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Effects of land management on large trees and carbon stocks

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Abstract

Large trees are important and unique organisms in forests, providing ecosystem services including carbon dioxide removal from the atmosphere and long-term storage. There is concern about reports of global decline of big trees. Based on observations from Finland and the United States we report that trends of big trees during recent decades have been surprisingly variable among regions. In southern Finland, the growing stock volume of trees larger than 30 cm at breast height increased nearly five-fold during the second half of the 20th century, yet more recently ceased to expand. In the United States, large hardwood trees have become increasingly common since the 1950s, while large softwood trees declined until the mid 1990's as a consequence of harvests in the Pacific region, and then rebounded when harvesting there was reduced. We conclude that in the regions studied, the history of land use and forest management governs changes of tree populations especially with reference to large trees. Large trees affect greatly the carbon density of forests and usually have deeper roots and relatively lower mortality than small trees. An accumulating stock of large trees in forests may have negligible direct biophysical effects on climate because from changes in transpiration or forest albedo. Large trees have particular ecological importance and often constitute an unusually large proportion of biomass carbon stocks in a forest. Understanding the changes in big tree distributions in different regions of the world and the demography of tree populations makes a contribution to estimating the past impact and future potential of the role of forests in the global carbon budget.

1 Introduction

Carbon, which is removed from the atmosphere by forest ecosystem processes, is stored both in vegetation and soils (e.g. McGuire et al., 2001). If carbon stocks of ecosystems build up, the carbon content of the atmosphere is reduced. Conversely, if the carbon stocks in ecosystems were to diminish, the rate of increase of carbon diox-

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ide in the atmosphere would be much faster than currently observed (Reich, 2011). The large potential of trees for either removing CO_2 from the atmosphere or adding it was discovered in early research about forests, the carbon cycle, and climate (Dyson, 1976; Brown and Lugo, 1982; Cooper, 1983; Woodwell et al., 1983). More recently, research has highlighted other mechanisms about how forest canopies affect the radiative forcing of the atmosphere by modifying the albedo (Betts, 2000) and evapotranspiration (Swann et al., 2010).

Global forests are extremely diverse and provide a variety of ecosystem services such as carbon sequestration, industrial raw materials, flood and landslide protection, biodiversity preservation, and aesthetic and health benefits (Pan et al., 2013). Forests are usually defined by the presence of trees and absence of non-forest land use, even though trees are also numerous outside forests in savannas, pasture lands, and in suburban areas and green city centers (Nowak and Greenfield, 2012). Large and old trees are exceptional entities in most tree populations and they have unique and special qualities beyond their climate mitigation function, yet there are concerns about human-caused losses of old and large trees of the world (Lindenmayer et al., 2012).

While covering only about one quarter of the global land surface, forests dominate the net removal of CO_2 from the atmosphere into land ecosystems (Pan et al., 2011a). Live vegetation, mostly trees, accounts for three quarters of the large and persistent sink of the global forests. The remaining one quarter is shared by dead wood, litter, soils and harvested wood products (Pan et al., 2011a).

In mix-aged forests, large trees are often a significant proportion of aboveground biomass and the carbon density of the site although only a few may be present (Slik et al., 2013; Luz et al., 2011; Martínez and Alvarez, 1998). Large trees also have statistically lower mortality rates compared to small sized trees (Coomes and Allen, 2007), which affects forest carbon dynamics. Large trees sequester carbon dioxide from the atmosphere into the tree itself, and transmit carbon into soils, in dead wood and in lumber products when removed from the forest. Large trees play a range of key ecological roles in different forest ecosystems and are essential for ecosystem biodiversity and integrity (Lindenmayer et al., 2012). They also provide other additional benefits, such as bringing recreational opportunities and engaging symbolic values in many cultural heritages (Blicharska and Mikusinski, 2013).

The size distribution of large trees and their long-term dynamics can be detected by surveying the demography of tree populations at annual or multi-annual time steps using forest inventory methodology (Lawrence et al., 2010). Observations on trees size distributions based on forest inventory measurements have not been compiled at the global level. However, regional data and time series are available from Finland and the United States, which provide multi-decadal statistics on the demography of tree populations and changes of the size-distribution of trees. The evolution of forest carbon for Finland and the United States has been described more broadly in Liski et al. (2006) and Birdsey et al. (2006), respectively. The longest time series to our knowledge on statistically representative measurements of timber resources is from a sub region in Finland, where the fieldwork was initiated in 1912 (Kauppi et al., 2010). The first national forest inventories from Finland were carried out in the 1920s and 1930s (Ilvessalo, 1927; Ilvessalo, 1942), and the national forest inventory in the United States was begun in the 1930s (LaBau et al., 2007).

We focus on large trees, broadly defined as the upper end of the size distribution of live trees. The objective of this research is to analyze the role of large trees in the evolution of the growing stock in regions within Finland and the United States representing different land management histories using data from statistically designed sample surveys. We discuss the impact of large trees on the carbon budget, albedo and evapotranspiration of forests, and the effect of land management on the stock of large trees.

2 Materials and methods

Forest inventory is based on measurements taken from a statistically representative sample of all trees within a forest region – for details of this approach, see Tomppo

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et al. (2011) and LaBau et al. (2007). Historical inventory data are available at approximately decadal time intervals from Finland (Kuusela, 1972, 1978; Kuusela and Salminen, 1991; Tomppo et al., 2011; Ylitalo, 2011, 2012; Korhonen et al., 2013) and from the United States (Smith et al., 2009). We extracted data from these published inventories specifically by five sub regions (Fig. 1). The two regions of Finland combined equal all Finland, whereas for the United States we selected three diverse regions. We also looked at nation-wide forests of the United States compiling statistics of tree size distributions divided as hardwoods (deciduous trees) and softwoods (conifers).

We prepared time series estimates of the growing-stock volume of large trees and the distribution of growing-stock volume by tree-size classes. Growing stock-volume (in cubic meters, m^3) refers to the volume of the tree stem as defined by common merchantability standards. The historical inventories report estimates of growing-stock volume based on consistent definitions.

The volume of growing stock is correlated with the vegetation carbon stock. The ratio of carbon stock/growing stock decreases with tree size; in other words, the contribution of stem biomass becomes increasingly large as trees grow in size (e.g. Lehtonen et al., 2004; Jalkanen et al., 2005; Kauppi et al., 2006). Tree size distributions were constructed based on Diameter at Breast Height (DBH) to separate cohorts of trees representing different size classes. The total stem volume (in millions of m^3) was estimated for trees within each size cohort and each region. We also included estimates of growing-stock volume of all size classes for both countries to highlight the general trends.

Data from Finland referred to nine inventory cycles as follows: 1951–1953 => 1960–1963 => 1964–1970 => 1971–1976 => 1977–1984 => 1986–1994 => 1996–2003 => 2004–2008 => 2009–2012. Finnish data were analysed separately for two regions (southern Finland – about 11.3 million forest ha; and northern Finland – about 11.5 million forest ha; Fig. 1). Measurement teams travel within and across regions. During some years measurements are taken in southern but not in northern Finland, and vice versa. The main part of rural lands in southern Finland has been in

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private ownership since the middle ages. Forests in southern Finland were severely over harvested in the 19th century – early 20th century. In northern Finland, the lands are largely state owned.

The data from the United States covered the period 1953–2007, and contained five inventory cycles. Forest area of the United States in 2007 was 304 million hectares. Three sub regions within the United States were selected for more detailed analysis covering a total of 91 million ha (Fig. 1; Table 1). Regions represent the diverse history of land management and impacts on large trees: the northeast which is largely composed of forests that are re-growing on agricultural land that was abandoned over the last century; the southeast where much of the forest land is intensively managed on short rotations for timber products; and the Pacific Northwest where old-growth forests were still being cleared and regenerated through the mid-1980s but have since been preserved.

Detailed analyses have been published elsewhere on the conversion from growing stock to biomass and carbon stock. A key concept in this conversion is Biomass Expansion Factor (BEF), which has been empirically determined for many tree species and for many regions of the world. An analysis for Finland is available in (Eerikäinen 2009) and in Härkönen et al. (2011).). The biomass for each tree component is modeled by the main tree species (Repola, 2008, 2009). Thereafter, BEFs were calculated by dividing total tree biomass by stem volume within tree diameter classes (Lehtonen et al., 2004). Typically, for conifers in Finland, one m^3 of stem wood volume including bark corresponds to a whole tree biomass of 0.6 to 0.8 t dry matter. The carbon concentration of dry woody biomass is 45 to 50 % (Lehtonen et al., 2004).

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3 Results

3.1 Results for Finland

The growing stock of Finland's forests accumulated from 1400 million m^3 in 1960–1963 to the latest estimate of about 2300 million m^3 in 2009–2012 (= +60 %). Even though the rate of accumulation was almost the same in southern Finland as in northern Finland, there were interesting differences between the two regions in the development of the tree size distributions. The stock of large trees hardly changed in northern Finland, where the accumulation of biomass and carbon was concentrated in small trees less than 30 cm in DBH. In southern Finland the growing stock of large trees increased nearly five-fold from about 70 to 340 million m^3 between 1951–1953 and 1996–2003, respectively (Table 2). Even though the volume accumulated in southern Finland, the share of trees > 30 cm DBH was still less than one quarter of the growing stock in 2009–2012 (Fig. 2).

The growing stock of Finland's forests consisted predominantly of small and medium sized trees (≤ 30 cm DBH). The stock of such small and medium sized trees increased from about 1230 in the 1960s to 1840 million m^3 in 2009–2012. The relative contribution of large trees to the total growing stock first increased from 10 to 21 % between 1951–1953 and 1996–2003; then declined to 19 % in 2009–2012.

3.2 Results for the United States

Trees in the United States are larger in general than those in Finland. In the United States, trees larger than 33 cm in DBH account for more than half of the growing stock. The growing-stock volume of the largest trees in the United States (DBH > 53 cm) declined from 5.9 to 4.6 billion m^3 between 1953 and 1987 and then recovered to 5.9 billion m^3 by 2007 (Fig. 3). Large softwood trees in old-growth forests were still being harvested until the late 1980's especially in the Pacific Northwest region, after which most harvesting of old-growth was stopped to preserve their remaining areas for con-

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servation goals. In contrast, the volume of the largest hardwood trees, which are more common in the eastern United States, has increased steadily since 1953 on lands that were abandoned from agricultural use and now have forests that are maturing.

In the Pacific Northwest region which is dominated by softwood species and has the largest population of larger trees in the United States, there is a contrasting pattern of change over time in the growing stock of trees greater than 33 cm compared with trees less than 33 cm (Tables 3 and 4). In a pattern similar to the national totals, the growing stock of large trees in the Pacific Northwest declined from 1953 to 1987 and then nearly recovered to their prior stocking by 2007, reaching 3.4 billion m^3. In contrast, the growing stock of trees less than 33 cm increased from 1953 to 1977 and then stabilized at about 1.1 billion m^3. In the Southeast United States, the growing stock of trees greater than 33 cm doubled between 1953 and 2007, while that of trees less than 33 cm increased only until 1977 then was relatively stable. These changes reflect the increasing influence of industrial plantation forestry over the period. In the Northeast United States where hardwoods predominate, the pattern is similar to the southeast except that the growing stock of trees greater than 33 cm more than tripled between 1953 and 2007, indicating forests that are increasing in age coupled with the absence of significant harvesting or stand-replacing natural disturbances.

4 Discussion and conclusions

In the southern Finnish region during the second half of the 20th century, the change in growing stock was mainly driven by the expansion of the large trees cohort. Likewise regarding hardwoods in the United States, the increase in growing stock of trees larger than 33 cm in DBH accounted for most of the density change since 1977. Northern Finland was an exception among the five study regions in the sense that the growing stock of the large tree cohort did not increase during the last six decades.

In the United States there have been regional differences in the role of large trees as well as differences between softwoods and hardwoods. Where hardwoods are pre-

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dominant in the eastern part of the country, there has been a steady and significant increase in biomass of large trees since 1953. Softwood biomass in the southeast has increased mainly in the middle diameter classes; whereas softwood biomass in large trees of the Pacific Northwest declined and then increased since 1987.

Globally, forest vegetation has become increasingly dense (Rautiainen et al., 2011). Forest biomass and the carbon stock have expanded even though the global forest area keeps decreasing (Pan et al., 2011a). Ultimately in the successional process, the biomass of forest ecosystems saturates, if losses in tree mortality match the gains of biomass increment. In central Europe, the forest carbon sink was recently reported to show early signs of saturation, likely because large areas of forests have approached their maturity (Nabuurs et al., 2013). The five study regions of this research in Finland and USA did not show similar signs.

Forest vegetation biomass has increased in many parts of the world, removing carbon dioxide from the atmosphere, and accounting for three quarters of the estimated gross forest sink of about $4\,\mathrm{Pg\,C\,yr^{-1}}$ (Pan et al., 2011a). Trees contain carbon in stems, branches, foliage and roots and provide carbon for the stocks of forest soils, and downstream water and sediments (Richey et al., 2002). Large trees have deep roots, which transfer carbon into the lowest layers of the forest soil. As trees die, the largest individual trees decay most slowly thus maintaining for some time the carbon stocks in snags or coarse woody debris that are standing or laying in forests (Harmon and Hua, 1991; Krankina and Harmon, 1995; Pan et al., 2011a). Trees may be transformed into wood based products, which contain significant amounts of carbon and are widely used as a sustainable raw material (Skog et al., 2004).

The interaction of forests with the climate system is complex. In high latitudes as biomass expands in areas with low forest density, the mitigating impact of carbon sequestration on the radiative forcing of the atmosphere may be offset by the unwanted effects of decreasing albedo and increasing transpiration on radiative forcing (Betts, 2000; Bonan, 2008; Swann et al., 2010). Promoting the expansion of large trees on existing forest areas would selectively favor carbon sequestration with little or no impact on albedo or transpiration. Inside the surface layers of the stem, large trees contain heartwood which is rich in carbon but does not contribute to transpiration nor have an albedo impact.

Forests of the world are diverse and the definition of “big tree” is perhaps only relative. The biggest tree measured by the stem volume is the General Sherman growing in Sequoia National Park, California. It contains about 1500 m^3 of stem wood and thus 300–400 tC (Alaback, 1991; Pan et al., 2013). In the boreal forests of Finland, all trees are smaller than 20 m^3 in stem volume, and a tree with a stem of just two m^3 can be considered “large”. On average, trees in the United States are larger than those in Finland, and exceptionally large in global comparisons are the conifers of Pacific region of the United States (Waring and Franklin, 1979).

Measuring carbon sequestration directly is difficult, and in this research we rely on the relationship between growing-stock volume and tree biomass to estimate the vegetation carbon content (Brown et al., 1989; Lehtonen et al., 2004; Härkönen et al., 2011). Carbon sequestration of forest ecosystems is positively and strongly correlated with the accumulation of biomass into tree stems. As the size distribution of trees shifts to larger diameters and stem volumes, large trees gain relative importance, and the carbon stock of forest vegetation accumulates thus sequestering CO_2 from the atmosphere.

In temperate zones and also in Finland, most natural forests have been greatly altered by human activities (Pan et al., 2013; Fritzbøger and Søndergaard 1995). The current forest demography and tree-size distributions generally reflect such a disturbance legacy (Clawson, 1979; Foster et al., 1998; Pan et al., 2011b). The patterns of land use were driven by a historical switch from subsistence agriculture to modern farming many decades ago. Forest transition subsequently switched the sign of change of forests from sources to sinks of carbon as the timber stock started to increase (Mather, 1992; Rautiainen et al., 2011). The rate of biomass accumulation as a national average in both countries has been 0.5–1.0 per cent per year consistently for many decades.

In Finland, the forest resources have been utilized intensively for centuries. Tar production – a heavy consumer of stem wood – had an important role in the foreign trade of Finland until the 1820s. Shifting cultivation, a primitive form of agriculture, had a highly destructive effect on the forests of southern Finland. It was widely practiced until the late 19th century on fertile forest lands, which have the highest potential for producing large trees. In reporting the results of the first national forest inventory, Ilvessalo (1927) emphasized the detrimental effect of cattle grazing on the forests of southern Finland. In Finland's exports, tar was replaced by saw mill products, which continued to be the single-most important product group until the early 20th century, only to be gradually replaced by products of pulp and paper industries. Forests situated near reasonable transport routes were heavily exploited. Cutting methods were based on removing the largest and most valuable trees and the remaining tree populations were usually incapable of fully utilizing the growth potential of the site (Fritzbøger and Søndergaard 1995).

The United States saw a general progression of harvesting large trees from the east to the west over the last 150 yr. Beginning 100 yr or so ago, eastern forests began regrowing on abandoned agricultural land and now these forests have reached an age where large trees are becoming common once again (Pan et al., 2011b). In the far western US, large trees were still being harvested in significant quantities until about 25 yr ago so their numbers were declining, but now that trend has been reversed with most remaining old-growth forest areas set aside for other purposes besides timber production.

Southern Finland and the hardwood region in eastern United States are similar in their forest history with severe forest degradation especially in the 19th century followed by the recovery in more recent decades. Hence the expansion of large tree biomass in these two regions during the latter part of the 20th century indicates a recovery from man-made degradation and disturbances of the past.

Forest carbon density can increase in two alternative or mutually reinforcing ways: (1) as trees in forests become more numerous; or (2) as the average tree of the forest becomes larger over time. New research is needed here, since this analysis cannot fully separate the relative contribution of the two mechanisms. Understanding the dynamics of tree populations is important for efforts not only to predict the impact on forest carbon balance, but also for evaluating forest structure and function related to other ecosystem services. For instance, in Pacific Northwest, some at-risk plant and animal species need different habitats that are associated with old forests or more opened forests (Buchanan et al., 2010). Large trees often play key ecological roles, such as characterizing forest growth form and structural complexity, and they are essential for ecosystem stability and biodiversity (Lindenmayer et al., 2012). Because of unique ecological roles and ecosystem services that large and old trees provide, the reported global decline of such trees has drawn many concerns about how to balance the need of conservation and forest management (Aerts, 2013; Lindenmayer et al., 2013).

We have shown in this research that an expansion of the stem biomass of large trees, as measured in m^3 of the growing stock volume, has been an important driver of biomass expansion in some areas over certain periods of time. However, the dynamics of the population of small trees has had a decisive role in other cases. Biomass has accumulated in all five regions virtually uninterrupted for 60 yr and none of the regions are showing signs of biomass and carbon saturation. We conclude that forest management and conservation has made a significant impact on the increasing populations of large trees and their relative contributions to carbon stocks recently observed in Finland and the United States.

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Table 1. Statistics and forest management history of the sub regions addressed in this research. Forest area estimates for Finland include poorly productive land called scrub land (Smith et al., 2009, Ylitalo, 2012).

Region	Forest area (1000 ha)	Stem volume (million m^3)	Biomass (Tg C; aboveground)	Forest management history
US Northeast	34 316	3896	2041	Most forestland cleared for agriculture by 1850; current forests regrowing after agriculture abandonment.
US Southeast	35 567	3589	1873	Most forestland cleared for agriculture by 1850; current forests regrowing or re-planted after agriculture abandonment.
US Northwest	21 225	4499	1561	Most forestland harvested for wood products during the 20th century; harvesting of old-growth suspended in the 1980s.
Finland North	11 318	786	227	Forest land largely state owned. Forest and land management intensified since 1950.
Finland South	11 459	1546	418	Most forests privately owned and recovering from severe degradation of the 19th and early 20th century.

Table 2. Growing stock of trees with Diameter at Breast Height (DBH) larger than 30 cm in southern and northern Finland.

Inventory period	**Southern Finland*** Trees > DBH 30 cm (Growing stock, million m^3)	**Northern Finland*** Trees > DBH 30 cm (Growing stock, million m^3)
1951–1953	69	82
1960–1963	96	77
1964–1970	139	82
1971–1976	190	83
1977–1984	234	83
1986–1994	304	92
1996–2003	338	91
2004–2008	320	88
2009–2012	337	92

* Regions: see Fig. 1.

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Table 3. Growing-stock volume of trees with Diameter at Breast Height (DBH) greater than 33 cm by region, United States, million m^3.

Inventory date	Northeast	Southeast	Pacific Northwest
1953	582	856	3652
1977	828	1263	3035
1987	1147	1476	2963
1997	1443	1603	3188
2007	1834	1752	3431

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Table 4. Growing-stock volume of trees with Diameter at Breast Height (DBH) less than 33 cm by region, United States, million m^3.

Inventory date	Northeast	Southeast	Pacific Northwest
1953	1209	1327	784
1977	1955	1900	1016
1987	2028	1944	1106
1997	1988	1880	1032
2007	2062	1837	1068

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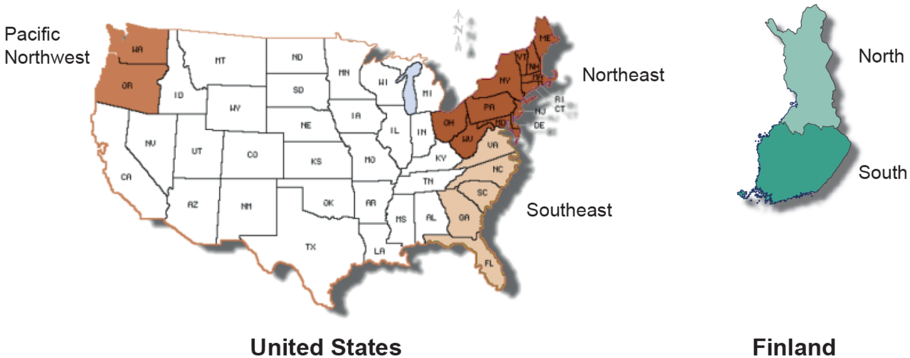

Fig. 1. The location of study regions in the United States and Finland.

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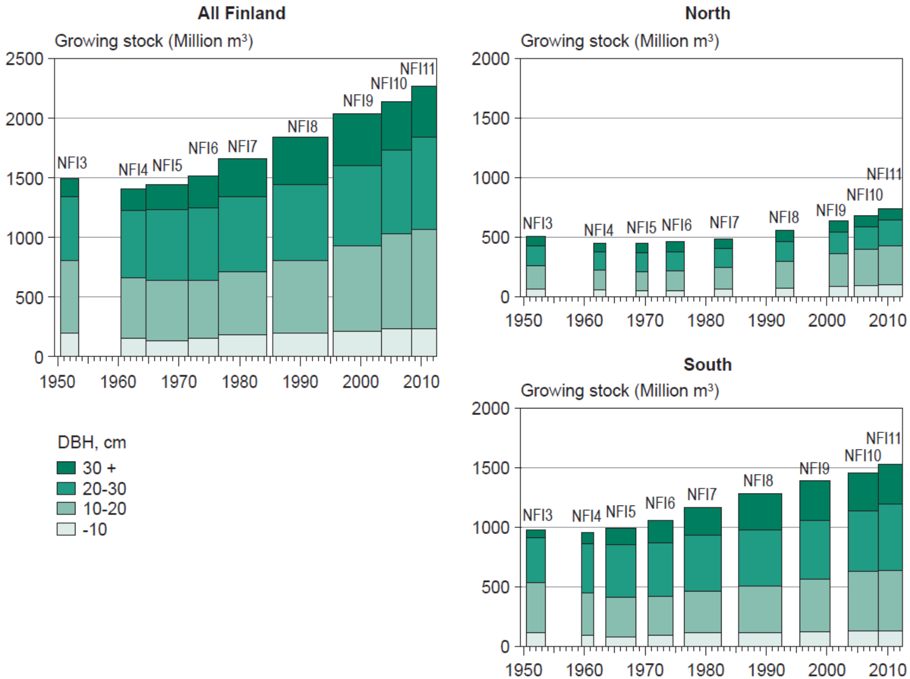

Fig. 2. The distribution of growing stock (during 1951 to 2012, in million m^3) by the size classes (Diameter at Breast Height, DBH). In Finland (left), and specifically for north (upper right) and south (lower right) region. The height of bars indicates growing-stock volume and their width indicates years of field measurement.

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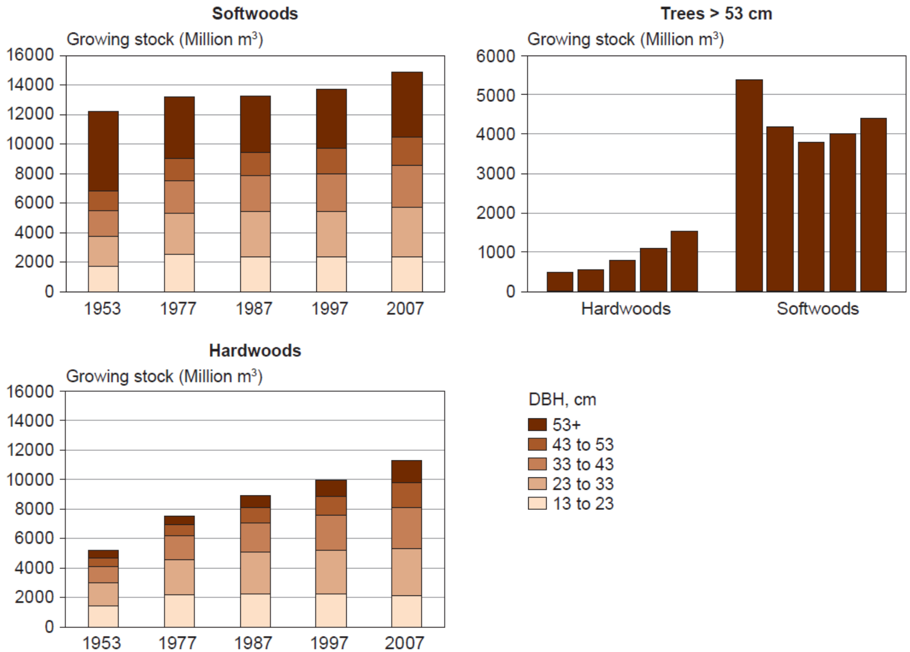

Fig. 3. Volume of growing stock (million m^3) by diameter class (cm) and year, United States. Data from Smith et al. (2009).

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