Conception of a scenario funnel for simulating climate- and site-sensitive forest development by the example of Scots pine (*Pinus sylvestris* L.) in Lower Saxony

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Abstract

In response to contemporary challenges in German forestry, this study predicts the deeply uncertain future development of Scots pine in Lower Saxony. Focusing on climate- and site-sensitive growth simulations, this research introduces a deterministic scenario funnel approach. As a start, we provide a historical context of site-productivity modeling and forest development types. Hereupon, simulation settings are aligned by cultivation area and harvest time. By integrating climate, site and pruning data into simulations, on National Forest Inventory plots, we predict forest composition until 2062 and distinguish silvicultural and climate variability as dimensions over time. The findings quantify the human impacts (silviculture/ climate change) on pine abundance, foretelling the inertia of adaption efforts for forest restoration.

Keywords: *Pinus sylvestris*, forest development types, uncertainty, simulation, pruning

1 Challenges and information needs

It is of increasing concern that forest health is deteriorating as climate change affects the landscape (BMEL 2023). Statements on future forest composition, therefore, depend on anticipating change in the face of deep uncertainty. Even when climate- and site-sensitive growth simulators are coupled with the newest business-as-usual (BAU) silvicultural concepts (Borrass et al. 2017, NLF 2021) to predict forest development, our knowledge is limited. One possible way to deal with 'unknown unknowns' is to use deterministic scenario funnels (Kosow & Gaßner 2008, Marchau et al. 2019).

Scots pine exemplifies this deep uncertainty. It is the most abundant tree species among North German forests and exhibits contradictory behavior: On the one hand, *de jure* silvicultural guidelines promote its cultivation even on very adverse sites (Böckmann et al. 2019). Hereby, expert-based assignments assume a high adaptability of *P. sylvestris* in times of climate change, based on its broad genetics and distribution range (Huston Durrant et al. 2016, Leuschner & Ellenberg 2017, Brichta et al. 2023). On the other hand, *de facto* the current cultivation area is decreasing due to the comparably low growth potential (Beinhofer & Knoke 2010, BMEL 2015), weak shade-tolerance (Wagner & Huth 2010) and comparably long rotation periods (Fischer & Mölder 2017). Moreover, model-based studies imply unseen challenges under persistently more arid and extreme climate (Bose et al. 2020, Rehschuh & Rühr 2021, Haberstroh et al. 2022).

Stakeholders involved in forest development, particularly nature conservation and national economy, need information on *P. sylvestris* abundance. It is home to many specialized taxa (Heinrichs et al. 2020, Brandl et al. 2020) and markedly contributes to value added in the forestry and timber cluster (BMEL 2016, Leuschner et al. 2022).

Besides natural hazards, i.e. mortality risks, exact statements on forest development are hampered by the broad scope of decision making and in terms of climate model selection and forest management practices. To facilitate forest policy impact assessment, this proceeding aims to

(1) identify main influences of forest development by harvest time and cultivation area,

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(2) conceptualize a scenario funnel by the outermost feasible BAU scenarios, and
(3) provide exemplary results for Lower Saxony.

2 Material and methods

This paper assesses current BAU silvicultural strategies and implements them in simulation software. Analyses were conducted using R version 4.3.1 (R Core Team 2022) and the package *sf* (Pebesma 2018).

In general, the forest development is influenced by the cultivation area and harvest time. Using the example of Scots pine, we span a three-dimensional scenario funnel over time, silvicultural management scenarios and climate model variability, in order to predict prospective pine's shares. For this reason, contrasting climatic and silvicultural scenarios are simulated for 50 years using the single-tree growth simulation software *WaldPlaner* (Hansen & Nagel 2014).

To be climate- and site-sensitive, in addition to dendrometric data, simulations rely on adapted soil water properties, site indexes (SI) and tree selection information. Therefore, simulation software is coupled with the *baklawa*-algorithm (Hamkens et al. 2022) and the *cssi*-package developed by the NW-FVA (Schick et al. 2023).

2.1 Study region and dendrometric data

This paper focuses on the German federal state of Lower Saxony (NI). Forest development on site-mapped permanent plots from the third German National Forest Inventory (NFI) is simulated from 2012 until 2062. The site amplitude ranges from lowlands to hill country (between -3 m and 971 m a.s.l.) and span a wide range of soil moisture (SML) and soil nutrient level (SNL). Precipitation ranged from 561 to 1,593 mm a^{-1} and mean annual temperatures ranged between 6.5 and 10.4 °C in the period 1991-2020 (DWD 2022). Pine has its current natural distribution focus in the North German lowlands.

The German NFI is conducted as a permanent stratified one-phase systematic cluster sampling where the strata possess different sampling densities. The sample plot (cluster, tract) holds four subplots (corners) and when located in the forest, a field survey is carried out. Riedel et al. (2017) and Kleinn et al. (2020) give further information on NFI scope, design and analysis. In total, 3,520 subplots on 1,443 tracts were considered for simulations based on site mapping which is equivalent to 93.5 % of the forest cover.

Site information on public and privately owned forests were both available. To increase the site mapping rate from 63,8 to 93,5 %, preliminary modelling results (Schirrmeister et al. 2023), as described by Köhler et al. (2016), contributed to the study. Accordingly, missing available water capacity (AWC) values were estimated following Overbeck et al. (2011) by means of the pedotransfer function by BGR (2005).

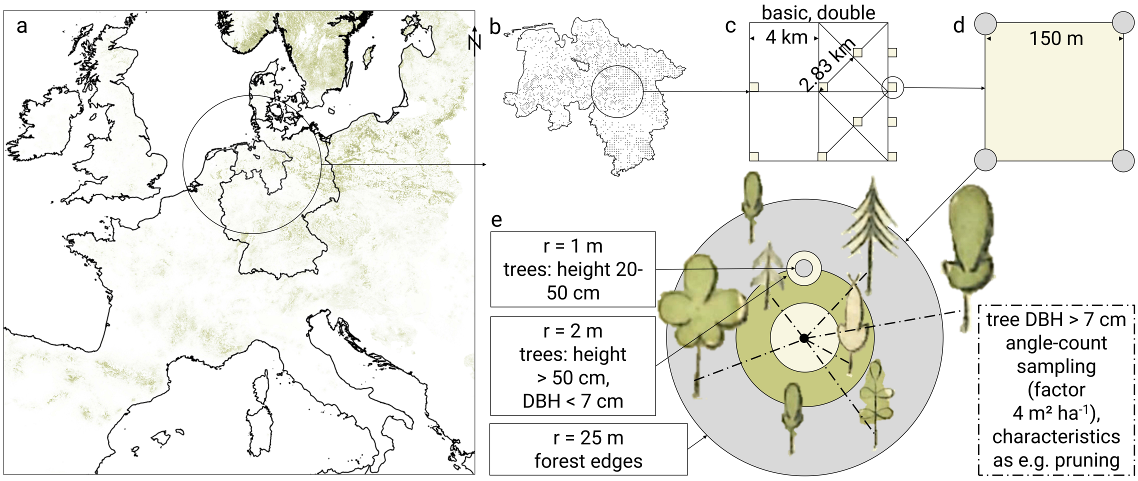

Figure 1: a Current Scots pine distribution (green; de Rigo et al. 2016) in Europe, Germany and NI. b Study area with differing intensities (strata) and c basic/ double sampling design. d Clustered plot design and e concentric subplot circles of radii r with relevance for our work. Figure based on Guimpel (1819) and BMEL (2015), borders by © GeoBasis-DE/BKG (2022) & EEA (2018)

The dendrometric data was spatially joined with forest planning records we received from the NI State Forest Administration for state owned land (see 2.3.1). Furthermore, some strict conservation stands were detected (Steinacker et al. 2023).

2.2 Influences on cultivation area

2.2.1 Site dynamics and changing SI

We account for climatic changes that cause shifting site-characteristics and a variation in the SI.

The biggest difference within the representative concentration pathway (RCP) 8.5 of climate projections lies between statistical and dynamic downscaling of climate data. Thus, from the CMIP5-generation out of the ReKliEs-De ensemble (Hübener et al. 2017) we selected the 'Hadley Centre Global Environment Model' (HadGEM2) and its statistical regional 'Wetterlagenbasierte Regionalisierungs-methode' (WettReg13). This was chosen to represent the most extreme climate projection (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 (Hazeleger et al. 2012).

Consequently, climate change is one dimension contributing to the uncertainty of future forest development.

While SNL (cf. Fig. 5d) is held constant over time, soil water properties must be aligned when the climate becomes more arid. The climatic water balance (CWB) was considered a suitable variable to make site changes dynamic. Following the FAO-standard, it is calculated for a grass cover following the Penman-Monteith formula (1948, 1965, Allen et al. 1998, Sutmöller et al. 2021). The CWB is determined as a 30-year average for the growing season. This is dynamically calculated, i.e. the length of growing season also varies depending on the respective climate (Menzel & Fabian 1999, Nuske 2022). The CWB-magnitude is visualized in Figure 5a-c.

For tree spp. selection (see 2.2.2), CWB is then considered to be the site water balance (SWB; Grier & Running 1977), which is the sum of CWB and AWC (effective root zone of 1 m). Bogs, swamps and other azonal sites we globally considered to be 300 mm m^{-2} a^{-1} CWB.

With site changes, productivity changes, too. Historically, the site-dependent performance of tree spp. was spotlighted by Pfeil (1860), who first referred to this relationship, albeit in name only (Hasel 1982, Bartsch et al. 2020). However, site-productivity-relationships were not described until the 1960's (Pretzsch & Preuhsler 2013). Even though indirect site indexing is widely used (e.g. Wiedemann 1943), as early as 1845, Heyer appealed a direct determination of yield capacity that uses site characteristics such as water and nutrient supply as well as climate. This study complies with this call: Site mapping was used in order to derive site-sensitive estimations of the height (SI).

The SI is one major predictor in the *WaldPlaner*'s height increment function. It is predicted using site, climate, N-deposition and geographic location data using the generalized additive model of Schmidt (2020). To run the model by means of the *cssi*-package (Schick et al. 2023), soil moisture level (SML) and SNL were also considered. The climate variables 'temperature sum in the growing season' and 'precipitation sum in the growing season' were dynamically averaged over the stands' lifespan and the respective projection period. The length of growing season also varies depending on the respective climate (see above). The N-deposition is based on the results of Schaap et al. (2018) and is also averaged. Hence, for each simulation step, the respective SI is updated for each subplot, layer and species.

2.2.2 Forest Development Types

For some time, there have been calls to make tree spp. selection more dynamic, in order to account for changing environmental factors (Reif et al. 2010, Spathelf et al. 2016, Albert et al. 2017, Riek et al. 2020). Silviculture in NI today manages tree spp. as admixtures. Within growth districts, the selection is executed by SWB, SNL, and the Forest Development Type (FDT) (Böckmann et al. 2019). The latter operationalizes long-term targets for a controlled forest evolution and gives a quantitative mechanism in order to achieve a site-specific composition and structure of mixed stands (Larsen & Nielsen 2007).

FDT precursors were invented by Abetz (1935; BrLFA 1931) and launched in the Harz mountains

(Hildebrand 1935) with whole northern Germany following soon after (RFA & PrLFA 1938, Borchers 1949, Wagenknecht 1955). From the beginning the feedback has been that the silviculture and the sites potential should not be narrowed by too few or too precise FDT, nor should prescriptions be broadened in such a way that silvicultural treatment is no-longer given (Hartmann 1937, Ehwald 1949). Nowadays FDT can be found worldwide (Larsen & Nielsen 2007, Mason et al. 2018) and are continuously being developed in order to adapt woodlands towards climate change (Schröder et al. 2023).

Depending on the current situation (e.g. suited/unsuited stocking or clearing), different FDTs can be realized on comparable sites to benefit from natural processes. There is, therefore, an open-ended component in FDT application. In mature forests, from a regional (growth districts) set of recommended FDTs, a site-specific subset can be selected for standwise forest planning – a bottom-up approach. Hereby, one FDT per stand is selected. In addition, global targets for species-share are set by the NI State Forest Administration, in a top-down approach (Böckmann et al. 2019). However, despite contingency planning for unforeseen events, globally targeted species shares are unlikely to be achieved exactly. Also, according to Lawrence (2017), there is uncertainty in FDT realization by the local practitioner. It is inherent in the system that, in the decadal forestry planning, a range of variation or uncertainty in realization possibilities arises in the future tree spp. composition.

Within this study, for NI 195 different FDT were considered (Böckmann et al. 2019) and assigned by the *baklawa*-algorithm (Hamkens et al. 2022). Here, tree spp. admixture is given as a spanned stocking target (min.-max. ratio) relative to its stand basal area (BA). Within an FDT with n spp., for the *WaldPlaner* input we calculated the ratio r relating to the stocking target of a species i as:

$$\mathrm{r_i} = \frac{\mathrm{r_{i\,(max)}}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{r_{i\,(max)}}} \qquad (1)$$

Hence, every FDT was standardized as 100 % spp. share.

2.3 Influences on cutting time

2.3.1 Target diameter: Pruning status

Pruning aims to produce high value timber, for which reason the target diameter for harvesting was raised from 45 cm diameter at breast height (DBH) to 55 cm for pine (Ikonen et al. 2009, Böckmann et al. 2019). Hence, on the stand level, the occurrence of A-grade timber increases from ca. 2 % up to 9 % (Offer & Staupendahl 2009). In Germany, pruning was carried out in four waves with peaks around the years 1790, 1870, 1930 (Mayer-Wegelin 1936) and 1990, and recorded in the forest planning but not necessarily by the NFI's.

Due to the confidentiality of both inventory (Päivinen et al. 2023) and planning data, for simulations, the initial spatial join of these two datasets was conducted by the Federal Thünen-Institute of Forest Ecosystems. Since forest planning information are not always spatially explicit (Böckmann et al. 2000), we linked stand records which list past pruning to the subplot location, supplementing the NFI survey of pruning. We accepted matches, if there was ≤ 20 % difference in stand age of the planning and inventory data. Only overstory trees ≤ 3rd Kraft's class (1884) are considered as pruned growing stock (Bossel et al. 1934).

2.3.2 Treatment: Thinning regime

Thinning influences the diameter development and hence the harvest time (del Río et al. 2017, Aldea et al. 2023). Since the silvicultural prescriptions operationalize the intensity by stocking degrees (S°) for a given top height, yield tables become relevant. In NI, for Scots pine, the yield tables from Wiedemann (1943) are obligatory. German forestry traditionally executes age-dependent thinning ‘early, often and moderately’ (Heyer 1854). Today, starting at 12 m stand top height, the target BA in NI should not be below S° of 0.7 and from 18 m on not below S° of 0.8 (NLF 2021).

We implemented target BA for pine in the *WaldPlaner* simulation software. As practitioners use yield tables and not theoretical maximum densities (Assmann 1970, Spellmann et al. 1999), we thus improved the software by functionalizing these tables: A nonlinear model derived from Levenberg-Marquardt (1944, 1963) was used, which was computed using the minpack.lm-algorithm (Elzhov et al. 2023). The Chapman-Richards equation (1961, 1959) was preferred to the Hossfeld-IV formula for fitting and applied with parameters $a_1 - c_2$ dependent on stand age t and SI:

$$BA = a_1 - a_2 SI \left(1 - e^{(b_1 e^{(b_2 SI)})t}\right)^{(c_1 e^{(c_2 SI)})} \quad (2)$$

Estimates express the target BA in m² ha⁻¹as prescribed by means of the yield tables (NLF 2021).

Next to the thinning, simulations of a harvest regime comprise harvesting of different intensities depending on the succeeding stand.

2.3.3 Treatment: Following stand

For harvesting of Scots pine, shelterwood/ seed tree systems (Wagner et al. 2010) were simulated as a common denominator of silvicultural systems between forms of ownership.

German forestry nowadays aims to achieve mixed stands (Bolte et al. 2009, Mason et al. 2018). Besides climate change, uncertainty in forest development results from scope in decision making. Thus, through stand treatment, forest planning influences another dimension of the scenario funnel we conceptualize. As scenarios, two silvicultural variants are contrasted, in which today's forest stands are either regenerated with light-demanding or shade-tolerant taxa. In the simulations, pine is maximized or minimized on every NFI plot (Fig. 2).

This is executed by different stand maturity definitions (percentage BA above target DBH when final harvest starts), periods and cycles of operations as well as maximum densities of the overstory (Tab. 1).

Table 1: Prescribed BAU-harvest regime of Scots pine in the WaldPlaner per silvicultural variant

criterion	pine max.	pine min.
maturity[%]	50	25
period [a]	20	40
cycle [a]	5	5
maximum density	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

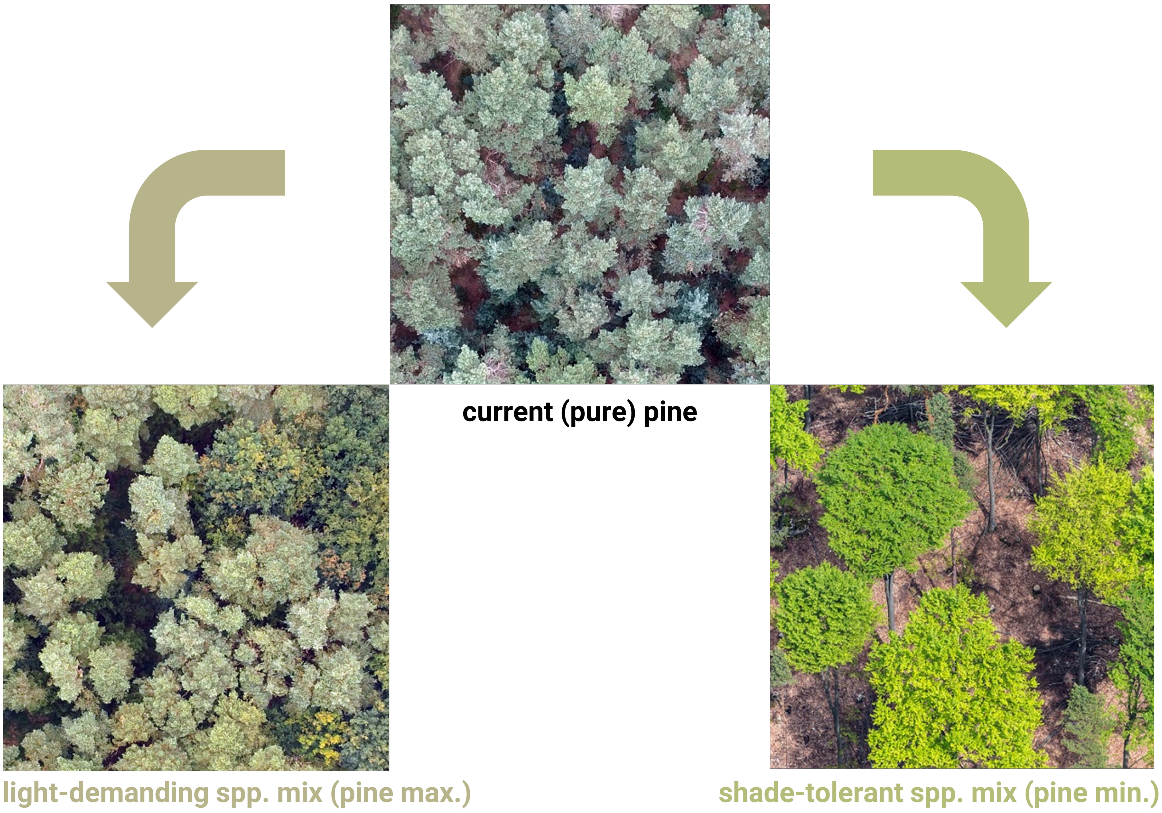

Figure 2: BAU-harvest regime of different succeeding stand types, as considered in simulations, span a two-dimensional uncertainty space. Images by NW-FVA (2023) & © Leidorf (2018).

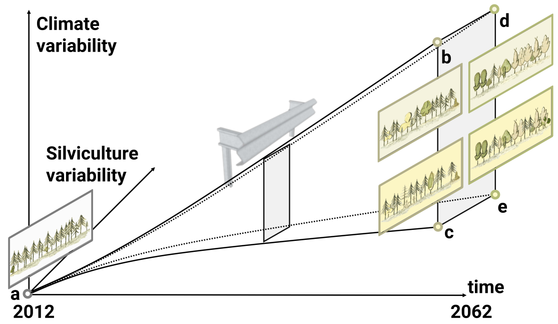

Figure 3: Starting point of simulations and scenario funnel with spanned uncertainty space. a Current forest stands as per NFI. b-e Equally likely scenarios with FDT guard rails prescribed under different climate for the period 2071-2100, with silvicultural management maximizing (b-c) or minimizing (d-e) pine shares. Note that FDT's species share must not be reached within a time window. Figure based on Guimpel (1819) and © pngegg (2023).

2.4 Scenario funnel and settings

In summary, future forest development of Scots pine is primarily influenced by cultivation area and harvest time. For simulations however, we distinguish climate and silviculture variability over time as dimensions. Thus, within the RCP 8.5 strand, we either promote or reduce the percentage of pine by applying the FDT that possess the highest or lowest ratio of this species and thus function as boundaries (guard rails).

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 height, DBH and species. The simulations were executed for a period of 50 years from 2012-2062 and computed in steps of 5 years.

For thinning and final harvest 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 conservation areas, no thinning or final harvest is simulated and forest growth is bound only by regionally different maximum density functions and yield levels (Döbbeler & Spellmann 2002).

3 Results

3.1 Thinning regime

Essential for the prediction of a realistic forest development is the derivation of target BAs as shown in Figure 4. A difference of only approx. 5 m² ha⁻¹ between the SI's is depicted. According to the BAU silviculture guidelines the BA does not increase after the age of 60. The patterns of the curves fits to the yield level as expressed by the maximum density and marks a difference of about 15 m² ha⁻¹ over 100 years. The target BA of SI=36.5 m, which is 29.28 m² ha⁻¹ at age 100, only accounts for approx. 67 % of the maximum BA.

3.2 Guard rails of pine shares

Figure 5 depicts the variation of different FDT that can be seen as guard rails of future pine share in NI. Since FDT canalize every silvicultural operation towards a targeted admixture, they are central to this process.

In moderate climate and when minimizing pine (scenario d, Fig. 5e) only very poor sites (cp. Fig. 5d) are planned for pine cultivation (Emsland and Lüneburg Heath). However, under extreme climate and when maximizing pine through silvicultural management, it can be utilized on almost every site as a leading tree spp. (scenario c, Fig. 5f), even in the Harz mountains.

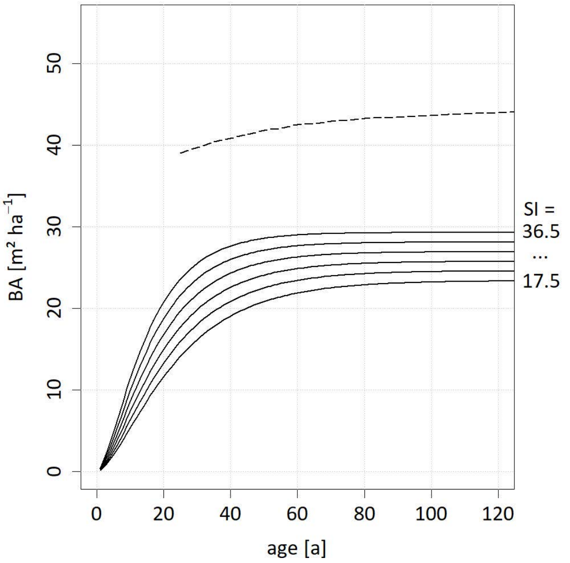

Figure 4: SI-dependent target BA of P. sylvestris (solid lines) in NI after BAU silviculture guideline referring to the yield tables of Wiedemann (1943; residual SE 38.6 %) and maximum density (dashed lines; Döbbeler & Spellmann 2002) for top heights of greatest pictured SI.

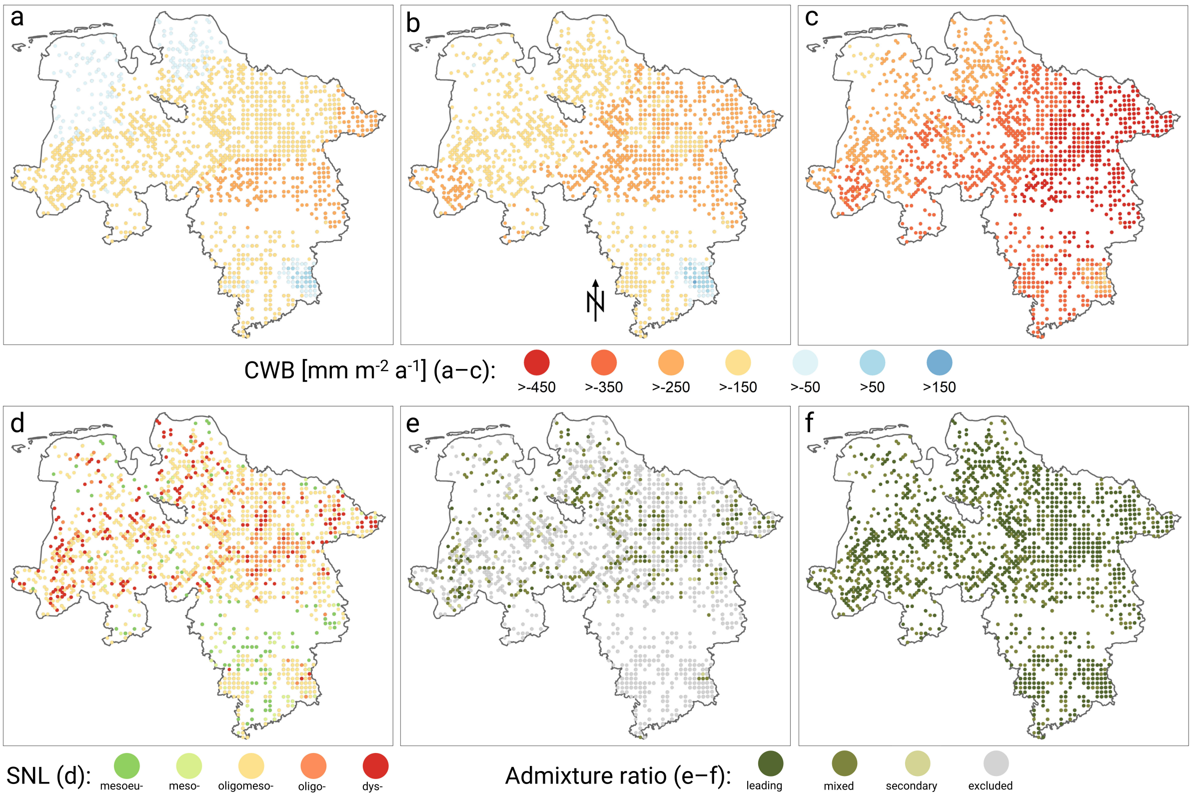

Figure 5: a-c Decreasing mean CWB-class per tract over time and climate model. a With recent climate data (1991-2020), b using RCP8.5 EC-EARTH12 from 2071-2100 (moderate) and c using RCP8.5 hadGEM2 from 2071-2100 (extreme). d constant SNL per plot is reported as fitted value, i.e. the most plausible score, resulting from an estimated cumulative logit model (Fahrmeir et al. 2013) including plot number as random intercept component. This modeling step avoids manipulations, such as empirical mean calculation, that are not suitable for the ordinal scale of the SNL outcome. e-f 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 scenario d (min. pine moderate climate) and c (max. pine extreme climate) are shown. Note that space between points (tracts) does not state forest cover but sampling density.

3.3 Predictions

The estimated cultivation area for Scots pine in NI is shown in Figure 6. Overall, in simulations to 2062, Scots pine's extent is decreasing in every scenario from 0.3 million hectares (m. ha) in 2012 (scenario a): The greatest reduction in extent is to 0.191 m. ha (scenario d), while the smallest until 0.261 m. ha (scenario c). Accordingly, the absolute uncertainty range is about 70,000 ha. Pine's share comprises 29.5 % in 2012 and develops towards maximum 24.9 % (scenario c) and minimum 18.3 % (scenario d), meaning a relative uncertainty of 6.6 % for site mapped forest cover in NI.

The current stocking in NI reveals an unequal age class distribution (Fig. 6, column a). This inequality is not adjusted in any scenario up to 2062 (b-e). If certain age classes are examined in isolation, pine's share in scenarios b-c accumulates in comparison to scenarios d-e for age classes under age 60. Pine over this age accumulates significantly.

Other tree spp. were simulated for validation. Thus, in pine-minimizing scenarios (d-e) under the age of 60, Norway spruce increases, whereas shade-tolerant *Abies* spp. are subsumed. The impression of almost non-existent pine share in ages ≤ 20 is complemented by an indentation in age class 41-60. In comparison to 2012, in 2062 other deciduous trees with long life expectancy (ODL, such as *Fraxinus* spp.) and other deciduous trees with short life expectancy (ODS, such as *Betula* spp.) will have decreased in new established stands of age < 50.

While pruned growing stock accounts for approx. 1 % (0.9 m. m³) of pine's total stocking in 2012, according to NFI, this study reveals an increase towards 5.3 % (4.5 m. m³) when data from forest planning records are also considered.

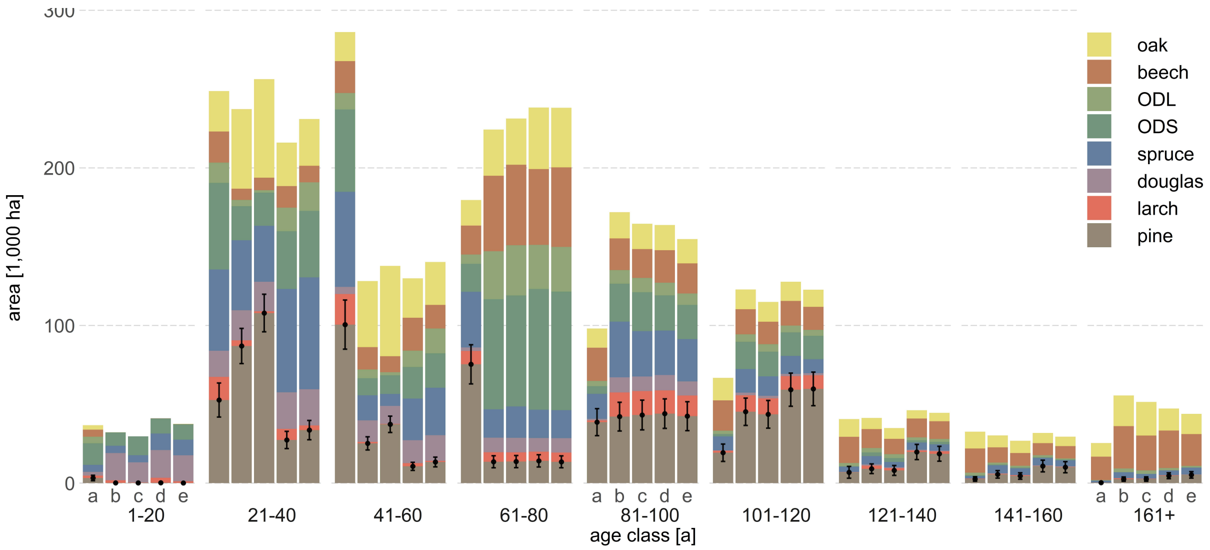

Figure 6: Estimated area of tree spp. groups depending on the age class. According to BMEL (2015) compact wood in 2012 (a) and the scenarios (b-e) in 2062 (assigning other pine than P. sylvestris to larch) are shown. Error bars for pine depict ±CI95. Colors based on PrMLDF (1912).

4 Discussion and conclusions

This proceeding accounts for site changes using the CWB in order to select tree spp. dynamically. As the current pine forest health status and other studies show, also temperature maxima (Brandl et al. 2020, Haberstroh et al. 2022) or an indicator adapted to the regular evaporation regime, such as SPEI (Vicente-Serrano et al. 2010), should also be considered throughout the future. As early as 1845, Heyer mentioned the need for such indicators.

The changes to SI modelled using such indicators contribute to a more detailed simulation approach and contain varying trends for pine (Albert et al. 2018). The *WaldPlaner* software was intensively validated (Vospernik et al. 2015, Sprauer & Nagel 2015) and also considers over- or underyielding. However, error propagation could not be quantified, while the deep uncertainty could not be reduced: Major influences, such as politics or biotic and abiotic risk factors (Albert et al. 2015, Lawrence 2017) could not be assessed. Nevertheless, this work contributes to quantifying the silvicultural and climate component on uncertainties in forest development.

We briefly summarize the origin and relevance of FDT as they are key for driving forest development. From our point of view, however, the silvicultural freedom or variability in stand management is seen as uncertainty, since the scope (leeway) in decision making accounts for about 70 k. ha or 6.6 %.

Pruning was only captured conservatively in the NFI data in certain (present) cases. However, planning data captures pruning properly, even if compartments are not always spatially explicit. Therefore, stand age is recorded accurately by rolling cultivation age forward. In contrast, the NFI field survey did not necessarily include owner's data and age, which are less exact in old stands. We conclude, that pruning records are plausible if age or location matches with inventory data.

The present work reveals that there were four pruning waves in Germany and fivefold higher pruned stocks for *P. sylvestris* than previously estimated in NI. Pruned timber of Scots pine (A-grade timber) is currently sold for about double the price of unpruned timber (Kubatta-Große 2023, LWK 2023). The extra pruned timber amounts to 3.7 m. m³. This is still a conservative estimate of pruned growing stock, since data from private forest could not be investigated and data matches might therefore be more abundant. Moreover, this implies substantively longer rotations.

By enhancing the *WaldPlaner* with new thinning regimes that are oriented to the yield tables actually used and not theoretical maximum densities, this work depicts reality and BAU silviculture more accurately. While the Chapman-Richards equation shows an overall continuous fit, an adjusted Hossfeld-function did not convince. Our model only considers input values up to stand age of 110, due to partly decreasing BAs after this age, which matches with the time frame in which thinning of Scots pine is usually carried out (Fischer & Mölder 2017).

The critical stocking density, that comprises 0.8-0.9 for Scots pine (Assmann 1970), is clearly undercut in NI. However, single tree stability, vitality and diameter growth are promoted by this operational concept (Döbbeler & Spellmann 2002, del Río et al. 2017).

Our work indicates, that the area of Scots pine in cultivation will decrease, even if it is promoted by silvicultural management. This matches other results (Spellmann et al. 2015, Wördehoff et al. 2017). Furthermore, the indentation in the age class 41-60, which is actually an initial model artifact, coincidentally reflects the actual calamities. Admittedly, the increasing area in age classes > 81 years contributes to pine's biodiversity (Turmukhametova et al. 2020) but also challenges the economy, with large dimensioned timber (Schrade 2002, Knocke et al. 2023) and weakens forest health (Przybylski et al. 2021).

Our work documents the inertia of forest development. We call for more effort in site mapping and assessment on impacts of forest policy. To enhance the information flow between stakeholders and facilitate forest restoration, predictions must be developed further and include current stocking peculiarities with more accuracy, encompassing, above all, their mortality risk.

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