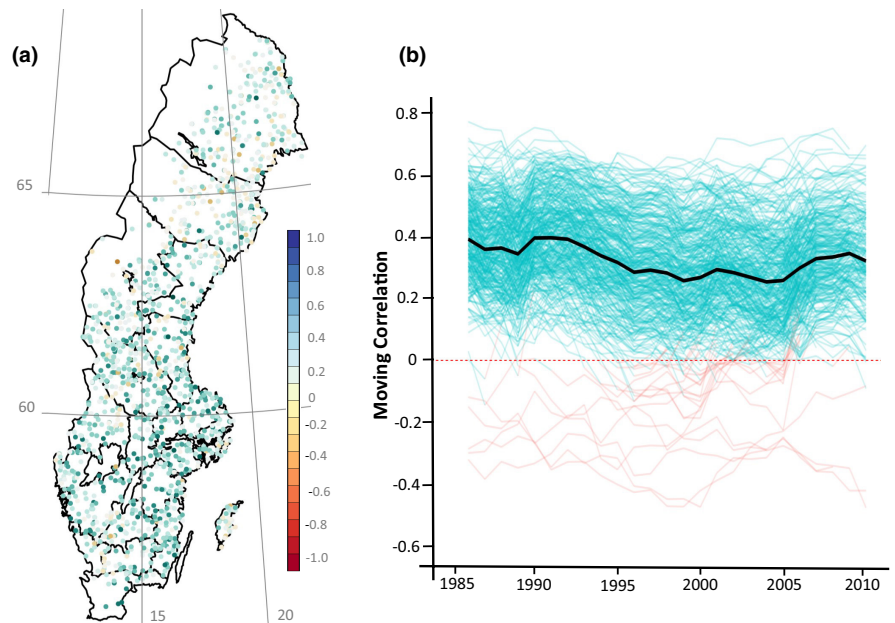


FIGURE 3 Partial dependence plots for the most important predictors of drought damage risk for Scots pine: March and April mean temperature (a), accumulated annual precipitation (b), CCI (c), tree crown length (d), stand density (e) and basal area proportion of Norway spruce in the stand (f). “yhat” is the measure of change in the target variable. Low values of the Conrad-Pollak continentality index denote an oceanic climate.

FIGURE 4 Spatial distribution of the bootstrapped correlations (a) and moving correlation analysis (b) between Scots pine growth and mean March and April temperatures. The x-axis shows the final year of each 25-year window of analysis (1960–2010) in (b). Colored lines denote positive (blue) or negative (red) correlation. The black line represents mean bootstrapped correlation coefficients. Map lines delineate study areas and do not necessarily depict accepted national boundaries.



detect the unusual negative relation between winter temperatures and Scots pine growth described by Mäkinen et al. (2022) in some sites at northern latitudes, but to understand when, how, and why it

occurs, more research is required. Summer drought also severely reduces Scots pine growth (Lévesque et al., 2014), but the methodology used in this study did not detect this pattern.

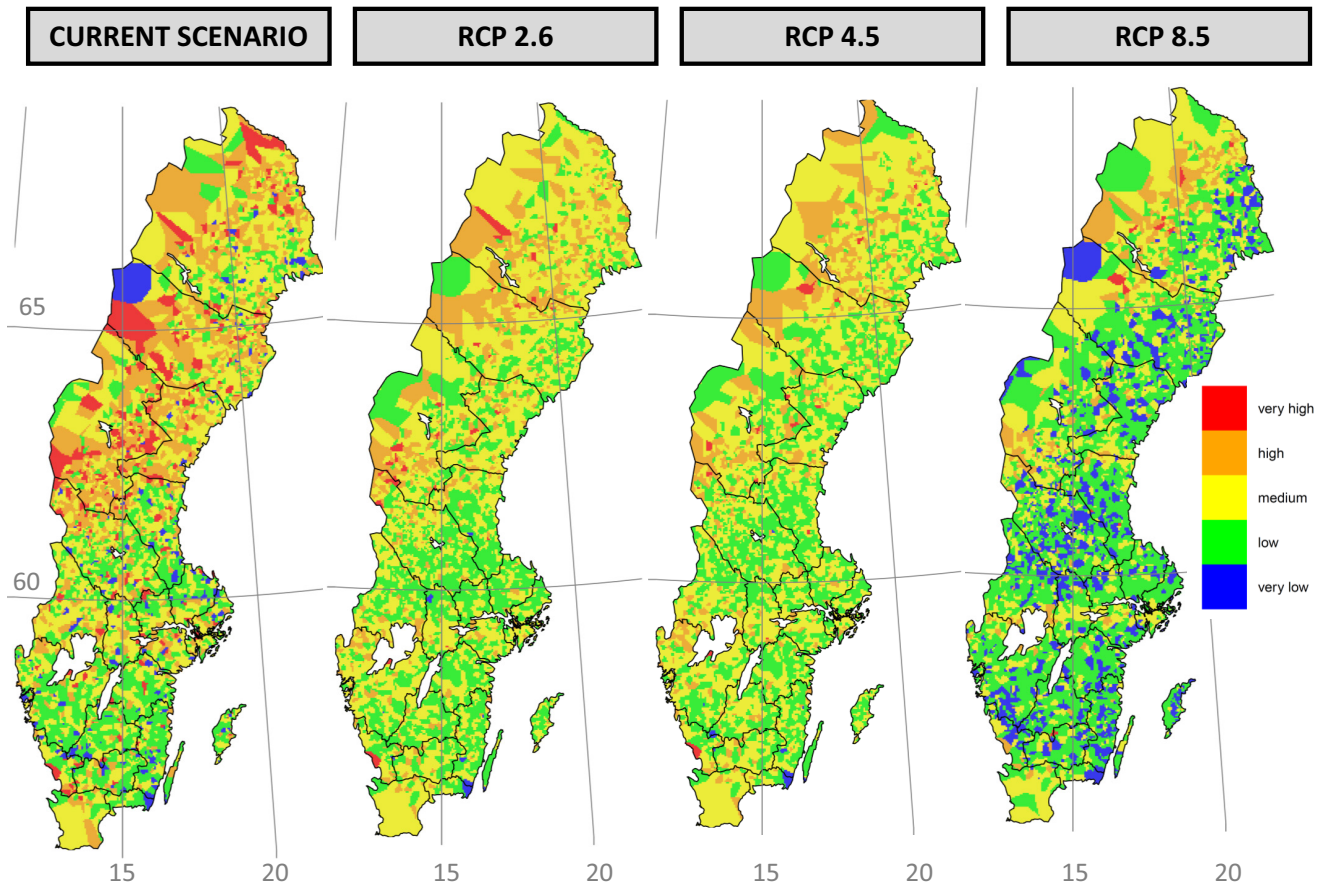


FIGURE 5 Maps of drought damage risk calculated for Scots pine under current conditions and for three greenhouse gas emission scenarios (RCP) during 2041–2070. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

Drought damage for birch was associated with mean annual temperature (Figure 6a), so severe growth reduction is more likely on sites with high evaporative demand during the vegetative period. Accordingly, Matisons et al. (2022) observed that a summer water shortage could heavily restrict birch growth in the hemiboreal zone.

Comparison among species concerning the risk of drought damage must be done with care, since their ecology is different and their habitat preferences are seldom random. However, our future predictions are valid for the coming decades, assuming the same management and the same choice of tree species in the regeneration stage.

Climate models indicate a significant increase in drought probability even for boreal forests (Balting et al., 2021; Hammond et al., 2022), which is consistent with our results. We observed that climate change projections will sharply increase the probability of drought damage for Norway spruce south of 60°N if management is not adapted to drought risk. Schmied et al. (2023) similarly observed that Norway spruce is suffering a long-term decline in resilience in central Europe, indicating a higher vulnerability to future droughts. However, the projection that Scots pine will see less area affected by drought damage, regardless of climate change scenario, was unexpected. This is because we were only able to identify drought damage that coincided with cold temperatures, but not with heat. Consequently, warmer winters would improve pine growth at

northern latitudes (Girardin et al., 2022). We also expect that future drought damage for Scots pine will increase due to extreme summer droughts as has recently been observed, especially in southern Sweden (Buras et al., 2020; Kjellström et al., 2018). Models predict greater temperature and precipitation increases in the winter than in the summer (Lind & Kjellström, 2008) with shorter freeze-thaw periods in early spring and reduced winter drought (Sarady & Sahlén, 2016). In this scenario, the soil would thaw with warmer temperatures, allowing precipitation and snow melt to slowly infiltrate the soil, increasing water availability. Increases in winter temperature and annual precipitation will be higher in northern compared to southern Sweden (Chen et al., 2021; Kjellström et al., 2018), consistent with our study's drought damage predictions for Scots pine. Accordingly, Neumann et al. (2017) found that reduced cold-induced mortality could compensate for increased mortality related to peak temperatures in a warmer climate scenario. Our results agree with Goude et al. (2022) who found that Norway spruce could suffer from high temperatures in southern Sweden and Scots pine production could increase in northern regions where temperatures were originally lower. Climate change will also increase drought damage risk for birch throughout Sweden, especially in northern and central regions where higher temperature increases are projected. If summer drought becomes more severe in the south, this species may also suffer severely from water stress (Matisons et al., 2022;

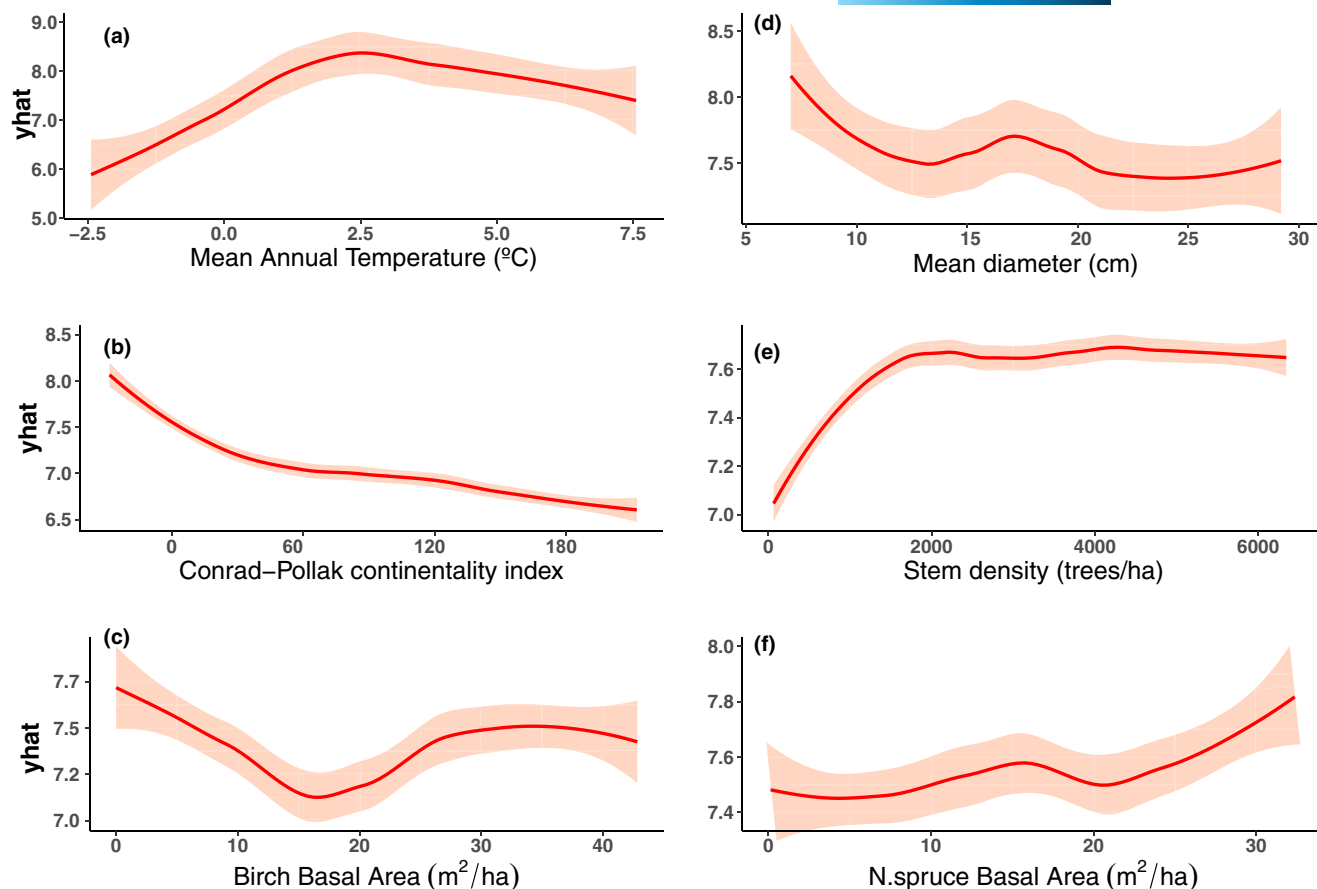


FIGURE 6 Partial dependence plots for the most important predictors of drought damage risk for birch: mean annual temperature (a), CCI (b), basal area of birch in the stand (c), tree mean diameter (d), stand density (e) and basal area of Norway spruce in the stand. “ \hat{y} ” is the measure of change in the target variable. Low values of the Conrad–Pollak continentality index denote an oceanic climate.

Oksanen, 2021). It is noteworthy that there were not larger differences between the three climate change scenarios for Norway spruce and birch (Figures 2 and 7). Temperature anomalies will mainly affect the northern Sweden where the current drought damage risk is low, so the high-risk classes should not be frequent for any species there. In addition, warmer temperatures would be partially countered by a general increase in late-winter precipitation throughout the country (SMHI, 2022) which would decrease the drought damage risk.

Drought damage risk was also modulated by other intrinsic and environmental drivers. Oceanic climate sites showed a higher risk for all tree species. In Sweden, this would mean just the southernmost region, and hence the sites with the highest maximum summer temperatures.

We expected that drought would be exacerbated by topography (Cartwright et al., 2020), but it was a minimally important predictor in the algorithm. This may be because Sweden's forest land is mainly flat, with little variation in slope.

Large Norway spruce trees would be very susceptible to drought in pure stands (Figure 1d,e). Pretzsch et al. (2018) found similar results that drought can favor small trees' growth relative to big trees in mature stands of Norway spruce. In addition, there is evidence that large trees are suffering drought-induced mortality globally (Ryan, 2015).

Mixtures of Norway spruce and Scots pine might be more resistant to drought than pure stands of either species, although the benefit would depend on the duration of the drought (Aldea et al., 2022). In our study, drought damage risk increased with stem density for both conifers (Figure 1e,f and Figure 3e), which would agree with several studies showing significantly higher tree resilience at lower stem densities (Sohn et al., 2016; Steckel et al., 2020).

We also observed that longer tree crowns decreased the probability of drought damage for Scots pine (Figure 3d), which may correlate with a combination of a higher social dominance and low tree competition for this species (Saarinen et al., 2022).

According to our results, low stand basal area and small trees at high densities (Figure 6c–e), typical of young development stages, would increase drought vulnerability for birch. Natural regeneration of birch involves much denser stands compared to conifer plantations, leading to high competition for light and water in young stands and reduced root systems. Such circumstances might deplete soil water faster, intensifying the risk of drought damage. Mixtures with Norway spruce (Figure 6f) may escalate competition for light and water and reduce birch growth in mature stands, as has been reported in field experiments in southern Sweden (Holmström et al., 2021).

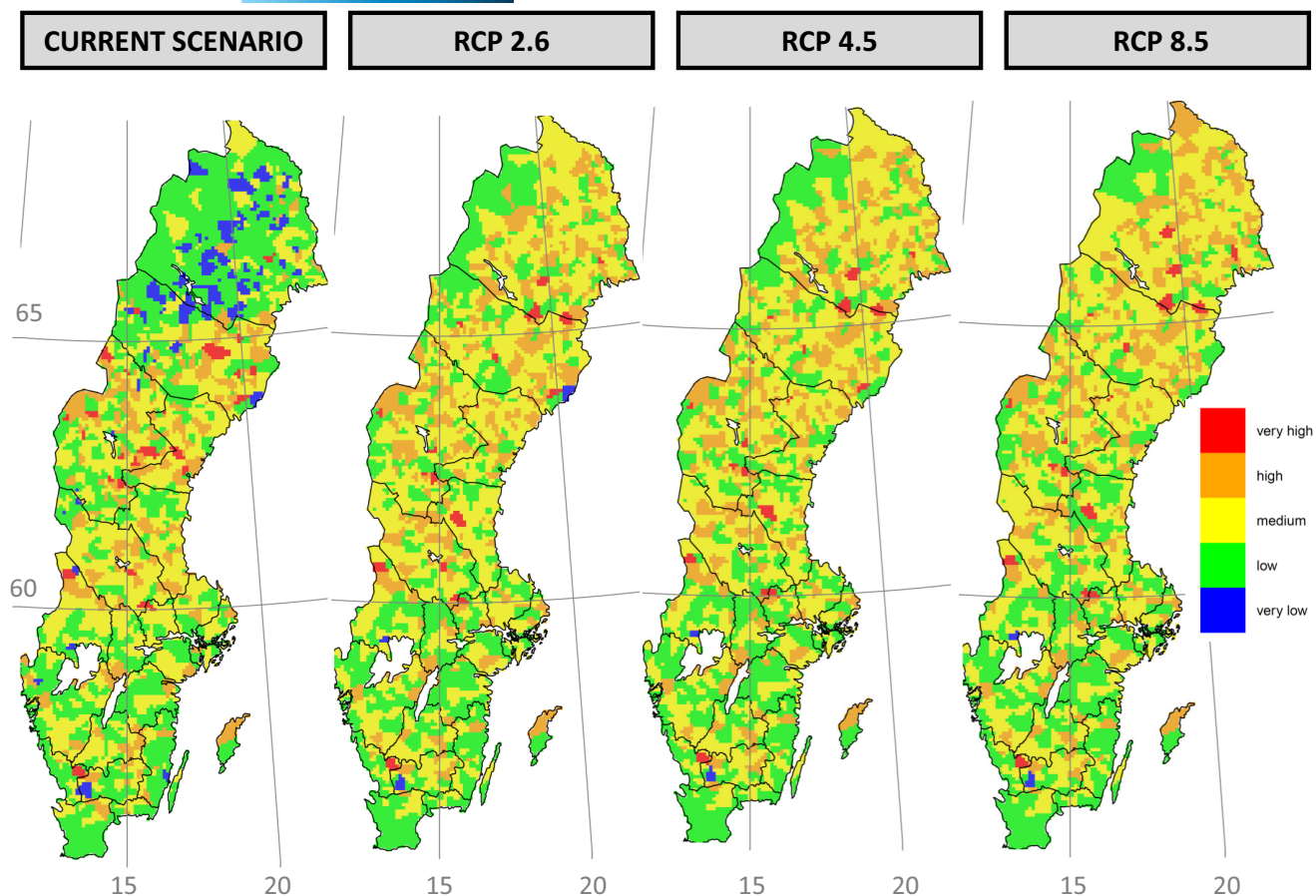


FIGURE 7 Maps of drought damage risk calculated for birch under current conditions and for three greenhouse gas emission scenarios (RCP) during 2041–2070. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

4.2 | Adaptive forest management proposals

Our results provide a powerful tool for communicating drought vulnerability to owners and forest managers and establishing the basis for future forest policy support. Management practices should be adapted to reduce drought susceptibility in boreal forests. An adequate selection of tree species is an important approach, since under current management, Norway spruce will suffer much more from drought in southern Sweden. Scots pine is also susceptible to browsing damage, diseases such as blister rust, and even drought-induced mortality in the highest quality sites (Socha et al., 2023). Therefore, we recommend diversifying the tree species in the regeneration stage, and adapting spacing, thinning, and rotation lengths to reduce drought damage risk. Species diversity also improves biodiversity, production, aesthetics, and recreational possibilities (Felton et al., 2020), as well as reducing bark beetle vulnerability (Jönsson & Lagergren, 2018). Mixed forests have several advantages compared to pure stands, such as more stable production (del Río et al., 2022), ecosystem service provisioning (Felton et al., 2020), and less vulnerability during drought (Chen et al., 2023; Fichtner et al., 2020). Mixtures of Norway spruce and Scots pine may reduce drought damage risk for both species (Aldea et al., 2022). However, mixtures are

more complicated and expensive to manage than monocultures (Coll et al., 2018). In addition, uneven-aged forests may improve resilience to drought (Piedallu et al., 2022; Pretzsch et al., 2022). Management could also be adapted to reduce competition within forest stands (Kulha et al., 2023). For example, Sohn et al. (2016) observed that heavy thinning improved growth responses following drought in both conifers and broadleaves, although it could be sometimes offset by increased soil water evaporation (Pretzsch et al., 2018). Finally, assisted migration appears to be highly advantageous since native populations and plant breeding have a great potential for adaptation to new climatic conditions. Birch has high plasticity and genotypic variation, which may give it an excellent acclimation capacity in rapidly changing environments (Oksanen, 2021).

4.3 | Upcoming research paths

Future efforts must be directed to reducing the socioeconomic and ecological consequences of changes in productivity and species distributions. Responses that change with time, and are sometimes species specific, complicate predicting trees' drought responses to climate change (Wilmking et al., 2020). Accordingly,

our approach should be complemented by long-term, spatially extensive tracking of mortality dynamics to verify differences in mortality rates between vulnerability classes. Nevertheless, our results are similar to the mortality patterns described by Neumann et al. (2017) verifying that low growth indeed would be related to tree mortality in Sweden. We used “zChron” but ideally, a sensitivity analysis using different pointer-year detection methods could strengthen the conclusions reached here. Although several methods have been employed to differentiate the drought effect on growth from pests and mast years (Lee et al., 2017), it is still complicated without site-specific historical records of such events. Further research is required for birch, and for all species in the southernmost part of Sweden where there are few NFI plots and drought is expected to be more frequent. More within-plot sample replication would strengthen the site chronology signal, although it would also involve a trade-off with economic and logistical costs. We also assumed a directly proportional relationship between extremely low tree radial growth and drought damage risk, although the process of drought-induced tree mortality in mechanistic models is commonly a threshold-type pattern depending on meristematic cell condition (Mantova et al., 2022). The advantages and disadvantages of using process-based modelling versus machine-learning algorithm approaches have been well discussed in ecology, but without a clear conclusion (Razavi, 2021). For example, machine-learning techniques have little relation to the underlying physiology while reportedly doing a superior job in fitting data, even in out-of-sample prediction.

5 | CONCLUSIONS

Our findings can support forest owners and policymakers who wish to keep forest ecosystem services sustainable under climate change, with increasing drought frequency and intensity. The studied species' performance and survival can be compromised in a drier climate. In the future, southern Sweden may face a high risk of drought damage for Norway spruce, which could lead to a higher mortality rate. Vulnerability maps can help managers to adapt forests to new climate realities and, hence, reduce the important ecological and socio-economic consequences of climate change. We encourage an active selection of tree species, promoting mixtures, and reducing tree competition through thinning interventions as a promising strategy for adapting northern European forests to future droughts. These outcomes advance the understanding and anticipation of future drought events and contribute to science-based adaptive management strategies under climate change.

AUTHOR CONTRIBUTIONS

Jorge Aldea: Conceptualization; formal analysis; funding acquisition; methodology; visualization; writing – original draft. **Jonas Dahlgren:** Data curation; investigation; writing – review and editing.

Emma Holmström: Investigation; resources; writing – review and editing. **Magnus Löf:** Funding acquisition; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflict of interests.

DATA AVAILABILITY STATEMENT

The data and main scripts used in the modeling process that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.10171312>.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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