

# Changes of tree stem biomass in European forests since 1950

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**Abstract:** Based on the measurements of the biomass of the stems of 3 699 trees of Scots pine, Norway spruce, and silver birch in Europe since 1950, it has been shown that these tree species show a reduction in biomass and wood density. These results contradict the fact that the volume of wood is directly converted to biomass using the historical values of the conversion rates. From 1950 to 2020 the biomass of 1 m<sup>3</sup> of the stem with bark decreased on average by 80 kg (–17%) for Scots pine, by 105 kg (–22%) for Norway spruce and by 92 kg (–15%) for silver birch. The results obtained should be taken into account when assessing the technical properties of wood and estimating carbon sequestration by forest biomass. Since decreasing trends in stem biomass have been identified for several tree species, the phenomenon may have a large degree of generality. Such studies should be continued both at the regional and national level and at the global level.

**Keywords:** biomass model; climate change; individual tree; wood basic density

Studies of recent decades show that there has been a change in the dynamics of forest stands and their species composition (Pretzsch et al. 2014b; Alekseev, Sharma 2020; Dubenok et al. 2020; Kiseleva et al. 2020). Climatic changes and various methods of silvicultural management applied to forests in different periods are indicated as the main reasons for the ongoing changes in forests (Searle et al. 2021). The intensification of forestry, the improvement of forestry systems contribute to an increase in growth and in forest productivity. For example, the transition to mixed forest management provides an increase in forest productivity compared to single species forest stands (Corona 2019).

A large number of studies have been devoted to changes in forests as a result of climate change.

In the forests of Central Europe, against the background of climatic changes over the past 100 years, the main forest-forming species show faster growth, an increase in volume and accumulation of standing stock (Pretzsch et al. 2014a, b). Reportedly in Europe there has been an increase in the site index of forest stands (Sharma et al. 2012; Socha et al. 2021). The results of long-term observations in the central part of European Russia also show the acceleration of forest growth, increase in their productivity and the intensive emergence of broad-leaved species into the forest canopy (Lebedev 2019; Dubenok et al. 2020). The causes of changes in forests are indicated by an increase in temperature, a change in precipitation, an increase in atmospheric nitrogen deposition, and in the

concentration of CO<sub>2</sub> (Pretzsch et al. 2014b; Etzold et al. 2020; Socha et al. 2021).

The ongoing global changes have created new conditions for forestry. They are primarily associated with a reduction in logging age, an increase in forest productivity, a change in the species composition of forests, and a change in the ranges of pests and pathogens (Marini et al. 2012; Jandl et al. 2019). To prevent the consequences of these changes, it is necessary to support initiatives to preserve natural landscapes and promote the principles of sustainable forest management (Brack 2019). The trajectories from the current state of the forests to the future are unclear, so foresters need to use all the years of experience to devise suitable adaptive management plans for future forests (Jandl et al. 2019).

The biomass of forests and their constituent trees is an important ecosystem component of the global carbon cycle. It has an essential role in understanding the carbon exchange between living organisms and the atmosphere. With an increase in anthropogenic loads of ecosystems the role of forest biomass increases (Ni et al. 2001; Usoltsev et al. 2018). Forest biomass shows temporal variability. In long-term changes, the main drivers include improved forest management especially for artificial forests, topographical factors, climate change and human activities (Qian et al. 2021).

Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and silver birch (*Betula pendula*) are among the most widespread tree species in Europe with a predominance of forests performing important ecological functions. Their wood is widely used in the woodworking industry. This study aims to determine whether tree biomass can be considered as a long-term constant with other things being equal or whether it is subjected to temporal trends as demonstrated, e.g. for stem volumes (Kangas et al. 2020) and wood density (Pretzsch et al. 2018). The presence of systematic trends in biomass will relate not only to environmental issues such as wind resistance of trees or the ability to store carbon but also to economic and technological issues such as the suitability of wood for construction and energy use.

## MATERIAL AND METHODS

**Data collection.** The study uses data from the Eurasia Tree Biomass Database (Usoltsev 2020).

The biomass database contains data on 15.2 thousand felled trees for the basic forest-forming species of Eurasia. The dataset includes information from the literature that provided estimates of tree biomass components. The database includes information on location, tree age, diameter, height and stem volume, crown length and width, and tree part biomass (stem, bark, branches, foliage and roots). Conventional methods were used to determine biomass (Zianis et al. 2005; Usoltsev 2020). The biomass of the individual parts of the tree is determined in terms of the dry matter content. To determine the dry biomass, disk samples were taken from the stem, for which the basic wood density was calculated.

For the study, the most complete data were selected from the database, excluding outliers. For Europe, data on the biomass of Scots pine, Norway spruce, and silver birch trees since 1948 are presented. For the analysis, 3 699 observations were selected, made on 165 forest areas in Ukraine, Russia, Switzerland, Sweden, Finland, Germany, Czech Republic, Belarus, Great Britain, and other countries (Figure 1). The largest number of model trees was selected on the territory of Ukraine (39.7%), Russia (32.5%), Switzerland (7.9%), Sweden (4.3%), Finland (4.3%), and Germany (3.7%). For Scots pine 2 179 observations of biomass (58.9%) were selected, 931 (25.2%) for Norway spruce and 589 (15.9%) for silver birch.

Summary statistics for the dataset including the mean, minimum, maximum, standard deviation, and the number of observations for diameter at breast height, tree height, stem volume, and stem biomass with bark according to tree species are shown in Table 1. The dataset includes a wide range of tree sizes. For example, for Scots pine the diameter range is from 0.5 cm to 58.0 cm, for Norway spruce from 0.6 cm to 98.2 cm, and for silver birch from 0.5 cm to 37.0 cm.

**Statistical analyses.** Regression analysis was performed using linear mixed-effects models (LMM) to test the hypothesis of the influence of the calendar year on the biomass of tree stems. All statistical analyses were performed in R programming language (Version 3.6.3, 2020). Packages used: lme4 (Version 1.1-23, 2020), merTools (Version 0.5.2, 2020), lmerTest (Version 3.1-2, 2020), performance (Version 0.5.1, 2020).

Stem biomass is the main part of tree biomass. Therefore, in the study of Boudewyn et al. (2007),

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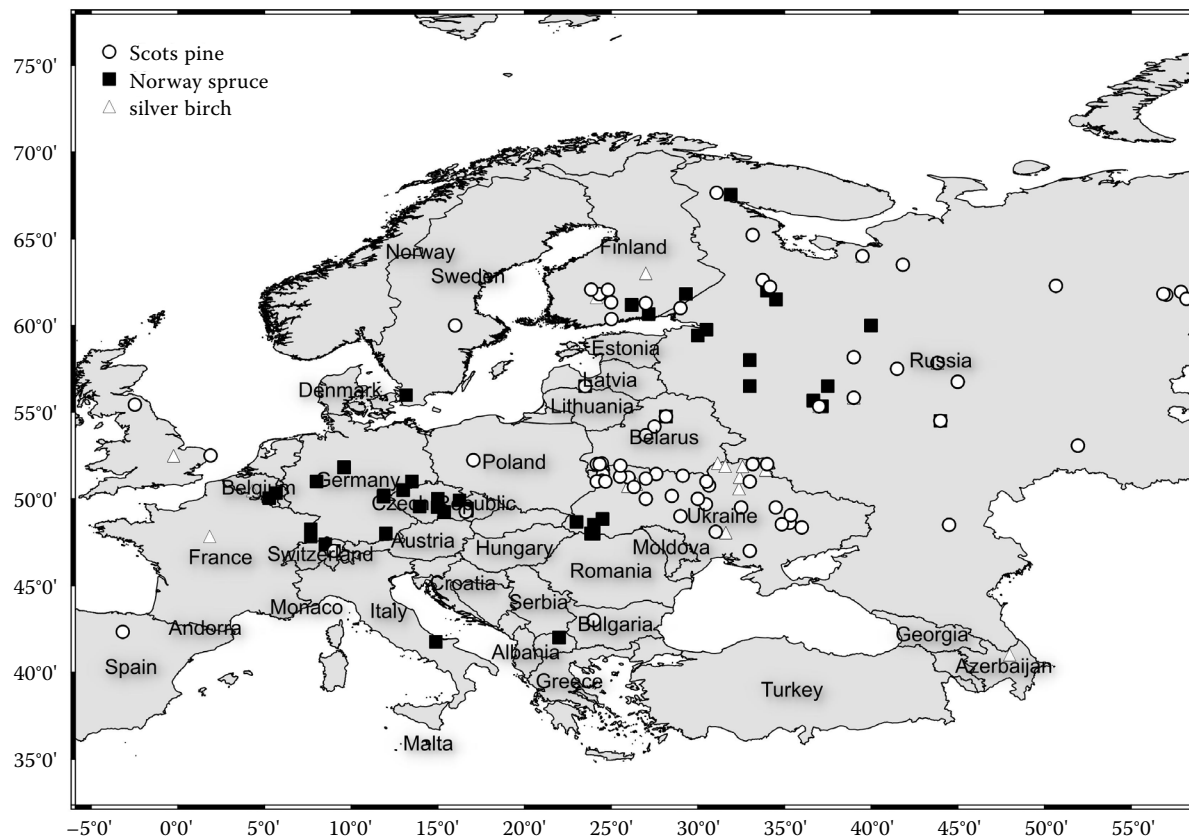


Figure 1. Locations of European tree biomass data collection sites

it is recommended to consider the allometric dependence of biomass on stem volume as a primary model. The basic density of wood is determined

by the content of dry wood per unit volume. Then the biomass of dry wood can be determined by multiplying the density of wood by its volume. With the addition of the calendar year and random effects, the model takes the form:

Table 1. Descriptive statistics for sample trees

Variable	Mean	SD	Min	Max	N
Scots pine					
Diameter (cm)	16.035	10.681	0.500	58.0	2 208
Height (m)	13.747	7.161	1.360	36.6	1 836
Volume (dm <sup>3</sup> )	285.007	470.586	0.050	3 985.0	1 725
Stem biomass (kg)	105.381	183.959	0.002	1 653.0	2 179
Norway spruce					
Diameter (cm)	18.083	13.548	0.600	98.2	1 148
Height (m)	16.540	9.054	1.500	44.8	1 019
Volume (dm <sup>3</sup> )	403.972	789.156	0.300	6 839.0	544
Stem biomass (kg)	182.867	390.627	0.031	4 122.0	931
Silver birch					
Diameter (cm)	14.170	8.205	0.500	37.0	588
Height (m)	15.818	6.443	1.800	26.8	466
Volume (dm <sup>3</sup> )	195.499	213.109	0.400	1 100.0	391
Stem biomass (kg)	102.822	122.987	0.060	800.0	589

N – number of observations

$$\ln(M_{it}) = \beta_0 + \beta_1 \times YEAR_{it} + \ln(v_{it}) + b_i + \varepsilon_{it} \quad (1)$$

where:

$M$  – tree stem biomass (kg);

$v$  – tree stem volume (dm<sup>3</sup>);

$YEAR$  – calendar year;

$i$  – trial plot index;

$t$  – point in time index;

$\beta_0, \beta_1$  – fixed effects parameters;

$b_i$  – random effect of a trial plot [ $b_i \sim N(0, \tau^2)$ ];

$\varepsilon_{it}$  – random error [ $\varepsilon_{it} \sim N(0, \sigma^2)$ ];

$N$  – normal distribution function;

$\tau$  – standard deviation;

$\sigma$  – standard deviation.

As the second basic model for fixed effects, the allometric equation of Schumacher and Hall (1933) was used, which is often used in biomass modelling (Zianis et al. 2005; De Araújo et al. 2018; Romero et al.

2020). Taking into account the calendar year and random effects, the equation has the following form:

$$\ln(M_{it}) = \beta_0 + \beta_1 \times \ln(d_{it}) + \beta_2 \times \ln(h_{it}) + \beta_3 \times YEAR_{it} + b_i + \varepsilon_{it} \quad (2)$$

where:

$d$  – diameter at breast height (cm);

$h$  – tree height (m);

$\beta_{0-3}$  – fixed effects parameters.

The reliability of the models was assessed using estimates of the conditional coefficient of determination, marginal coefficient of determination ( $R^2$ ) and the likelihood ratio test. The marginal  $R^2$  takes into account only the variance of the fixed effects and indicates how much of the variance of the model is explained only by a part of the fixed effects. The conditional  $R^2$  considers both fixed and random effects and shows how much of the variance is explained by the “full” model (Lüdecke et al. 2020).

## RESULTS

The models obtained in the study are characterized by quite high values of the conditional coefficient of determination. In all cases, its values are in the range from 0.986 to 0.998 (Table 2). Since the conditional coefficients of determination are higher than the marginal ones, the inclusion of random ef-

fects in the model makes it possible to explain most of the variance of the dependent variable compared to using only fixed effects. The likelihood ratio test showed that the mixed effects model is better than the fixed effects model ( $P < 0.05$ ).

Our fitted biomass models show (Table 3) a statistically significant effect ( $P < 0.05$ ) for all input variables (stem volume, diameter, height, and calendar year). Estimates of the parameters of Equations (1) and (2) show that with the same values of the volume, diameter, and height of the stems their biomass has been decreasing since 1950. Estimates of the coefficients of the  $YEAR$  variable for Equations (1) and (2) are somewhat different due to the smaller number of observations of the volume of stems in the sample compared to the diameter and height.

According to Equation (1), the change in stem biomass from 1950 to 2020 is –17% for Scots pine, –22% for Norway spruce, and –15% for silver birch. To obtain a clear view, we visualized the Equation (1) outcomes (Figure 2). According to Equation (2), the change in stem biomass from 1950 to 2020 is –18% for Scots pine, –25% for Norway spruce, and –10% for silver birch. The decrease in biomass does not exceed the increase in stem volumes. For example, from 1960 to 2000 the change in the average volume of Norway spruce trees in Central Europe is +34% (Pretzsch et al. 2014). A decrease in biomass must be taken into consideration when studying the effect of accelerating forest growth.

From 1950 to 2020 [Equation (1)], the biomass of 1 m<sup>3</sup> of stem with bark decreased by 80 kg for Scots pine, by 105 kg for Norway spruce and by 92 kg for silver birch. According to Equation (2), when the trees reached, for example, the target diameter of 20 cm and height of 25 m, the decrease in stem biomass was 32 kg for Scots pine, 45 kg for Norway spruce and 19 kg for silver birch. These changes can have serious implications for forest management, timber industry, and the functioning of forest ecosystems.

Wood density exhibits variations both between trees and within individual trees (Chmielowski et al. 2018). In the forests of Europe, on average, the basic density of wood samples was reported 284–783 kg·m<sup>–3</sup> for Scots pine (Aleinikovas, Grigaliūnas 2006; Janusz, Danilov 2018; Šilinskas et al. 2020; Konofalska et al. 2021), 300–579 kg·m<sup>–3</sup> for Norway spruce (Gryc, Horáček 2007; Janusz, Danilov 2018; Šilinskas et al. 2020), and 345–598 kg·m<sup>–3</sup>

Table 2. Estimates of the coefficients of determination and likelihood ratio test of models

Equation	Tree	$R^2$		$\chi^2$	P-value
		marginal	conditional		
1	Scots pine	0.994	0.997	1 020.9	< 2.2E–16
	Norway spruce	0.996	0.998	118.3	< 2.2E–16
	silver birch	0.996	0.997	22.4	2.172E–06
2	Scots pine	0.978	0.986	393.1	< 2.2E–16
	Norway spruce	0.984	0.986	76.8	< 2.2E–16
	silver birch	0.990	0.991	12.1	4.846E–04

$\chi^2$  – chi-squared

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Table 3. Results of approximation of stem biomass models; significant ( $P < 0.05$ ) parameter estimates are printed in bold

Scots pine, Equation (1)					
	variable	parameter	estimate	std. error	<i>P</i> -value
Fixed effects	intercept	$\beta_0$	<b>4.455E+00</b>	1.513E+00	0.004454
	year	$\beta_1$	<b>−2.682E−03</b>	7.533E−04	0.000716
	level	parameter	SD	–	–
Random effects	plot	$b_i$	0.1047	–	–
	residuals	$\varepsilon_{it}$	0.09394	–	–
Norway spruce, Equation (1)					
	variable	parameter	estimate	std. error	<i>P</i> -value
Fixed effects	intercept	$\beta_0$	<b>5.339E+00</b>	2.099E+00	0.0230
	year	$\beta_1$	<b>−3.114E−03</b>	1.054E−03	0.0102
	level	parameter	SD	–	–
Random effects	plot	$b_i$	9.678E−02	–	–
	residuals	$\varepsilon_{it}$	9.746E−02	–	–
Silver birch, Equation (1)					
	variable	parameter	estimate	std. error	<i>P</i> -value
Fixed effects	intercept	$\beta_0$	<b>3.756E+00</b>	1.170E+00	0.0059
	year	$\beta_1$	<b>−2.250E−03</b>	5.839E−04	0.00158
	level	parameter	SD	–	–
Random effects	plot	$b_i$	0.03672	–	–
	residuals	$\varepsilon_{it}$	0.09233	–	–
Scots pine, Equation (2)					
	variable	parameter	estimate	std. error	<i>P</i> -value
Fixed effects	intercept	$\beta_0$	2.078E+00	2.036E+00	0.31085
	$\ln(d)$	$\beta_1$	<b>1.722E+00</b>	1.951E−02	< 2E−16
	$\ln(h)$	$\beta_2$	<b>1.054E+00</b>	2.333E−02	< 2E−16
	year	$\beta_3$	−2.780E−03	1.015E−03	0.00777
	level	parameter	SD	–	–
Random effects	plot	$b_i$	0.1483	–	–
	residuals	$\varepsilon_{it}$	0.1998	–	–
Norway spruce, Equation (2)					
	variable	parameter	estimate	std. error	<i>P</i> -value
Fixed effects	intercept	$\beta_0$	<b>4.958403</b>	2.136007	0.027725
	$\ln(d)$	$\beta_1$	<b>1.638466</b>	0.043908	< 2E−16
	$\ln(h)$	$\beta_2$	<b>1.049691</b>	0.049654	< 2E−16
	year	$\beta_3$	<b>−0.004127</b>	0.001075	0.000639
	level	parameter	SD	–	–
Random effects	plot	$b_i$	1.753E−01	–	–
	residuals	$\varepsilon_{it}$	4.008E−01	–	–



Table 3. To be continued

Silver birch, Equation (2)					
	variable	parameter	estimate	std. error	P-value
Fixed effects	intercept	$\beta_0$	−2.844E−01	1.454E+00	0.8466
	$\ln(d)$	$\beta_1$	<b>1.895E+00</b>	4.299E−02	< 2E−16
	$\ln(h)$	$\beta_2$	<b>8.670E−01</b>	6.325E−02	< 2E−16
	year	$\beta_3$	<b>−1.515E−03</b>	7.291E−04	0.0491
Random effects	level	parameter	SD	—	—
	plot	$b_i$	0.05228	—	—
	residuals	$\varepsilon_{it}$	0.17628	—	—

$b_i$  – random effect of a trial plot;  $\varepsilon_{it}$  – random error

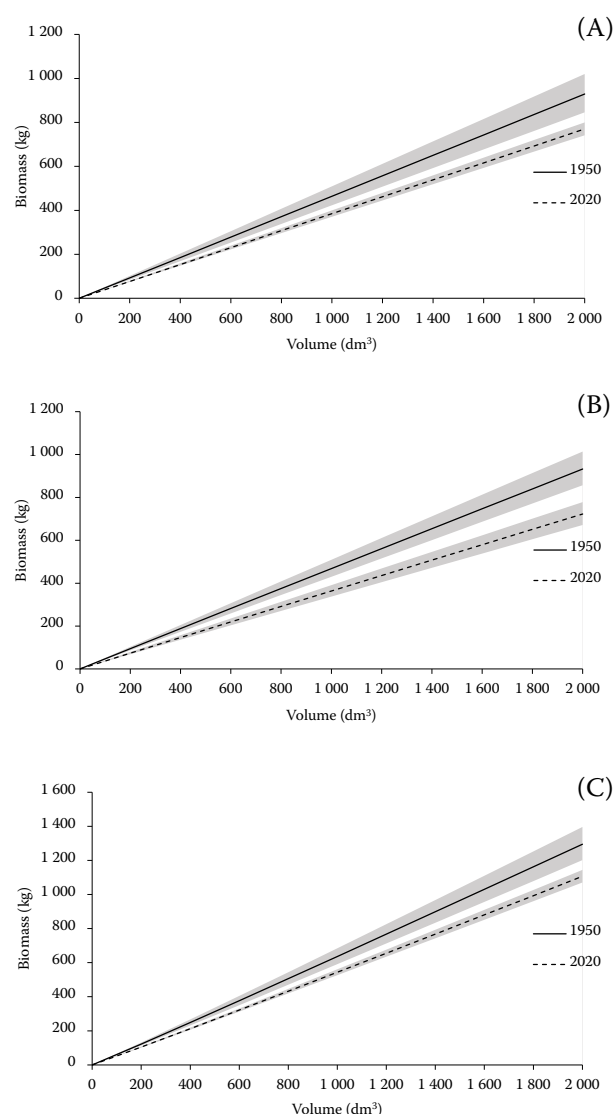


Figure 2. Predicted tree stem biomass values for 1950 and 2020 and 95% confidence interval for (A) Scots pine, (B) Norway spruce, and (C) silver birch

for silver birch (Liepins, Liepins 2017; Viherä-Aarnio, Velling 2017; Jakubowski et al. 2020). According to Equation (1), the average change in the basic density of wood from 1950 to 2020 was from 464 kg·m<sup>−3</sup> to 385 kg·m<sup>−3</sup> for Scots pine, from 468 kg·m<sup>−3</sup> to 363 kg·m<sup>−3</sup> for Norway spruce, and from 636 kg·m<sup>−3</sup> to 543 kg·m<sup>−3</sup> for silver birch. Each geographic area, each forest stand and each tree are individuals, therefore the indicated values demonstrate only the presence of a general trend in reducing the wood density.

## DISCUSSION

**Limitations of data set.** Tree biomass data are spatially uneven across Europe, and the tree sampling altitude ranges from 20 m to 800 m a.s.l. Thus, the sample is unbalanced across individual geographic areas. Also, for Scots pine and silver birch, there is unevenness over the years of biomass measurements: more than 50% of the data were obtained after 2000. Most methods for determining the biomass of trees involve their selection in undisturbed forests. It can be assumed that the proportion of observations in the sample from disturbed forests is insignificant. A desirable property is the balance of data on the calendar year and the geographic areas. Therefore, the results of changes in the biomass of Scots pine tree stems can be considered representative for the regions of Eastern and Northern Europe, Norway spruce for Eastern and Central Europe and silver birch for Eastern Europe. The highest amount of data is available for these regions. But with some assumptions, the results can be interpreted for other regions. We can assume that our data set allows us to determine

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changes in the biomass of tree stems, because there is a significant effect of the calendar year. Using LMM, we eliminate the effect of sample imbalance on the overall trend.

**Reasons for tree stem biomass changes.** Our modelling results show a decrease in the stem biomass of Scots pine, Norway spruce, and silver birch in Europe. A decrease in wood biomass is accompanied, among other things, by a change in its density. The observed declines can mainly be related to the ongoing climate change. During the 20<sup>th</sup> century in Europe, there was an increase in the concentration of carbon dioxide, a decrease in oxygen concentration, an increase in nitrogen deposition, an increase in air temperature and precipitation (Croisé et al. 2005; Churkina et al. 2010; Pretzsch et al. 2014b; Lebedev 2019). There was a redistribution of the annual precipitation according to the seasons of the year (Pretzsch et al. 2014b). It is also noted that the increase in precipitation did not compensate for the increase in the average annual air temperature (Dubenok et al. 2021).

The biomass of trees depends on the intensity of the action of climatic factors. Air temperature and precipitation amount are considered as the main ones in many studies (Li et al. 2006; Weng, Zhou 2006; Khan et al. 2019; Usoltsev et al. 2019, 2021). The response of trees to changes in precipitation and air temperature is not always straightforward. Climate change can contribute to both increases and decreases in biomass. In general, the patterns of biomass change in trans-Eurasian hydrothermal gradients depend on the species (Usoltsev et al. 2020).

There are alternative hypotheses for changes in wood biomass and density. Increased anthropogenic pollution (Conkey 1988; Franceschini et al. 2010) and a decrease in incoming solar radiation as a result of global shading (D'Arrigo et al. 2008) are cited as possible reasons. Another hypothesis is a “foam-like” behaviour of density, which is accompanied by a temporary compromise between growth and density (Bontemps et al. 2013). This hypothesis was confirmed by a seasonal time scale by Bouriaud et al. (2005).

Our modelling results show that with a decrease in biomass, there was a natural decrease in wood density. On the example of central Europe (Pretzsch et al. 2018), using wood samples from the oldest experimental sites, it was shown that the average density has decreased since 1870. This phenomenon is explained by a change in the ratio between

late and early wood, when, as a result of an increase in the growing season and the use of fertilizers, an increase in the proportion of looser and less dense early wood occurred. The decrease in wood density, and hence in its biomass, is moderate, but at the same time it exceeds the positive effect of accelerating tree growth. This poses a problem for forest carbon accounting (Bontemps et al. 2013; Pretzsch et al. 2018).

**Relevance for the management of forest ecosystems.** A decrease in wood biomass and wood density poses many problems for forestry and timber industry. A decrease in the density of wood leads to a decrease in its rigidity and strength. This will negatively impact the production of building materials and furniture (Hoffmeyer, Pedersen 1995; Lachenbruch et al. 2010). According to our data, the mass of cubic meter of wood in 2020 is lower by 80–105 kg compared to 1950. This leads to a decrease in the calorific value and thermal value of wood (Pretzsch et al. 2018). Changes in wood density and biomass should be considered when estimating carbon stocks. Although our estimates of the biomass decline are rough, this fact cannot be overlooked.

## CONCLUSION

Our research shows that the revealed tendency to decrease the biomass of Scots pine, Norway spruce, and silver birch tree stems and the density of their wood is typical of the entire area of Europe. Since decreasing trends in stem biomass have been identified for several tree species, the phenomenon may have a large degree of generality, and would thus be unduly neglected in carbon accounting approaches. Such studies should be continued both at the regional and national level and at the global level. Identifying trends in biomass changes and preventing their consequences should become an important task in the 21<sup>st</sup> century for forestry.

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