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# Reconstructed forest age structure in Europe 1950-2010

Running title: Forest age structure in Europe 1950-2010

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## Abstract

Forest age structure is an important factor for understanding the history of forests, their current  
functioning and their future development. It is, for instance, crucial information to be able to

1 assess sustainable harvesting potentials. Furthermore, since the development of growing stock  
2 and increment, and thus the patterns of net carbon exchange, are strongly affected by the age of  
3 the forest, information about the age structure is needed to understand the temporal variability of  
4 the greenhouse gas budgets and potential contributions of forest management (i.e. their  
5 additionality) to long-term removal of carbon from the atmosphere. European forests have  
6 changed drastically in recent decades, but to date no European level compilation of historical  
7 forest age structure data is available. In this study, country level historical age-class data was  
8 combined with a backcasting method to reconstruct the age-class structure for 25 European  
9 countries from 1950 to 2010 (total forest area in 2010: 118.3 million hectares). Based on the  
10 results, dynamic maps of forest age-class distributions on 0.25° x 0.25° grid were generated, and  
11 the change in the forest age structure was analyzed. Results show that the share of old forests  
12 (>100 years) has decreased from 26% in 1950 to 17% in 2010, and the mean age over the studied  
13 area decreased from 67 to 60 years. However, when looking at the change of the mean age from  
14 1950 to 2010 at country level, there is a large variation between the countries.  
15 We discuss implications of the results and argue that the development of forest age structure  
16 contributed less than previously thought to the carbon sink in European forests from 1950  
17 onwards.

## 1. Introduction

Europe's forests have changed drastically since the 1950s. The forest area increased by 30% between 1950 and 2000 (Gold, 2003), due to abandonment of low-productive agricultural lands and active afforestation in some countries. At the same time the timber volume in EU forests available for wood supply roughly doubled and the net annual increment increased substantially (cf. Spiecker et al., 1996). In addition to increased forest area, one important reason behind the increased growing stock is the recovery from large scale cuttings during and after World War II. During and especially after World War II large areas of mature and pre-mature stands were cut in western Europe as well as in central and eastern Europe, so that the average growing stock per hectare was relatively low in the 1950s in these areas. Also the development of better silvicultural methods improved the quality of existing forests for wood production (Gold, 2003).

To understand the history of forests and their likely future development, age structure is an important factor. Age structure provides insights into harvesting potentials (Verkerk et al., 2011a), and carbon stocks (e.g. Pregitzer and Euskirchen, 2004; Alexandrov, 2007; Böttcher et al., 2008), and it can be used as an indicator in assessments of biodiversity, recreation attractiveness and disturbance risk (Angelstam, 1998; Liira et al., 2007; Schelhaas et al., 2010; Edwards et al., 2011). Furthermore, since the development of growing stock and increment, and thus the patterns of net carbon exchange are strongly affected by the age of the forest, information about the age structure is needed to understand the decadal scale variability of the greenhouse gas (GHG) budgets and impacts of forest management on long-term removal of carbon from the atmosphere (Ciais et al., 2008; Kohlmaier et al., 1995; Kurz et al., 1995). The significance of disturbance legacy from the past on the present age class structure was highlighted for the US and Canada by Pan et al. (2010), tracking back anthropogenic and natural disturbances over centuries and at various scales. For European forests, forest management has been recognized as a key driver of the current and future carbon sink (Ciais et al., 2008; Eggers et al., 2008). A more realistic representation of age structure and forest management effects was found to be crucial to improve the modeling of the forest carbon balance (Zaehle et al., 2006; Ľupek et al., 2010; Bellassen et al., 2011) and to quantify the additionality of management

measures compared to the long-term carbon dynamics resulting from age structure (Böttcher et al., 2008).

Changes in the forest age structure were suggested to be one of multiple drivers explaining an almost uninterrupted increasing carbon sink in the European forest sector from 1950 to 1990 (Nabuurs et al. (2003). In addition, changes in age structure have been hypothesized (Schelhaas et al. 2003) and recently confirmed (Seidl et al., 2011a) to play an important role in the changing disturbance regimes of European forests. Despite the high relevance of historical age-class structure, no consistent European level compilation of historical age structure data is available to date. Large parts of the data, typically gathered by national forest inventories, have been available only in national reports, for which the history, methodology, resampling interval and reporting varies considerably between countries. Sample-based national forest inventories were initiated in the Nordic countries in the late 1910s and early 1920s, but were not introduced in other European countries until after World War II. Some European countries have only recently introduced sample-based inventories and thus historical data about the forest age structure in those countries are scarce (Tomppo et al., 2010). However, there have been earlier studies describing the historical development of European forest resources (Kuusela, 1994; Gold, 2003), which provide information about the development of forest area, growing stock and net annual increment in Europe from 1950 to 2000, but do not include information about the development of age structure.

Attempts to reconstruct European forest age structure have been made in two recent studies. Bellassen et al. (2011) reconstructed the forest age structure as part of their study on the carbon sink of European forests from 1950 to 2000 using the process-based vegetation model ORCHIDEE-FM. Seidl et al. (2011a) studied drivers behind intensifying disturbance regimes in Europe and reconstructed the forest age-class distributions for 23 European countries from 1958 to 2001. However, both reconstructions were based on reported age structure of a single year instead of using all the historical inventory data available. As the quality of backcasting will likely decline with time, the reliability of these reconstructions could be improved by assimilating historical inventory data into backcasting where available. Thus, the aim of this study was to present the first comprehensive age structure reconstruction for European forests

from 1950, combining available historical national inventory data with state-of-the-art backcasting. To choose the most robust backcasting approach, the two recent backcasting methods (Bellassen et al., 2011; Seidl et al., 2011a) were first evaluated against independent inventory data for selected, well documented countries. Next, the thus selected method was used to reconstruct historical age structure for 25 European countries. Based on the results, dynamic maps of forest age-class distributions on a  $0.25^\circ \times 0.25^\circ$  grid were generated, the change in the forest age structure from 1950 to 2010 was analyzed, and its implications for the European forest carbon balance were discussed.

## **2. Materials and methods**

### ***2.1 Inventory data***

National forest inventory reports, FAO forest resource assessments (UNECE/FAO 1985, 1990 and 2000), the EFISCEN Inventory database (Schelhaas et al., 2006) and the State of Europe's Forests 2011 Report (Forest Europe et al., 2011) were utilized to gather historical and current forest age-class distribution data from 1950 to present (Appendix A, Supplementary material). Age structure data was available for nearly all EU countries except for Greece, Cyprus, Malta and Spain. In most countries, similar age-class aggregations are in use, i.e. 20-year classes, with variation only in the threshold for the oldest age-class reported. There were however some countries with different age-class definitions: the data from Norway had 40-year age-classes and Irish data as well as part of the French data were reported in variable class-widths depending on the inventory. To make the different inventories comparable, we assumed a uniform distribution of forest area within age-classes, divided the data into one-year age-classes and reallocated the forest area into comparable age-classes. Middle year of the inventory period was assumed to be the reference year of the inventory, and if no age-class data was available for the year 2010 (i.e. the end point of our study period) we used EFSOS II projections (UNECE and FAO, 2011) instead of reported data. Only the forest area reported as even-aged was included in the study, which in 2010 was on average 81% of the total forest area in the studied countries (Forest Europe et al., 2011).

## 2.2 Backcasting

Since only a small number of countries have inventory data from 1950 onwards, missing data and gaps between the inventories had to be reconstructed. For the reconstruction of the past age-class distributions, two backcasting approaches recently developed by Seidl et al. (2011a) and Bellassen et al. (2011) were available.

The Bellassen et al. (2011) approach assumes that an earlier age-class distribution can be calculated backward from an observed age structure using the wood harvest statistics for this period. Assume, as an example, that 100 000 ha of forest were between 0 and 10 years old during the 1990 inventory. This area of forest has been harvested between 1980 and 1990, and we have to estimate the age of these 100 000 ha of forests at the time of this last harvest. To do so, wood from thinning simulated by ORCHIDEE-FM (Krinner et al., 2005) for the 1990s is first subtracted to the wood harvest statistics of the same decade. The remaining wood supply is then assumed to have come from clear cuts. Given the constraint of the surface area, growing stock per hectare in the harvested forest can be calculated. It is then matched with the average growing stock per age class to determine which age class has been harvested. Decades with a larger demand per area of surface thus require older forests to be harvested, assuming that older forests contain more wood. Minimum and maximum ages of, respectively, 40 and 150 years are set for this age guess, and the cohort of clear-cut forest can be distributed among two neighbouring age classes to improve the match to harvest statistics. This combined algorithm matches exactly the observed 1990 age structure. The evolution of total forest area (Gold, 2003; FAO, 2006) is also accounted for: a decrease in forest area between two decades is proportionally downscaled to all age classes, whereas an increase is entirely realized in the 0–10 age class that corresponds to new plantations. This algorithm is applied separately to conifers and broadleaves.

Seidl et al. (2011a) developed a simple age-class distribution backcasting method borrowing from the matrix model concept of EFISCEN (Schelhaas et al., 2007). Starting from reported age class distributions (class width  $n$  years) at the end of the study period (MCPFE, 2007) and assuming uniform distribution of forest area within each age class,  $1/n$  of each age-class area is transferred to the previous age class per backcasted year. Area from the first age class is routed to higher age classes assuming a country-specific age pattern of stand-replacing harvests, as used

in the continental scale EFISCEN simulations by Verkerk et al. (2011b). Annual changes in forest area are accounted for by updating the area routed from/to the first age class, i.e. decreases in forest area are assumed to result from land-use change after stand-replacing harvest and increases are assumed to stem from afforestation. Seidl et al. (2011a) used the reconstructed age class time series to derive median age, proportion of forest area older than 100 years, and skewness of the age distribution as indicators for the influence of age structure on natural disturbance regimes (Seidl et al., 2011a).

The main difference between the two backcasting methods is that while Bellassen et al. (2011) use information on growing stock and dynamic simulation results from ORCHIDEE-FM (to characterize thinned volume and the volume available through clearcuts) in addition to forest area by age class in their backcasting, Seidl et al. (2011a) solely rely on the information contained in age classes and assume time-invariant harvesting patterns.

### 2.3 Comparison of the backcastings

To select one backcasting approach for our reconstruction of historical age-class distributions, we compared backcasted data with the independently reported data on historical age-class distribution from forest inventories. For the comparison, we only selected those inventory datasets that had a reference year close to the year 2000, 1990, ..., 1950 (i.e. a reference year within the inventory period or within  $\pm 5$  years from an inventory), as initial backcasting results from Seidl et al. (2011a) and Bellassen et al. (2011) were available only for these years. For this initial comparison both approaches used only a single inventory year as starting point (i.e. 1990 for Bellassen et al. (2011), and 2001 for Seidl et al. (2011a)). As shown in Table 1, we had 24 inventory datasets from 5 countries suitable for comparison with Seidl et al. (2011a) and 20 datasets from the same 5 countries for Bellassen et al. (2011).

**Table 1:** Overview of data available for comparison of reported and backcasted data from Bellassen et al. (2011) (B) and Seidl et al. (2011a) (S) on age-class distributions

Year	Austria	Czech	Finland	Poland	Sweden
2000	S	S	S		S
1990	B/S	B/S	B/S	B/S	B/S



1980	B/S	B/S	B/S	B/S	
1970	B/S	B/S	B/S	B/S	B/S
1960	B/S	B/S	B/S		
1950		B/S	B/S		B/S

1

2 We compared the difference between reported and backcasted data using visual as well as  
3 statistical analyses. For the visual comparison we calculated and plotted cumulative distributions  
4 of area over age-classes and analyzed whether the backcasting approaches deviated substantially  
5 from reported inventory data. This approach was supplemented by a quantitative (statistical)  
6 analysis: First, we calculated the maximum differences between cumulative distributions of area  
7 over age-classes according to reported and backcasted data for both approaches separately, as  
8 well as for different countries and different points in time. This difference, comparable to the D  
9 statistic of a Kolmogorov-Smirnov test, is an indication of the level by which backcasted data  
10 matches or deviates from the age-class distribution reported by national forest inventories.  
11 Second, we applied a paired, one-sided Wilcoxon signed rank test using the calculated maximum  
12 differences to assess whether the approaches by Seidl et al. (2011a) and Bellassen et al. (2011)  
13 differed significantly. Third, we performed a Spearman's rank correlation test for the maximum  
14 class difference between the cumulative distributions of reported and backcasted data and the  
15 length of the backcasting period, testing for a decrease in prediction power with time backcasted.  
16 We used R 2.14.0 (R Development Core Team 2011) for all statistical analyses.

17

18 An example of the cumulative distributions of reported and backcasted data is presented for the  
19 Czech Republic in Figure 1; the distributions for other countries are shown in Appendix S1.  
20 Overall, the results according to the backcasting method developed by Seidl et al. (2011a)  
21 appeared to provide results more similar to reported data than the approach by Bellassen et al.  
22 (2011). This was supported by a paired, one-sided Wilcoxon signed rank test using these  
23 maximum differences for both approaches. We found that the backcasting by Seidl et al. (2011a)  
24 led to significantly ( $V=54$ ;  $p < 0.05$ ) smaller differences between the reported and backcasted  
25 data than did the backcasting by Bellassen et al. (2011).

Visual comparison of the backcasting results indicated that for shorter backcasting periods the backcasting by Bellassen et al. (2011) produced similar and in some cases slightly better results than did the backcasting by Seidl et al. (2011a). For both backcastings the difference between reported and backcasted data increased with the length of the backcasting period (Figure 2 and Appendix B), but this effect is stronger for the backcasting by Bellassen et al. (2011), especially when the backcasting period is 30 years or longer. This is supported by a Spearman's rank correlation test: for the backcasting by Seidl et al. (2011a), we found a weak correlation of backcasting deviation with time ( $\rho = 0.56$ ;  $p < 0.01$ ), whereas we found a strong correlation for the backcasting by Bellassen et al. (2011) ( $\rho = 0.81$ ;  $p < 0.001$ ). From these data we infer that the difference between backcasted and reported age-classes increases with the length of the backcasting period for both backcastings, and that the effect is stronger in the backcasting by Bellassen et al. (2011).

Based on visual analysis and statistical testing, we conclude that the backcasting developed by Seidl et al. (2011a) results in smaller deviations from observed data than does the backcasting developed by Bellassen et al. (2011). Hence, we adopted the approach by Seidl et al. (2011a) for further analysis, but keeping in mind that the differences between backcasted and reported age-class distribution can increase with increasing length of the period for which the backcast is made.

#### ***2.4 Reconstruction of the forest age structure from 1950 to 2010***

We used the Seidl et al. (2011a) backcasting approach to fill in the gaps between the inventory years as well as reconstruct the missing data from the last inventory until 1950. The average length of the backcasting period over Europe was 14 years, varying from 2.6 years in Sweden to 30 years in Italy and Slovenia (Figure 3). Reconstructions were done on country level, pooled for all tree species. The method was adapted to our data by changing the age-class width from the 10 year class used in Seidl et al. (2011a) to 20-40 years, depending on the country and the original data. To alleviate the effects of an apparent mismatch of forest area change data and inventory estimates of young forests for some countries we also introduced a 5% minimum area threshold for the first age-class.

1 The reconstructed country level age-class distributions were then used to calculate the age-class  
2 distribution in 1950 and 2010, the share of young and old forests, and the development of mean  
3 age from 1950 to 2010 in 25 European countries: EU 27 (– Greece, Cyprus, Malta, Spain) +  
4 Norway and Switzerland. The reconstruction assumes a uniform distribution of forest area within  
5 each age class. To compare assimilating historical data into backcasting to using only a single  
6 inventory year as backcasting starting point, we calculated the age structure over Europe both 1)  
7 using inventory data when available and only filling the gaps by means of backcasting, and 2)  
8 reconstructing the age structure using only the latest inventory data as a starting point and  
9 applying backcasting over the full study period.. For subsequent mapping and analysis of  
10 continental scale forest age trends the former approach (backcasting with data assimilation) was  
11 used.

## 12 *2.5 Deriving maps using remote-sensing based forest cover information*

13 The backcasted national area values were distributed over the forest area using a remote-sensing  
14 based forest cover map for Europe which was available from the European Commission Joint  
15 Research Centre (Pekkarinen et al., 2009), and aggregated to grid cells of  $0.25^{\circ} \times 0.25^{\circ}$ . The  
16 forest cover map was aggregated from 30m to 1km resolution by summing up the forest area in  
17 each 1km x 1km pixel. To distribute the age-class data, a ratio was calculated between the  
18 backcasted forest area per age class and the total forest area in the forest cover map, for each  
19 country and year. This ratio was used to scale the values in the forest cover map so that the forest  
20 area per country in the map would fit with the forest area of the respective age class in that  
21 country. In doing so, we assumed a homogenous distribution of all age classes over the forest  
22 area in a country. Since this assumption is certainly not valid at 1km resolution, the resulting  
23 time series maps at 1km x1km pixels were aggregated to grid cells of  $0.25^{\circ} \times 0.25^{\circ}$  size by  
24 summing up the forest area in each grid cell.

25 Since only some countries provide separate information on the oldest age class 141+ (Austria,  
26 Finland, France, Germany, Netherlands, Switzerland; also Sweden for most of the inventories),  
27 we decided to use 121+ as highest age class for the mapping. However, for several countries the  
28 highest reported age class includes also forests younger than 120 years. This was the case for  
29 Belgium, Bulgaria, Denmark, Hungary, Romania, United Kingdom and also Sweden for some  
30 inventories (oldest class 101+), Portugal (oldest class 61+) and Ireland (oldest class 41+). In the

maps of higher age classes these countries were grouped into an extra category. In the case of Norway, data was backcasted in 40-year intervals instead of 20-year steps. For the mapping exercise the backcasted values were equally divided between the applied 20-year intervals.

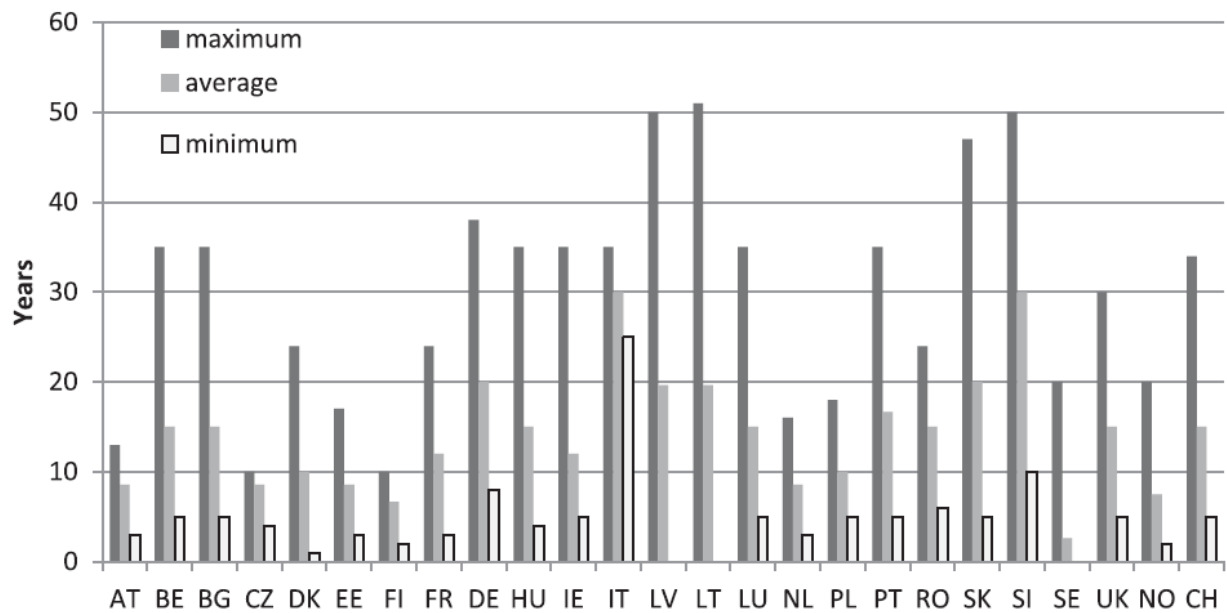
In addition to this analysis at the  $0.25^{\circ} \times 0.25^{\circ}$  scale, time series maps were compiled showing the percentage share of each age class at the country level.

### 3. Results

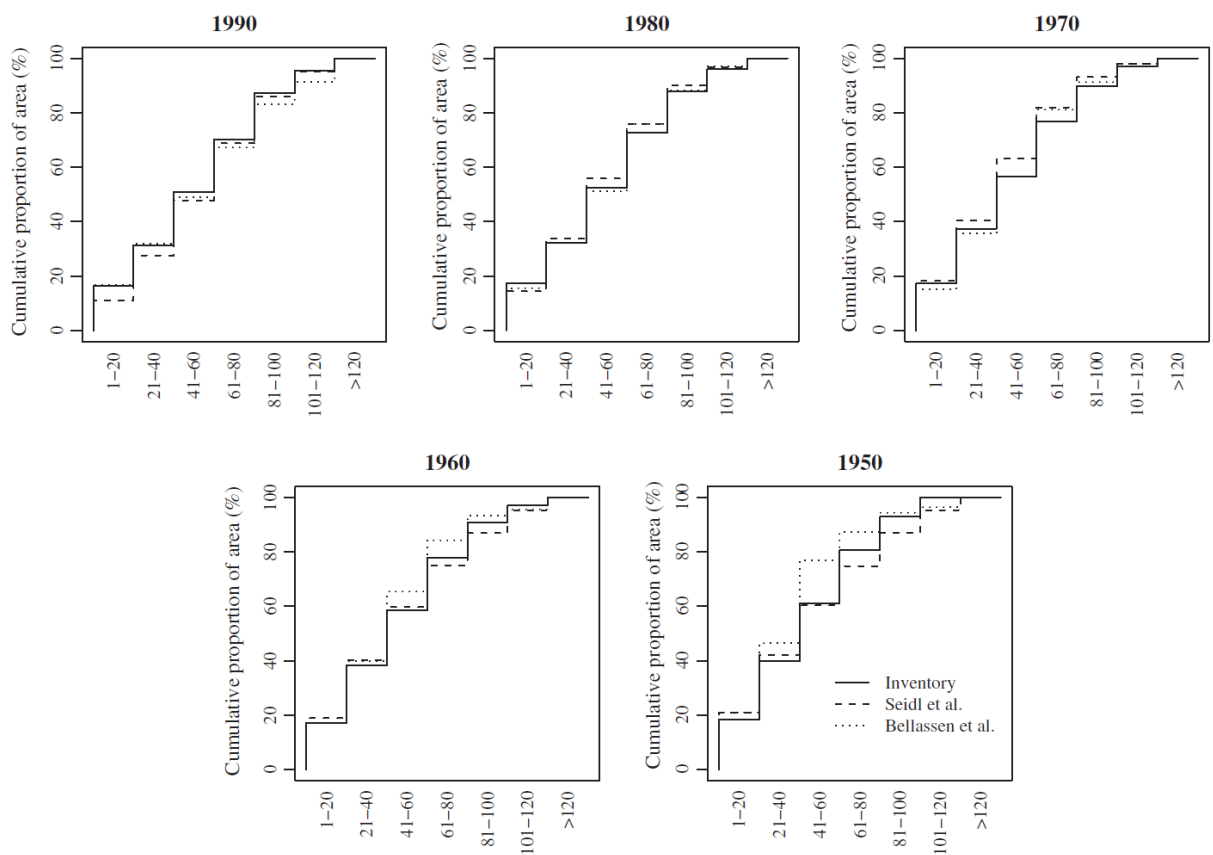
#### *3.1 Comparison of the backcasting methods*

To select one backcasting approach for our reconstruction of historical age-class distributions, the two available methods were compared with the independently reported data from forest inventories of five countries. An example of the cumulative distributions of reported and backcasted data is presented for the Czech Republic in Figure 1; the distributions for other countries are shown in Appendix S1. Overall, the results according to the backcasting method developed by Seidl et al. (2011a) appeared to provide results more similar to reported data than the approach by Bellassen et al. (2011). This was supported by a paired, one-sided Wilcoxon signed rank test using these maximum differences for both approaches. We found that the backcasting by Seidl et al. (2011a) led to significantly ( $V=54$ ;  $p < 0.05$ ) smaller differences between the reported and backcasted data than did the backcasting by Bellassen et al. (2011) over all countries.

**Figure 1.** Comparison of cumulative distribution of forest area over age-classes according to reported (inventory) and backcasted (Seidl et al. 2011a; Bellassen et al. 2011) data for the Czech Republic for the period 1950–1990.

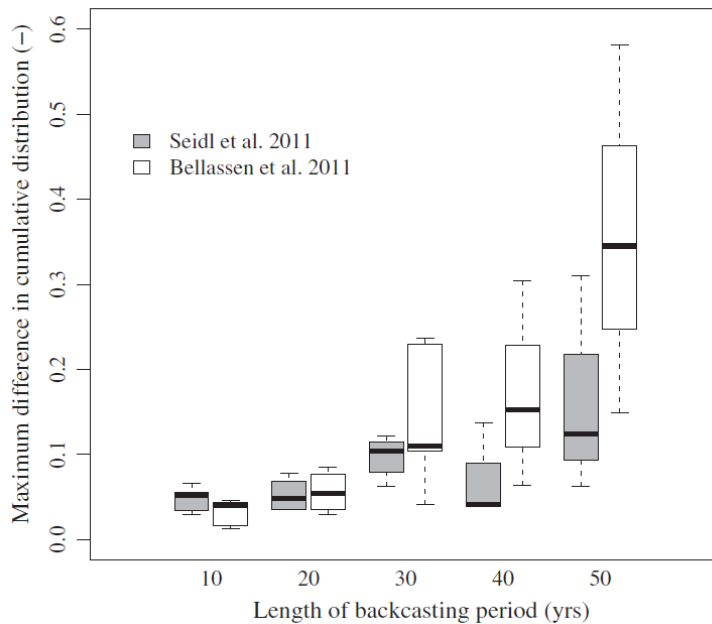


**Figure 2:** Effect of length of backcasting period on the maximum difference between cumulative distributions of area over age-classes between reported data and the approaches developed by Seidl et al. (2011a) and Bellassen et al. (2011).



Visual comparison of the backcasting results indicated that for shorter backcasting periods the backcasting by Bellassen et al. (2011) produced similar and in some cases slightly better results than did the backcasting by Seidl et al. (2011a). For both backcastings the difference between reported and backcasted data increased with the length of the backcasting period (Figure 2 and Appendix B), but this effect is stronger for the backcasting by Bellassen et al. (2011), especially when the backcasting period is 30 years or longer. This is supported by a Spearman's rank correlation test: for the backcasting by Seidl et al. (2011a), we found a weak correlation of backcasting deviation with time ( $\rho = 0.56$ ;  $p < 0.01$ ), whereas we found a strong correlation for the backcasting by Bellassen et al. (2011) ( $\rho = 0.81$ ;  $p < 0.001$ ). From these data we infer that the difference between backcasted and reported age-classes increases with the length of the backcasting period for both backcastings, and that the effect is stronger in the backcasting by Bellassen et al. (2011).

**Figure 3.** Maximum, average and minimum length of the backcasting period.



Based on these analyses, we conclude that the backcasting developed by Seidl et al. (2011a) results in smaller deviations from observed data than does the backcasting developed by Bellassen et al. (2011). Hence, we adopted the approach by Seidl et al. (2011a) for further

analysis, but keeping in mind that the differences between backcasted and reported age-class distribution can increase with increasing length of the period for which the backcast is made.

### ***3.2 Reconstructed age-class structure from 1950 to 2010***

The total forest area included in the study was 108.4 million ha in 1950 and 118.3 million ha in 2010. Based on our backcasting results, the area of forests under 80 years was larger in 2010 compared to 1950, whereas the share of forests older than 100 years was larger at the beginning of the study period compared to present values (Figure 4). The area-weighted mean age over the study area has declined from 67 years in 1950 to 58 years in 1980, but subsequently increased again to 60 years in 2010 (Table 2). However, when looking at the change of the mean age from 1950 to 2010 at the country level, there is a large variation between the countries. Mean age changes over this 60 year period vary from –39 years in Finland to +19 years in Slovenia (Table 2).

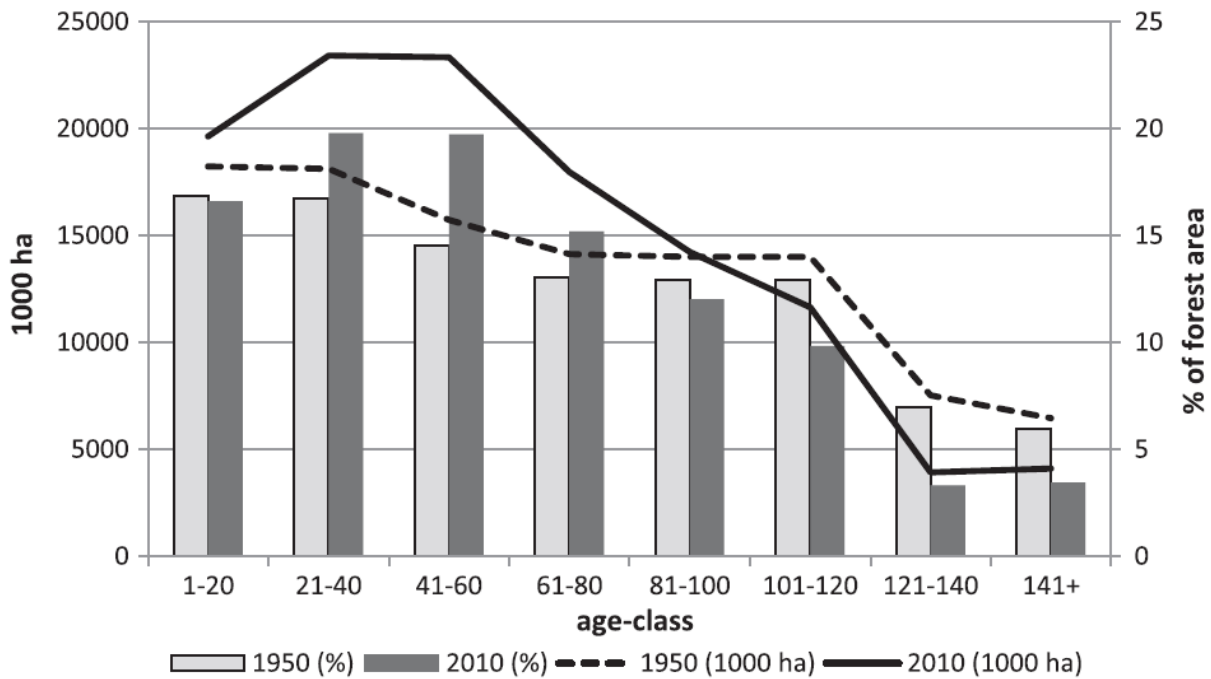
1 **Table 2.** Development of area weighted forest mean age from 1950 to 2010.

	1950	1960	1970	1980	1990	2000	2010	Change from 1950 to 2010
Austria	65	62	63	63	61	61	59	<b>-6</b>
Belgium	54	51	51	44	47	38	36	<b>-17</b>
Bulgaria	49	49	46	42	41	48	52	<b>3</b>
Czech Republic	51	54	55	59	60	62	64	<b>13</b>
Denmark	60	60	58	44	43	43	40	<b>-21</b>
Estonia	43	40	42	46	47	53	47	<b>4</b>
Finland	102	72	67	65	65	64	63	<b>-39</b>
France	73	73	60	52	66	68	72	<b>-1</b>
Germany	77	80	79	71	71	67	66	<b>-11</b>
Hungary	39	38	39	38	41	36	41	<b>2</b>
Ireland	38	36	31	27	25	25	19	<b>-19</b>
Italy	41	42	41	35	57	57	59	<b>17</b>
Latvia	56	55	54	55	57	61	50	<b>-6</b>
Lithuania	55	53	51	50	50	51	53	<b>-2</b>
Luxembourg	87	87	85	80	73	82	78	<b>-9</b>
Netherlands	43	38	43	35	48	56	56	<b>13</b>
Poland	61	54	50	51	53	56	55	<b>-6</b>
Portugal	22	22	23	27	29	31		<b>9*</b>
Romania	58	56	56	51	55	57	60	<b>1</b>
Slovakia	57	56	59	60	61	63	64	<b>7</b>
Slovenia	66	66	67	70	74	81	84	<b>19</b>
Sweden	58	59	60	65	57	56	54	<b>-4</b>
United Kingdom	44	43	35	36	43	45	48	<b>5</b>
Norway	68	67	66	62	63	70	67	<b>-1</b>
Switzerland	87	90	93	88	91	86	85	<b>-2</b>
Whole area	<b>67</b>	<b>62</b>	<b>59</b>	<b>58</b>	<b>59</b>	<b>60</b>	<b>60</b>	<b>-7</b>

2 \*The change for Portugal is from 1950 to 2000 – no data was available for 2010

3 **Figure 4.** Age-class distribution in European forests in 1950 and in 2010.

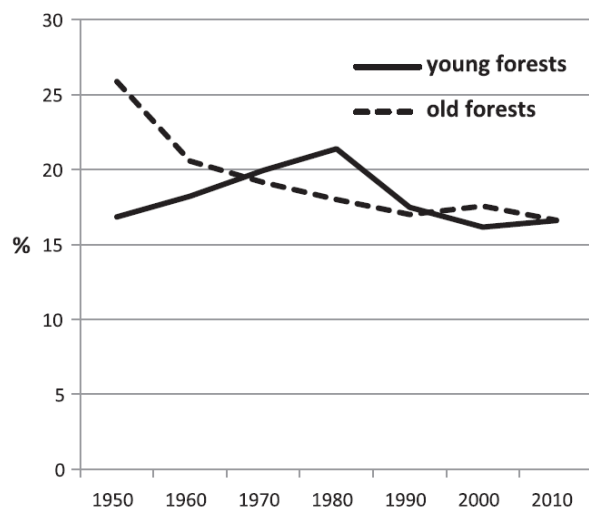




1

2 The share of young forests (<20 years) in Europe is now on a similar level as it was in 1950, i.e.  
 3 approximately 17% of the total forest area (Figure 5), but peaked during the study period,  
 4 reaching almost 22% in 1980. The share of old forests (>100 years) has decreased from 26% in  
 5 1950 to 17% in 1990 and has remained at around that level since.

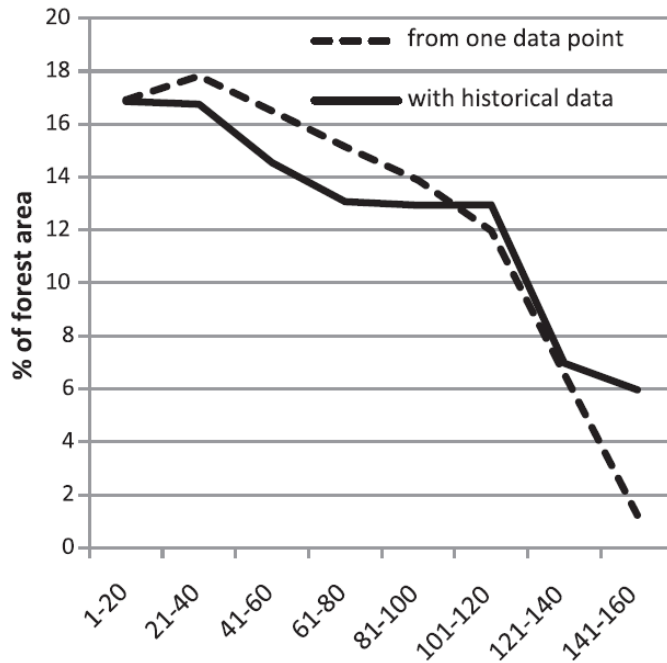
6 **Figure 5.** Share of young (<20 years) and old (>100 years) forests on total forest area in Europe  
 7 for the period 1950–1990.



8

To study the effects of assimilating historical data with backcasting instead of using one data point as a starting point for backcasting, we compared the age structure over Europe using these two methods (Figure 6).

**Figure 6.** Comparison of reconstructed 1950 age structure using backcasting with only one empirical data point (length of the backcasting period ~50 years) and combined with historical data (average length of the backcasting period 14 years).

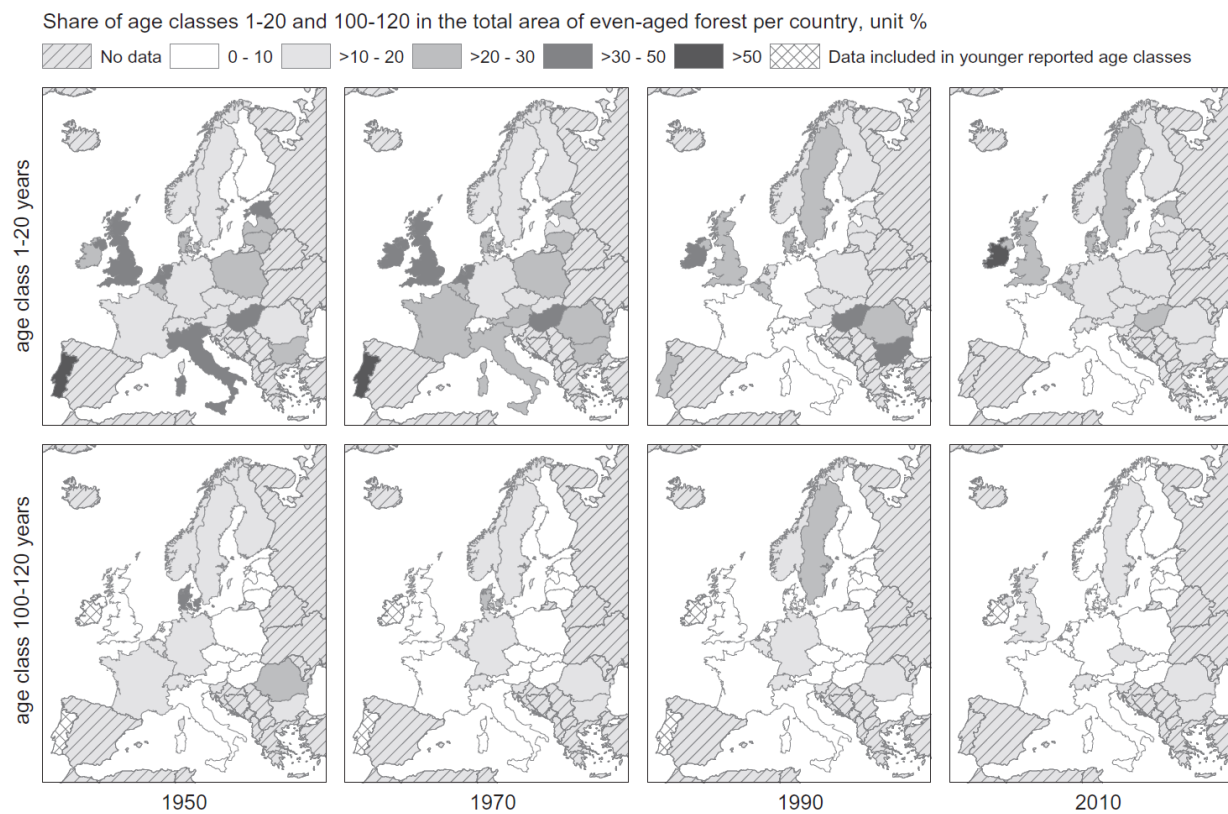


The comparison shows that the use of only one empirical data point as a start of the backcasting leads to overestimation of area of young and middle-aged forests and underestimation of old forests. The mean age in 1950 was only 62 years when only one empirical data point was used in backcasting, whereas it was 67 years when historical inventory data was used together with backcasting. That is partly because the backcasting method does not account for the changes in the forest management during the six decades study period. Thus, the use of historical age-class data together with backcasting improved the results significantly.

### 3.3 Time series maps

Country level time series maps were compiled that show the percentage share of age-classes and their development over time. Figure 7 illustrates an example of such time series for age classes 1–20 and 100–120 years. In addition, based on the country level data and remote-sensing based forest cover information, time series of gridded maps were produced. These maps were combined into a matrix view that shows temporal development on the horizontal axis and age classes on the vertical axis (Figure 8).

**Figure 7.** Development of forest age-class shares for the period 1950-1990.

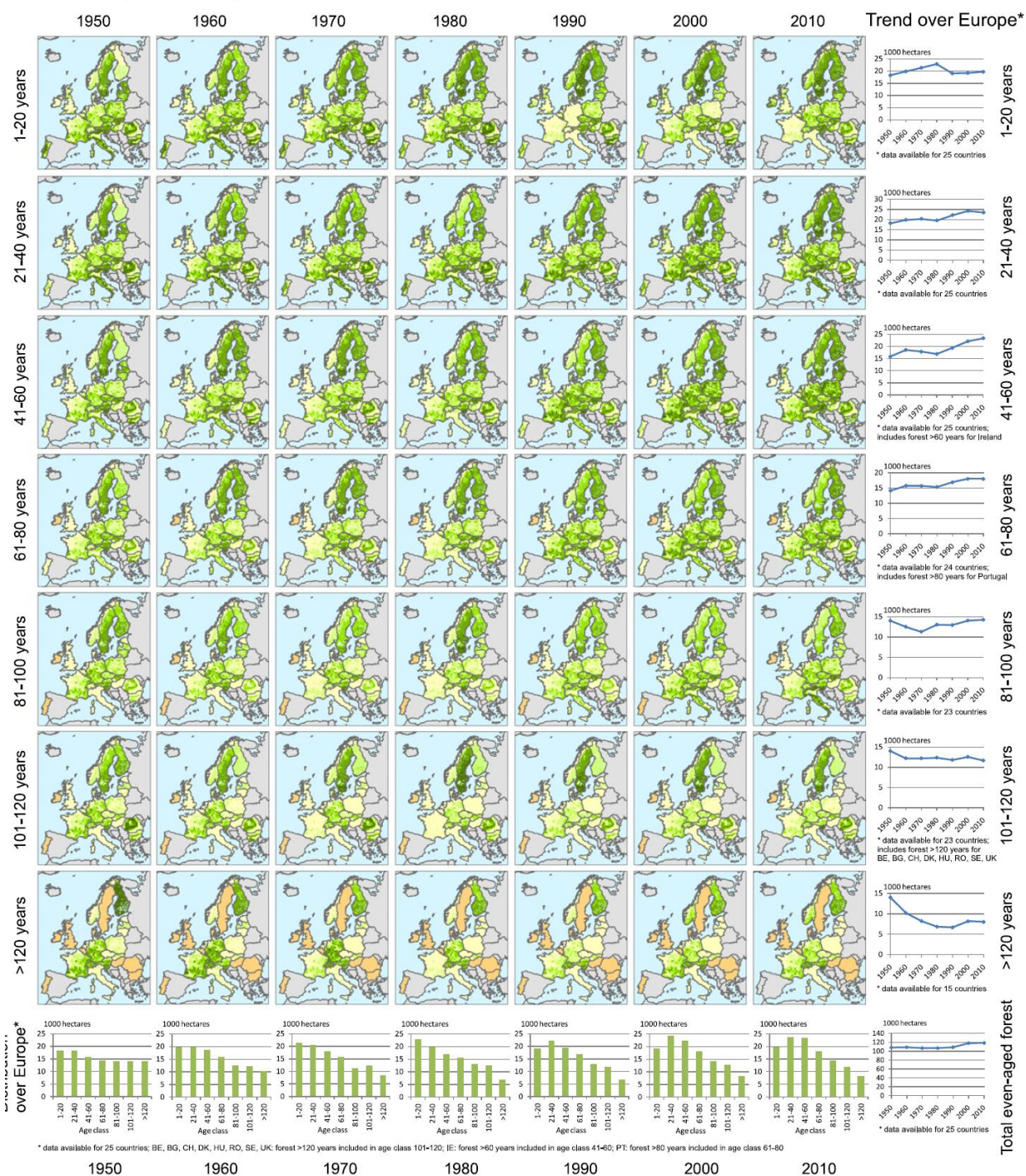


**Figure 8.** Development of forest area in different age classes for the period 1950-2010.

Forest area per grid cell (0.25 x 0.25 degrees), unit 1000 ha

No data 0 - 1 >1 - 2 >2 - 3 >3 - 5 >5 Data included in younger age classes

\* BE, BG, CH, DK, HU, RO, SE, UK: Forest >120 years included in age class 101-120; IE: Forest >60 years included in age class 41-60; PT: Forest >80 years included in age class 61-80





## 4. Discussion

### *4.1 Change of forest age-class structure from 1950 to 2010*

In this study we developed the first comprehensive age structure reconstruction for European forests from 1950, by combining available historical national inventory data with recently developed backcasting methods. Our reconstruction of the forest age-class distribution from 1950 to 2010 shows that the mean forest age over Europe has decreased by >10% in 2010 as compared to 1950, and that there is large variation between the countries. When comparing the situation in 1950 and in 2010, the mean age has decreased remarkably in several countries and the decrease is largest in Finland, Denmark, Ireland, Belgium and Germany (Table 2). In Finland, Denmark, Belgium and Germany the share of old forests (>100 years) has decreased respectively by 39, 26, 16, 12 percentage points since 1950. In Ireland, on the other hand, large afforestations explain the decrease in mean age. In Finland, the large decrease in the mean age and in the share of old forests is explained by large fellings due to war reparations and by the change of forest management from selective fellings of timber sized trees to silvicultural thinnings and regeneration fellings. Changes in silvicultural regimes happened probably to different degrees in all countries. Large areas of mature and pre-mature stands were cut after World War II also in western, central and eastern Europe (Gold 2006), explaining the decrease of old forest area in other countries. Following this period, the increasing demand for wood (Kuusela, 1994) had to be met through intensive management of medium aged stands and continued harvesting of the remaining mature stands, resulting in a further decline in the proportion of old forests. In parallel, in the first decades after World War II, major afforestation efforts were made especially in western Europe, but also in central and eastern Europe, to compensate for earlier clear cuttings and to achieve timber self-sufficiency, resulting in additional young forest areas (Gold et al., 2006). After 1980 the share of middle aged (41–80 years) and mature (81–100 years) forests started to increase, leading to an increase of mean age. At the same time the growth of the European forests has increased (Spiecker et al., 1996; Kahle et al., 2008). As a consequence, the ratio of fellings to increment decreased from around 90% in Western Europe in the 1960s to 70% in the 1990s (UNECE/FAO, 2005).

Nevertheless, there are also countries where the mean age has increased since the 1950s. In the Czech Republic, Italy, the Netherlands and Slovenia the mean age has increased by 13, 17, 13 and 19 years, respectively. In the Czech Republic, the forest area has remained quite stable from 1950 to 2010, with an increase only of 8% based on our data. That implies that there has not been any major afforestation which would have caused the decrease of mean age. In Italy and Netherlands, the share of forests under 40 years was high between 1950 and 1980 (~60%), and the increase of mean age resulted from aging of those forests. Instead, the uncertainty of the Slovenian results is very high due to the lack of historical data and the results should be interpreted with caution.

## **4.2 Implications**

Changes in forest age structure have a strong impact on the forest C balance (Ciais et al. 2008). Nabuurs et al. (2003) found an increasing trend in the accumulation of carbon in biomass in European forests during the period 1950–1999. Based on the general observation that older forests store more carbon per hectare (Pregitzer & Euskirchen 2004), they speculated that this trend in forest C could be attributed inter alia to aging forests throughout their study period. Our reconstruction of age-class structure for the continent did not support this hypothesis. Notwithstanding the limitations of simple age - C relationships (e.g., older forests being found more frequently on less productive sites), our findings suggest that before 1980 the previously reported sink was not primarily driven by changes in age. Alternative explanations include forest management (changed species composition, changed management practices), recovery from old unsustainable management practices (grazing and litter extraction) and increased N deposition and atmospheric CO<sub>2</sub> concentration (de Vries et al., 2009, Luyssaert et al. 2010). For the last two decades of the 20<sup>th</sup> century mean age of European forests increased slightly and this has likely contributed to the European forest C sink. This is in line with the observation by Ciais et al. (2008) that both stock and NPP strongly increased during the period 1970–1990 for conifer forests without a corresponding increase in area, and the observation by Rautiainen et al. (2010) that the net gain of carbon in European Union forest vegetation during 1990–2005 took place almost exclusively in areas which were forested already in 1990.

Besides implications for the forest C balance, changes in age structure also affect biodiversity. Early stages are generally associated with high diversity (Swanson et al. 2011). However, the

opposite is true for the relatively uniform conifer plantations initiated in many parts of Europe particularly in the first half of our study period (Spiecker et al. 2004). Moreover, a reduction in older forests generally means a decline in habitat for species and guilds depending on larger diameter trees, snags, and deadwood (Ranius et al. 2003). It, however, also results in a reduced susceptibility to disturbances such as wind and bark beetle (Seidl et al. 2011b).

### **4.3 Uncertainty**

#### **4.3.1 Data**

In this study, data from different sources were used to compile the best available information on historical forest age distributions. However, due to e.g. different definitions of forest, forest areas from different sources might not be completely comparable. Furthermore, even if the data source is the same, inventory methods might have changed over the years, which can also affect the results (Köhl et al., 1997). The 2010 age-structure data was taken either from State of Europe's Forests 2011 (Forest Europe et al., 2011) or if not available there, from EFSOS II projections (for Austria, Luxembourg, Romania, Slovenia and Norway) (UNECE/FAO, 2011). In some cases the Forest Europe et al. (2011) data differs a lot from earlier inventory data (e.g. for France) or is not updated from the latest inventory (Germany). Thus, the reconstruction of the most recent period has to be interpreted with precaution for these countries. Other data sources used in the backcasting approaches may also suffer from time-series inconsistency and lack of accuracy. For example, the wood harvest statistics used in Bellassen et al. (2011) are corrected for unreported informal wood harvest, in particular for fuel wood, without precise explanations on the correction method (FAO, 2005). Furthermore, only the area reported as even-aged forest is included in the backcasting, but change in forest area was derived from areas of exploitable forests and might include also uneven-aged forests (Kuusela, 1994). Estimation of the area of uneven-aged forests is difficult, however, since there is not much data available on their extent, and countries have different methods to deal with the uneven-aged forests in their inventories (e.g. leaving out the uneven-aged forests completely, distributing them to age-classes or defining a separate 'uneven-aged' age class). In addition, definitions of even-aged and uneven-aged forest vary between countries and some forests are non-categorized, i.e. reported as neither even-aged

nor uneven-aged (Forest Europe et al., 2011). Furthermore, the area of uneven-aged forests is likely to have changed over time, and since this category can include very different kinds of forests, it is not possible to generalize the average bias caused by uneven-aged forests in our study. However, since the area of protected forests has increased from the 1970's (Welzholz and Johann 2007) it is likely that the share of uneven-aged forests has increased and thus our results could underestimate the current area of old forests. Recently, there has also been a trend towards more close-to-nature and continuous cover forestry in Europe (Spiecker et al., 2004) but its implications on the average age of forests is difficult to assess.

#### 4.3.2 Backcasting

The used backcasting approach was selected on the basis of the comparison with the independently reported data on historical age-class distribution from forest inventories. In this comparison, the simpler backcasting developed by Seidl et al. (2011a) resulted in smaller deviations from observed data than the more elaborate backcasting by Bellassen et al. (2011). A possible reason for this finding is that the Bellassen et al. (2011) backcasting approach requires more data and is therefore subject to the uncertainty associated with these data needs. Furthermore, whereas the backcasting approach by Seidl et al. (2011a) relies strongly on inventory data, the Bellassen et al. (2011) backcastings also employs simulation modeling: harvesting and growth are derived from the process-based model ORCHIDEE-FM, which allows greater flexibility and improved process representation in backcasting, but also introduces an additional source of potential error.

The reliability of our backcasting results varies between countries and time steps. Since the accuracy of the backcasting decreases with increasing length of the backcasting period, there is high uncertainty in the results of countries where no historical data were available (e.g. Latvia, Slovakia, Slovenia, see Figure 2 and Appendix A). Also the assumption of a uniform age distribution *within* a 20-year age-class (Seidl et al. 2011a) might introduce uncertainties, particularly for countries in which past disturbances or afforestation programs have created large pulses of relatively even-aged forests. Consequently, the backcasting success differed between countries. As the Figure 5 in Appendix B shows, there is a large difference in the uncertainty of



1 results for the 50 years backcasting period between the countries used in the evaluation (Czech  
2 Republic, Finland and Sweden). The backcasting methods work well for the Czech Republic,  
3 while results for Finland by both Seidl et al. (2011a) and Bellassen et al. (2011) differ strongly  
4 from the inventory data. That is partly because the backcasting methods assume a similar forest  
5 management over the whole time period, and do not take into account the major change in the  
6 Finnish forest management from selective fellings into silvicultural thinnings and final fellings  
7 that took place during the study period. Also, the advanced regeneration of Norway spruce under  
8 birch as well as the effects of peatland drainage is difficult to take into account in modeling.  
9 However, this problem is alleviated in this study by including historical inventory data for  
10 Finland, which reduces the average length of the backcasting period to only 6.7 years for the  
11 country (Figure 3).

## 13 ***5. Conclusions***

14 This study presents the first comprehensive European level reconstruction of forest age structure.  
15 We combined historical inventory data with a backcasting method and were able to improve the  
16 accuracy of reconstructed European forest age structure significantly. The results show that  
17 despite the previously reported increased timber and carbon stocks in European forests, the  
18 average age is currently lower than it was in 1950. After a period of shifting towards younger  
19 forests, the average age has slightly increased from 1980 onwards, but is still 7 years below its  
20 1950 value. Thus, we argue that the development of forest age structure contributed less to the  
21 carbon sink in European forests from 1950 onwards than previously thought.

## 1 **Acknowledgements**

2 This study was part of the GHG-Europe project ('Greenhouse gas management in European land  
3 use systems', EU contract No. 244122) and the CARBONES project ('30-year re-analysis of  
4 carbon fluxes and pools over Europe and the Globe', EU contract No. 242316). R. Seidl received  
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7

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- 24

## 25 **Appendixes**

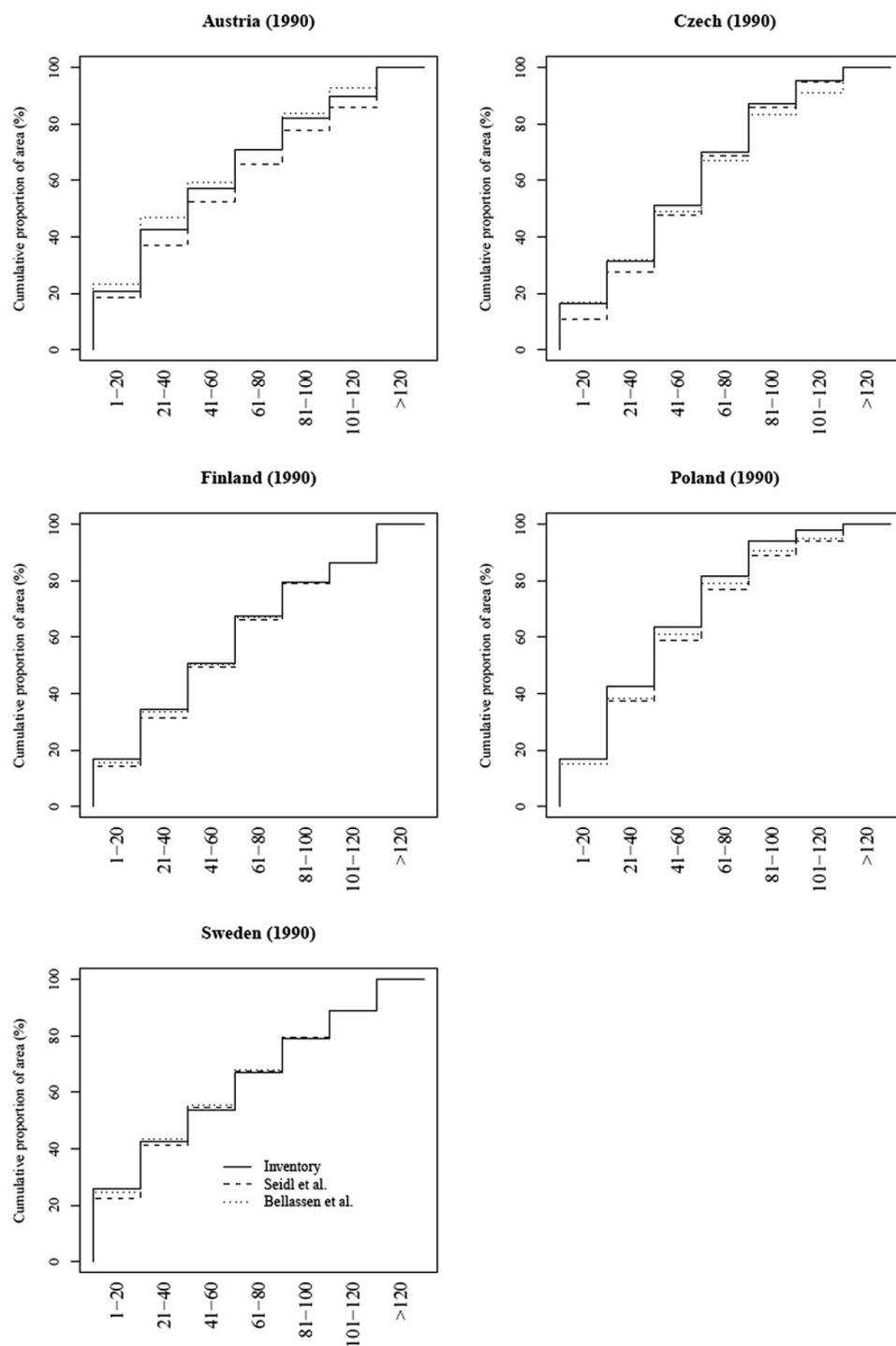
- 26 Appendix A. Reference years (and references) of the used age-class data

Country										
Austria	2010	2000-02	1992-96	1986-90	1971-80	1961-70	1961-64			
Belgium	2010	2005	1997-99	1985						
Bulgaria	2010	2005	1990	1985						
Czech republic	2010	2004	2000	1990	1980	1970	1960	1950	1930	1920
Denmark	2010	2006	2000	1976	1965	1951				
Estonia	2010	2007	2000	1994	1988	1975	1958			
Finland	2010	2004-08	1996-03	1986-94	1977-84	1971-76	1964-70	1960-63	1951-53	
France	2010	2005-09	1987-06	1976-98	1971-80					
Germany	2010	2001-02	1986-90							
Hungary	2010	2000	1996	1985						
Ireland	2010	2004-06	2000	1990	1985					
Italy	2010	1985								
Latvia	2010	2009	2000							
Lithuania	2010	2009	2001							
Luxembourg	2010	2000	1990	1985						
Netherland	2010	2005	1995-99	1980-83	1964-68	1952-63				
Poland	2010	2005	1995	1988	1978	1968				
Portugal	2000	1990	1985							
Romania	2010	1990	1980	1974						
Slovakia	2010	2005	1997							
Slovenia	2010	2000								
Sweden	2010	...	1993-97	1992-96	1991-95	1990-94	1989-93	1983-87	1968-72	1938-52
United Kingdom	2010	2005	1994-00	1980						
Norway	2010	2005	2000	1996	194	1986-93	1980-86	1964-76	1937-56	
Switzerland	2010	2004-06	1993-95	1983-85						

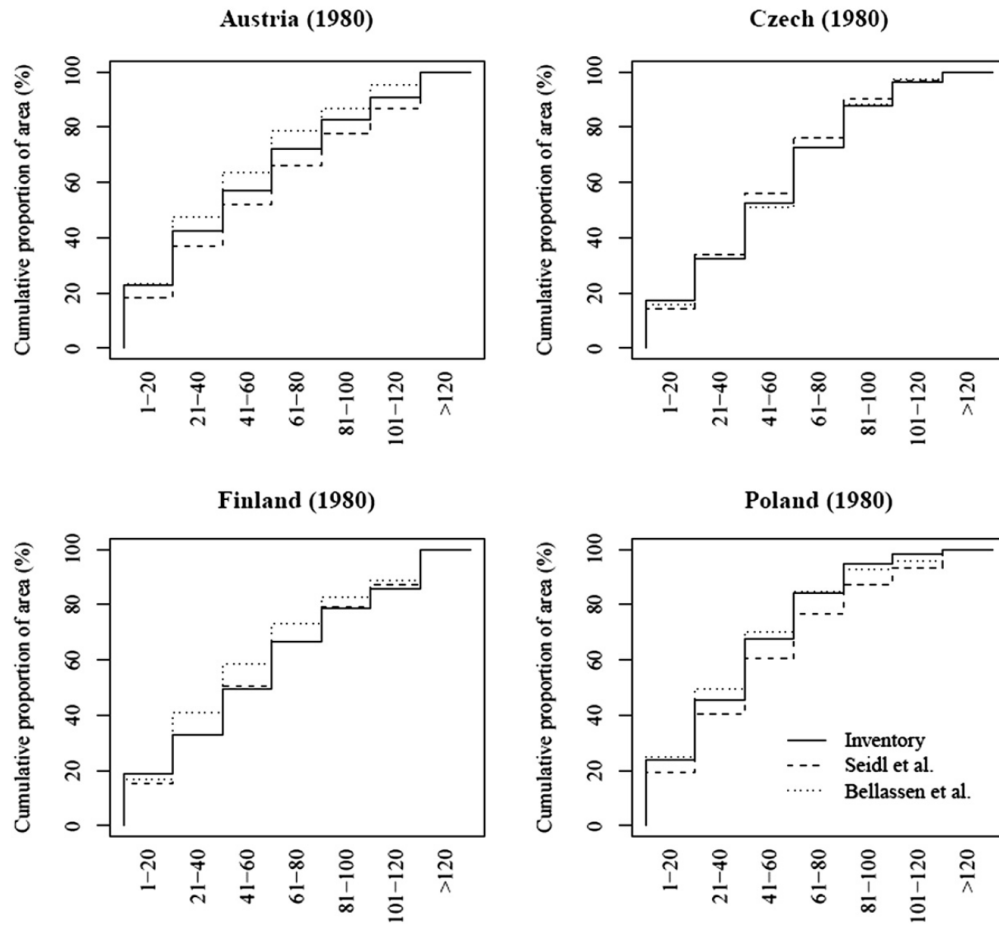
1

## 2 Appendix B. Comparison of the backcasting approaches

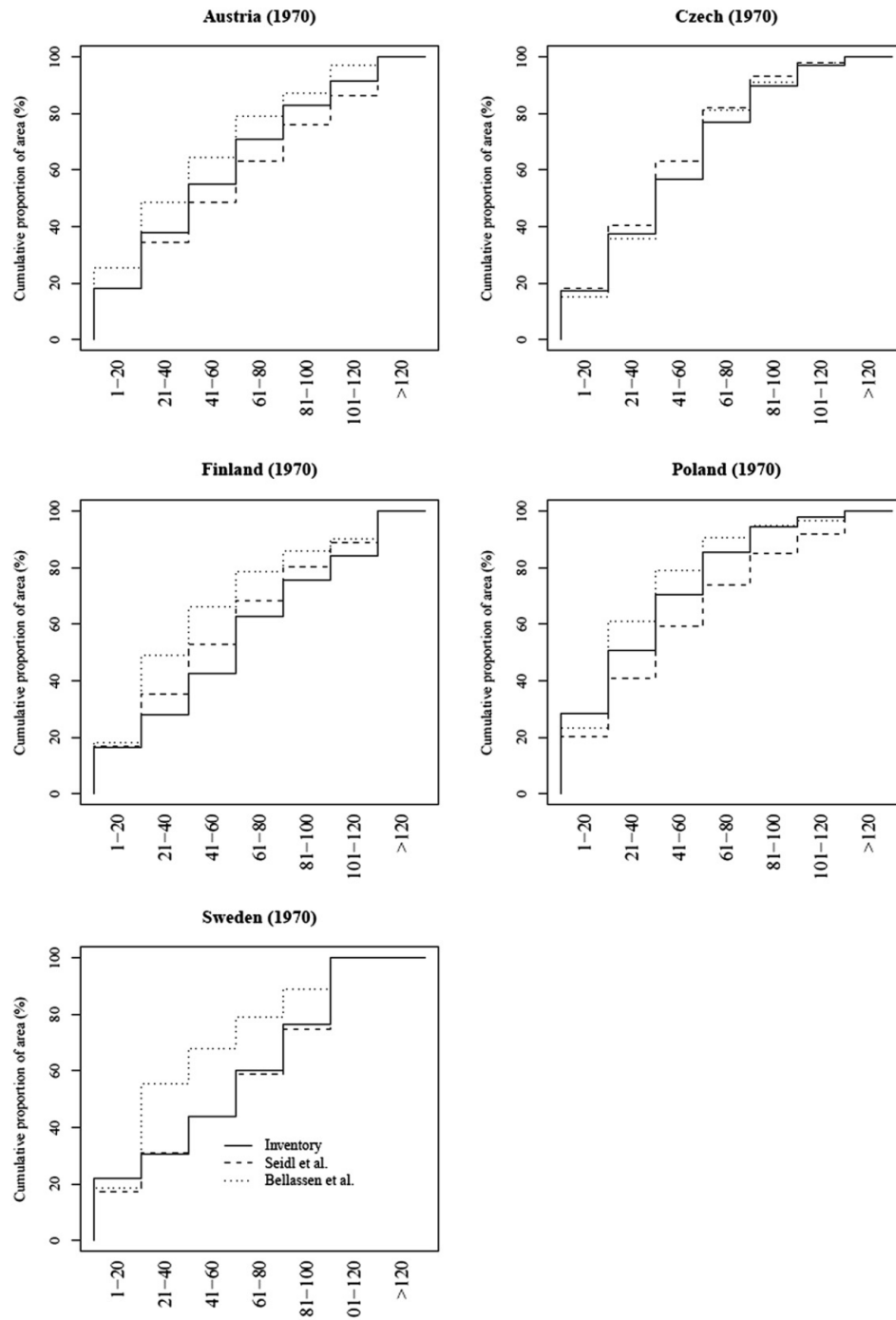




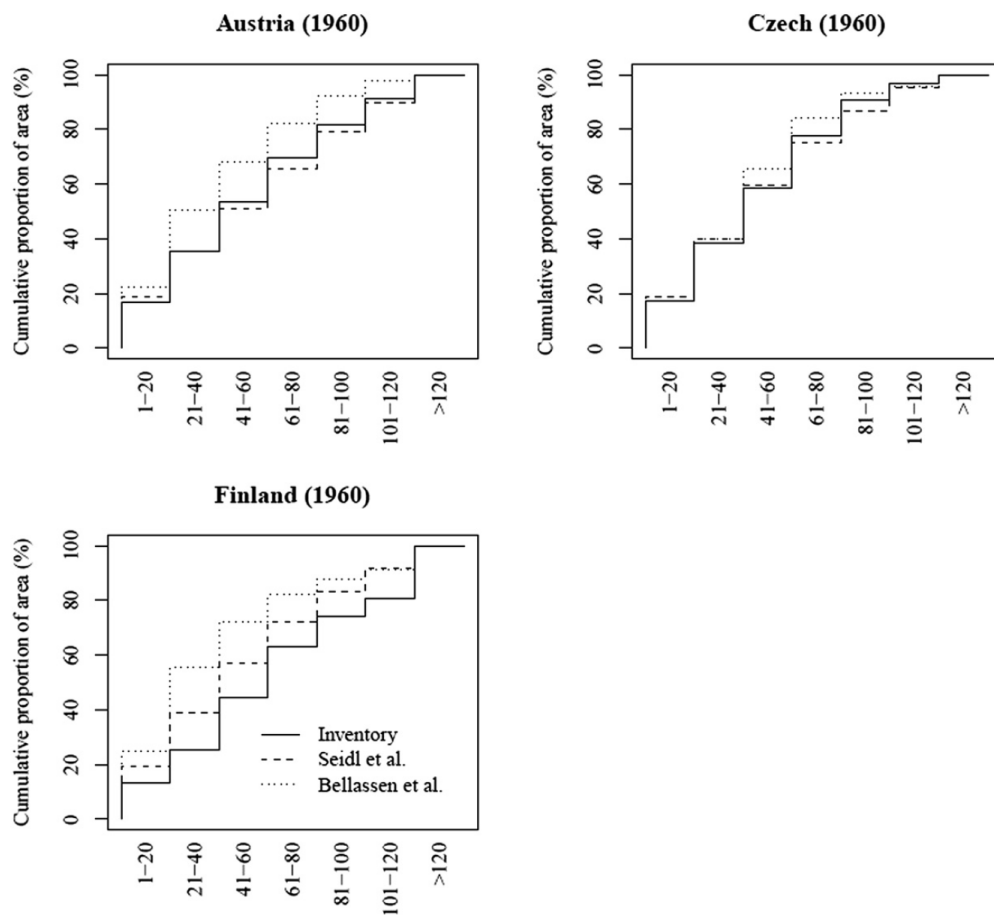
**Fig. B1.** Cumulative distribution of forest area over age-classes according to reported (Inventory) and backcasted (Seidl et al., 2011a; Bellassen et al., 2011) data for different countries for the year 1990.



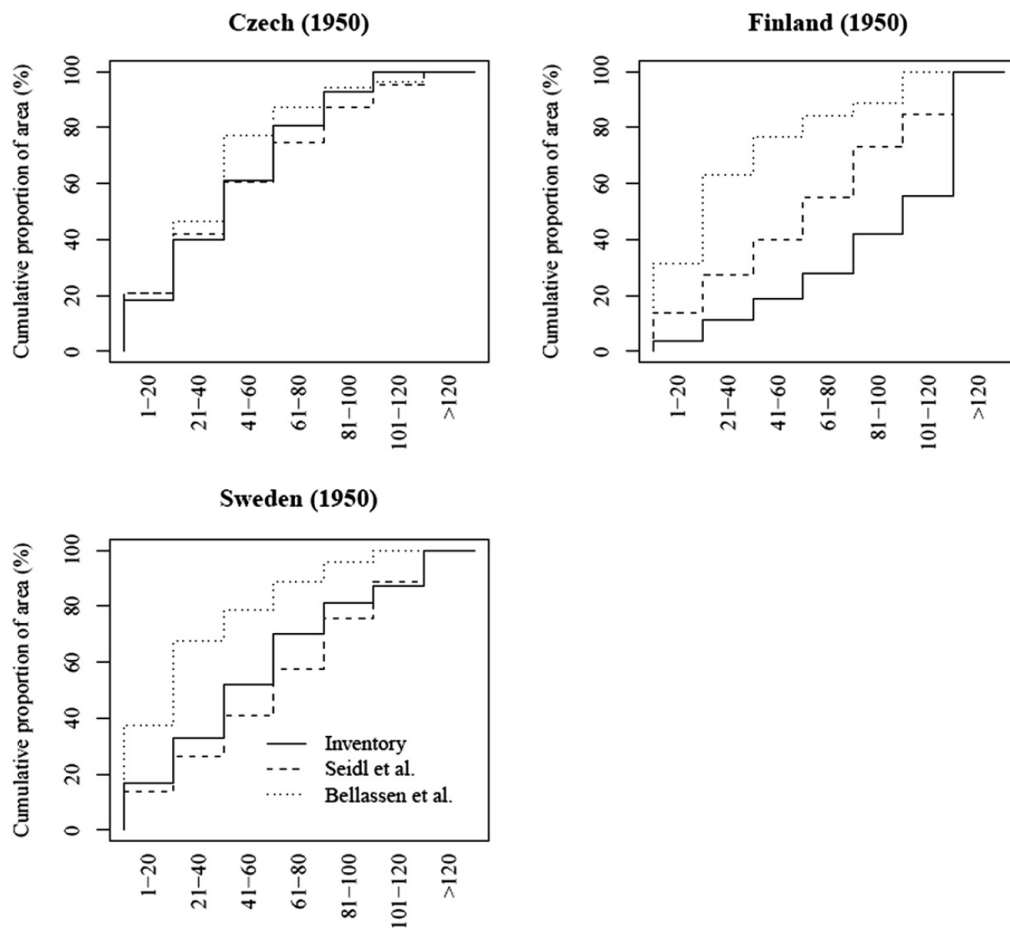
**Fig. B2.** Cumulative distribution of forest area over age-classes according to reported (Inventory) and backcasted (Seidl et al., 2011a; Bellassen et al., 2011) data for different countries for the year 1980.



**Fig. B3.** Cumulative distribution of forest area over age-classes according to reported (Inventory) and backcasted (Seidl et al., 2011a; Bellassen et al., 2011) data for different countries for the year 1970.



**Fig. B4.** Cumulative distribution of forest area over age-classes according to reported (Inventory) and backcasted (Seidl et al., 2011a; Bellassen et al., 2011) data for different countries for the year 1960.



**Fig. B5.** Cumulative distribution of forest area over age-classes according to reported (Inventory) and backcasted (Seidl et al., 2011a; Bellassen et al., 2011) data for different countries for the year 1950.

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