A New Method to Reconstruct Recent Tree and Stand Attributes of Temporary Research Plots: New Opportunity to Analyse Mixed Forest Stands

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Abstract

In the last decades, studying effects of mixing tree species is increasingly important. In particular, under changing growing conditions and social requirements, investigations on mixed forest compared to mono-specific stands are of special interest, for example, stability, resilience or ecosystem services. Permanent forest research plots are a unique data source, providing the required information but being time-consuming and costly to establish. Moreover, large data sets of such plots are missing but needed for generalising any findings. Temporary research plots provide ad hoc information of its status quo and require less effort than permanent plots. Usually, such plots provide no information of the recent tree and stand characteristics. We demonstrate a new method developed under the scope of COST action FP 1206 EuMIXFOR (European Network on Mixed Forests) to estimate retrospective tree dynamics and stand characteristics. The results of validation reveal its usefulness for reconstructing 5–10 years. Thus, the method provides new potential in establishing larger networks across several countries, in particular, for studying underlying processes when comparing mono-specific with mixed forest stands.

Keywords: temporary research plots, mixed stands, retrospective growth analysis, increment cores, reconstruction of stand dynamics, mixing effects

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1. Introduction

In the last decades, researches of forest growth and yield have increasingly focussed on comparing mono-specific forest stands with mixed forest stands [1–3]. Often, the main focus covers mono-specific and mixed forest stands involving coniferous species. In particular, the effects when mixing coniferous species with broadleaved species either with similar or contrasting functional traits are of special interest. From a historical perspective, mono-specific stands, in particular, those composed by coniferous species, have been silviculturally favoured due to their lower management costs and their seemingly higher productivity compared to broadleaved or mixed stands. Driven by the first empirical observation of yield growth, recommendations have been made of converting mixed forest stands towards mono-specific coniferous stands, when the former is composed by both coniferous and broadleaved species. For example, concerned about serious production losses in mixed stands, one of the founding fathers of forest science—Hartig [4]—recommended that ‘All mixed stands with coniferous and deciduous species should be converted into pure stands of the coniferous species, as soon as circumstances permit’. In addition, the increasing need for wood during the early and middle nineteenth century required high production forests with low rotation periods [5, 6]. Consequently, the first systematic long-term yield observations plots have been established in mono-specific stands [7, 8]. Those plots served as the data base to analyse stand growth dynamics and in developing yield tables, summarising age- and site-dependent stand productivity. The results of converting the forest into mono-specific stands composed by coniferous tree species are visible until today. San-Miguel-Ayanz et al. [9] characterised Europe’s forests and illustrate a predominance of mono-specific stands with superiority of approximately 50% coniferous, 27% broadleaved while only the remaining refer to mixed forest stands.

In the last decades, however, growth and yield research increasingly focus on productivity dynamics in mixed stands. Mixed stands are assumed to better resist biotic and abiotic damages and provide a broader range of ecosystem services [10–12]. Thus, the early investigations of comparing effects on yield growth when mixing tree species have been extended, for example, by Wiedemann [13], Assmann [14] or Schober [15]. For example, the results reveal the early findings and even show that mono-specific stands of Norway spruce or Douglas fir show by a far greater productivity than in any mixture on many sites in temperate and boreal zones [8, 13–15]. In addition, in the last decades, many mono-specific forest stands collapsed due to several biotic and abiotic reasons, for example, calamities, storm or socio-economic changes. Recent studies reveal that interspecific interactions in many cases can lead to higher rates of productivity in mixed stands compared to the mono-specific stands comprised by respective tree species [2, 3, 16–20]. Although many theories exist about the superiority of mixtures, the effects of mixing tree species and underlying processes are still poorly understood. Therefore, in the last decades, investigations on mixed forest stands compared to mono-specific stands widen their focus, for example, considering structural differences [3], stability [21–23] and resilience [22] for ecosystems services [3, 11, 24, 25]. Usually, permanent research plots provide a sufficient data source while covering attributes at tree and stand level. However, in order to generalise any finding, varying growing conditions and a sufficient number of plots similar in their stand characteristics, for example, growing condition, density, age and species composition, are crucial. Unfortunately, establishing networks

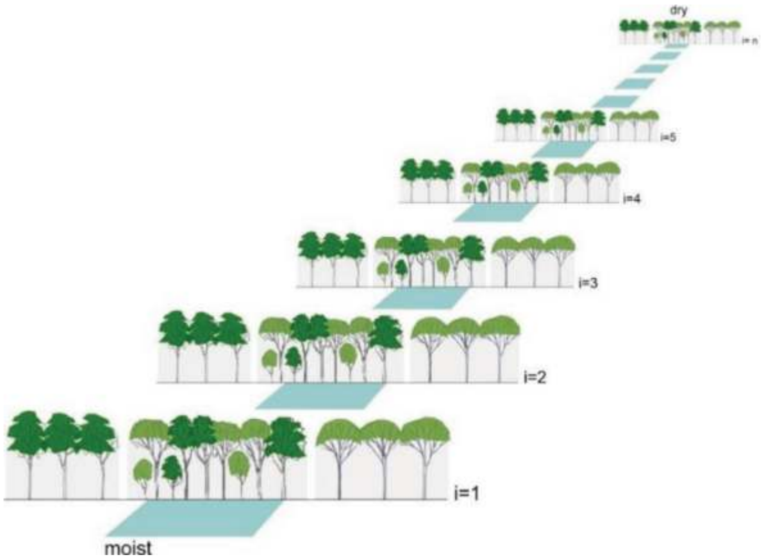


Figure 1. Principle of the transect study: an ecological gradient from moist to dry sites including 32 triplets (temporal plots), consisting of pure Scots pine stands, pure European beech stands, and mixed stands of Scots pine and European beech, which were established in 2014 within COST Action FP1206 EuMIXFOR (after Pretzsch et al. 2015).

are time-consuming, expensive and difficult to realise, in particular, if multiple countries are involved. In addition, it requires decades of continuous survey to get the first results. Alternatively, temporal research plots have been used to overcome these limitations but having the disadvantage of missing information of any historical stand situation. Researches with respect to yield growth are therefore based on increment cores and limited at tree level, unless all trees are sampled. To this extent, standardised valid methods to reconstruct the recent tree and stand development for a specific plot are missing.

Therefore, we demonstrate a new method to reconstruct recent tree and stand development for mono-specific and mixed forest stands, developed based on triplets study design established under the scope of COST action FP 1206 EuMIXFOR (European Network on Mixed Forests) [19, 26] (**Figure 1**). Thus, this topic is up to date and of particular interest when developing strategies of converting mono-specific stands into mixed forest stands. The introduced method aims to (1) predict recent retrospective diameter and height development at tree level, (2) predict recent stand characteristics, (3) develop standardised routines and (4) being extendible and applicable for multiple tree species.

2. Method and validation

2.1. Requirements of plot selection

The reconstruction of stand characteristics based on temporary plots requires a set of minimum sample trees, plot data and increment cores. For living trees and snags, the attributes like calendar and physiological (before, during or after a growing season) year of survey, tree number (nr), tree species, diameter at breast height (dbh), tree height (h) and age per tree species must be available. The diameter at breast height is required for all living trees and standing dead wood exceeding a defined threshold value, for example, 7 cm. In addition, for occurring stumps tree species, the estimated year of removal and the corresponding dbh are needed. Measurements of tree heights can either cover a full survey or being representative per species. While the former represents all height variation, the sample must strictly cover the complete range of heights per tree species. Missing individual heights will be derived by applying parameterised height curve functions. Usually, such functions are based on the height to diameter relationships, for example, Petterson, Prodan, Freese, Michailov or Korsun [27]. Here, the measured h-dbh pairs are used for parameterisation and should be species-specific. Species-specific age is required for each tree species and stand layer. For plot characteristic, only the size is required. Increment cores must cover a sufficient number of trees, for example, 20–40% of the living trees per plot and tree species. However, this depends on the stand structure and species composition. Nevertheless, the selected trees must represent the diameter range at plot and species level. Increment cores should be taken at a 1.30-m height, at least two cores per tree, for example, north and east direction.

2.2. Stand reconstruction based on tree and increment core data

The reconstruction aims to provide a tree list covering the diameter at breast height, tree height, basal area and volume per tree for pre-defined years. Here, the tree list per year represents artificial surveys and will be evaluated following DESER Norm [28]. The proposed method follows a three-step approach and implemented as standardised routines. In a first step, all increment cores are measured and the year ring widths synchronised, for example, following standardised methods [29–31]. The recent diameter at breast height will be derived for all cored trees and reconstructed for non-cored trees applying regression analysis. Second, standardised height curve functions, for example, Kennel [32] and Franz et al. [33], can be applied to derive retrospective tree heights. Finally, the individual tree's diameter, tree's height and species-specific form factors (f), for example, those provided by Franz [34], are used to calculated tree's volume per year with $v = dbh^2 * \pi/4 * h * f$.

2.2.1. Diameter reconstruction

For all cored trees, the retrospective diameter is derived from the measured and analysed increment cores and measured dbh in the years of survey. In case of non-cored living trees and standing dead wood, regression models are used to calculate the previous diameter. So far, an exponential (Eq. (1)) and quadratic model (Eq. (2)) are used. Here, the models predict the retrospective cumulative diameter increment based on a given dbh, assuming a constant bark width over time. The increment refers to a specific period covering a pre-defined number of years (growing season), while dbh characterises the diameter at the end of the corresponding period. For parameterisation, only cores that cover the full requested time range should be considered. Moreover, a minimum threshold number of cored trees, for example, five trees, can be considered prior to model parameterisation. The two implemented models are

$$id_i = a^* d_{i\_end}^b \tag{1}$$

$$id_i = a + b^* d_{i\_end} + d_{i\_end}^2 \tag{2}$$

with id_i as cumulative diameter increment (mm) of period i. The diameter at breast height at the end of period i is expressed by d_{i_end} (mm). The models are species-specific; however, tree species can also be linked to a particular species group, while a and b are function parameters to be estimated. The number of years (growing seasons) covered by each period i can vary. Thus, the overall time range is defined by the number of periods and their corresponding amount of years covered. Considering multiple years per period will smooth the diameter increment, for example, similar to repeated measurements of permanent research plots. By contrast, the parameterisation at annual level may better characterise its variability (**Figure 2a**–**c**). For the latter, it is particularly important to cover the overall diameter range per species and plot. In order to support the selection of one of the two models, we implemented a decision support routine. Here, from all trees, where cores are available, a user-defined number can be eliminated prior to model parameterisation. The parameterisation is based on the remaining trees, is species-specific, comprises both models and applied for a pre-defined time range. The number of years per period vary from 1 to 10 and cover the overall time range. For the eliminated trees, the retrospective diameter is calculated based on the model outputs. The results are compared with the derived diameter, considering the year ring widths. Here, the validation process covers all possible combinations of eliminating one or multiple trees. Graphical and numerical output summarise the validation. After selecting a model and defining a time range, the diameter reconstruction for all non-cored trees is realised by subtracting the functional values of period i from the diameter at the end of the corresponding period. Consequently, the result refers to the start diameter of period i-1. In addition, the cumulative diameter increment will be distributed linearly across the years of period i. Thus, we ensure to reconstruct any time range covered by the data, for example, when period i exceeds the last year considered. **Figure 2** illustrates an example of parameterising Eq. (1) for a mono-specific forest stand of Scots pine. **Figure 2** shows an example of different model outputs covering 1-year (**Figure 2a**), 3-years (**Figure 2b**) and 5-years (**Figure 2c**) per period. The black data points represent single trees. When considering multiple years, the variability of diameter increment slightly decreases (from **Figure 2a** to **c**). The diameter for all non-cored trees is based on the parameterised models (red lines). In case of negative functional values, the increment is set to zero. By default, both models have a flexible intercept; however, in particular cases, it may be useful to force the model through a zero intercept. Moreover, a constant bark width is considered during the reconstruction by default. If required, it is possible to utilise algorithms for calculating bark widths. Here, after the reconstruction, the bark width is initially calculated for the year of survey and subtracted for all diameters (a constant bark width over time), resulting in the diameter without a bark. Thereafter, the bark width is calculated and added to the corresponding diameter, resulting in the diameter over a bark. For final plausibility, the standardised graphical output supports the calculated recent diameter reconstruction (**Figure 3**). **Figure 3** exemplarily demonstrates the result of the diameter reconstruction for a mono-specific stand of Scots pine including a few oak trees which have been reconstructed

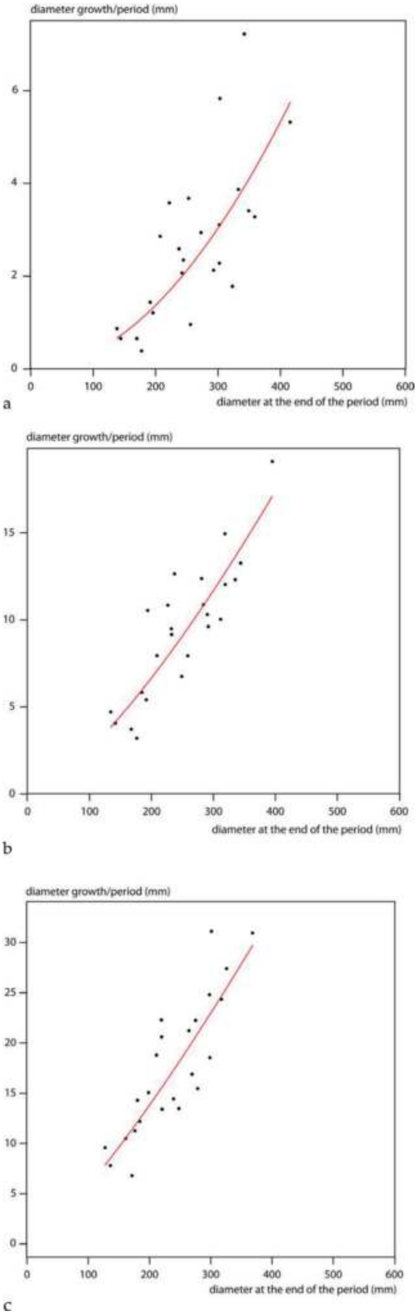


Figure 2. An example of output for Eq. (1) for 1 period covering 1-year (a), 3-year (b) and 5-year (c) resolution. Illustrated are cored trees with their dbh at the end of the period (x-axis, mm) and cumulative diameter increment (y-axis, mm) for the given period. Solid red lines represent the predicted models.

using the model of Scots pine. Thus, the specific behaviour of diameter development of the non-cored trees (triangles) is directly compared with that of the cored trees (circles). All diameter values are given in mm over bark. The reconstruction ends if a diameter falls below the user-defined minimum value, for example, 7 cm. For stumps, the diameter reconstruction follows a similar procedure (grey lines). In a first step, the stump is treated as a living tree with a given diameter (estimated for the year of removal). However, the initial diameter refers to the year of removal and thus may differ from the year of survey. Therefore, we firstly estimated the time between the survey and the year of removal. Secondly, the overall diameter increment for this period is estimated and added to the diameter at the year of survey. Finally, we repeat the diameter reconstruction as described earlier and drop all years between the survey and the year of removal. As a result, the diameter is reconstructed from the year of removal until the reconstruction time range, for example, grey lines shown in **Figure 3**.

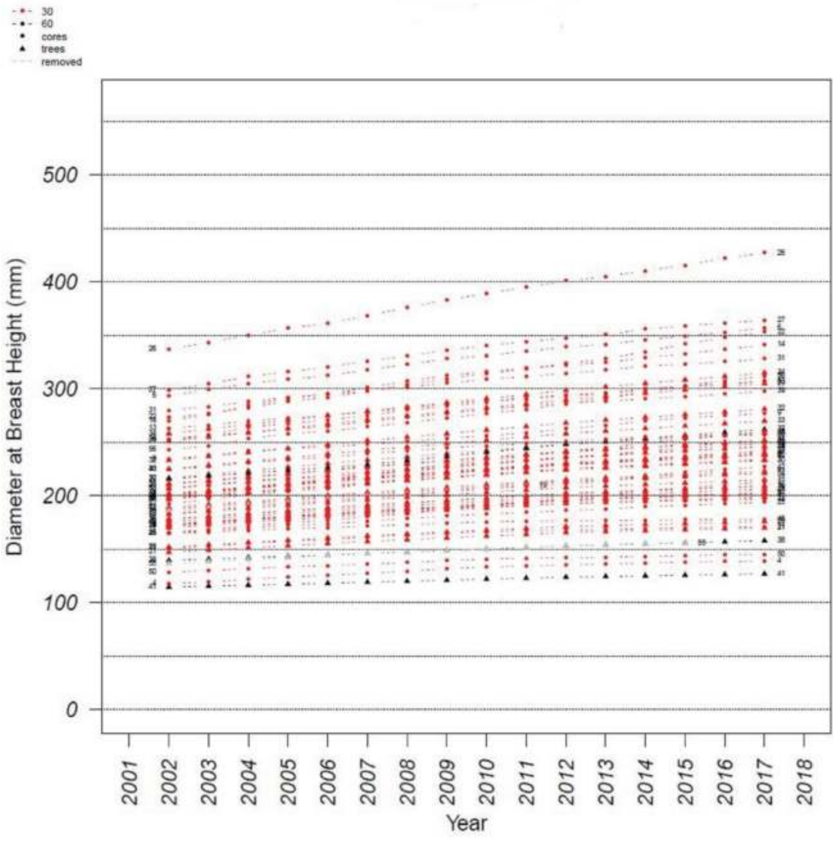


Figure 3. Reconstructed diameter at breast height (y-axis, mm) from year 2017 to 2002 (x-axis) is illustrated. Cored trees are characterised by circles and non-cored trees by triangles. The numbers indicate the specific tree number. Grey lines represent trees which have been removed (stumps). Red and black colour indicate Scots pine and sessile oak, respectively.

2.2.2. Height reconstruction

Uniform height curve systems provide a potential to predict retrospective heights. We implemented a system developed by Kennel [32] and transferred and parameterised for other species by Franz et al. [33]. Individual tree heights will be estimated for each pre-defined year as a function of their diameter [35].

$$h_i \;=\; 1.3 + \left(\frac{d_i}{b_0{}^{*}\, d_i + b_1}\right)^3 \tag{3}$$

where h_i and d_i refer to the individual tree height and diameter at the breast height of year *i*, respectively. The parameter values b_0 and b_1 are species-specific and depends on age, quadratic mean diameter (*dq*) and its corresponding height (*hq*). The parameters are required to be calculated at species level for each year. In a first step, the reversal point (drp*)* of the diameter-height relationship is calculated for each species, year and age (Eq. (4)). Second, b_0 is derived per year, considering *drp*, *dq* and *hq* (Eq. (5)). Third, b_1 is calculated by considering drp and b_0 (Eq. (6))

$$drp \;=\; 0.4 + \exp^{A+B*\ln(age_i)+C*age_i} \tag{4}$$

$$b_0 \;=\; \frac{1}{\exp^{\left(\frac{1}{3}*\ln(hq_i-1.3)\right)}} * \frac{1}{1+\frac{drp}{dq_i}} \tag{5}$$

$$b_1 \;=\; b_0{}^{*}\, drp \tag{6}$$

with age as species-specific age for year *i*, *hq* and *dq* as species-specific quadratic mean diameter and its corresponding height for year *i*. Parameters A, B and C are species-specific and depends on age [33]. Based on the given species-specific age at the time of survey, the retrospective age can be derived for each pre-defined years. Likewise, the quadratic mean diameter is calculated based on the tree list, including the reconstructed diameter. By contrast, the height of the quadratic mean diameter cannot be directly derived. Thus, we using height-age curves provided by yield tables in order to calculate *hq* for each pre-defined year. The species-specific height curves are selected using the corresponding age and mean height taken from the survey, respectively. Individual tree heights are then calculated for each pre-defined year by applying Eqs. (3)–(6). Following this approach, the method cannot be applied for tree species not covered by a yield table. Instead, heights will be estimated during the stand level evaluation using the available heights to parameterise a Petterson height curve function [35]. Here, Eq. (3) is parameterised based on the reconstructed heights. **Figure 4** exemplarily represents the result of height reconstruction for a mono-specific stand of Scots pine, including few oak trees. The reconstruction covers a 15-year time range with a 1-year resolution (15 periods with 1 year). Based on the visualisation and corresponding tree list, implausible height reconstruction can be detect and deleted. Missing tree heights will be calculated during the stand level evaluation.

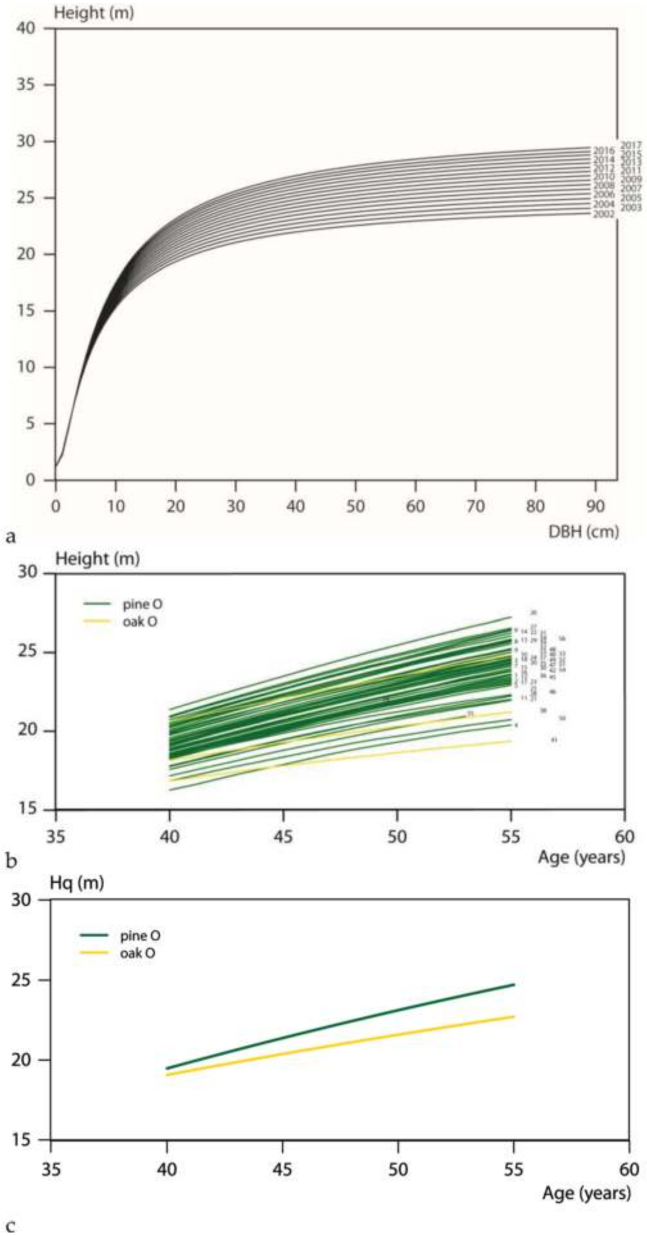
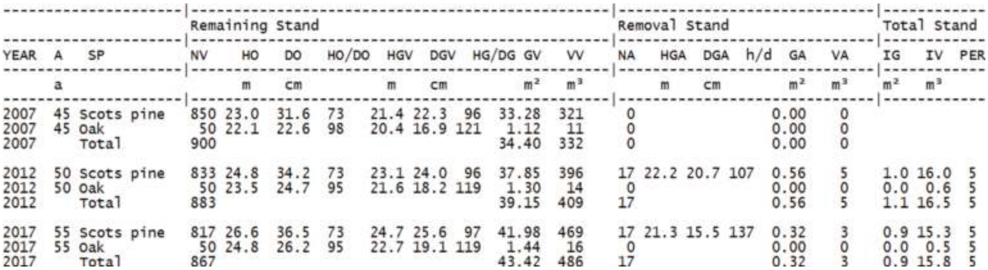


Figure 4. An illustration of height reconstruction for Scots pine and oak in a mono-specific stand of Scots pine. The standardised height curves used (a) are shown in a 1-year resolution from 2017 to 2002 (number right at each curve), exemplarily for Scots pine. Reconstructed tree heights for Scots pine and oak (b) show individual heights (y-axis) for 1-year resolution. Tree numbers are assigned right to individual curves. The relationship of quadratic mean height and species-specific age is illustrated for both species in 1-year resolution for the same time range (c). Green colour is used for Scots pine green yellow colour for oak.

2.2.3. Stand level evaluation

The diameter and height reconstruction results in a tree list for each pre-defined year. Stand characteristics (**Figure 5**), for example, the mean tree dimension, basal area (BA m^2 ha^{-1}) and volume stock (V m^3 ha^{-1}) per hectare, will be derived according to the guidelines of DESER-Norm 1993 [28, 29]. Here, we apply a software which is available at the Chair of Forest Growth and Yield Science, TU München [37]. For each pre-defined year, missing tree heights are calculated by parameterising a species-specific height curve [35] based on the reconstructed heights. Here, species can be grouped. Individual trees' diameter (d_i), height (h_i) and species-specific form factor (f_i) [34] are applied to $v_i = d_i^2/4*h_i*f_i$ with i being a pre-defined year. Tree-specific volume (v_i) and basal area increment (ba_i) are derived by $v_i = (v_i - v_{i-n})/n$ and $ba_i = (ba_i - ba_{i-n})/n$, respectively, where i refers to the ith year and n to the number of years to the previous year. **Figure 5** exemplarily provides the result of stand level evaluation for the mono-specific pure stand used earlier. **Figure 5** summarises the result stand level evaluation based on the tree list for the years 2017, 2012 and 2007. The stand characteristics of the remaining and removed stand per year at species and stand level, respectively, are shown. For the latter, only aggregated information is described. Individual tree volume was calculated, using form factors for Scots pine and oak provided by Franz et al. [34].



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---------------------|-------------------------------------------------|-----------------------------|------------
                     Remaining Stand                                    Removal Stand                 Total Stand
---------------------|-------------------------------------------------|-----------------------------|------------
YEAR  A   SP         NV    HO    DO   HO/DO  HGV  DGV  HG/DG GV     VV   NA   HGA  DGA  h/d  GA     VA  IG   IV  PER
---------------------|-------------------------------------------------|-----------------------------|------------
      a                    m     cm          m    cm             m²   m³        m    cm        m²   m³   m²   m³
---------------------|-------------------------------------------------|-----------------------------|------------
2007  45 Scots pine  850 23.0  31.6  73    21.4 22.3  96 33.28  321   0                 0.00    0
2007  45 Oak          50 22.1  22.6  98    20.4 16.9 121  1.12   11   0                 0.00    0
2007      Total      900                                 34.40  332   0                 0.00    0

2012  50 Scots pine  833 24.8  34.2  73    23.1 24.0  96 37.85  396  17 22.2 20.7 107   0.56    5   1.0 16.0  5
2012  50 Oak          50 23.5  24.7  95    21.6 18.2 119  1.30   14   0                 0.00    0   0.0  0.6  5
2012      Total      883                                 39.15  409  17                 0.56    5   1.1 16.5  5

2017  55 Scots pine  817 26.6  36.5  73    24.7 25.6  97 41.98  469  17 21.3 15.5 137   0.32    3   0.9 15.3  5
2017  55 Oak          50 24.8  26.2  95    22.7 19.1 119  1.44   16   0                 0.00    0   0.0  0.5  5
2017      Total      867                                 43.42  486  17                 0.32    3   0.9 15.8  5
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Figure 5. An example of stand characteristics after a reconstruction time of 10 years, with 2 periods with 5 years. The following are shown: calendar year (Year), species-specific age (A), tree species (SP) remaining stand characteristic with trees per hectare (NV [ha^{-1}]), top diameter (DO [cm]) and height (HO [m]) including their relationship (HO/DO), quadratic mean diameter (DGV [cm]) and height (HGV [m]) including their relationship (HGV/DGV), basal area (GV [m^2 ha^{-1}]) and volume stock over bark (VV [m^3 ha^{-1}]) per hectare; removed stand characteristics with trees per hectare (NV [ha^{-1}]), quadratic mean diameter (DGA [cm]) and height (HGA [m]) including its relationship (DGA/HGA), basal area (GA [m^2 ha^{-1}]) and volume over bark (VA [m^3 ha^{-1}]) per hectare; increment of basal area (IG [m^2 ha^{-1}]) and volume increment (IV [m^3 ha^{-1}]) per hectare and year and period length (PER [number of years]).

The diameter and height reconstruction are standardised procedures implemented in the statistical software R [38].

2.3. Validation of results

For validation, we used three different data sources. First, we reconstructed individual tree's diameter for eight research plots covering mono-specific stands of Douglas fir (n = 401). The primary goal of the experimental plots is to analyse reaction pattern on growth at stand level under varying spacing treatments. For each plot, complete stand surveys are available in 2009, 2004, 1999 and 1994. In addition, 6–10 dominant/subdominant trees have been felled in March 2010 and stem discs were taken at 1.30 m. Thus, the retrospective diameter increments for those trees are available. The diameter reconstruction was applied as described above and the results compared with the empirical observations. Second, to validate tree height reconstruction, we used a data set covering five mono-specific plots of Scots pine and Norway spruce. In addition, five plots with both species in mixture are tested. For Scots pine and Norway spruce, six trees per plot have been felled and the shoot length measured from top to down. Thus, the height reconstruction for those trees is validated based on the empirical measured values. Third, we used long-term research plots to validate the reconstruction at stand level.

2.3.1. Diameter reconstruction

Stem discs of the felled trees have been measured and analysed with the digital positiometer after Johann (Biritz + Hatzl GmbH, Austria). The results have been used for model parameterisation comprising three periods with a 5-year resolution, respectively (2009–2005, 2004–2000 and 1999–1995). Based on the fitted models, the diameter for all non-felled trees was calculated. We applied both models (Eqs. (1) and (2)) with and without considering bark width, respectively. The reconstructed diameter is compared with the observations available from stand survey for the years 2004, 1999 and 1994, using only remaining trees (non-felled). **Table 1** provides the overview of the results. We show the average arithmetic difference between reconstructed and observed dbh for the year 2004, 1999 and 1994. Besides the average difference, the corresponding standard deviation per plot and year are shown for Eqs. (1) and (2), respectively. In addition, we include the effect when bark width is not considered (no) and considered (yes). On average (total), the results indicate an increasing difference from 2004 until 1994 with a lower effect when bark width is considered. For both models, the difference exceeds 1 cm only in 1994 when bark width is considered. By contrast, this can be confirmed only for the year 2004 in the other case. The standard deviations vary only slightly between Eqs. (1) and (2). **Figure 6** illustrates, exemplarily, the results for Eq. (2) and plot 2. Here, we demonstrate the effect of considering bark width. The results for plot 2 show the effect when bark width is considered (**Table 1** and **Figure 6**). While marginal difference occurs for the year 2004, it significantly increased for 1999 and 1994. As opposed to the results of considering bark width (**Figure 6b**), a slightly systematic deviation can be observed when bark width is not considered (**Figure 6a**). In particular, this tendency increases from 2004 to 1994. The highest deviation occurs for trees with dbh below 15 cm.

PlotID	**bark width**	**n**	**2004**		**1999**		**1994**	
			Eq. 1	Eq. 2	Eq. 1	Eq. 2	Eq. 1	Eq. 2
			avg ± sd	**avg ± sd**	**avg ± sd**	**avg ± sd**	**avg ± sd**	**avg ± sd**
2	no	50	2.1 ± 8.6	1.7 ± 8.6	8.1 ± 13.4	7.2 ± 13.1	17.1 ± 17.8	15.8 ± 17.5
	yes	50	−1.8 ± 7.9	−2.2 ± 7.9	1.8 ± 12.3	0.8 ± 12.1	8.1 ± 16.3	6.6 ± 16.1
3	no	53	10.1 ± 8.2	9.4 ± 8.1	17.5 ± 10.9	15.4 ± 10.9	26.9 ± 10.7	25 ± 10.7
	yes	53	6.3 ± 8.8	5.6 ± 8.4	10.8 ± 11.7	8.5 ± 11.6	16.7 ± 11.7	14.6 ± 12.1

PlotID	**bark width**	**n**	**2004**		**1999**		**1994**	
			Eq. 1	Eq. 2	Eq. 1	Eq. 2	Eq. 1	Eq. 2
			avg ± sd	**avg ± sd**	**avg ± sd**	**avg ± sd**	**avg ± sd**	**avg ± sd**
4	no	47	11.8 ± 13.1	11.7 ± 13.7	18 ± 25.3	18 ± 26.2	24.2 ± 32.4	22.1 ± 31
	yes	47	8.7 ± 12.4	8.6 ± 13.1	12.8 ± 24.7	12.9 ± 25.6	16.1 ± 30.8	13.9 ± 29.1
5	no	47	10.2 ± 9.7	9.9 ± 11.1	18.7 ± 16.3	18.1 ± 18.1	29.5 ± 21.3	28.3 ± 22.9
	yes	47	7.1 ± 9.2	6.8 ± 10.5	13.4 ± 15.4	12.7 ± 17.1	20.7 ± 19.4	19.3 ± 20.9
7	no	53	6 ± 12.9	6.9 ± 12.6	10.4 ± 26.4	12.5 ± 27.1	16 ± 26.6	17.8 ± 27.1
	yes	53	2.5 ± 12.6	3.4 ± 12.2	4 ± 26.4	6.6 ± 27.2	6.2 ± 25.4	8.4 ± 25.7
9	no	49	9.2 ± 10.2	7.8 ± 9.1	13.3 ± 17.8	11.1 ± 15.9	20.4 ± 21.8	17.2 ± 20.4
	yes	49	6.7 ± 9.6	5 ± 8.6	8.5 ± 16.6	6.1 ± 14.8	12.9 ± 19.7	9.3 ± 18.3
11	no	53	8 ± 10.8	7.4 ± 10.6	12.8 ± 16.4	11.9 ± 15.8	18.1 ± 18.5	16.5 ± 18.4
	yes	53	4.9 ± 11.1	4.2 ± 10.6	7.4 ± 17.2	6.3 ± 16.1	9.4 ± 19.2	7.6 ± 18.8
12	no	49	7.3 ± 11.4	6 ± 11.3	13.5 ± 19.1	11.2 ± 18.9	21.5 ± 29.4	17.8 ± 29.2
	yes	49	4.5 ± 10.9	3.1 ± 10.9	8.6 ± 18.3	6 ± 18	13.7 ± 28	9.6 ± 27.7
total	no	401	8 ± 11	7.6 ± 11	14 ± 19	13.1 ± 19.2	21.6 ± 23.3	20 ± 23.1
	yes	401	4.8 ± 10.8	4.3 ± 10.8	8.3 ± 18.7	7.4 ± 18.9	12.8 ± 22.3	11.1 ± 21.9

With individual plot, PlotID; considering bark, bark width (no = no bark width was considered, yes = bark was considered); number of trees, n; average difference (reconstructed-observed diameter), avg. and its standard deviation, sd.

Table 1. Average differences are shown between reconstructed and observed diameter (in mm) for the years 2004, 1999 and 1994 for each plot and total.

2.3.2. Height reconstruction

In order to validate tree height reconstruction, we used 161 felled trees in autumn 2013 with measured shoot lengths of the last 40 years. In total, individuals of 32 Scots pine and 40 Norway spruce are available from mono-specific stands of each species. In addition, stands with both species in mixture cover 37 trees of Scots pine and 52 trees of Norway spruce [39]. For each felled tree, shoot lengths have been measured from stem top downwards the trunk. Thus, by stepwise subtracting from the total tree height, we derived tree heights per year from 2013 to 1973. Moreover, stem discs are taken at a 1.30-m height for each felled tree. In a first step, the stem discs were measured and analysed. Tree age was estimated based on the stem discs at plot and species level. Applying Eq. (1), the individual tree's diameter at breast height was calculated for all non-felled trees, using four periods with 5 years (2013–2009, 2008–2004, 2003–1999 and 1998–1994). Likewise, the retrospective tree height was calculated, applying the method described earlier by plot and species-specific age estimated from the stem discs. For all felled trees, we then compared the reconstructed heights with the measurements for the years

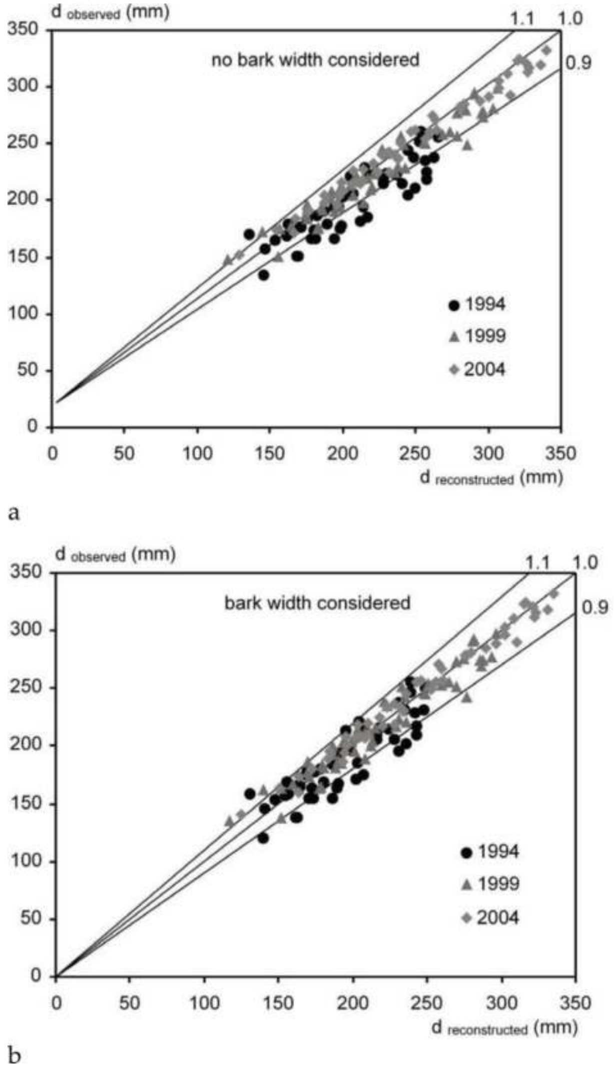

Figure 6. The diameter reconstruction based on three periods with 5 years applying Eq. (2) for plot 2 when no bark width is considered (a) and considered (b) is represented. Data points refer to single trees for year 2004 (grey, rectangular), 1999 (grey, triangle) and 2004 (circular, black). Solid black lines refer to 1:1, 1:1.10 and 1:0.9 reference lines (equal diameter, +10% and -10% deviation, repetitively).

2009, 2004, 1999 and 1994. **Table 2** provides the overview of minimum, maximum and average difference when comparing reconstructed (h_{rec}) and observed (h_{obs}) heights for Scots pine and Norway spruce (h_{rec}-h_{obs}). The results indicate higher average differences in mixed than mono-specific stands for both species. For Scots pine, the average difference exceeds 1 m in 1999,

	2009		**2004**		**1999**		**1994**	
	mixed	*pp*	*mixed*	*pp*	*mixed*	*pp*	*mixed*	*pp*
Norway spruce								
n	52	40	52	40	52	40	51	40
avg ± sd	−2.26 ± 1.83	−0.15 ± 1.51	−2.02 ± 2.01	0.15 ± 1.77	−1.8 ± 2.01	0.47 ± 1.82	−1.71 ± 1.87	0.49 ± 1.98
min	−5.84	−4.25	−6.30	−3.82	−5.90	−3.51	−4.96	−3.70
max	3.00	2.55	3.61	3.00	4.55	4.08	4.72	4.63
Scots pine								
n	37	32	37	32	37	32	37	0
avg ± sd	0.54 ± 1.18	−0.02 ± 1.34	0.73 ± 1.25	0.09 ± 1.2	0.98 ± 1.24	1.13 ± −1.8	1.22 ± 1.18	0.6 ± 1.05
min	−1.72	−2.21	−1.54	−1.78	−1.88	−1.80	−1.65	−1.81
max	2.99	3.18	3.00	2.94	3.29	2.88	3.41	2.83

Represented are the minimum (min), maximum (max) and average difference (avg) with its corresponding standard error (avg ± se) for both species in mixed (mixed) and mono-specific stand (pp). Minimum, maximum and average values are given in m.

Table 2. An overview of the average difference between reconstructed and observed tree heights (in m) for the years 2009, 2004, 1999 and 1994.

vshowing an increasing tendency from 2009 to 1994. The accuracy in mono-specific stands is similar to those of the mixed stands. The standard deviation is only marginally different over time in both stand types. By contrast, Norway spruce shows larger differences in the behaviour of mono-specific and mixed forest stands. While the result for the former is comparable to those of Scots pine, the latter show a much higher deviation. Moreover, from 2009 to 1994, we detect a decrease in the average difference. The standard deviations are similar in both cases.

2.3.3. Stand level evaluation

For testing the effects of reconstruction at stand level, we evaluated permanent research plots. In a first step, based on 5-cm dbh classes, 25% trees per class are randomly chosen for parameterising Eq. (1). Here, we used four periods with 5 years. The cumulative diameter increment refers to the consecutive surveys of the selected trees, and the diameter for the non-selected trees was reconstructed based on parameterisation of Eq. (1). For each tree, the retrospective heights were calculated applying the method described earlier. We used the yield table from Assmann und Franz [40] and Wiedemann [13] to derive the quadratic mean heights. Following the methods for diameter and height reconstruction, we created a tree list for the years of survey for the last 20 years. Each plot was evaluated as described earlier. In addition, all plots have been evaluated based on the recorded observation. Thus, we compared both results with respect to the quadratic mean diameter and its corresponding height, basal area per hectare, volume stock per hectare and their increment. **Table 3** provides the overview of comparing reconstructed with observed stand characteristics for the overall time range. **Table 3** shows the results of comparing reconstructed with empirical recorded tree list at stand level. The results for quadratic mean diameter, DQ (cm) and its corresponding height, HQ (m), basal area, BA (m^2 ha^{-1}) and volume stock, V (m^3 ha^{-1}) per hectare, basal area, IBA (m^2 ha^{-1} $yr.^{-1}$) and volume, IV (m^3 ha^{-1} $yr.^{-1}$) increment per hectare and year are demonstrated. Here, we used the relation referenced at empirical observation, for example, x_{recon}/x_{obs}, with x either DQ, HQ, BA, V, IBA or IVA. The upper and lower confidence intervals (CI_{upper} and CI_{lower}) have been calculated based on the 95% significance level. For each attribute, we detect no difference for the last 20 years at stand level.

	min	**max**	**avg ± se**	**CI_{upper}**	**CI_{lower}**
DQ	0.74	1.04	0.98 ± 0.02	1.02	0.94
HQ	0.81	1.09	1 ± 0.02	1.04	0.97
BA	0.81	1.06	0.97 ± 0.02	1.01	0.94
V	0.85	1.02	0.98 ± 0.01	1.01	0.95
IBA	0.87	1.4	1.06 ± 0.04	1.14	0.98
IV	0.8	1.27	0.96 ± 0.03	1.02	0.91

Relations between reconstructed and observation are represented for quadratic mean diameter (DQ), its corresponding height (*H*Q), basal area per hectare (BA), volume per hectare (V), basal area increment per hectare (IBA) and volume increment per hectare (IV). The minimum (min), maximum (max), average, (avg), standard error (se), upper (CI_{upper}) and lower (CI_{lower}) confidence interval are shown.

Table 3. Results of the comparing stand level and yield characteristics for 15 permanent forest research plots considering tree lists for real observation and reconstruction for 20 years.

3. Discussion

Long-term experiments are irreplaceable for forest science. They are the unique way to study long-term dynamics at tree and stand level and can reveal the cause-effect relationships of various treatment options as they are established under controlled, ceteris paribus conditions. However, for dealing with many urgent topics such as mixing effects, climate change, transition from pure to mixed stands or introduction of foreign tree species, long-term experiments are simply not available. Moreover, networks of such experiments, including multiple countries, are rare. In this case, temporary plots with a back-tracing of their history by increment coring or stem analyses are a makeshift to get ad hoc data for new upcoming topics, not covered by existing long-term experiments. The proposed method reconstructs recent tree and stand characteristics based on a given survey and increment cores. Occurring stumps and standing dead wood can be considered when the year of removal (calendar year) and the corresponding dbh are available. In principle, this allows to extend the application from fully stocked stand towards treated stands. The reconstruction is mainly based on diameter increment provided by the increment cores; therefore, it is of special importance that they are representative for the diameter range, ideally at tree species level. For diameter reconstruction, the implemented models differently reflect the relationship of diameter and its cumulative increment. However, its selection is crucial and should be inspected before, for example, validation based on increment cores. In addition, for tree species with a high variability of bark width, for example, Douglas fir, its consideration will increase the accuracy. To this extent, the height reconstruction is species-specific and based on a standardised height curve system. This approach requires (species-specific) quadratic mean height for the reconstruction interval. Here, yield tables of the corresponding species are used; however, any other sufficient method will extend the application, for example, in case of missing yield tables. For example, felling sample trees and measuring shoot lengths [39] are expensive and difficult to realise, in particular, for broadleaved species. Another possibility is the use of artificial time series. In contrast to real-time series (long-term observations), they use measurements of plots covering different age classes and are spatially closed [36, 41]. However, the probability of finding suitable plots varies between the tree species under investigation and may be difficult to realise. The results of validation demonstrate that the method is applicable for recent stand development, for example, 5–10 years. With any larger time interval, the inaccuracy may increase, in particular, for managed forests where trees are regularly removed and no information regarding stumps is available beyond 10–15 years. However, the proposed method serves for both analysing and modelling mixed species stands. In a first step, mixed species stands need to be better understood in there structure and functioning. In order to design the establishment and management of mixed species stands, models that take into consideration relevant and known mixing effects are required. Such models will be essential tools for the development of silvicultural prescriptions by scenario analysis and for the quantitative formulation of guidelines. The introduced methods provide data such as stand structure and growth rates, which are essential for parameterisation of individual tree growth models [42]. Next steps will be to analyse how many trees of which size need to be sampled, cored and measured in order to reliably reconstruct the stand dynamics. The methods introduced here for retrospective analysis of stem growth might be extended to reconstruction of crown and root growth. The restriction of retracing the tree and stand development more than 10–20 years earlier might be overcome by the establishment of artificial age series. If temporary plots of, for example, age 20, 40 … 100 years are established and analysed retrospectively over 20 years, an artificial time series of tree and stand growth can be compiled, which overcomes the restriction of a retrospective analyses from just one plot far backwards.

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