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Changes in forest production, biomass and carbon: Results from the 2015 UN FAO Global Forest Resource Assessment ☆

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ABSTRACT

Forests are important sources of livelihoods to millions of people and contribute to national economic development of many countries. In addition, they are vital sources and sinks of carbon and contribute to the rate of climate change. The UN Food and Agriculture Organization has been collecting and presenting data on global forest resources and forest cover since 1948. This paper builds on data from FAO's 2015 Global Forest Resource Assessment (FRA) and presents information on growing stock, biomass, carbon stock, wood removals, and changes of forest area primarily designated for production and multiple use of the world's forests.

Between 1990 and 2015, the total growing stock volume has increased in East Asia, Caribbean, Western and Central Asia, North America, Europe (including the Russian Federation), and Oceania with the highest relative increase in East Asia and the Caribbean. In all other subregions the total growing stock volume decreased. North and Central America, Europe and Asia report forest C stock increases while South America and Africa report strong decreases and Oceania reports stable forest C stocks. The annual rate of decrease of forest C stock weakened between 1990 and 2015.

The total volume of annual wood removals including woodfuel removals increased between 1990 and 2011, but shows a remarkable decline during the 2008–2009 economic crisis.

Forest areas designated for production purposes differ considerably between subregions. The percentage of production area out of total forest area ranges between 16 percent in South America and 53 percent in Europe. Globally about one quarter of the forest area is designated to multiple use forestry.

The balance between biomass growth and removals shows considerable sub-regional differences and related implications for the sustainable use of forests.

1. Introduction

Forests are important sources of livelihoods to millions of people and contribute to national economic development of many countries. In addition, they are vital sources and sinks of carbon (C) and contribute to the rate of climate change.

Forest ecosystems cover roughly one third of the global land area and are among the most biologically rich and genetically diverse ecosystems on earth. They contribute to soil formation and water regulation and are estimated to provide direct employment to at least 10 million people, apart from being a source of livelihoods to millions more (FAO, 2010). It is estimated that about 410 million people are highly dependent on forests for subsistence and income, and 1.6 billion people depend on forest goods and services for some part of their livelihoods (Munang et al., 2011). Wood and manufactured forest products add more than $450 billion to the world market economy annually, and the annual value of

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internationally traded forest products is between $150 billion and $200 billion.

Since 1948, the FAO has been conducting the Global Forest Resources Assessments (FRA) which are now produced every five years. It aims to provide a consistent approach to describing the world's forests and how they are changing. FRA has become a major source of information on global forests for policy making and for the development of international programs and initiatives. In this paper we report on the results of FRA 2015 on the state and trends of forest production, biomass and carbon. Specifically, we analyze the latest trend in growing stock, biomass, carbon, wood removals, production and multiple use forest area changes.

2. Methods

FRA 2015 provides reports on 234 countries and territories, of which 155 come from country reports prepared by national correspondents nominated by government agencies responsible for forestry. The remainder comes from desk studies, which since FRA 2000 have been used to provide estimated values for forest statistics in countries which have not provided a country report. While the number of desk studies is high, in total they represent only 0.5% of global forest area. Data for this study were kindly made available by FAO.

FRA 2015 utilizes a questionnaire approach to collect forest related national statistics. The data collection process for FRA 2015 was undertaken collaboratively with Forest Europe, Montréal Process, International Tropical Timber Organization and l' Observatoire des Forêts d'Afrique Centrale using a Collaborative Forest Resources Questionnaire (CFRQ) and the data were reported in the Forest Resources Information Management System (FRIMS) hosted by FAO in Rome. This information collection process is not a sample based survey and thus does not permit the application of probability based procedures for estimating sampling errors and confidence intervals. Data submission is not mandatory and the individual countries are responsible for reporting comprehensive, up-to date, reliable and representative data. For further details on the collection and validation of national data for FRA 2015 see MacDicken (2015).

2.1. Growing stock

184 out of 234 countries and territories reported the growing stock volume estimates for the reference year 2015. These countries and territories represent 93.5% of the global forest area. For some countries, growing stock data were reported for 2015, but missing for some of the other reporting years. We made the following estimations to get global and sub-regional estimates for growing stock in 2015. First, in order to have complete time series for countries that had reported growing stock for at least one year, estimates were made by multiplying forest area for the missing years by growing stock density ($m^3\,ha^{-1}$) for the closest year reported. Sub-regional growing stock densities were then calculated. Secondly, estimates were made for countries that did not report any value by multiplying the sub-regional mean growing stock density by forest area for the country and reporting year in question. The estimated data for these latter countries were not considered in our trend analyses.

2.2. Biomass and carbon

Most Country Reports included reporting on carbon (C) stocks, but not all included complete reporting. A total of 173 countries representing 98% of the global forest area reported biomass C stocks (Fig. 1). Of these, 167 countries representing 84% of the global forest area reported a complete time series (including 1990, 2000, 2005, 2010 and 2015). As expected, there were significantly more missing values for dead wood, litter and soil C stocks.

We made estimates for missing values in order to evaluate sub-regional and global totals. Missing values were categorized in two main classes: (1) at least one value was reported but time series is incomplete, and (2) no value was reported for any year. In order to have complete time series for countries that had reported C stock for at least one year, estimates were made by multiplying forest area for the missing years by C stock density ($Mg\,C\,ha^{-1}$) for the closest year reported. Sub-regional mean C stock densities were then calculated. In order to make estimates for countries that did not report any value, the sub-regional C stock density was multiplied by forest area for the corresponding missing year. No country in East Asia reported on C in litter, so the sub-regional average of South and Southeast Asia was used instead. No country in Central America reported on C in soil, so sub-regional average from Caribbean was used instead. Most countries reported soil C to the specified common soil depth of 30 cm. A few countries used other soil depths, but this was not adjusted for because it does not affect the trend over time as the same soil depth was used for all reporting years.

2.3. Wood removals

Wood removals have been reported in the FRA since 2000. Before 2000, FRA utilized the attribute "Production", which is more or less synonymous to removals. Wood removals refer to the total volume that is actually removed from forests and does not include the volume of cut trees, logs and logging residuals left in the forest. Thus, the volume classified as wood removals is generally smaller than the volume of fellings. However, in rare situations the volume of removals can exceed the volume of fellings, such as when harvesting operations are utilized to remove timber from fellings in earlier periods or trees killed or damaged by natural causes. Wood removed from the forests is either used for energy production or as raw material for the production of goods. The term "woodfuel removals" is used for the wood removed for energy production purposes, regardless whether for industrial, commercial or domestic use, the term "industrial roundwood removals " describes the wood removed (volume of roundwood over bark) for production of goods and services other than energy production (wood fuel) (FAO, 2010).

For the period from 1990 to 2011 countries were provided annual data on wood removals from FAOSTAT and were asked to check and correct whenever necessary. A total of 171 countries provided information for 1990. The number of countries that reported information on wood removals consistently increased over time, with 196 countries provided information for 2011. The global forest area covered by the reporting increase from 92 percent in 1990 to 98 percent in 2011. Adjustments for missing data were not applied because wood removals are driven by human interventions that cannot be approximated using simple imputations.

2.4. Production and multiple use forest area changes

The FRA reporting categories differentiate between

- production forest, which is the forest area designated primarily for production of wood, fiber, bioenergy and/or non-wood forest products and
- multiple use forest, which is the forest area designated for more than one purpose and where none of these alone is considered as the predominant designated function.

The multiple use concept applied in FRA does not imply that multiple use forests take into account all of forest functions

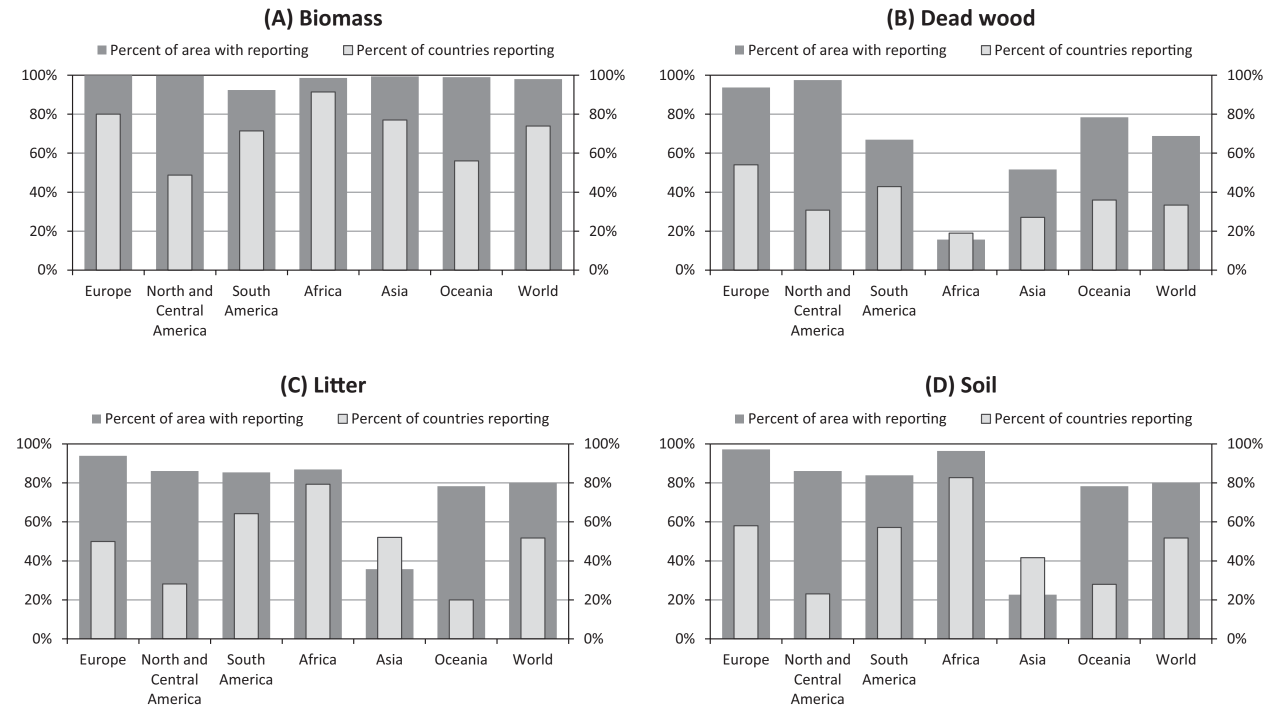

Fig. 1. National reporting on forest C stocks in FRA 2015 Country Reports.

simultaneously. But these forests are managed to serve more than a single primary designated function.

The "primary designated function" refers to the primary function or management objective assigned to a management unit either by legal prescription, documented decision of the landowner/manager, or evidence provided by documented studies of forest management practices and customary use. No adjustments were made for non-responses.

2.5. Categories

Results are presented for three different stratification categories:

(1). Domains (Boreal, Temperate, Subtropics, Tropics)
(2). Subregions (Caribbean, North America, Central America, South America, Northern Africa, Western and Central Africa, Eastern and Southern Africa, Europe, Western and Central Asia, East Asia, South and Southeast Asia, Oceania)
(3). Income groups (see Table 1).

For further details see MacDicken (2015).

3. Results

3.1. Growing stock and biomass

The total global growing stock estimate is 530.5 billion m^3 for 2015. This is 3.6 billion m^3 (0.7%) more than the total growing stock in 1990. Between years 1990 and 2000 the global growing stock volume was slightly decreasing, thereafter slightly increasing. Between 1990 and 2015, the total growing stock volume has increased in 6 out of the 12 subregions: East Asia, Caribbean, Western and Central Asia, North America, Europe, and Oceania (Fig. 2). In relative terms, highest increase took place in East Asia and the Caribbean, over 40% in both subregions. The increase of growing stock volume in the Caribbean subregion is explained by the increase of forest area by almost 50% between the years 1990 and 2015. In East Asia, both forest area and mean stocking per hectare increased. In absolute terms, the increase was highest in North America (7.1 billion m^3) and Europe (10.9 billion m^3). In both of these sub-regions, the increase of growing stock volume is explained by increased mean stocking per hectare (Table 2).

Between 1990 and 2015, the growing stock volume decreased in 6 sub-regions: Central America, Eastern and Southern Africa, South and Southeast Asia, Northern Africa, Western and Central Africa, and South America. In relative terms, the highest decrease took place in Central America (16.1%) and Eastern and Southern Africa (12.6%). In absolute terms, the largest decrease took place in South America (10,843 million m^3).

The average forest growing stock per hectare in 2015 varies by sub-regions from less than 60 $m^3\,ha^{-1}$ in Eastern and Southern Africa and North Africa to more than 200 $m^3\,ha^{-1}$ in Oceania (Table 2). Between 1990 and 2015 the average growing stock increased in most of the sub-regions and clearly decreased only in South and Southeast Asia. Very slight decrease is observed also in the Caribbean sub-region and North Africa. In most of those sub-regions where total growing stock volume decreased, the decrease has been primarily caused by loss in the forest area, not by degradation or shifts from older to younger age class distributions caused by natural disturbance or harvesting (Fig. 3). Two sub-regions, South & South-East Asia and North-Africa show decrease both in mean stocking and forest area. In North-Africa both these changes are nominal, whereas in South & South-East Asia both the decrease in forest area and decrease in mean stocking are remarkable leading a clear decrease in total growing stock (Fig. 2). In 4 sub-regions, Central America, South America,

Table 1
Income groups as defined by the World Bank (Source: http://data.worldbank.org/about/country-and-lending-groups).

Income group	Index	GNI per Capita
Low income economies	L	⩽US$ 1.045
Lower middle income economies	LM	US$ 1.046 to US$ 4.125
Upper middle income economies	UM	US$ 4.126 to 12.745
High income economies	H	⩾US$ 12.746

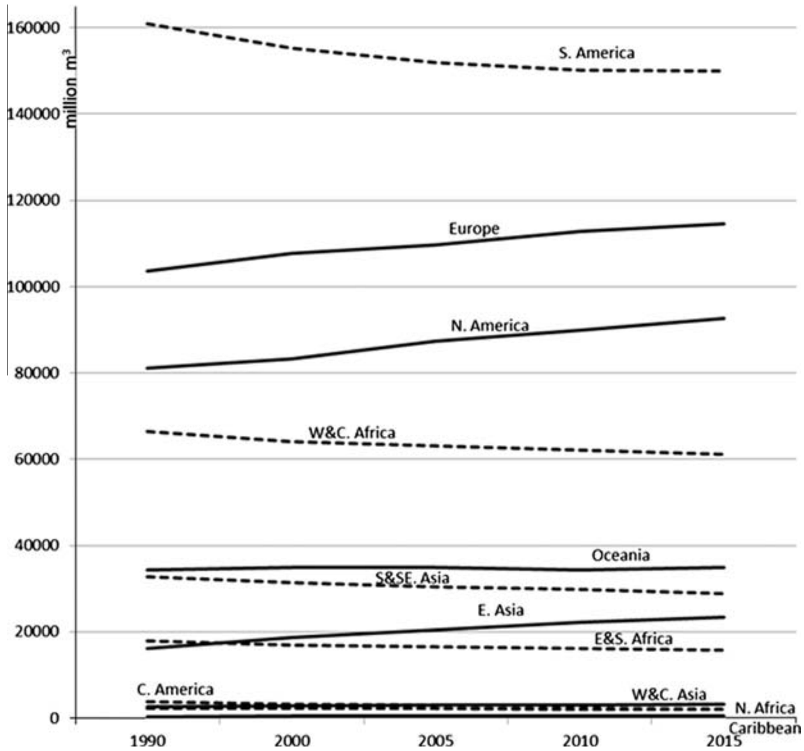

Fig. 2. Volume of growing stock (million m^3) 1990–2015 by sub-regions.

Table 2
Mean volume (m^3/ha) of growing stock in forest from 1990 to 2015 by sub-regions. Only countries that have reported both forest area and growing stock volume included for each reporting year.

Subregion	Year				
	1990	2000	2005	2010	2015
Caribbean	78.8	86.7	89.3	78.1	78.0
Central America	141.7	140.6	140.5	139.9	158.5
East Asia	76.8	82.4	84.2	88.5	90.8
Eastern and Southern Africa	56.2	56.1	56.5	56.8	57.2
Europe	104.3	107.4	109.2	111.2	112.9
North America	112.6	115.7	121.4	124.4	128.1
Northern Africa	59.2	61.7	58.2	58.0	58.3
Oceania	194.2	196.4	197.9	200.0	201.7
South America	172.8	174.4	175.0	176.1	178.2
South and Southeast Asia	102.8	105.1	102.9	100.9	98.5
Western and Central Africa	191.5	193.0	193.8	194.7	195.5
Western and Central Asia	68.6	70.6	70.0	71.8	73.7

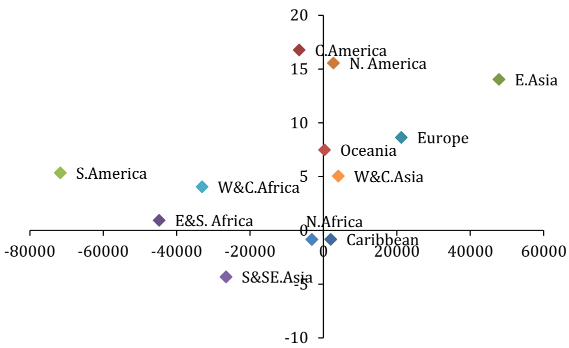

Fig. 3. Change in mean volume (y-axis, m^3/ha) vs. change in forest area (x-axis, 1000 hectares) from 1990 to 2015 by sub-regions.

Western & Central Africa and Eastern & Southern Africa the forest area change is negative but mean stocking positive. In all these sub-regions, the increase in mean stocking is too low to fully compensate the decrease in forest area, leading to decrease in total growing stock. The positive trend in mean stocking may be caused by plantations in these sub-regions. In 5 sub-regions, North America, East Asia, Europe, Oceania, Western & Central Asia both the forest area and mean stocking trends are positive. Naturally, the total growing stock has increased in these sub-regions. Caribbean is the only sub-region where the mean stocking has decreased and forest area increased. The changes in mean stocking is nominal and therefore the total growing stock has slightly increased in the Caribbean sub-region (Fig. 2).

3.2. Carbon

Forest C stocks declined by 13.6 Pg C between 1990 and 2015 (Fig. 4). Most of this decline occurred in living biomass. The global trend in dead wood & litter C stocks was driven by increases in Europe and North America, where these stocks are the largest (Fig. 5) and where natural disturbances transfer large quantities of C from living to dead pools (e.g. Kurz et al., 2008). The global trend in soil C stocks is one of weakening decline (the short-lived gain during 2000–2005 is likely an artifact of the approach we used to fill in missing data; few countries reported soil C stock trends and most of these used Tier 1 (least reliable) methods). North and Central America, Europe and Asia report total forest C stock increases while South America and Africa report strong decreases and Oceania reports stable forest C stocks. The rate of forest C stock decline decreased from 0.84 Pg C year^{-1} during 1990–2000 to 0.34 Pg C year^{-1} during 2010–2015.

Forest C stock densities vary sub-regionally, with the highest reported densities in Western and Central Africa, and the lowest densities in Western and Central Asia (Fig. 5). The highest biomass C densities were reported in tropical sub-regions, chiefly South

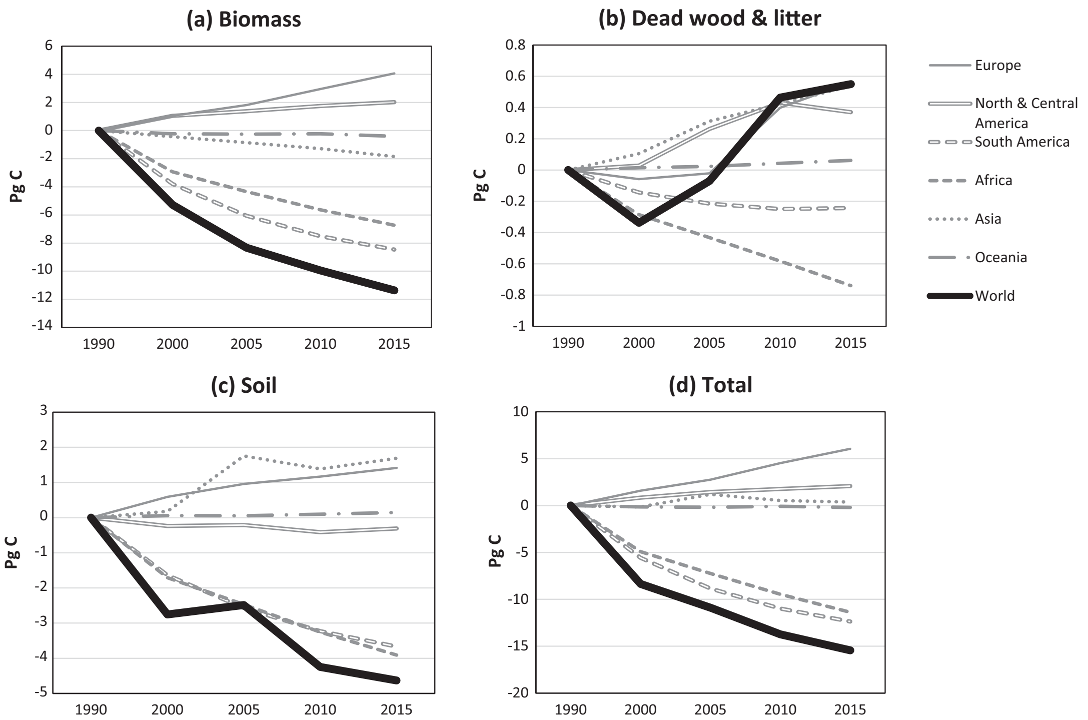

Fig. 4. Forest carbon stock changes since 1990 (1 Pg = 10^{15} g = 1 billion tons).

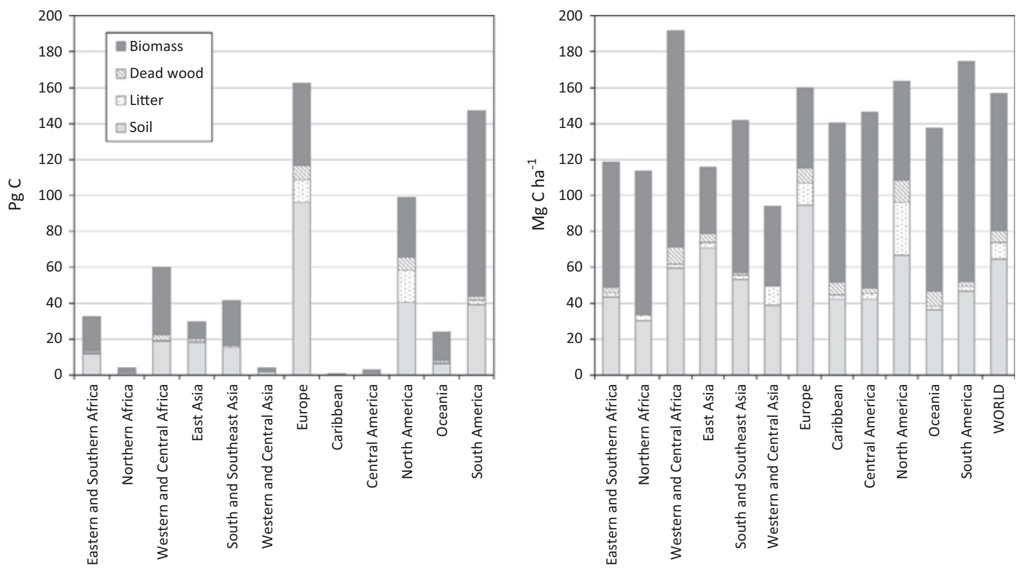

Fig. 5. Forest C stocks and C stock densities in global forest sub-regions, 2015.

America (122.4 Mg C ha^{-1}) and Western and Central Africa (120.6 Mg C ha^{-1}). The highest dead wood and litter C densities were reported in North America (12.1 and 29.5 Mg C ha^{-1}, respectively). The highest soil C densities were reported in Europe (94.6 Mg C ha^{-1}), a sub-region that is dominated by the extremely large forest area in the Russian Federation, making Europe the sub-region most dominated by forests of the boreal biome. Forest C stocks are largest in Europe, South America and North America because these sub-regions host the largest forest areas (26%, 22% and 16% of the world's forest area, respectively).

3.3. Wood removals

The total volume of annual wood removals increased from 2.75 billion m^3 to around 3.0 billion m^3 from 1990 to 2011 as reported. Fig. 6 presents the development of wood removals for (a) countries that reported for all points in time and (b) the data provided for a specific point in time, which includes countries that missed reporting for one or more reporting periods. The similarity in the shape of both curves and their pronounced difference in 1993 suggest that non-response was mainly a problem in the time

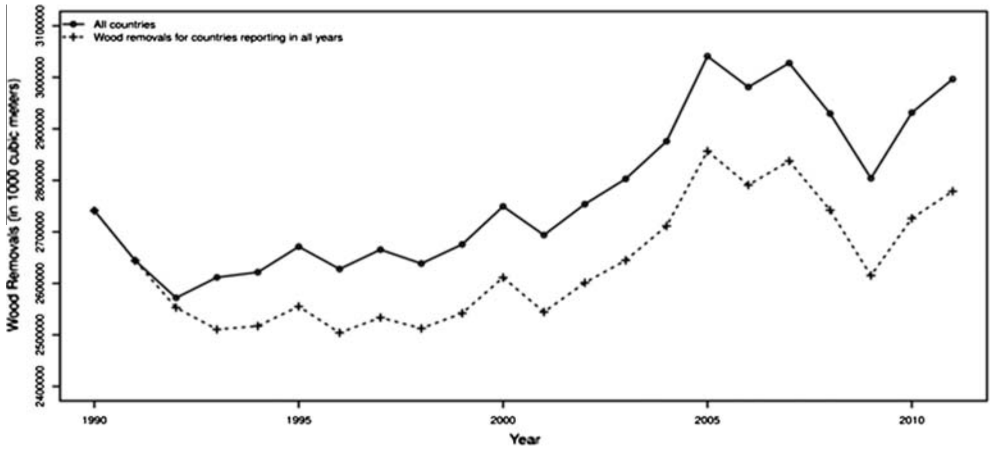

Fig. 6. Wood removals between 1990 and 2011.

period from 1990 to 1992. The development of annual wood removals over time was not continuous. Between 1990 and 1993 the total volume of timber declined, followed by a constant increase until 2005. In 2008 and 2009 a reduction was recorded, coincident with the global economic crisis. In 2010 and 2011 the total volume of wood removals recovered to the levels reported for the period 2005 to 2007 for both the countries that reported in every year and for all countries that reported (Fig. 6).

Woodfuel removals show a different development but it should be noted that woodfuel statistics maintained by FAO is largely based on estimation methods (Whiteman et al., 2002). For 80% of the reported volume the woodfuel removals were estimated for the year 2011 compared with 84% for the year 2000, over time data is improving and share of estimates decrease for historical data as national data becomes available. They increased almost continuously between 1990 and 2011, starting at 1134 million m^3 in 1990 and reaching 1343 million m^3 in 2011 (Fig. 7).

Wood removals are highest in the Tropics and lowest in the Subtropics. The global decline in 2008 and 2009 (Fig. 6) can only be observed in the Boreal and Temperate domains (Fig. 8). While the total volume of wood removals shows a notable increase in the Tropics, it remains constant in the Subtropics. In the Boreal domain a clear decline between 1990 and 1996 is followed by a recovery until 2005. The wood removals in the temperate domain fluctuated between 1990 and 2007 before the economic crisis of 2008.

With reference to domains, the total volume of woodfuel removals shows the same ranking as wood removals: they are highest in the Tropics, followed by the Temperate, Boreal and Subtropics domain. A relatively continuous growth is observed in the Tropics, while moderate changes are found for the other domains (Fig. 8).

Fig. 9 gives a more detailed picture. Wood removals were highest in North America, Western and Central Asia and South and Southeast Asia and lowest in the Caribbean, Central America, Western and Central Africa, East Asia, and Oceania. Compared with the figures on forest areas mainly designated for production, as presented in Fig. 11, reveals substantial differences in area related utilization rates in the sub-regions. Europe takes an intermediate position in the total volume of wood removals, but reported the largest amount of areas primarily designated for production. In contrast, North America realizes most wood production in multiple use forests (Fig. 13). In Western and Central Asia the level of wood removals is high while only a relatively small forest area is primarily designated for production forest or multiple use. For most subregions wood removals increased over time. South America shows a decline between 1997 and 2000. In Europe a pronounced decline between 1995 and 1996 is followed by a recovery until 2007. Both subregions, North America and Europe show a downturn in 2007 and 2008, coincident with the economic crisis, while other sub-regions did not indicate any reduction.

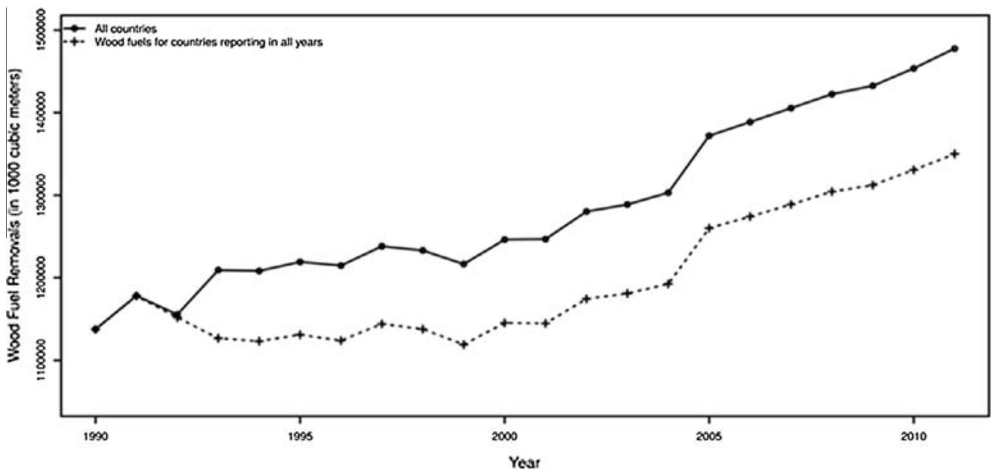

Fig. 7. Woodfuel removals between 1990 and 2011.

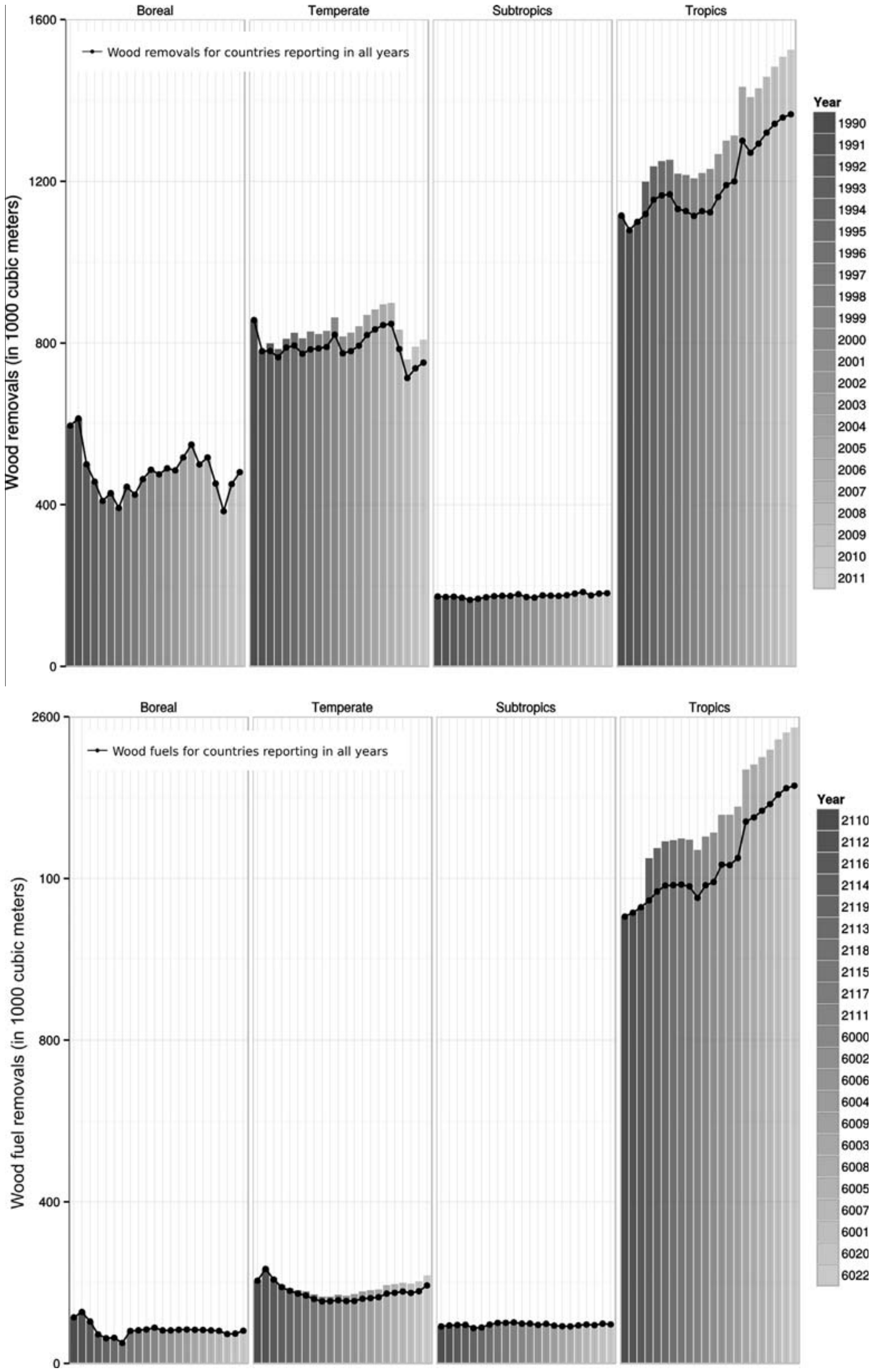

Fig. 8. Wood removals (above) and Woodfuel removals (below) by domains 1990–2011.

Woodfuel removals are highest in South and Southeast Asia. Western and Central Africa, Eastern and Southern Africa, South America, and Europe take a central position, in all other subregions woodfuel removals are low. In Eastern and Southern Africa, Europe, and South and Southeast Asia woodfuel removals are consistently increasing, with the largest increase in South and Southeast Asia. At least in Europe the increase is likely driven by the increasing demand for renewable energies. The EU Renewable Energy Directive (EU, 2009) requires the EU to fulfill at least 20% of its total energy needs with renewables by 2020, which should be achieved

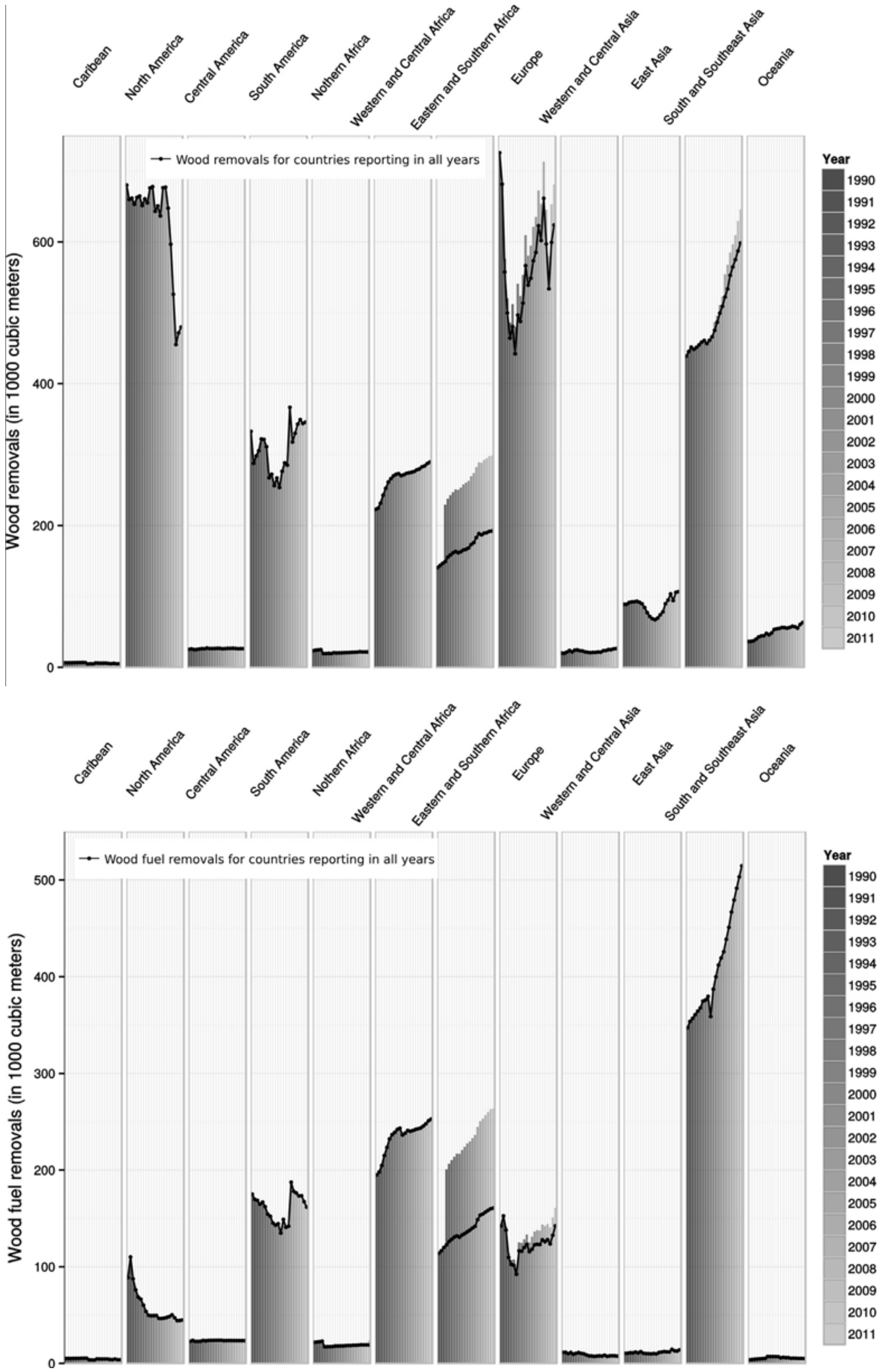

Fig. 9. Wood removals (above) and Woodfuel removals (below) by sub-region 1990–2011.

through the attainment of individual national targets. All EU countries must also ensure that at least 10% of their transport fuels come from renewable sources by 2020.

A comparison of wood removals with income groups shows a mixed pattern (Fig. 10). The level of wood removals increased with income groups except for the upper middle income group, where wood removals are slightly higher than for the low income group. In the low and lower middle income group wood removals increased over time, while in the upper middle and high income groups substantial fluctuations can be observed. In the high income group a depression during the first seven years of the reporting period is followed by an increase and a relatively steady

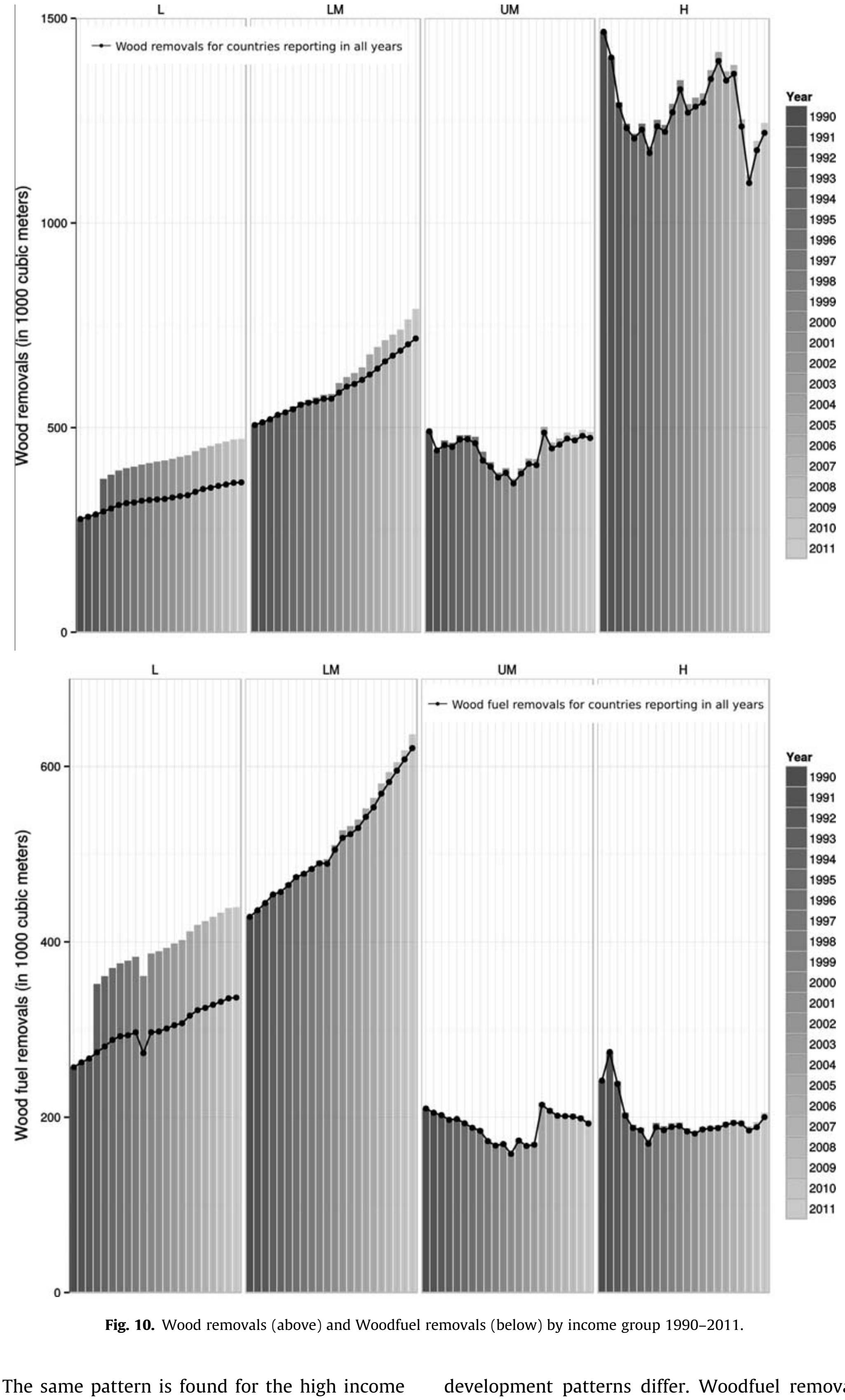

Fig. 10. Wood removals (above) and Woodfuel removals (below) by income group 1990–2011.

state since 2005. The same pattern is found for the high income group, except for the decline in 2007 and 2008.

Woodfuel removals are highest in the low middle income group, followed by the low income group. In both groups wood removals are increasing over time. The level of woodfuel removals is comparable in upper middle and high income group, but the development patterns differ. Woodfuel removals decrease from 1990 to 2001 in the upper middle income group followed by a pronounced increase between 2004 and 2005 and a slight decrease from 2005 to 2011. A downturn between 1991 and 1996 can be observed in the upper income group with a subsequent small fluctuation after 1998. In some countries, wood removals from trees

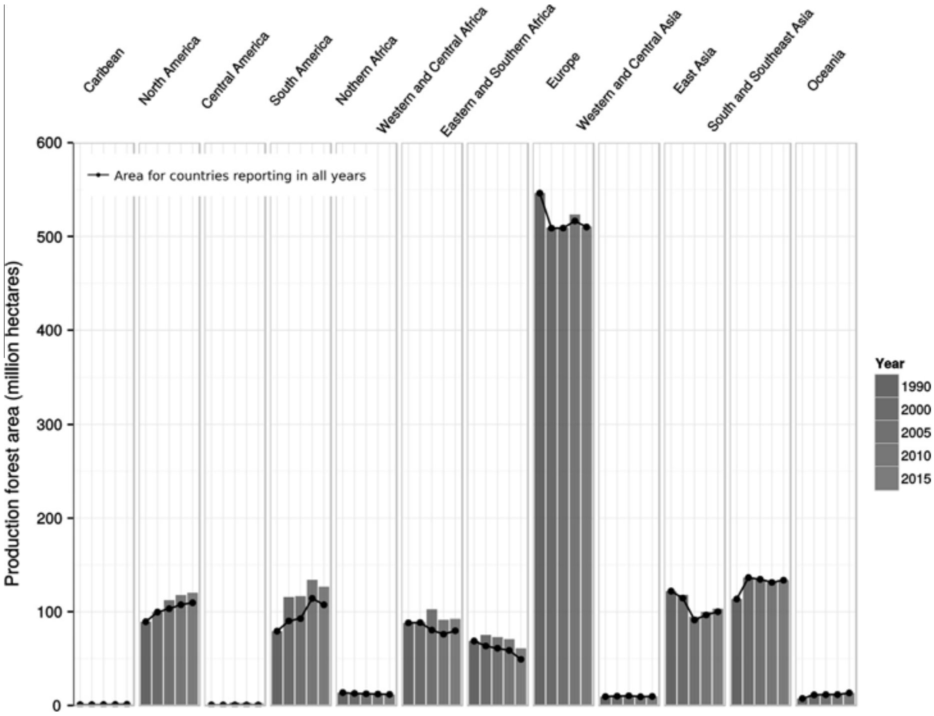

Fig. 11. Area of production forests by sub-region.

outside of forests (i.e. other lands with tree cover) may be considerable, but here we make no distinctions between woodfuel removals from forests versus harvesting trees outside of forests.

3.4. Production and multiple use forest area changes

In 2015, 190 countries representing 97 percent of the global forest area reported on production forest area. The number of countries reporting on multiple use forest area is smaller (183 countries or 95 percent of the global forest area). There are marked differences between sub-regions in the designation of forest areas for production purposes (Fig. 11). In Europe more than 500 million hectares or 52 percent of forests are designated primarily for production, a number that is significantly larger than in other sub-regions. In the Caribbean, Central American, Northern African, Western and Central Asian and Oceania sub-regions the area of production forests is smaller than 20 million hectares. In the remaining sub-regions the respective areas range between 60 million and 120 million hectares. In Western and Central Africa 30 percent of the total forest area are designated as production forest and in Eastern and Southern Africa 22.3 percent, in North America 16.7 percent, in South America 16.2, in Western and Central Asia 23.3, in East Asia 44.5, and in South and Southeast Asia 45.7 percent.

Fig. 11 presents the development over time for the total of the reporting countries (bars) and the countries that reported in all years (lines). In Africa the area of production forests decreased over time, which could be caused by the general reduction of forested area. In North and South America as well as in South and Southeastern Asia and Oceania the area of forests primarily designated for production increased since 1990. In East Asia a decline from 1990 to 2005 was followed by a slight increase until 2015. In Europe there is a pronounced decrease between 1990 and 2000, followed by a steady state in 2005, 2010 and 2015. The decrease could be a result of European activities for an increase of areas mainly designated for conservation and protection, such as the EU Habitat Directive on the protection of natural habitats and of wild flora and fauna (EU, 1992).

Assigning the area of forests mainly used for production to income levels gives a relatively uniform picture; most of the forest area designated for production is found in higher income countries (Fig. 12). Production forests in low income countries is roughly 100 million hectares while more than 600 million hectares are designated primarily for production in areas with high income. The trends over time indicate only minor differences.

About 26 percent or 1.049 million hectares of the total forest area are primarily designated for multiple use. Between 1990 and 2015 the area of forests designated for multiple use decreased in North America, Western and Central Africa, Europe and South and Southeast Asia, while in South America and East Asia an increase can be seen. In Eastern and Southern Africa the decline between 1990 and 2010 could be reversed, so that in 2015 more areas are designated to multiple use forestry than in 1990 (Fig. 13).

4. Discussion

The results presented are based on the best information that countries can provide. Even so, the quality and reliability of individual figures varies considerably because not all countries have well established forest inventory and monitoring programs. The number of countries providing data for the different information groups requested by the questionnaire varies and thus response rates show differences between reporting years, sub-regions and attributes. The data are weakest for trend analysis, just as they were in previous FRA (Marklund and Schoene, 2006; MacDicken, 2015). Where changes are driven by biophysical processes, such as climate, site index or soil carbon, statistical interpolation for filling missing values might be an appropriate measure to increase data completeness. Where developments are mainly a result of human interventions (e.g. wood removals, land-use change, forest management), spatial and temporal changes are subject to complex interrelations of a variety of agents. In these situations it is not advisable to fill data gaps by interpolation or other probability based approaches. Therefore we undertook gap filling for missing growing stock, biomass and carbon stock data, but not for wood

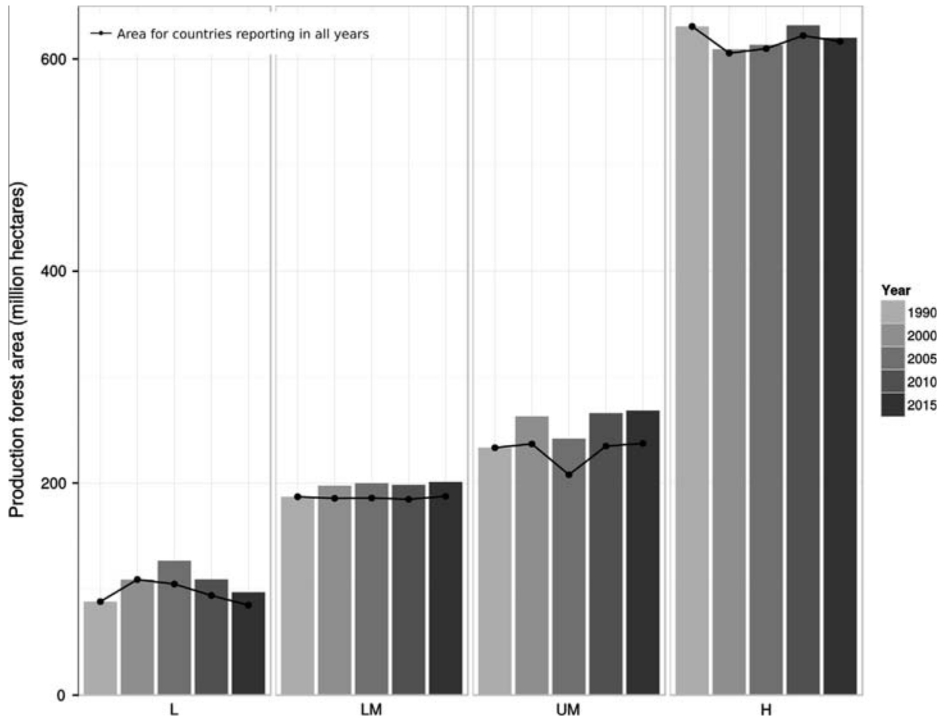

Fig. 12. Production forest area by income 1990–2015.

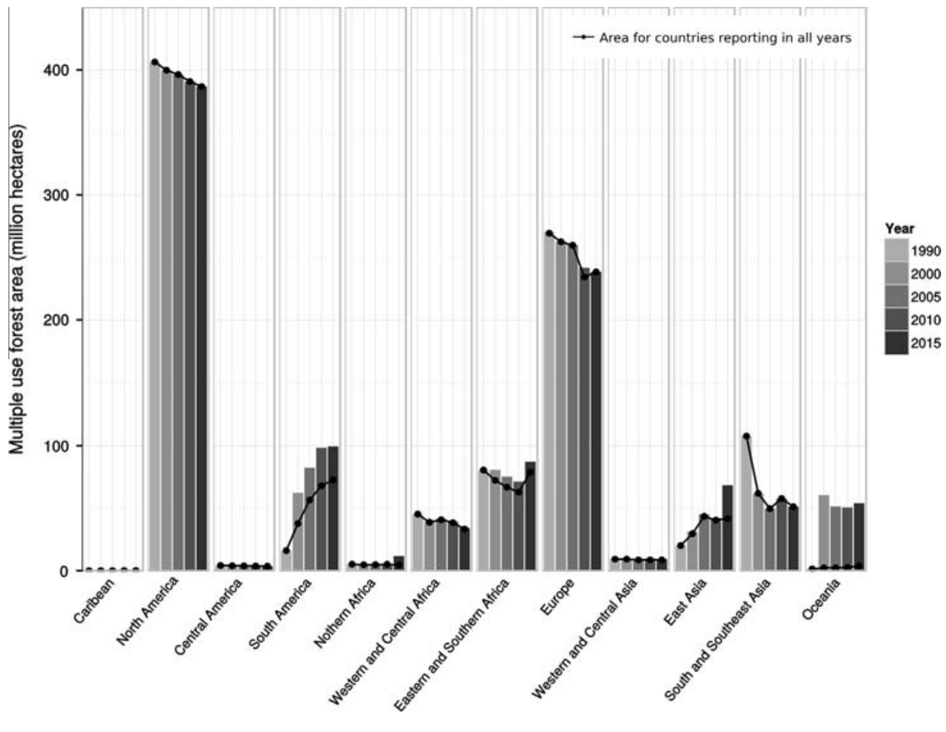

Fig. 13. Multiple use forest by sub-region 1990–2015.

removals or forest areas designated to specific uses. Some diagnostics reveal problematic national reporting data and it is tempting to apply corrections to these data before analyzing them. For example, biomass conversion and expansion factors (BCEF) implied by the growing stock and biomass C stock data reported by countries do not all appear to be reasonable (Fig. 14). But the largest countries that are most influential on sub-regional and global means and totals appear to have reasonable implied BCEF values, and the overall global BCEF of 0.91 in the FRA 2015 data set is almost identical to the 0.92 in FRA 2010 (FAO, 2010). Considering the diversity of national circumstances in the more than 200 countries reporting, it is expected that some of the data will look strange. Overall, however, the data appear to be plausible and they are useful for the purposes of sub-regional and global assessment.

Between 1990 and 2015, the total growing stock volume has increased in East Asia, Caribbean, Western and Central Asia,

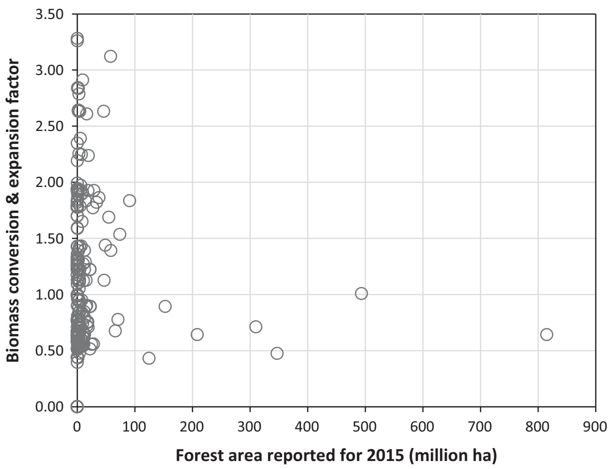

Fig. 14. Biomass conversion and expansion factors (BCEF) derived from country reports, calculated as above-ground biomass C stock (t C) converted to biomass stock (t) assuming 0.5 t C per t biomass and divided by growing stock (m^3). The derived BCEF for three countries exceeds 3.50.

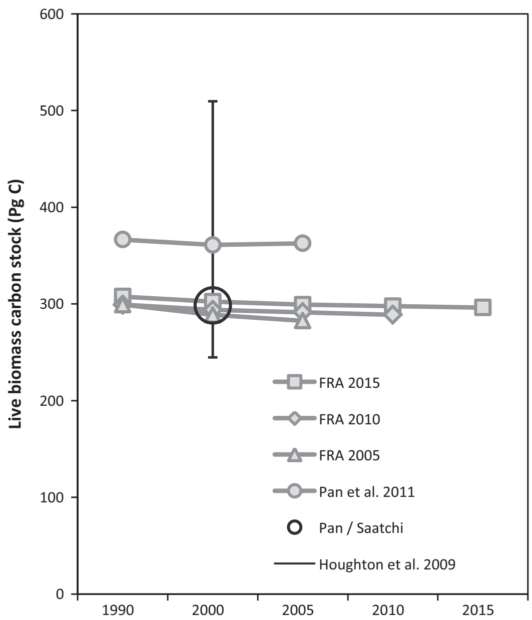

Fig. 15. Global forest carbon stocks in live biomass carbon stocks (including above- and below-ground) reported in this paper compared with previous FRA (Marklund and Schoene, 2006; FAO, 2010) and peer-reviewed scientific papers.

North America, Europe (including the Russian Federation), and Oceania with the highest relative increase in East Asia and the Caribbean. In all other subregions the total growing stock volume decreased. North and Central America, Europe and Asia report forest C stock increases while South America and Africa report strong decreases and Oceania reports stable forest C stocks. The global annual rate of forest C stock decline decreased between 1990 and 2015.

On a first glance the decrease of global carbon stocks and the simultaneous increase of global growing stocks appear contradictory. However, the carbon decrease found in the FRA 2015 data is mainly driven by the decreases in South America and Western and Central Africa. Here the carbon densities of forests are highest in the world and thus reductions of growing stock have a higher impact on forest carbon balances than in other sub-regions. Increases of growing stock in other sub-regions cannot compensate for the carbon losses in South America and Western and Central Africa.

Just how large the C stock densities are in tropical forests remains in some dispute and this is an important dispute. We must know tropical forest C densities in order to know the greenhouse gas impacts of tropical deforestation (Houghton et al., 2009). Pan et al. (2011) report live biomass C stock densities (including above- and below-ground live biomass) of 134.5 t C ha^{-1} while Saatchi et al. (2011) report 100.5 t C ha^{-1}. The FRA 2015 biomass C stock densities reported for tropical sub-regions range around the Saatchi et al. estimate, the highest being South America at 122.4 t C ha^{-1} and the lowest being Eastern & Southern Africa at 69.5 t C ha^{-1}. Fig. 15 shows that global forest biomass C stocks reported in FRA 2015 are quite consistent with those reported in previous FRA (FAO, 2010; Marklund and Schoene, 2006) but substantially lower than those reported by Pan et al. (2011). If the Pan et al. estimates are based on over-estimates of tropical forest biomass C stocks, then this would explain the discrepancy. The data point labeled "Pan/Saatchi" in Fig. 15 shows the value we get by adding boreal and temperate forest biomass C stock estimates reported by Pan et al. with a tropical forest biomass C stock calculated as the tropical forest area from Pan et al. multiplied by the tropical forest biomass C stock density estimated by Saatchi et al. The positioning of this point on the *y*-axis (298.4 Pg C) is approximate because we applied the mean tropical forest biomass C density reported in Saatchi et al. to the forest area categorized as tropical in Pan et al., which are not exactly the same study areas. This crude calculation is, however, sufficient to demonstrate the importance of uncertainty about tropical forest biomass C stock densities to the estimation of global forest biomass C stocks. It also suggests that the tropical forest biomass C densities used by Pan et al. (2011) to estimate the global forest C sink may be high. The uncertainty bars for circa 2000 are taken from Houghton et al. (2009), and one might argue now that the upper end of this range can be brought down.

The importance of forest C estimates relates, of course, to the need to better understand the contribution of forests to the global C cycle. Global cumulative anthropogenic emissions of carbon dioxide (CO_2) will reach about 535 ± 55 Pg C for 1870–2013, of which about 30% is from land use change (145 ± 50 Pg C) (Le Quéré et al., 2014). Only a portion of these emissions remains in the atmosphere, however, because the world's oceans and terrestrial ecosystems act as important CO_2 sinks. Le Quéré et al. (2014) estimated that the global terrestrial CO_2 sink is 2.7 ± 0.9 Pg C $year^{-1}$. This estimate was calculated using the residual of other, better known fluxes. Its actual size and location remains highly uncertain. Using forest inventory data and long-term ecosystem studies, the total C sink in established forests globally has been calculated to be 2.4 ± 0.4 Pg C $year^{-1}$ for the period 1990–2007 (Pan et al., 2011). Pan et al. also calculated that tropical forest land-use changes contributed a source of 1.3 ± 0.7 Pg C $year^{-1}$ during this same period. Together, these fluxes comprise a net global forest sink of 1.1 ± 0.8 Pg C $year^{-1}$.

Carbon budgets of terrestrial and forest ecosystems have also been investigated at the sub-regional and national scales. For South Asia, the annual net carbon flux from land-use change was −0.014 ± 0.050 Pg C $year^{-1}$ in 2000–2009 largely as a result of tree plantation establishment (Patra et al., 2013). In North America, net ecosystem exchange (NEE) for a 7-year period (ca. 2000–2006) was estimated to be a −0.327 ± 0.252 Pg C $year^{-1}$ sink (Hayes et al., 2012). These sinks are counteracted by the C source estimated for the Other Lands sector of 0.218 Pg C $year^{-1}$, where much of the forest and crop products are assumed to be returned to the atmosphere. The terrestrial C balance of East Asia during 1990–2009 using three different approaches are: −0.293 ± 0.033 Pg C $year^{-1}$ from inventory–remote sensing model–data fusion approach, −0.413 ± 0.141 Pg C yr^{-1} (not considering biofuel emissions) or

-0.224 ± 0.141 Pg C year^{-1} (considering biofuel emissions) for C cycle models, and -0.270 ± 0.507 Pg C year^{-1} for atmospheric inverse models (Piao et al., 2012).

The net balance of tropical forest biomes globally has been estimated to be 0.2 ± 0.4 Pg C year^{-1} (not significantly different from zero) over both periods 1990–1999 and 2000–2005 (Malhi, 2010). There were also a number of estimates at the national and sub-regional levels including for: tropical Pacific islands (Donato et al., 2012), China (Wei et al., 2014; Guo et al., 2010; Ren et al., 2011; Tan et al., 2011; Liu et al., 2012; Lun et al., 2012), Australia (Haverd et al., 2013), Russia (Dolman et al., 2012), Canada (Stinson et al., 2011), and the USA (Peckham et al., 2012).

If the world's forests are acting as net sinks for atmospheric CO_2, then how can global and sub-regional forest C stocks be in decline? Fig. 16 shows the net global forest C sink calculated by Pan et al. alongside the forest C stock changes reported in FRA 2010 and FRA 2015.

Federici et al. (2015) used the FRA 2015 data to estimate that forests were a net source of CO_2 emissions of 1.47 Gt CO_2 year^{-1} in the period 1991–2015 (1.47 Gt $CO_2 * 12/44 = 0.40$ Pg C), so the answer may lie in the FRA 2015 data. Like data reported for previous FRA, these data have some peculiarities (Marklund and Schoene, 2006). The quality and reliability of individual figures reported by countries varies considerably with many of the reported data having lower tiers (less reliable). For example, only 5% of countries representing 9% of the forest area provided Tier 3 data for soil carbon stocks. But the discrepancy between the sink reported by Pan et al. (2011) and the C stock loss calculated from FRA 2015 data is not entirely caused by problems in the FRA data. First, not all CO_2 taken up by forests is sequestered in forest ecosystem C pools. Some is transferred laterally out of the forest and sequestered or emitted back into the atmosphere elsewhere. Global wood removals in 2005 totaled 3.0×10^9 m^3, which amounts to roughly 0.3 Pg C year^{-1}. Cole et al. (2007) conservatively estimate that 1.9 Pg C year^{-1} are transferred from terrestrial ecosystems to inland waters, but only a portion of this is transferred from forests.

The second reason for the apparent discrepancy between Pan et al.'s sinks and FRA's reported C stock losses arises from differences in how tropical forest C dynamics are estimated and reported. Many countries rely on Intergovernmental Panel on Climate Change (IPCC) default expansion factors (IPCC, 2003) to calculate their C stocks for FRA, or they only have an estimate of forest C stocks from one point in time, which was used by them (or us, see Section 2.2) to calculate C stock density and apply to the forest areas in the other years to calculate C stocks for those years. Fig. 17 shows these countries clustered along the vertical, zero percent change in biomass C density axis. According to the

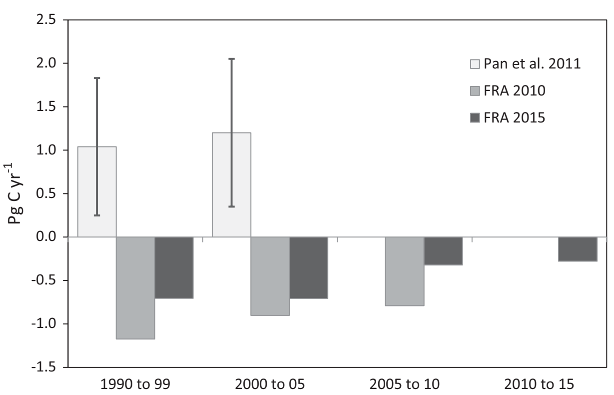

Fig. 16. Global net forest ecosystem C sink calculated by Pan et al. (2011) for the periods 1990–1999 and 2000–2007 shown alongside forest C stock changes reported in FRA 2010 and FRA 2015 for the corresponding and more recent periods.

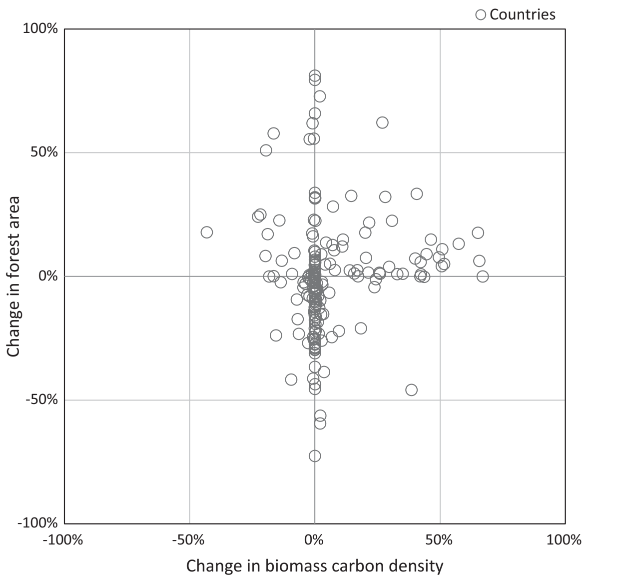

Fig. 17. Country-level forest area and carbon density changes between 1990 and 2015.

FRA 2015 data, the average C density of the world's forests increased by 0.6% between 1990 and 2005 and by 0.1% between 2005 and 2015. Pan et al. reported a 2.0% increase in forest C density between 1990 and 2007, including a 22.5% increase in tropical forests that are recovering from past deforestation and logging, and a 5.0% increase in tropical intact forests. Permanent sample plots in tropical intact forests are few, but they indicate that these forests are accumulating biomass and C (Baker et al., 2004; Phillips et al., 2008; Lewis et al., 2009). Pan et al. estimate that tropical intact forests are accumulating C at a rate of 1.1 Pg C year^{-1}. In contrast, the FRA 2015 data only report an accumulation of 0.1 Pg C year^{-1} in these forests. This difference accounts for the majority of the discrepancy between Pan et al. and FRA in Fig. 16. Considering our discussion of tropical biomass C stock densities, above, and the equally large (and important) uncertainties about dead wood, litter and soil C stocks and stock changes, much work remains to be done to refine our knowledge of the world's forest C stocks and fluxes.

The total volume of annual wood removals including woodfuel removals increased between 1990 and 2011. Wood removals show a remarkable decline in 2009, but recovered until 2011. Forest areas designated for production purposes differ considerably between subregions (16.2 percent in South American and 52 percent in Europe). Globally about one quarter of the forest area is designated to multiple use forestry.

5. Conclusions and recommendations

The FRA provides comprehensive information on the current state and trends of the global forest resources. Over time it has become a frequently cited information source, which is used for a wide scope of applications from scientific studies to international negotiations for political decision making. When utilizing and interpreting the data on growing stock, carbon, removals and areas designated for production and multiple-use, it should be taken into consideration that data have been made available by countries and thus are subject to various assessment schemes and differ with respect to data quality and reliability. We strongly recommend the restriction of analyses to sub-regions as the smallest units of reference and to consult additional information on data reliability when information on the country level is referenced.

Recent international efforts to streamline global forest reporting and strengthen collaboration among international reporting processes (e.g. NRCan, 2012) have resulted in better alignment of international data reporting requirements, reduced reporting burden and increased consistency of reporting. The most tangible example of this is the development of the Collaborative Forest Resources Questionnaire, created by six international organizations representing some 100 countries and 88% of the global forest area. These organizations now jointly collect and share data on about 60% of the total number of the variables collected through the FRA process. These data are then shared among the CFRQ partners so that countries are asked only once for this information. This both reduces the reporting burden and increases data consistency across organizations. The reporting data compiled for FRA 2015 on growing stock, biomass and carbon stocks are remarkably complete considering the diversity of geo-political circumstances and institutional capacities amongst countries.

Reporting has also improved thanks to the development of new forest monitoring technologies and their improved accessibility (Giri et al., 2013; Wulder and Coops, 2014). FRA will continue to be a key source of data for global forest assessments, especially assessments of cultural forest variables (such as designated functions of forests) that cannot be assessed using remote sensing data. FRA will also remain important as a source of national reporting statistics that have been vetted by local forestry officials and experts.

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