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Wood density reduced while wood volume growth accelerated in Central European forests since 1870

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ABSTRACT

Forest stand growth dynamics in Central Europe have accelerated since 1870 due to a rise in temperature, extended growing seasons, and other components of climate change. Based on wood samples from the oldest existing experimental plots in Central Europe, we show that the dominant tree species Norway spruce (*Picea abies* (L.) H.KARST.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.), and sessile oak (*Quercus petraea* (MATTUSCHKA) LIEBL.) exhibit a significant decrease in wood density since more than 100 years. While stand and trees grow faster with respect to wood volume, we can show that wood density decreased by 8–12% since 1900. These results object a naïve direct transformation of volume growth trends into an accelerated biomass production. Since 1900, stand biomass increment increased 9–24 percentage points less compared to volume increment (29–100% increase reduces to 20–76%). For a given stem diameter and annual ring width, tree stability against windthrow, wood strength, energy content and C sequestration are even reduced under recent conditions. The generally decreased late wood density, partly going along with an increased early wood fraction, suggests the observed extension of the growing season and fertilization effect of dry deposition as the main causes.

Our results indicate that current increased wood volume growth rates must not be straightforwardly converted into sequestrated C and biomass harvest potentials assuming historic values for wood density. This should be taken into account in monitoring, modeling, and utilization of carbon and biomass in forests under global change.

1. Introduction

Recent studies provide a growing body of evidence on acceleration of forest growth dynamics in Central Europe and worldwide caused by environmental changes (Bussotti et al., 2014; Fang et al., 2014; Kauppi et al., 2014; Pretzsch et al., 2014a, 2014b; Reyer et al., 2014; Boisvenue and Running, 2006). While drought events may temporarily cut down growth rates (Hartmann, 2011; Pretzsch and Dieler, 2011; Rötzer et al., 2013), the overall level is still unprecedentedly high. Recently, most of the authors of this study authored a paper which clearly substantiated these trends for Norway spruce and European beech in Central Europe, the most important coniferous and broadleaved tree species in that region (Pretzsch et al., 2014b). Based on long term observations of a rather unique set of research plots with first observations dating back as far as the 1870ies, an accelerated forest stand growth in terms of wood volume was shown to be statistically significant. Corresponding scenario analyses with the ecophysiological forest model BALANCE (Grote and Pretzsch, 2002) suggested that mainly the rise in temperature and extended growing seasons contribute to the observed growth acceleration, in particular on fertile sites. The study also gave a rough estimate of the additional C sequestration in Central Europe due to the substantiated growth trends in wood volume. However, this estimate assumed a constant wood density. This assumption must be questioned as climatic factors have shown to be among the most important determinants of wood properties (Zhu et al., 2015; Roderick and Berry, 2001), and as several publications identified links between climate change and wood density (Franceschini et al., 2012, 2010; Bouriaud et al., 2005; Jacoby and D'Arrigo, 1995).

The study at hand strives to clarify if the wood density of important Central European tree species can be legitimately taken as a long-term constant or if it undergoes systemic temporal trends in a similar way as could be shown for wood volume growth. We chose the tree species Norway spruce (*Picea abies* (L.) H.KARST.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.), and sessile oak (*Quercus petraea*

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(MATTUSCHKA) LIEBL.) as they represent roughly ¾ of Central Europe's forest area with Norway spruce and Scots pine accounting for about 25% each, European beech 15% and sessile oak 10%. Besides their ecological importance, these species also dominate the market of domestic timber. Systematic trends in their wood density would not only relate to ecological issues like resistance against wind breakage, biomass accumulation and C sequestration, but also to economic and technical matters like the usability of wood for constructive and energetic purposes.

For this study we took an extensive sample of increment cores from long-term forest research plots which are among the longest observed ones worldwide. For the species Norway spruce and European beech these plots largely overlap with those, where Pretzsch et al. (2014b) showed recently accelerated growth as mentioned above. These cores were used to measure wood density and related properties together with stem diameter growth on an annual basis for more than a century back before the sampling date.

We analyzed our data with respect to the questions, whether a tree ring's (i) mean wood density, (ii) earlywood density, (iii) latewood density, and (iv) early wood fraction depend on the calendar year.

2. Materials and methods

2.1. Long term research plots sampled for this study

We chose altogether 41 long term forest growth and yield trials in Southern Germany for taking the samples required for this study. The plots are maintained and regularly surveyed under responsibility of the first author and his group. Among them are the oldest forest research plots worldwide, e.g. the European beech trial Fabrikschleichach (FAB 15) is under continuous observation since 1870. For Norway spruce and European beech, there is a broad overlap with the trials used by Pretzsch et al. (2014b) for substantiating accelerated stand and tree volume growth. From each trial we selected the plot which was fully stocked and had undergone either no or only minor silvicultural treatment in the past. With this selection procedure we made sure not to include confounding effects on wood density which might come from treatment or especially from treatment changes. The 41 plots which were eventually selected break down to 13 in Norway spruce stands, 11 in Scots pine 9 in sessile oak and 8 in European beech. All stands are monospecific, even aged and were established either by planting or by seeding, their ages at the time of sampling – after the growing season of 2014 – were between 31 and 194 years. The plots cover a range of northern latitudes between 47.852° and 50.375°, and eastern longitudes between 7.750° and 13.308°. Their altitude above sea level are between 320 m and 820 m (Table A.1). The spatial distribution of the plots (Fig. A.1) mirrors typical site and climate conditions for the occurrence of the four investigated species in Central Europe. The Norway spruce plots are mostly in the south and east parts of Southern Germany, while Scots pine plots concentrate in the north east part. Most beech and oak plots are in the north and extreme west part of the region.

The long term mean annual temperature of all plots together is between 5.7 °C and 8.4 °C, the mean annual precipitation ranges between about 500 mm and 1400 mm (Table A.2). The DeMartonne aridity index (calculated as $P/(T+10)$ with P being the mean annual precipitation in mm and T being the mean annual temperature in °C) covers a range of 30 up to almost 90. While this indicates a considerable variation, even the smallest value stands for humid conditions; only index values of 20 and below would mean an arid climate (Blüthgen, 1980).

As can be taken from Table A.2, the pine plots are generally growing under lowest precipitation, highest temperatures and consequently under the least humid conditions when compared with the other species. The opposite is true for Norway spruce, which is associated with pronouncedly more humid climates. A similar, albeit less distinct difference is visible for sessile oak and European beech, where the beech plots generally show more humid conditions than the oak plots.

Following the nomenclature of the German forest site classification system (Arbeitskreis Standortskartierung, 1985), the plots are distributed among 13 ecoregions and 17 sub-ecoregions (Table A.3). Most frequently, the plots are covered with clayey or sandy soils. Hereby, the pine and oak plots tend to be associated with the more sandier sites, whereas the spruce and beech plots cover the more clayey sites. With regard to soil types, the oak and beech plots are dominated by brown soils, the pine plots growing on pseudogleys or podzols, and the spruce plots were most often established on parabrown soils and brown soils.

2.2. Sampling procedure, sample preparation and measurements

All the selected plots are embedded in a buffer zone, where the silvicultural treatment (including omission of treatment) is the same as on the plot itself. In this zone around each plot, we sampled about ten dominant trees following the social tree class definitions by Kraft (cited after Assmann, 1961), see Table A.4 for the precise sample sizes. This social class of trees (class #2 after Kraft) contributes most to wood volume and increment in even-aged stands. From each tree we took a core at breast height (1.3 m) with a standard increment borer (Haglöf Mora Coretax, diameter 5.15 mm), attempting to hit the centre of the stem in order to cover as many growth rings as possible. The stem diameter at breast height (dbh) and total tree height of the standing tree were measured in addition (girth tape, Haglöf Vertex IV height measuring instrument). In order to prepare the cores for the subsequent wood density measurements, they were air-dried and accurately glued, with the vessels pointing in vertical direction, onto wooden slides. After that, they were honed first with a belt sander, then by hand, and sand paper down to a grain size of 1200 in order to achieve a surface as even as possible. Abrasive dust was carefully removed using a compressed air cleaner.

For the wood density measurements we used a LIGNOSTATION™ high frequency densitometer. The measurement method relies on the principle that electromagnetic waves propagate differently in dielectric materials like wood, depending on the material's density. To this end, an extremely small high frequency transmitting and receiving electrode system (Fig. A.9) is moved along the wood sample of interest. The transmitting electrode emits a 10 MHz sinusoidal signal which partly propagates through the wood sample to the receving electrode. The strength of the received signal is positively correlated with the local density of the wood sample (Spiecker et al., 2003). While high frequency densitometry is a simple and fast measuring method, the quality of the sample surface, which has to be absolutely plane, is crucial for achieving usable results (Wassenberg et al., 2014). Therefore, the above-mentioned sample preparation and all other steps were executed with painstaking care.

The measurement procedure yielded a wood density profile for each core with a resolution of 1/100 mm. Growth rings were detected by a combination of an algorithm implemented in the LIGNOSTATION software, which evaluates wood density gradients, with visual assessment. Besides the growth ring widths, we used the density profiles to calculate the mean wood density (MWD) per growth ring, as well as the earlywood density (EWD) and the late wood density (LWD) respectively. According to the LIGNOSTATION standard procedure, the earlywood-latewood border was defined as the point, where the local wood density was 50% of a given growth ring's maximum wood density. Besides the density values above, this allowed us to calculate the earlywood ratio (EWR) which is the width (in growth direction) of a growth ring's earlywood divided by the total ring width. An overview of sample sizes, mean values and the range of the above-mentioned variables is given in Table 1. The species-wise distributions of the backwards calculated diameters at breast height and corresponding growth ring widths are visualized as boxplots in Fig. 1.