RESEARCH

Quo vadis Scots pine forestry in northern Germany: How do silvicultural management and climate change determine an uncertain future?

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Abstract
Scots pine is of greatest importance in northern Germany regarding its cultivation area and expected capability to perform in climate change. However, pine predominantly occurs in monocultures. Therefore, future pine forestry depends on an adaptation to climate change while improving ecological and economic forest functions. Yet future development of pine remains uncertain due to leeway in silvicultural guidelines and future climate. This study questions: (*i*) what is the range of future pine shares under climate change and different silvicultural management in northern Germany, (*ii*) how will the current stands develop and (*iii*) what is the range of uncertainty arising from climate models and silvicultural options? To answer these issues we (*i*) selected forest development types site- and climate-sensitively to either minimize or to maximize pine shares, (*ii*) simulated four, now practiced forest management scenarios for 50 years based on the German National Forest Inventory and (*iii*) analyzed the differences, to be interpreted as uncertainty. Novel to our approach is the site- and climate-sensitive selection of forest development types on large scales which emphasizes the contrasts of the different management guidelines. The results show that growing stock and cultivation area will decrease even if pine is promoted in forestry. The predicted restoration rate ranges from 50 to 72% depending on scenario and previous thinning regime. In conclusion, under the given management concepts and considering today's high proportion of old pine, restoration is alarmingly slow. Amid the rapidly changing climate, we recommend to further adjust the management guidelines to accelerate forest restoration.

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Introduction

Forests are constantly changing. Regarding climate change, the restoration of pure towards mixed stands in the temperate zones can be seen as the most important task for today's European forestry (Mason et al. 2018; DVFFA 2019; Zerbe 2019; Graf et al. 2022). Already previously, single-species stands were far from a natural vegetation in most cases (Tüxen 1956; Hennenberg et al. 2017) and vulnerable to abiotic and biotic risks (von Sponeck 1819). The stability of recent forest communities decreases due to a warming and aridizing climate even more than ever (Hanewinkel et al. 2013; Buras and Menzel 2019; Mette et al. 2021; Hinze et al. 2023).

The so-called German *Waldumbau* from pure to mixed stands in the face of climate change has to be contextualized in the framework of forest restoration. It entails that partly degraded communities are rehabilitated i.e. converted

structurally and functionality wise, towards more natural forests. It is termed Forest Landscape Restoration (FLR), if choices about scope, socioeconomic constraints, and larger forest scales are considered (Stanturf 2016, pp. 5–8). In northern Germany, Scots pine (*Pinus sylvestris* L.) is the most common tree species. It predominantly can be found in even-aged monocultures of low structural complexity (BMEL 2015, p. 21).

However, among European tree spp., Scots pine naturally occurs on very adverse sites where it forms extremely rare and vulnerable habitat types, such as lichen pine forests from the Dicrano-Pinion community (Leuschner and Ellenberg 2017, pp. 581–598). Although today's key growing area of pine moved on sites with low to even medium quality, its cultivation is highly recommended expert-based even with the lowest water supply (Albert et al. 2017). Besides being the native tree species with the largest site amplitude, third-most specialized arthropods are linked to Scots pine, thus underlining its ecological importance (Brändle and Brandl 2001). Pine also meets yield and economic requirements making it one of the most relevant taxon in silviculture under climate change (Leuschner et al. 2022; Brichta et al. 2023). However, the proportion of pine is decreasing currently, especially in young age classes, because it shows a relatively lower growth potential (Beinhofer and Knoke 2010; BMEL 2016, p. 11), low shade-tolerance in the face of currently practiced continuous cover forestry (Wagner and Huth 2010), as well as comparatively long rotations (Mason and Alía 2000; Fischer and Mölder 2017).

Currently prevailing silviculture with Scots pine in northern Germany is reviewed by Spathelf and Ammer (2015). They depict a diversification in management practices which is e.g. expressed in different forest development types (FDT). Operationalizing the long-term targets for a controlled development, FDT give a quantitative mechanism to achieve a site-specific composition of mixed stands for close-to-nature forestry (Larsen and Nielsen 2007). Although FDTs are used for goal-oriented managing, the past FLR of pine has been identified as the slowest (Fischer and Mölder 2017). FLR progress generally is influenced by many factors such as current age class distribution, site, management intensity, seedling availability, calamities, climate, economy and policies (Knoke et al. 2001; Kint et al. 2009; BMEL 2016, p. 50; Graf et al. 2022; Suárez-Muñoz et al. 2023).

The forecast of future forest composition and FLR outcome is hampered by uncertainties. Since predictions in environmental shifts on local scales remain vague, there is an uncertainty associated with the assumed climate change (Millar et al. 2007; Albert et al. 2015): For example, water supply of sites can no longer be expected to be constant over time. Thus, climate change increases uncertain growth potentials while different management i.e.

silvicultural options also contribute to uncertainty (Albert et al. 2017; Bauhus 2022). This is exacerbated by model-based contradictory assessments of Scots pine suitability for cultivation when considering its vulnerability to heat in combination with drought or warm winters (Bose et al. 2020; Rehschuh and Rühr 2021; Haberstroh et al. 2022).

To our knowledge, uncertainties arising from differing silvicultural prescriptions and climate change have been poorly quantified. Precisely, because FLR is dependent on many interacting factors, future forest compositions cannot be foreseen, especially when considering timber harvesting potential. This is why in other simulation studies the initial tree spp. percentage is held constant over time, or tree spp. selection is not site specific while site changes are not considered (BMEL 2016 p. 8; Oehmichen et al. 2018; Rosenkranz et al. 2023).

In this study we want to increase prediction abilities with a detailed site-specific approach. Four different silvicultural Business As Usual (BAU) scenarios are simulated in order to investigate realistic future forest composition. We focus on Scots Pine in northern Germany, using the single-tree growth simulator *WaldPlaner* (Hansen and Nagel 2014).

Our prescriptive modelling provides insight in the range of magnitudes and direction of possible future changes. We imitate the BAU (German multifunctional forestry; Borrass et al. 2017) when forest owners obey best practice recommendations of the State Forest Administrations as *homo oeconomicus*. BAU silviculture guidelines were recently updated in every federal state to particularly emphasize adaptation to climate change (e.g. Thurm and Wirner 2023). While considering forest cover *ceteris paribus*, optimal circumstances such as fructification, seedling availability and timber marketing are assumed. We refrain from including risk i.e. potential disturbances in the simulation in order to clearly identify the effects of silviculture and climate change on forest development. However, disadvantages of persistently drier climates are accounted for in BAU tree spp. selection. Site changes and the resulting change of site index (SI) on permanent inventory plots are considered dynamically.

Different outcome of management practices has important implications in the macroeconomic sense for timber markets as well as landscape ecology. Therefore this study questions:

i   What are the guard rails of future pine shares (FDT) under climate change and leeway in management guidelines in six northern German states,

ii How will the current forest stands develop between climate and silvicultural scenarios and

iii What is the range of uncertainty arising from climate change and silvicultural options?

Material and methods

In order to answer the three questions formulated above we apply a climate-sensitive algorithm to select future FDTs (Hamkens et al. 2022) and use a single-tree growth simulator supported by a climate-sensitive SI-model (Schmidt 2020) to predict forest development.

Material

Study region and dendrometric data

This study encompasses the six German federal states of Brandenburg, Hesse, Mecklenburg-Western Pomerania, Lower Saxony, Schleswig-Holstein and Saxony-Anhalt under which (for further comparisons) Brandenburg, Mecklenburg-Western Pomerania and Saxony-Anhalt are considered eastern and the others as western.

This study representatively simulates forest development on plots from the third German National Forest Inventory (NFI) with available site information. This corresponds to about 86.6% of the total forest area (4,477,858 ha) within the study region and covers mainly parts of the north German lowlands as well as the central German hill country. Elevations range between -3 and 1,141 m a.s.l. within oceanic to hemiboreal climate. In Saxony-Anhalt, on small areas also cold semi-arid and subarctic climate occurs (Beck et al. 2018). Soils with the widest possible range of water and nutrient supply have developed in the study area. A map indicating the soil nutrient level (SNL) is supplemented (Fig. S1). Mean annual precipitation sum ranges from 449 to 1,799 mm a^{-1} and mean annual air temperature from 3.9 to 11.5 °C within the period 1991–2020 (DWD 2022). Due to often medium to poor and rather dry soils, Scots pine has its current and natural distribution focused here (BMEL 2015; Leuschner and Ellenberg 2017). The total forest area includes about 77% of the German Scots pine's spatial occurrence while being equivalent to only 39% of the German forest area.

The dendrometric data with reference date 2012 was retrieved from the NFI: It is characterized by a permanent stratified one-phase systematic cluster sampling design where the strata consist of geographic regions differing in sampling density (Fig. 1; Kleinn et al. 2020). The sample plot (cluster, tract) comprises corners (subplots) that, if located within the forest, are surveyed. Trees with diameter at breast height (DBH) ≥ 7 cm are selected by angle-count sampling and tree regeneration is assessed on circles with radii up to 2 m. We refer to Riedel et al. (2017) for further information. In total, 17,551 subplots on 6,508 tracts with site mapping data were included in this study.

In order to supplement the NFI survey of pruning (Fig. 1), the NFI dendrometric data was spatially joined with information on pruning available from Forest Administration records (Table 1). Furthermore, sample plots that are located within strictly preserved forest areas (unmanaged forests, e.g. national parks) were identified using maps from Steinacker et al. (2023) where no active management was simulated (see "Simulating forest development" section).
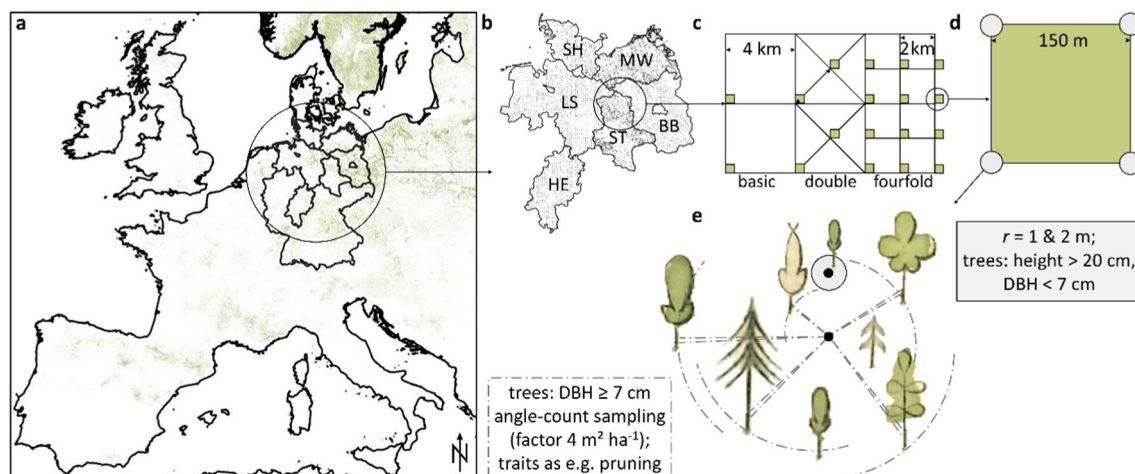

Fig. 1 a Current Scots pine distribution (green; de Rigo et al. 2016) in Europe, Germany and examined federal states. **b** Study area with differing intensities (strata) and sampling design: **c** Basic (Brandenburg BB, Hesse HE, Lower Saxony LS), double (Lower Saxony) and fourfold (Mecklenburg-Western Pomerania MW, Schleswig-Holstein SH, Saxony-Anhalt ST). **d** Clustered plot design and **e** concentric subplot circles of radii r with relevance for our work. Figure based on Guimpel (1819, p. 119) and BMEL (2015, pp. 44–45), borders by © GeoBasis-DE/BKG (2022) & EEA (2018)

Site and climate data

At the site-scale, the selection algorithm for FDTs and the SI model mainly depend on the edaphic factors soil moisture level (SML) and soil nutrient level (SNL). We assume constant SNL, however, water properties must be aligned with changing climate conditions.

In order to span a wide range of climate effects on tree spp. selection and forest growth, the largest possible difference of climate models actually used in north German forestry was identified. This results from a statistical and a dynamic downscaling within the ReKliEs-De core ensemble from the CMIP5-generation of seven regional models for the representative concentration pathway (RCP) 8.5 (Hübener et al. 2017).

Thus, the 'Hadley Centre Global Environment Model' (HadGEM2) and its statistical regional 'Wetterlagen-basierte Regionalisierungsmethode' (WettReg13) was chosen to represent the most extreme climate projection (Martin et al. 2011; Kreienkamp et al. 2013). Contrary to this, the global 'European Centre Earth System' model (EC-EARTH12) and its dynamical 'Regional Atmospheric Climate Model' (RACMO) are considered as a moderate projection in RCP8.5 (van Meijgaard et al. 2008; Hazeleger et al. 2012).

As a suitable common denominator to align site water properties to climate outcomes, we use the climatic water balance (CWB, Fig. 2). The CWB is defined as the difference of precipitation and potential evapotranspiration (Sutmöller et al. 2021). CWB is determined as a 30-year average for the growing season which is dynamically calculated, i.e. the length of growing season also varies depending on the respective climate (Menzel and Fabian 1999; Nuske 2022).

Site dynamics

Due to its very heterogeneous data, this approach has to deal with two different methods as to how water properties could be projected climate-sensitively. In Hesse, Lower Saxony, Schleswig-Holstein and Saxony-Anhalt for site dynamization CWB is directly considered as site water balance (Grier and Running 1977), which is the sum of CWB and available water capacity (effective root zone of 1 m). For sites in Brandenburg and Mecklenburg-Western Pomerania the CWB is used indirectly by shifting climate humidity districts (CHD).

Actually, the states of Brandenburg and Mecklenburg-Western Pomerania introduced CHDs to create comparable current climate conditions where only a subset of FDT is suitable (Thurm and Wirner 2023; Schröder et al. 2023). Therefore, we assume that today's tree spp. assessment is fixed to CHD peculiarities. Hence, in this study for each CHD level, the statistical location parameters of the CWB dataset for the current climate period 1991–2020 were determined on the basis of the NFI subplots. The threshold of a CHD level was then delineated by its lower quartile value and acting as a lower limit, up to which the FDT subset is recommended. With future changes in CWB-values at the NFI-subplots, the CHD assignment will thus shift (Fig. 3).

Methods

Selection of FDT

Research question *i* assumes that restoration is executed on all sites with a feasible FDT. It thus neglects the current stand types. In practice, the BAU-assessment of site-specific
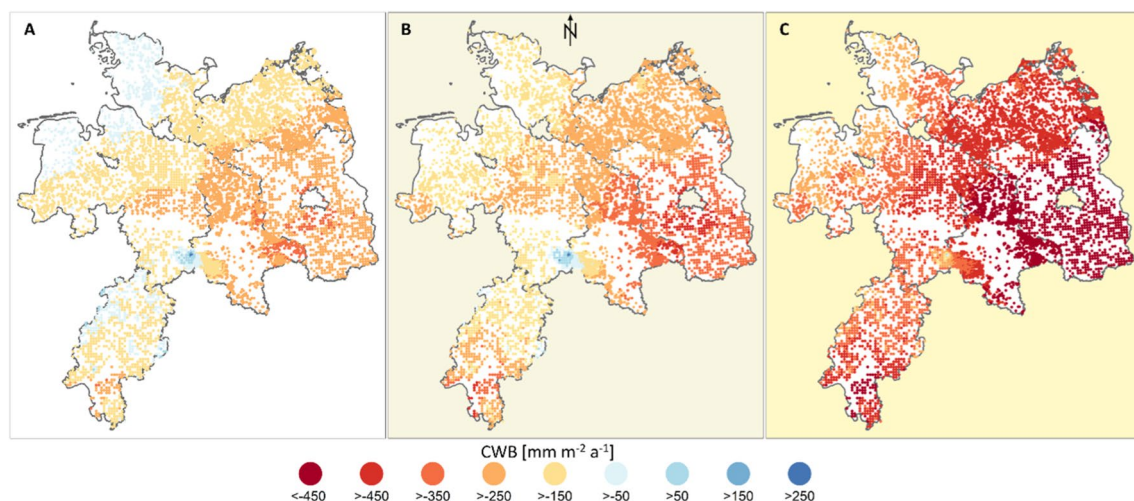

Fig. 2 Decreasing mean CWB-class per tract over time and climate model. **A** With recent climate data (1991–2020), **B** using RCP8.5 EC-EARTH12 from 2071 to 2100 (moderate) and **C** using RCP8.5 HadGEM2 from 2071 to 2100 (extreme)
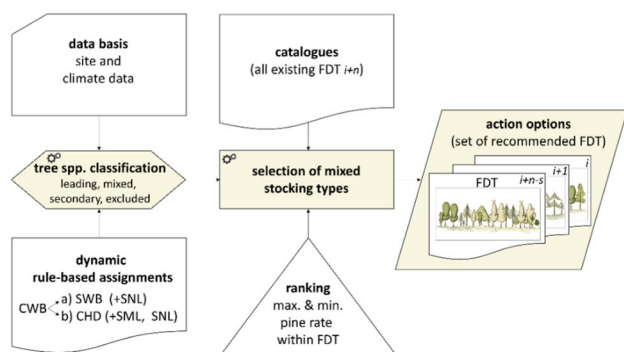
Fig. 3 Flowchart of dynamic FDT selection aligned to the algorithm of Hamkens et al. (2022). Out of all existing FDT $i + n$ on a given site s only a set of FDT is recommended. Due to Germany's federal structure these are obtained either by a) altering site water balance (Hesse, Lower Saxony, Schleswig-Holstein, Saxony-Anhalt) or by b) shifting CHD (Brandenburg, Mecklenburg-Western Pomerania). Figures based on Hamkens et al. (2022) and Guimpel (1819)

tree spp. (and accordingly FDT) requirements are currently performed expert-based (Riek et al. 2020; Buresch et al. 2023; Schröder et al. 2023). Each German federal state has defined its own FDT catalogue (Fig. 3) for the respective state forests (overview: Albert et al. 2017; Buresch et al. 2023, pp. 59–60). For private forest owners, however, these FDTs are mandatory by following best practice or if subsidies are accepted.

According to the BAU, for each site and climate condition there are different silvicultural variants possible at the same time (Fig. 3), enabling e.g. to minimize or to maximize pine shares, thus representing the guard rails. Therefore, algorithm-based we selected the most contrasting final cut variants in order to constitute a scenario funnel (Kosow and Gaßner 2008, pp. 15–17).

Firstly, while following the silviculture guidelines of the federal states, in a possible short and intensive forest restoration relating to hemeroby level, stands led by light-demanding tree spp. were targeted (Fig. 3). Here, out of the set of recommended FDTs, we chose the one with highest pine share, applying the selection algorithm by Hamkens et al. (2022). If the secondary tree spp. (< 10% basal area, BA) were not explicitly listed and if *P. sylvestris* was already selected as leading species ($\geq$ 50% BA) or mixed ($\geq$ 10% BA), we prescribed also light-demanding *Quercus* spp., *Betula* spp. or *Salix* spp. as secondary taxon. Hereby, future stands with leading shade-tolerant spp. were also selected in order to place pine at least as a mixed or secondary tree spp. on these sites.

Secondly, in a forest restoration following a longer time period and less intense cuttings, stands dominated by shade-tolerant tree spp. were considered for cultivation (Fig. 3). Comparatively, we chose the FDT of lowest pine share whilst emphasizing shade-tolerant taxa. Likewise,

future stands with pine were selected in order to prescribe a FDT for adverse sites at all. Depending on the leading tree species, the FDT which had undefined secondary spp., were enriched with the shade-tolerant *Fagus* spp., *Tilia* spp. or *Carpinus betulus*.

Consequently, resulting from Figs. 2 and 3, two differing FDT site sets exist for each management variant. Thereupon, in this study we contrast four scenarios b–e as shown in Fig. 4.

Simulating forest development

Regarding research question *ii*, we used the *WaldPlaner* (version 2.2). The simulation software is based on the forest growth library 'Tree Growth Open Source Software' (TreeGrOSS, Hansen and Nagel 2014) and requires the FDT site set list, SI values and management settings.

In order to predict forest development climate-sensitively, changes in SI are accounted for depending on the respective climate model applied. The SI is one major predictor in the *WaldPlaner*'s height increment function. SI is predicted using site, climate, Nitrogen deposition and geographic location data applying the generalized additive model by Schmidt (2020). To run the model, SML and SNL from the different site mapping schemes of the six German states were unified (Benning et al. 2015). The climate variables 'temperature sum in the growing season' and 'precipitation sum in the growing season' were dynamically averaged over the past or projected stands' lifespan. The length of growing season also varies depending on the respective climate (see "Site and climate data"). The Nitrogen deposition is based on the results of Schaap et al. (2018) and averaged, too. Hence, for each simulation step, the respective SI is updated for each subplot, layer and species.

Growth simulations with the *WaldPlaner* require management settings. Therefore, we operationalized management intensity, maturity as well as cutting period and cycle of final harvest as prescribed in the BAU (Table 1).

Thinning intensity is oriented towards an age-dependent and SI-specific target basal area (BA). This target BA is defined by the stocking degree S_y° derived from yield tables. We used the particular silvicultural guidelines for Scots pine. Here, differences concerning the BA exist, having lower S_y° in the western region (yield table by Wiedemann 1943) in contrast to the eastern region (yield table by Lembcke et al. 1975). Hence, the respective data from the two pine yield tables was functionalized: A nonlinear model derived by the Levenberg–Marquardt method (1944, 1963) was used and computed by *minpack.lm*-algorithm (Elzhov et al. 2023). For the target BA as given from the yield tables and reduced by the silvicultural guidelines (S_y° range from 0.7 to 0.9), we decided to fit

Fig. 4 Starting point of FLR and scenarios with spanned uncertainty space. **a** *Status quo*: Current forest stands as per NFI with forest restoration obligations. **b–e** Equally likely scenarios with FDT prescribed under different climate of the period 2071–2100 by silvicultural management maximizing (**b**, **c**) or minimizing (**d**, **e**) pine shares. Note that FDT's species share must not be reached within a time window. Figure based on Guimpel (1819)
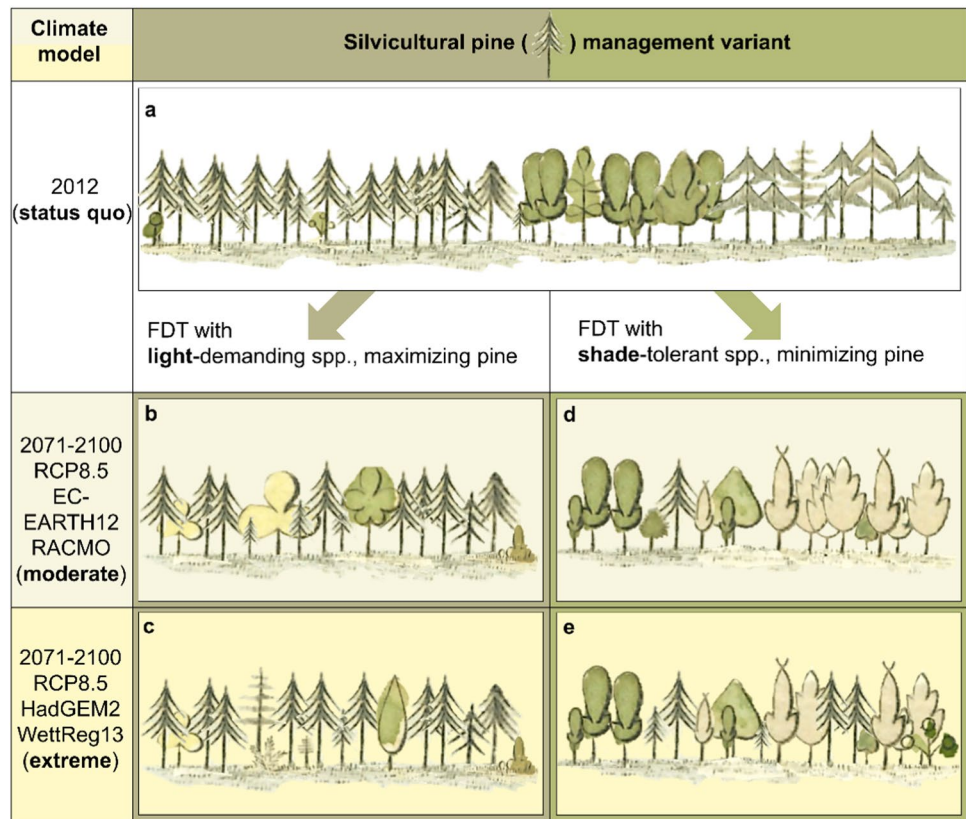

Table 1 Prescribed management regime of Scots pine in the *WaldPlaner* following the particular guidelines of the federal states per silvicultural variant of FLR

Criterion	Silvicultural FLR variant	
	Light	Shade
Tree spp. selection (scenario)	Light-demanding, maximizing pine (b, c)	Shade-tolerant, minimizing pine (d, e)
Number of future crop trees west/east [N/ha]	160/135	160/135
Target DBH unpruned/pruned [cm]	45/55	45/55
Start of final cuts (= maturity) [% BA > target DBH]	50	25
Period & pattern of final cuts [a]	20, large openings (shelterwood cut)	40, small openings (shelterwood cut)
Cycle of final cuts [a]	0, 5, 10, 15, 20	0, 5, 10, 15, 20, 25, 30, 35, 40
Maximum density of final cut cycle [rel.]	0.3, 0.25, 0.15, 0.1, 0.05	0.5, 0.45, 0.4, 0.35, 0.3, 0.25, 0.19, 0.12, 0.05
Min.–max. removal per operation at thinning/final cut [m^3 ha^{-1} over bark]	10–80/10–300	10–80/10–300
Remaining stock (e.g. remnant trees) [% fully stocked]	5	5

a Chapman–Richards equation (1961, 1959) with parameters $a_1 - c_2$ that is dependent on stand age t and SI:

$$BA = \left(a_1 - a_2 SI\right)\left(1 - e^{\left(b_1 e^{(b_2 SI)}\right)t}\right)^{\left(c_1 e^{(c_2 SI)}\right)} \quad (1)$$

The used parameters and region-specific estimations are supplemented (Table S1). Next, thinning regime was defined as from above, and future crop tree oriented. During the tending phase, different numbers of future crop trees are promoted in the states, depending on the guideline and standing in line with the thinning regime so that at higher BA less future crop trees are promoted and *vice versa* (Table 1).

For final cuts of Scots pine, shelterwood respectively seed tree systems (Wagner et al. 2010) were simulated as a common denominator between the BAU of the states. The *WaldPlaner* was then refined by implementing an adjustable maturity as a threshold where final cuts start.

Other than the performed thinning type, shelterwood cuts are technically executed as a heavy cutting from below (Table 1): As soon as 50/25% (restoration towards stands led by light-demanding/shade tolerant spp.) of the BA is provided from trees that have reached 45 cm (unpruned)/55 cm (pruned) DBH the final cutting starts. Firstly, 50% of the BA is to be removed until the aimed maximum density is reached, with trees being chosen at random that fall within the target diameter. Secondly, the remaining 50% of the BA are harvested from the residual stand, including understory trees, in order to promote light supply for the following regeneration (Wördehoff et al. 2017, p. 23; Huth et al. 2022).

Based on the maturity definition, large or small openings are created in the variants, which results in cutting cycles of 20 or 40 years (Table 1; Kint et al. 2006). In both thinning and final cutting, the maximum removal volumes, which are due to stand preservation, do not impair the cutting cycle. A final liberation cut is not executed in order to preserve remnant trees (Borrass et al. 2017).

In total, nine silvicultural prescriptions were set in the *WaldPlaner* environment: two regions (western/eastern states) × two target diameters (pruned/unpruned) × two silviculture variants (max./min. pine) + strictly preserved stands. While pine's silviculture was adapted as described above, the other tree spp. were simulated with the default settings of *WaldPlaner* which are similar to the BAU of the states and do not consider differences between the regions.

For growth simulations, first of all, the dendrometric data of each subplot is used to generate model forest stands with a uniform size of 0.2 ha. Hence, each tree is represented e.g. by its position, height, DBH and species. The simulations were executed for a period of 50 years from 2012 to 2062 and computed in steps of 5 years.

For thinning and final cutting during the simulation, the species share of the current stand was used to gradually work towards the particular FDT definition and finally replaced by a new stand with the species share of the particular FDT. The new forest stand is then simulated accordingly.

On sites in preserved areas, no thinning nor final cutting is simulated and forest growth is just bound by regionally different maximum density functions and yield levels (Döbbeler and Spellmann 2002; Assmann 1970, p. 164).

Range of uncertainty

Concerning research question *iii*, we assess the uncertainties as the difference between forest development in scenarios b–e, measured by cultivation area and its goal achievement in relation to the FDT, growing stocks as well as the FLR.

For every subplot with predicted pine share by the *WaldPlaner*, per scenario (b–e) a target achievement percentage $A\%$ is calculated. It is computed as

$$A\% = 100 - \left| \sum_{h=1}^{L} W_h \frac{1}{m_h(P)} \sum_{i=1}^{n_h} \sum_{j=1}^{m_i} \left(r_{hij}(p) - r_{hij}(g) \right) \right| \quad (2)$$

with $m_h(P)$ total number of subplots with predicted pine in stratum h and $r_{hij}(p)$ denotes the performed pine's percental ratio per subplot in 2062. Then $r_{hij}(g)$ is the target (goal) pine percentage within a FDT.

Furthermore, from the *WaldPlaner* results, we considered the change rate (z) of pure stands by computing

$$z = \frac{\overline{x}''}{\overline{x}'} = \frac{\sum_{h=1}^{L} W_h \overline{x}_h''}{\sum_{h=1}^{L} W_h \overline{x}_h'} \quad (3)$$

with $\overline{x}_h'$ as the estimated mean cultivation area in stratum h for time t, $\overline{x}_h''$ as the estimated strata mean cultivation area for time $t + 50$ and W_h as the stratum weight. *FLR%* is then derived by $(1 - z) \times 100$. The variance is calculated by a combined ratio estimator (Cochran 1977, p. 165)

$$v(z) = \frac{1}{\overline{x}'^{\,2}} \sum_{h=1}^{L} W_h^2 \left(v(\overline{x}_h'') + z^2 v(\overline{x}_h') - 2z \, cov(\overline{x}_h'', \overline{x}_h') \right) \quad (4)$$

Subsequently, we used $v(z)$ to calculate the 95% confidence intervals (CI) with $\alpha = 0{,}05$ and a t-value of 1.96 was chosen due to the large sample size (see "Study region and dendrometric data").

For details on the basic components of the NFI estimation design, see supplemented eq. S1–S4 and Riedel et al. (2017).

Results

Guard rails of pine shares

The variation of different FDTs is shown in Fig. 5 and can be seen as maximum or minimum guard rails of future pine shares. The blue circles highlight exemplary areas analyzed in more detail below. Thus, the Harz mountains sites (big circle in Fig. 5b), elevation of 1,141 m a.s.l., mainly comprises mesotrophic SNL (Fig. S1) and positive CWB in EC-EARTH. Consistently, low pine shares resulted, whereas at deteriorating CWB in HadGEM pine shares increase, even at high elevations (circle in Fig. 5c). In 2012 large spruce forests were stocking in the Harz mountains, therefore pine can only be cultivated once spruce is mature. Different pine's evaluation of two neighboring states is shown between borders of Saxony-Anhalt and Brandenburg at comparable

Fig. 5 Guard rails of pine share within FDT classified as a leading (≥ 50% BA), mixed (≥ 10% BA), secondary (< 10% BA) or excluded (0% BA) tree species. Means per tract between scenarios **b**–**e** are shown. Note that space between points (tracts) does not state forest cover but sampling density
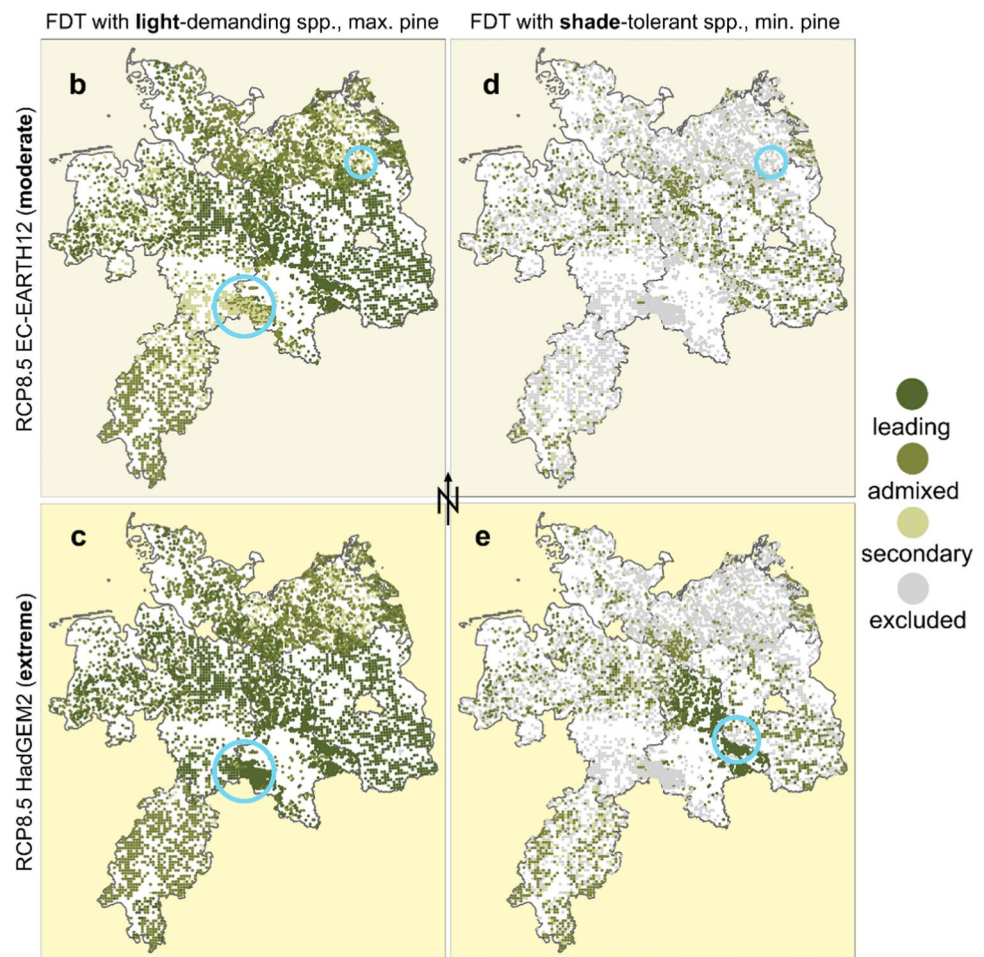
mid-low SNL: In the Fläming hill country (circle in Fig. 5e) pine shares vary significantly between the two states. On sites with overall rich SNL (Fig. S1) even at low CWB as in the Strelitz territory in Mecklenburg-Western Pomerania (small circles in Fig. 5b and d) the ratio of pine within FDT never exceeds mixed level.

Comparing the effect of climate models (b, d vs. c, e) it can be seen that the variation of pine's FDT shares is comparatively lower in Brandenburg and Mecklenburg-Western Pomerania whereas it tends to be greater in Hesse, Lower Saxony, Schleswig-Holstein and Saxony-Anhalt.

Prediction of forest development

Essential for the prediction of forest development is the derivation of the differing target BAs of the two thinning regimes shown in Fig. 6. Here, a difference of up to approx. 10 m^2 ha^{-1} for the uppermost SI and still about 3 m^2 ha^{-1} for the lowermost SI is depicted. Note that the plotted SI between west and east are not exactly equal as a result of different SI-systems. According to the silvicultural guidelines the BA in western states does not increase

much after the age of 60 while in the eastern states it is more or less held level until the age of 100. The patterns of the curves fits to the unequal yield levels as expressed by the maximum density and marks a difference of about 7 m^2 ha^{-1} over 100 years.

Overall Scots pine's extent is decreasing from currently (a) 1.358 million hectares (m. ha) towards a minimum of 0.919 m. ha (d) and at most 1.123 m. ha in scenario (c).

The current north German forests reveal an uneven age class distribution (Fig. 7, columns a). This unevenness is not balanced in any scenario until the year 2062 (b–e). The mean stratum-weighted pine stand age is 73 years in 2012 (a) and varies then over 16 years from 63 years (c) to 79 years in (d) in the year 2062. If only certain age classes are examined, pine's share in scenarios b–c accumulates in comparison to scenarios d–e which is notably depicted in age ≤ 60. Subsequently, in these pine-minimizing scenarios d–e of age ≤ 60 Norway spruce increases, under which shade-tolerant *Abies* spp. are subsumed. The impression of almost non-existent pine share in age ≤ 20 is completed by an indentation in age class 41–60. While other deciduous trees with long life expectancy (ODL), such as *Acer* spp. and *Fraxinus* spp.,

Fig. 6 SI-depending target BA of *P. sylvestris* (solid lines) per region after particular silviculture guidelines referring to **W** yield tables of Wiedemann ([1943](#); residual SE 38.6%) or **E** Lembcke et al. ([1975](#); residual SE 32.6%) and maximum density in respective yield level regions (dashed lines; Döbbeler and Spellmann [2002](#)) for top heights of greatest pictured SI
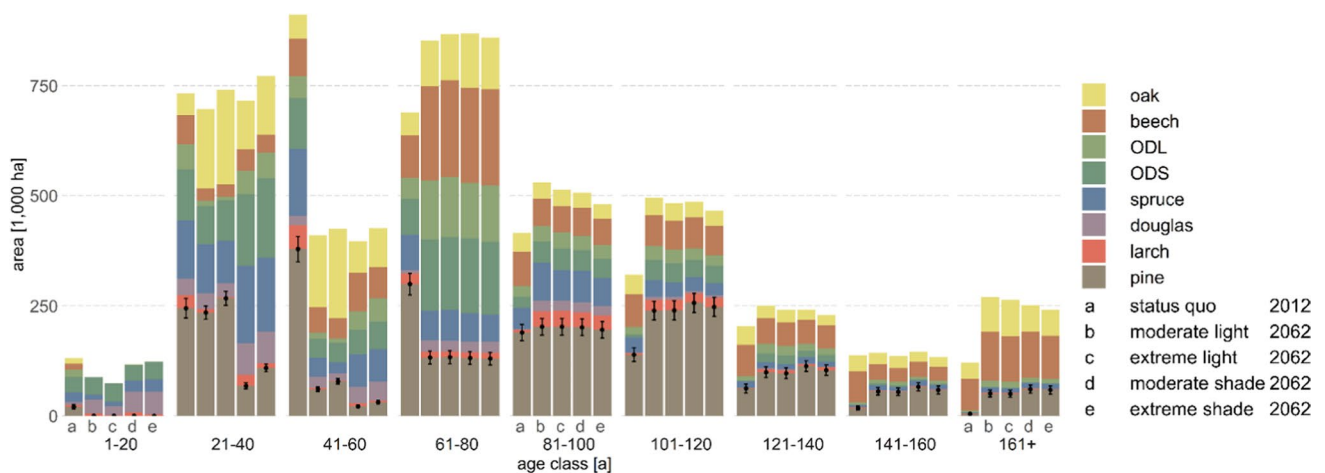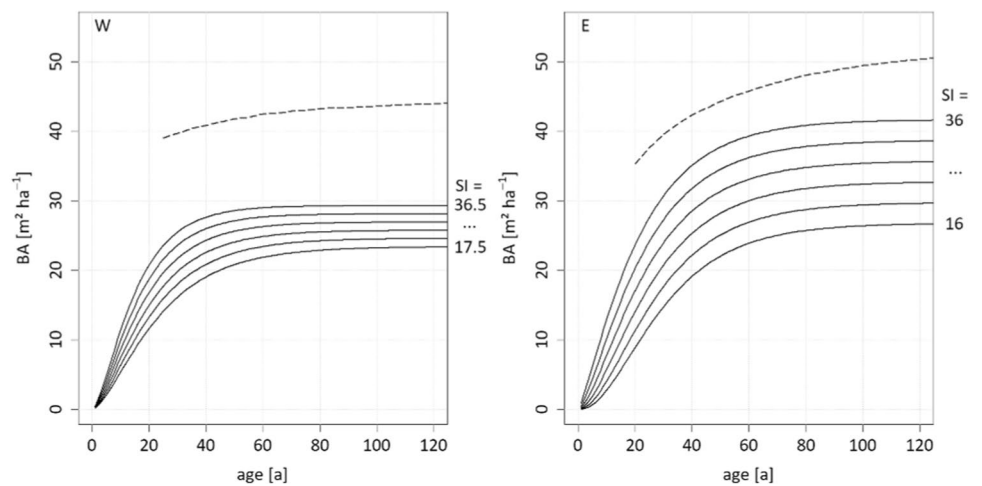

Fig. 7 Estimated cultivation of tree spp. groups depending on the age class. According to BMEL ([2015](#)) compact wood in 2012 (a) and the scenarios (b–e) in 2062 (assigning other pine than *P. sylvestris* to larch) are shown. Error bars for pine depict ±CI95

decrease in all scenarios b–e, other deciduous trees with short life expectancy (ODS), such as *Betula* spp. and *Populus* spp. increase.

FLR of pine tends to be slower if the reduction between scenario d, e and b, c is examined for ≥ 101 year old stands (when shade-tolerant spp. are emphasized). Strikingly, old stands ≥ 101 and especially > 161 years are increasing for all scenarios b–e again with higher pine shares in scenario d–e.

We defined *A%* as the difference of performed pine's share per subplot in 2062 and targeted share as per FDT (cp. Fig. [5](#)). For this evaluation all subplots with predicted pine were taken into account. In 2062 *A%* eventually reaches (b) 69.6%, (c) 62.7%, (d) 68.6% and (e) 68.6%. Hence, scenario (b) achieves the particular target best and scenario (c) worst. From the growing stocks of pine (Fig. [8](#)) currently (a) 1.9% are under strict protection on site mapped forests which increases to 3.0–3.8% in 2062 within all scenarios (b–e).

Currently the growing stock of all spp. amounts to (a) 1,193 million cubic meters (m. m^3) whereas in 2062 it differs between scenarios from 1,391 (c) to 1,484 m. m^3 (d). While Scots pine volume amounts to 424 m. m^3 in 2012, in 2062 it almost stays constant with 427 m. m^3 in scenario (d) whereas the other scenarios predict decreasing volumes as a result of a dismantling management with minimum 340 m. m^3 in scenario (b).

Regarding the pine growing stock for trees near to the target diameter/large-dimensioned timber ≥ 50 cm (i.e. diameter classes ≥ 41 cm), under all scenarios there is a considerable increase compared to the current volume (Fig. [8](#)). This increase is largest if shade-tolerant regeneration is emphasized (classes 51–70 cm for scenarios d–e). Volume over bark for thin trees ≤ 40 cm DBH in all scenarios is comparatively low in comparison to *status quo* (a) which expresses renunciation due to FLR. However, in scenarios where pine shares are maximized
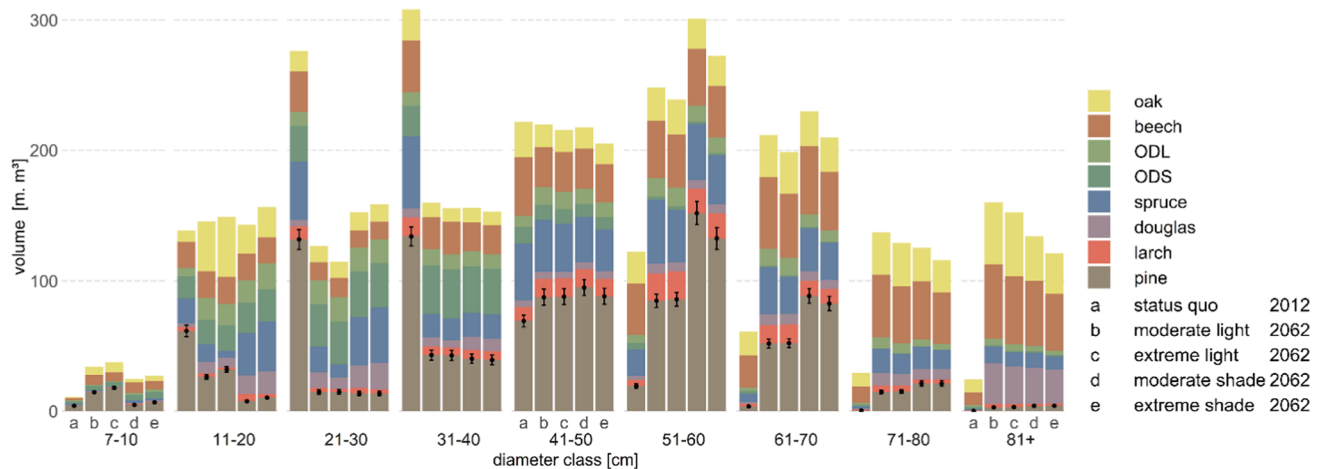
Fig. 8 Estimated volume (growing stock) over bark of tree spp. groups depending on the diameter class. According to BMEL (2015) compact wood in 2012 (a) and the scenarios (b–e) in 2062 (assigning other pine than *P. sylvestris* to larch) are shown. Error bars for pine depict ± CI95

(b–c), growing stocks increase slightly for trees ≤ 20 cm DBH in comparison to scenarios d–e. But in 2062 in every scenario the pine stocks (≤ 20 cm) remain less than the *status quo* (a) in 2012.

Uncertainties

Recapitulating uncertainties between BAU scenarios, it is evident that silvicultural impact on cultivation area or growing stocks is about four times higher than climate models effect (Table 2). In the north German forests, pine has an overall relatively lesser growing stock than cultivation area, expressed by a total of 35.6% volume on 37.1% area. Growing stock as well as cultivation area are decreasing even if pine is prospectively emphasized in forest planning. The precision of estimation (CI95) decreases over time and is lowest in scenarios d–e where shade-tolerant spp. are promoted.

About two thirds of the studied pine extent lies within the eastern states which as a result influences regional uncertainty. In the following, pure stands with ≥ 90% pine BA per plot are considered. Monospecific stands have highest risk and forest restoration priority. From their respective total cultivation area per region, this leaves 36% of stands in the

west and 71% in the east. This subset is represented in Fig. 9. Besides this regional difference, a comparable behavior of uncertainties between all scenarios b–e is visible: Uncertainty is greater between silvicultural variants than between climate models.

By contrasting the western and eastern states it is clear that in Brandenburg, Mecklenburg-Western Pomerania and Saxony-Anhalt there are exceeding five times more pure pine stands than in the west. Pine's FLR progress absolutely seen is higher in the eastern region because the natural setting possesses higher pine content. In both regions most pure stands are replaced by mixed forests in scenarios d–e. Absolute uncertainty range expressed as a difference between all scenarios b–e, is higher in the eastern region and varies from 28,000 ha (east) to 13,000 ha (west).

However, besides the great absolute progress in FLR of pure Scots pine in the eastern region, a relative comparison detects a lower FLR rate of monospecific stands here (Fig. 10D). Regardless of the maturity threshold when final cuts start, for both silvicultural variants it can be stated that the FLR rate between regions is more than 11.3–19.3% slower in the east (Table 2). Besides their extent, western and eastern pine monocultures can be seen as comparable when considering their site, age and SI (Fig. 10A–C).

Table 2 Summary of uncertainties arising from forest planning between climate models and silvicultural variants in scenarios b–e in 2062. Numbers show relative value of total area/stock

Variable	Variant	Light	Shade	| Δ silviculture |
Area [%] (a) = 37.06 ± 4.33	moderate	(b) 28.79 ± 4.46	(d) 24.64 ± 4.81	**4.15**
	extreme	(c) 30.01 ± 4.30	(e) 25.06 ± 4.74	**4.95**
	| Δ climate |	**1.22**	**0.42**	–
Stock [%] (a) = 35.57 ± 4.40	moderate	(b) 23.58 ± 4.92	(d) 28.75 ± 5.00	**5.17**
	extreme	(c) 25.28 ± 4.74	(e) 28.08 ± 5.22	**2.80**
	| Δ climate |	**1.70**	**0.67**	–

Fig. 9 Estimated cultivation area of pure stands for the western and eastern study regions (≤10% BA mixed by another tree spp. per tract). According to BMEL (2015) compact wood in 2012 (a) and the scenarios (b–e) in 2062 (assigning other pine than *P. sylvestris* to larch) are shown. Error bars for pine depict ±CI95
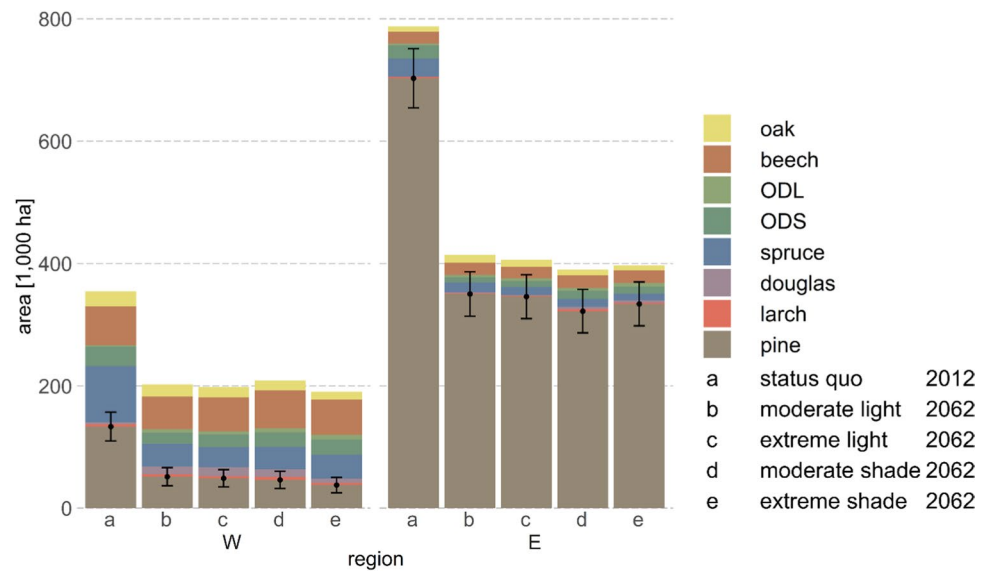

Fig. 10 **A–C** In current (a) pine monocultures between regions (W, E) at comparable SNL, stand age and SI there are **D** different FLR rates of pure stands evolving in all scenarios b–e. Trophic key adapted from Schmidt et al. (2015). **A–C** Violin-plots depict data density, mean value: red point; median: black line. **D** Error bars show ±CI95. SNL per plot is reported as fitted value, i.e. the most plausible score, resulting from an estimated cumulative logit model (Fahrmeir et al. 2013, pp. 312–316) with including plot number as random intercept component. This modeling step avoids manipulations, such as empirical mean calculation, that are not adequate for the ordinal scale of the SNL outcome
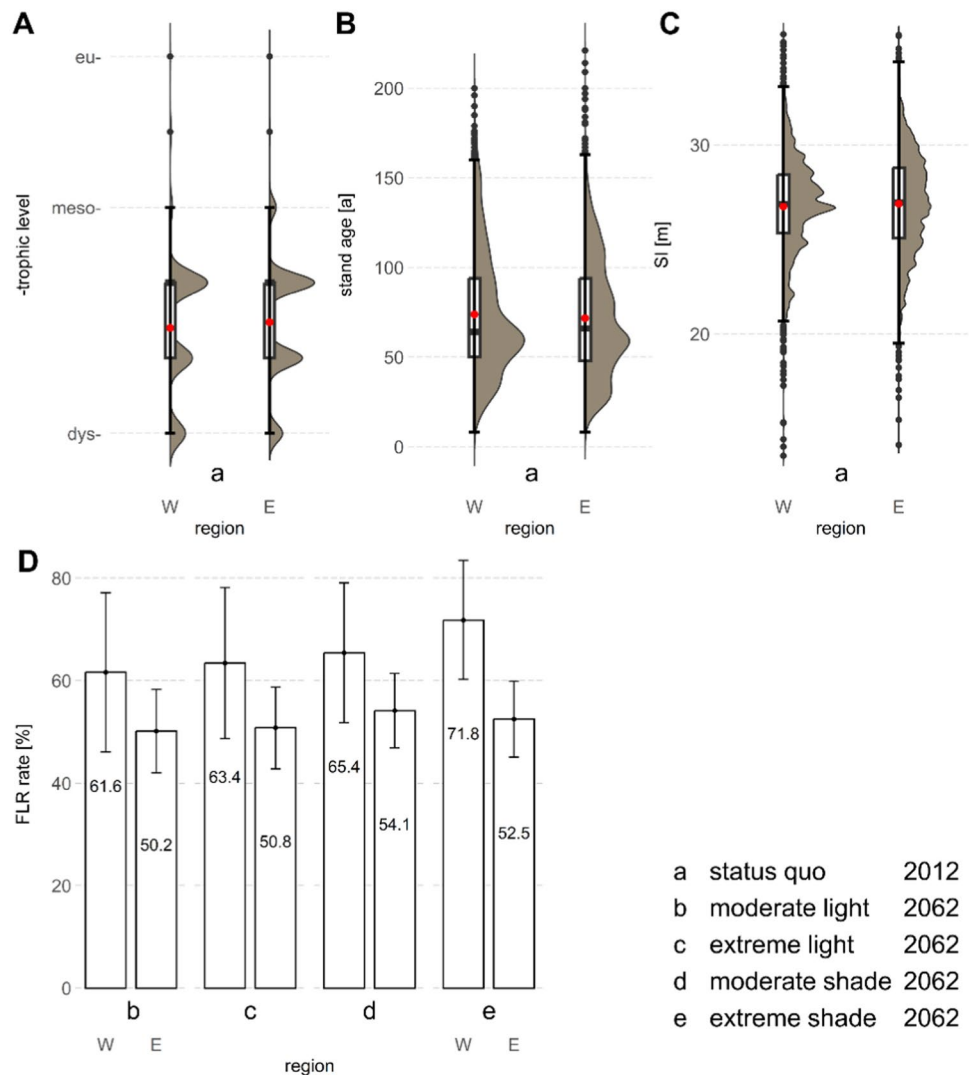
Surprisingly, relative FLR rate in shade-tolerant tree spp. emphasizing scenarios d–e is higher for both regions although earlier underplanting, longer cutting period, higher canopy cover and stockpiling (Fig. 8) influences stands here. Relative uncertainty range expressed as difference between all scenarios b–e is almost three times higher in the western region (10.2%) than in the eastern region (3.9%). Uncertainty ranges between climate models is again smaller than between silviculture variants. Estimation ranges (CI95) are highest in western stands and especially in scenarios d–e where shade-tolerant spp. are promoted.

Discussion

Critical remarks on material and methods

Uncertainty in forest resource assessment and modelling is caused by sampling, measurement, and prediction errors (Kangas and Kangas 2004). Uncertainties in climate predictions arise from internal variability of climate on the planet, response uncertainty is due to different models and scenario uncertainty because future human behavior cannot be foreseen (Hawkins and Sutton 2009). In silviculture, however, uncertainty is not used yet to describe the outcome of adaptive management, it is rather seen as plurality of action options (Ehwald 1949). Remarkable impact can be furthermore drawn from politics (Lawrence 2017) and calamities (Rosenkranz et al. 2023).

While the present work identifies sampling errors by using variances, prediction errors accumulation in *WaldPlaner* are not assessed. With every simulation step an error propagation within scenario strand must be expected. Therefore the simulation was only executed for 50 years length which is already more than the recommended 40 years (Hansen and Nagel 2014, p. 29). However, climatic uncertainty is expressed by contrasting moderate and extreme realizations.

TreeGrOSS is parameterized with a profound data set derived from long-term experiments as well as inventory data. It has been intensively validated (Vospernik et al. 2015) and is frequently applied for forest scenario simulations in northern Germany (e.g. Hentschel et al. 2017; Albert et al. 2018). The *WaldPlaner* indirectly also considers effects of species mixture, such as overyielding (Sprauer and Nagel 2015), that can be seen throughout as positive for Scots pine (Pretzsch et al. 2015, 2021).

When regenerating forest stands, *WaldPlaner* does not establish a certain seedling density but regeneration placeholders. Feasible stand densities are firstly considered when ingrowth in compact wood occurs to avoid overstocked plots with possibly > 100,000 trees ha^{-1} prior. However,

density-related measures such as volume could be affected by the placeholder density. In contrast, the cultivation area is not density-related but standardized, based on plot size.

Moreover, we see five improvements in our predictions compared to not site specific simulations expressed by a smaller uncertainty space (Oehmichen et al. 2018; Rosenkranz et al. 2023): Next to (1) different management intensities and future crop tree numbers (2) the *WaldPlaner* considers realistic FDT guard rails from silvicultural guidelines. Whilst (3) tree spp. are selected site-specifically, (4) density-related and (5) climate-sensitive tree growth from representative north German yield levels is taken into account (Wördehoff et al. 2017, p. 22). However, spatial extension of the two yield levels is static relating to climate change.

The current study uses data from the NFI with reference year 2012. Certainly data from 2012 can be considered as outdated after the severe calamities that have occurred since then (Rosenkranz et al. 2023). Still, the used data of the NFI serves to show trends and directions of future undisturbed forest development.

We acknowledge that site data is heterogeneous as shown by site water balance or climate humidity districts in order to select tree spp. dynamically. Also next to the Baltic Sea, climate water balance-values begin to increase (Fig. 2B). This results from downscaling due to an absence of climate stations on the sea. From this we conclude that tree spp. selection must be enhanced e.g. by measures of drought as the Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al. 2010) or temperature extremes (Brandl et al. 2020; del Río et al. 2022). Since an area-wide available water capacity is not given in Mecklenburg-Western Pomerania, dynamic tree spp. selection must still rely on soil moisture level and climate humidity districts with only minor outcome differences between climate models (Thurm and Wirner 2023, pp. 61–65).

In addition, we want to point out the difficulties by creating stand information from sampling data. Since NFI data originates from angle count sampling, exact tree neighborhood influences remain unknown (Fischer and Mölder 2017). Also stem quality is not surveyed in German NFI that would affect the tree selection for shelterwood cuts and the partial understory removal. Notwithstanding the plot size that was chosen due to computing capacity, results are only valid for aggregated measures at large sample size. The sample unit of the German NFI consists of the clustered plot. However, as every subplot could show different soil nutrient level and thus FDT, model stands were not generated and simulated per plot which contradicts to the above NFI basic idea. However, pure stands were again defined in accordance with the sampling definition on the plot level. These units, defined as ≥ 90% monospecific species per plot, would have occurred to a greater extent if considered at the subplot level.

The shown magnitude of FLR rate and difference between the regions, however, is similar.

Following common definitions in German forestry, the bottom layer of a stand is divided into understory and young growth (Bartsch et al. 2020, p. 186) and only the latter can be seen as an adequate regeneration. As long as overstory density is $S_y^\circ \geq 0.5$, stands are typically subsumed by their top layer (main stand; BMEL 2015, p. 49).Thus, FLR rate would be influenced negatively if vertically mixed understory is only considered when overstory is very light. Since the *WaldPlaner* does not consider stand layers automatically, we assumed understory trees that are compact wood, also contribute to restoration of forests despite their layer affiliation or quality. We recognize that the overstory may not have been adequately cut yet in each case and that FLR may not yet have occurred in terms of regeneration (generation change).

Assessment on results

Differences in silvicultural concepts

Figure 6 depicts the different thinning regimes between the federal states implemented in the *WaldPlaner* environment. These operational concepts correspond to the current BAU of the particular region. The Chapman-Richards-equation shows an overall continuous fit (Table S1; Fig. 6).

On the one hand, more intense thinning regimes (i.e. lower BA compared between regions, Fig. 6W) undercut the critical stocking density (Vospernik et al. 2015). On the other hand, biodiversity, single tree stability, diameter growth and vitality are promoted, although the stability against snow and wind is initially lower after tending (Lust et al. 2001; Hentschel et al. 2017; del Río et al. 2017; Bauhus 2022). Comparatively lower stocks and higher thinning yields in the western part of the study area express risk-averse behavior.

In the eastern region an extensive thinning regime (i.e. higher BA compared between regions, Fig. 6E) is currently practiced. On the one hand, this operational concept holds the critical stocking density (Assmann 1970, p. 231, p. 329) and relies on stand stability but showing comparably lower stem diameters at a time and higher h/d-ratios (Döbbeler and Spellmann 2002). Other studies show that under higher stocking and later thinning the highest proportion of logs can be assumed, thus, leading to a greater amount of sequestered Carbon in wood products and earlier in the stocking biomass (Garcia-Gonzalo et al. 2008). On the other hand, lower tree health can be expected by smaller crowns and also weaker drought adaption (Sohn et al. 2016; del Río et al. 2017; Bauhus 2022). In times of climate change higher S_y° express a rather risk-affine management.

Until today for scientific usage, FDT were assigned as expert-based but not automatically (e.g. Rudolph et al.

2015; Wördehoff et al. 2017; Albert et al. 2017). Hence, the algorithm of Hamkens et al. (2022) means a great advance: Aside from this work, they actually use seven RCP8.5 climate models and recommend tree spp. dependent on whether a single tree species was selected multiple times in all models. In a multi-criteria approach the tree species itself and no longer entire FDT are assigned to a given site (cp. Fig. 3) for which reason mixed stands (FDT) are compound if the particular spp. are recommended. However, the tree spp. classification results in the same classification as used by Albert et al. (2017).

Figure 5 can be interpreted as a measure how much State Forest Administrations rely on Scots pine in climate change. This is expressed by its multiple increase (Fig. 5c) or overall almost cancellation (Fig. 5d) which would negatively affect e.g. γ-biodiversity or reinforce calamity risk (von Sponeck 1819; Hentschel et al. 2017). This mainly results from related site water balance or climate humidity district thresholds between the states where pine is recommended. Besides this, in Brandenburg and Mecklenburg-Western Pomerania we firstly have to question if the climate humidity district shifts through changing climate water balance values are sensitive enough and secondly if the FDT set per climate humidity district is sufficiently different. Furthermore, it has to be argued, whether all the current vitality problems resulting from pine's biology are considered reasonably in the silvicultural guidelines (Bose et al. 2020; Rehschuh and Rühr 2021; Haberstroh et al. 2022) and, when weighed, justify an increase cross-regionally. After all, economic and yield aspects play a central role in the discussion about the future cultivation suitability of coniferous tree species such as pine (Leuschner et al. 2022; Brichta et al. 2023). We also observed that the cultivation recommendation for pine is based on expert knowledge to this day and has not changed over time (Pfeil 1856; Wagenknecht 1955).

Uncertainties in pine's cultivation area

For the estimate of $A\%$, every subplot with eventually planned pine was considered and compared to the predicted FLR outcome in 2062. If the Harz, which is dominated by Norway spruce in 2012, should be regenerated into pine as well, then $A\%$ is consequently low (Fig. 5c). If alternatively current high pine population is regenerated with pine again and is not introduced in new areas such as rich sites, $A\%$ is greatest (Fig. 5b). Schelhaas et al. (2015) conducted an Europe-wide simulation study on NFI plots until 2070. They describe species shifts induced by a climate envelope approach from Hanewinkel et al. (2013) as very inert. From areas with restoration obligations only 36% changed. Inertness here is caused by uneven age-class distributions and the number of spp. and stands to convert. The present study achieves higher $A\%$ because pine is still

scheduled at all as opposed to the results by Hanewinkel et al. (2013). Also the north German age class distribution and mean ages of pine in 2012 are convenient for FLR. Inertness and age influence is also proved by Albert et al. (2015) and Lindner (2000). What emerges further is that Brandenburg and Saxony-Anhalt have different evaluations on where to cultivate pine in extreme climate (Fig. 5e).

The depicted high planning share of pine in the Harz mountains (Fig. 5c) can be discussed as unrealistic, since here major precipitation occurs and even highly productive Norway spruce's key growing area is also contemplated. However *P. sylvestris* is still represented in the current FDT set for those sites which speaks e.g. for a diminution of the FDT variety between landscapes to achieve higher γ-diversity (Heinrichs et al. 2019).

If FLR is considered, future cultivation area of Scots pine decreases as other studies document on different scales (Wördehoff et al. 2017; Vrška et al. 2017; Oehmichen et al. 2018; Rosenkranz et al. 2023). An uncertainty of 0.204 m. ha as found in the present study can be considered low: Oehmichen et al. (2018) simulate NFI data nationwide until 2052 and implement a not site specific FLR by emphasizing either coniferous or broadleaved trees and disregarding climate data. For pine an uncertainty of 0.69 m. ha can be derived from their results. For our research area this equals to 0.46 m. ha. Rosenkranz et al. (2023) simulate NFI for 200 years throughout Germany until the year 2211 and imply as well a not site specific FLR. They distinguish between high and low intensive adaptations with different proportions of natural succession and risk levels. In 2062 uncertainties for *P. sylvestris* of about 0.4 m. ha uncertainty for our study area.

Pine's area remains unevenly distributed when considering age-classes. While the peak in age class 21–40 coincidentally corresponds to actual calamities (Rosenkranz et al. 2023), it actually results from the assumed optimal regeneration circumstances. Thus, it has to be asked, how realistic the outcome is, if light-demanding spp. are promoted. Hence, we point out, that prospectively pine's fructification and recruitment will alter (Matías and Jump 2012), timber marketing might impede FLR (Knoke et al. 2001) as the adaption effort is high (Albert et al. 2017; Bolte et al. 2021) and steady seedling availability of other spp. is not guaranteed. Also, private forest owners might not take part in FLR that intensively (Wördehoff et al. 2017; Stockmann et al. 2024). As future potential natural vegetation might be composed totally differently (Hanewinkel et al. 2013; Buras and Menzel 2019; Mette et al. 2021; Hinze et al. 2023) we deduce nevertheless that all silvicultural endeavors must concentrate on FLR.

Increasing mean stand ages in scenarios d–e in comparison to scenarios b–c correspond to the respectively longer cutting periods and comprise about 10–16 years. This might affect tree vitality since older pine show higher crown defoliation (Przybylski et al. 2021; Bauhus 2022).

Uncertainties in pine's growing stocks

All scenarios (b–e) conceal an increase of volume among all tree spp. groups in the absence of risk which is also described by other authors (Wördehoff et al. 2017; Oehmichen et al. 2018) whereas in turn others predict a decreasing total volume whilst considering risk and climate change (Rosenkranz et al. 2023).

Regarding growing stocks of Scots pine a decrease in scenarios (b, c, e) and a stable amount in scenario (d) is visible from the predictions. Regardless of risk, a dismantling management of coniferous stocks and especially pine is well known as other simulation results prove (Rudolph et al. 2015; Wördehoff et al. 2017; Oehmichen et al. 2018; Rosenkranz et al. 2023) and retrospective studies show or experts anticipate (Höher 1994; Schmitz 2019). In this case macroeconomically important leakage effects are expected (Bösch et al. 2015). An oppositional increasing pine stock in cross-regional simulation studies was also found by Suárez-Muñoz et al. (2023) who predicted *Pinus* spp. development in Spain until 2100. Here the trend of light rising biomass in *P. sylvestris* was explained with comparatively young mean stand ages and more favorable climate was also considered. In fact, the present work also has highest mean ages in case of the rising pine stock. Suárez-Muñoz et al. (2023) furthermore state, that more intense management, as comparable to scenarios (b–c) in this study, led to higher FLR and lower growing stocks. Generally, due to the extent of warming and aridizising climate in RCP8.5, future volume development of pine will be hampered (Matías and Jump 2012; Haberstroh et al. 2022; Suárez-Muñoz et al. 2023). Comparatively, due to mixing of other tree spp., growth will be promoted (del Río et al. 2017; Diers et al. 2022; Vospernik et al. 2023) or drought vulnerability at least relieved (Steckel et al. 2020) which enlarges uncertainty. For old pine trees however, we only expect low effects of altered climate on SI and growing stocks (Albert et al. 2015).

The present work shows comparably low pine stocks for trees ≤ 31 cm DBH. We assume this to be probably a methodological artifact of *WaldPlaner*'s regeneration placeholders (see "Critical remarks on material and methods") and the result of only low pine ratio within every FDT, which was discussed by Wördehoff et al. (2017, p. 26).

We do not expect increasing stocks in diameter classes ≥ 41 cm to be caused by remnant trees, which are only up to 11 m. m^3 at expansion. Preserved areas with growing

stock similar to Engel (2020, pp. 43–46) are also ruled out as explanation for the increase. Furthermore, especially large-dimensioned timber ≥ 50 cm, from our point of view results are due to exalted maturity definitions, since the cutting cycle and maximum removal amount per operation do not narrow down opportunities (Wördehoff et al. 2017, p. 23). Additionally, it has to be considered, that the 5 years volume increment is up to 50 m^3 ha^{-1} which also has to be removed at every cutting cycle. Moreover tree diameters ≥ 50 cm will challenge stakeholders in the forestry and timber cluster: Due to the popular profile hogging technology in central European sawmills, large-dimensioned timber reduces the feed rate or even prevents the cutting (Schrade 2002; Knocke et al. 2023). High valuable pine timber, especially stocking in pruned stands and having a higher target diameter of 55 cm, however requires other processing techniques. In 2012, this high-quality assortment accounts for only about 5% of pine's total growing stock and can therefore also be ruled out as the cause of the increase in large-dimensioned timber where all qualities are subsumed.

To our knowledge, in reality a cutting cycle of 5 years cannot be met because organizational units have increased tremendously, as elsewhere (Lawrence 2017). Thus, uncertainty is heightened in terms of whether the thinning or final cutting operation takes place or not. Schall and Ammer (2013) indicate the need of high maintenance in pine forests. Especially with increasing site quality more silvicultural interventions are needed to increase stand heterogeneity which is linked to stability (Döbbeler and Spellmann 2002; del Río et al. 2017), resistance (Sohn et al. 2016; Hentschel et al. 2017) and biodiversity (Lust et al. 2001; Kint et al. 2006). Pretzsch et al. (2022) found asymmetric competition and mortality to homogenize Scots pine stands with increasing site quality. However, cutting cycles of 5–6 years are recommended (Kint et al. 2009; Huth et al. 2022) as well to promote mixed minority taxa.

Uncertainty or silvicultural plurality?

The comparison of relative differences in FLR explains its influence by silviculture to be four times as high as climate (Table 2). For *Pinus* spp. Suárez-Muñoz et al. (2023) found the same magnitude while also considering RCP4.5 besides RCP8.5. An interplay of climate models and management scenarios was also found by Garcia-Gonzalo et al. (2008) who optimized management plans that targeted timber production and carbon sequestration by simulating forest dynamics for 100 years. They found silviculture impact being twice as high as the climate component. Our findings express that high variability in silviculture and only little bandwidth from considered climate models are used for adapting forests towards climate change in northern Germany (Table 2). Thus, the range is not expressing

the indecisiveness of State Forest Administrations but in fact it has been claimed as plurality and freedom to act (Ehwald 1949). For other stakeholders than forestry itself however, we interpret the differences as uncertainty. To our knowledge, especially inside regions, the relative decrease and the uncertainty range of the future outcome of forest dynamics, will affect the forestry and timber cluster as e.g. sawmills (Bösch et al. 2015; Leuschner et al. 2022). Another stakeholder *s.l.* is biodiversity where many species are relying on a certain pine extent: After *Quercus* spp. and *Salix* spp., as to light-transmission, Scots pine supports the most specialized insects and mites (Brändle and Brandl 2001), which increases with tree age (Turmukhametova et al. 2020). The visible spread in estimation width in scenario d–e in comparison to b–c is expressing success in FLR due to more variable forests as greater structural complexity arises when shade-tolerant trees are promoted (Pretzsch et al. 2016).

Accelerating FLR rate

Pure pine stands are particularly at risk in times of climate change which is mainly caused by drought, heat, insects, windthrow and fire (Hille 2006; Brandl et al. 2020; Brichta et al. 2023).

On a relative scale, pure stands are five times more present in the east resulting from historically different operational concepts (Nelson 2005, pp. 161-170). Regardless of the region Figs. 9 and 10 depict relative FLR progress being faster even under more dense overstories and longer cutting periods (scenario d–e; Table 1). Compared to common German forestry that considers stand layers, we reason this by disregarding vertical stand structures so that every evolving tree during the understory reinitiation stage (Stanturf 2016, p. 42) that holds compact wood is assessed. However, this does not state a *WaldPlaner* artifact but a realistic and layer-overarching FLR success. Also in scenarios b–c there might be pine regenerated with pine again which temporarily leads to pure stands even if the FDT does not target monocultures. Overall, FLR rate of about 65% within 50 years corresponds to other studies (Höher 1994, p. 50; Vrška et al. 2017) and still experts call for quadrupling FLR in order to be finished by 2050 (Bolte et al. 2021). Generally, the FLR rate can be interpreted as the inertia and lag time until active forest management induces adaptiveness (Schelhaas et al. 2015; Puettmann and Bauhus 2023).

But much more than all that, the FLR gap between the regions remains similar. If the absolutely seen higher progress in the eastern states would be realized (for impediments see "Uncertainties in pine's cultivation area"), which is highly questionable for both regions, still there are more pure stands remaining in the east. We explain this by the systemic lower thinning regime (Fig. 6;

Garcia-Gonzalo et al. 2008; Kint et al. 2009; Suárez-Muñoz et al. 2023). In contrast to the accumulation of growing stocks and large-dimensioned timber, which is positively affected by the maturity definition, the FLR rate is thus negatively influenced by lower tree diameters and less future crop trees (as a result of thinning intensity i.e. hemeroby). We acknowledge that the states of Brandenburg and Mecklenburg-Western Pomerania have also defined target diameters that allow final cuts from about 40 cm DBH onward. However, in order to clearly identify effects of silviculture and climate change on forest development (research question *ii*), different target diameters within a region would complicate comparisons.

Admittedly, the shortening of rotation periods or reducing target diameters, as demanded frequently (Hartard and Schramm 2009; Bolte et al. 2009; Oehmichen et al. 2018) might have negative influences on the long run when timber harvest rate might decline (Bösch et al. 2017). Schelhaas et al. (2015) reported only 4% higher FLR rate by shortening the rotations by 10–20 years. We also caution about the negative impacts on biodiversity if final cuts are brought forward in time (Mason and Alía 2000; Hartard and Schramm 2009; Turmukhametova et al. 2020). Additionally, pine's rotation periods in the recent decades already decreased due to frequent tending and thinning from above (Oehmichen et al. 2018).

In the literature, a target diameter framework for Scots pine from 40 to 60 cm DBH is occasionally proposed (Rudolph et al. 2015; Bartsch et al. 2020, p. 459). Therefore we line up and suggest, in a spatial coexistence, acceleration and retardation of final cuts both have to be achieved (Nagel 2016; Wördehoff et al. 2017). Hence vulnerable pine stands (e.g. high risk due to h/d-ratio, monotonous forest districts) and sheltered stands of high value and productivity side by side would meet economic and ecological demands.

All in all, target attainment (*A*%) ranging from 63 to 70% and restoration rate (*FLR*%) ranging from 50 to 72% show related pairs of values to each other. On the one hand this illustrates that forest restoration assessed at plot level is more difficult to reach than achieving the FDT target per subplot. On the other hand, values of *A*% and *FLR*% are overlapping and similar due to the often unmixed pine distribution in 2012.

Conclusion

Altogether, the present work confirms the expectation of European forests underlying tremendous changes in the twenty-first century. We showed that the effects of chosen climate model and silvicultural variant were modulated by forest planning, which had different influence on the resulting FLR.

Since uncertainty ranges from other climate-sensitive studies considering RCP4.5–8.5 (Suárez-Muñoz et al. 2023) are smaller than the presented funnel, we conclude that the ReKliEs-De RCP8.5 core ensemble spans sufficient space. It also stands in line with typical forestry conservative predictions. Furthermore we conclude the following:

Ad *i*.)

1. No matter which bandwidth of silviculture variants (i.e. FDT guard rails) and climate models are chosen from forest planning, Scots pine area will decrease further. Still, pine's key growing area will be on poor and dry sites in the north German lowlands.
2. In order to reduce uncertainty and promote γ-diversity, FDT sets between landscapes should be restricted.

Ad *ii*.)

3. The implementing of region-specific BA, i.e. thinning regimes for Scots pine, revealed different FLR rates if target diameters are equal.
4. If FLR rate should speed up, thinning intensity must increase and maturity definitions (proportion of trees above target diameter) need to decrease. Changing the target diameters is a less effective measure to increase FLR.
5. We call for a differentiated target diameter framework to meet economic and ecological goals equally by spatial coexistence of acceleration and retardation of pine's timber usage depending on dendrometric and site data.
6. If large-dimensioned timber share should not rise, especially maturity definitions must lessen and cutting cycles of 5 years must be followed.

Ad *iii*.)

7. In 2062, relative uncertainties in cultivation area and growing stocks are at most 5% (Table 2). This might seem low but for local enterprises or ecosystems it can be very important how much pine and which diameters occur, especially when political or risk-based uncertainty is added in conclusion.

On balance, further research is needed to specify timber amount and involve risk i.e. calamities in simulations and refine silvicultural prescriptions. With searing concern we point out the necessity to actively change forests in terms of climate change.

Declarations

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