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Changes in planted forests and future global implications ☆

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ABSTRACT

This paper focuses on an analysis of planted forests data from the 2015 Forests Resources Assessment of the U.N. Food and Agriculture Organisation (FRA 2015). It forms one of a series of papers in the FRA 2015 special issue of this journal.

While total forest area decreased from 4.28 billion hectares to 3.99 billion hectares from 1990 to 2015, with percent global forest cover dropping from 31.85% to 30.85%, the area of planted forests increased from 167.5 to 277.9 million hectares or 4.06% to 6.95% of total forest area. Increase was most rapid in the temperate zone, and regionally in East Asia, followed by Europe, North America, and Southern and Southeast Asia.

However the annualised rate of increase in area of planted forests slowed in the 2010–2015 period to 1.2%, below the 2.4% rate suggested is needed to supply all of the world's timber and fibre needs.

The majority of planted forests comprised native species with only 18–19% of the total area being of introduced species. Introduced species were dominant in the southern hemisphere countries of South America, Oceania and Eastern and Southern Africa where industrial forestry is dominant.

Twenty countries accounted for 85% of planted forest area and a different 20 countries for 87% of planted forest roundwood supply. As with forest area, roundwood supply from planted forests also showed an increasing trend although this was based on minimal data. There was a mismatch in composition and rankings of the top 20 countries with top forest area and roundwood production suggesting that there are substantial opportunities to increase roundwood production in the future, especially in China which has the largest area but is currently ranked 3rd in roundwood production.

Outlook statements were developed for the FAO sub regions based on past changes in planted forest area, population growth, and climate and forest health risks to identify key issues for the future. The overall view from this study suggests that climate impacts, especially from extreme climatic events will affect planted forests in the future and that forest health impacts can also be expected to increase. Outlooks vary regionally. Europe and North America are likely to be most concerned with climate and health risks; Asia will experience population pressure that will impact on land availability for new forests and risks from extreme weather events, and will need to make the most of its existing forests; Africa will need to increase planted forest area to offset continuing deforestation and rapid population growth; and Oceania, the Caribbean, Central and South America are likely to be most concerned with climate impacts.

To ensure the continued contribution of planted forests, a number of responses will be required to both maintain existing and also to develop new forests. Intensification of production in existing forests will lessen the need for greater forest areas and offset any land use conflicts related to food security; climate adaptation strategies will need to be developed as a matter of urgency, and forest health focus must remain a priority for research. Establishment of new forests will be eased through greater community

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and stakeholder engagement. Application of models such as WWF's New Generation Plantations, which recognises the importance of society and the need to consider the full range of forest products and services within the wider landscape and spectrum of land uses, will be important.

We recommend that to enable deeper analysis related to planted forests future FRA Assessments consider ways to better gather data specific to planted forests such as productivity so that this important component of global forests can be better understood.

1. Introduction

The 3rd International Congress on Planted Forests was held in 2013 to discuss the current state of knowledge on planted forests globally and regionally (ICPF, 2013). Amongst a number of findings (Payn et al., 2014) the congress noted that planted forest areas continued to increase and that the goods and services provided by these forests were becoming increasingly diverse. The interaction of planted forests with other land uses within landscapes and their contribution to poverty alleviation and food security was identified as deserving attention. Risks to planted forests from climate change, socio-economic pressures and responses to these risks were seen as important. A global analysis indicated the importance of planted forests for economic, environmental and social values. Regional perspectives indicated that expansion of planted forests varies regionally as do issues affecting them. Africa for example has challenges regarding governance, and the opportunity to expand farm forests and woodlots. In contrast, Asia is constrained in its ability to further expand its commercial planted forest area and will need to increase production from existing forests.

The availability of a new comprehensive dataset from FAO's Forest Resources Assessment 2015 project provided the opportunity to explore some of the issues emerging from the 3rd International Congress on Planted Forests in more detail both at the global and regional scale. The FRA 2015 dataset covers all forests and the period 1990 to 2015 (www.fao.org/forestry/FRA2015/database). For this study, one of a series commissioned by FAO, we concentrate on planted forests and interrogate the latest available data on planted forests in the context of current and future climate and population pressures. We further present an outlook for the forests globally and regionally.

There have been significant studies on planted forests previously. These, for example, include data trends and projections (Carle and Holmgren, 2008), plantations, biodiversity and climate change (Pawson et al., 2013); the impact of planted forests on the global forest economy (Buongiorno and Zhu, 2014); timber investment (Cubbage et al., 2014); and multi-purpose plantations (Paquette and Messier, 2009). Although extending beyond only planted forests, the recently released Global Forest Expert Panel report on forests and food security also treats important related issues (Vira et al., 2015).

2. Methods

2.1. Planted forests

2.1.1. Definition of planted forests

Since 1980, the Food and Agriculture Organisation of the United Nations (FAO) through its Forest Resources Assessments (FRA), has been collecting data on forest areas for two main categories of forests: natural forests and forest plantations. In 2005, the FRA introduced two additional forest categories: modified natural forests and semi-natural forests (Evans, 2009), which resulted in five major forest categories based on the degree of human intervention and the silvicultural methods of forest regeneration. These include (1) primary forest; (2) modified natural forest; (3) semi-natural forest, comprising natural and planted regeneration (SNPF); (4) plantations comprising productive and protective plantations; and (5) trees outside forests. Productive and protective plantations, together with SNPFs, constituted the subgroup 'planted forests' (FAO, 2010). The FRA 2015 definition (FAO, 2012) refined this to: forest predominantly composed of trees established through planting and/or deliberate seeding, where the planted/seeded trees are expected to constitute more than 50 percent of the growing stock at maturity. They include coppice from trees that were originally planted or seeded and rubberwood, cork oak and Christmas tree plantations.

2.2. FRA dataset and analysis

The FRA 2015 dataset contains a number of variables (FAO, 2012) directly related to planted forests that allowed us to explore various aspects of trends in planted forests over the period 1990 to 2015. Other variables were derived from the core variables. From these data we analysed trends globally, sub-regionally and by climate domain in: 1. Planted forest area; 2. Proportion of total forest area made up of planted forests; 3. Proportion of exotic and natural species within the planted forest resource; and 4. The relationship between population trends and planted forest area.

A second stage of the analysis focussed on planted forest area at the country level. This focussed on the top 20 countries and evaluated areas, species mix, and population relationships.

Overall the planted forest data formed a small subset of the full FRA database, and in a number of instances it was not possible to view planted forest attributes of a specific variable. These included issues such as the proportion of forest used for production or protection purposes, or roundwood supply specific to planted forests. In other instances, such as forest productivity or forest health, the available data were very limited. To add value to the analyses we therefore sought data sources supplementary to the FRA dataset.

2.3. Additional data sources

2.3.1. Jürgensen et al. (2014) roundwood study

To investigate timber production from planted forests we utilised data gathered as part of an FAO study (Jürgensen et al., 2014). This allowed us to investigate levels and trends of production in planted forests. The FAO analysis focussed on industrial roundwood production from forest plantations in 78 countries and information on roundwood production from the semi natural and planted forest (SNPF) category from only 17 countries as many countries could not provide information on roundwood production for this category. We present 2012 data for the proportion of roundwood sources from natural and planted forests (SNPF and plantations combined); regional production levels in planted forests; and production levels from the top 20 country producers of planted forest roundwood. The Jürgensen et al. (2014) study covers most of the important planted forest countries. However, they missed some countries and we have filled in these gaps using the FRA database for 2010 industrial roundwood production for total forest. We assumed in these cases that the wood comes from natural forest. So the overall roundwood estimates for planted forests

will therefore be somewhat conservative. We also calculated 2012 roundwood per unit of planted area in 1990 as a crude estimate of productivity across the climate domains and sub regions.

2.3.2. FAO planted forests thematic study

The FRA dataset apportions forests depending on their proposed use; production, multi-use, and protection categories. These statistics are for all forests combined. The intended use of planted forests is important to know when looking at future timber supply so we sourced data from the thematic study of planted forests (Del Lungo et al., 2006) where 61 countries were surveyed in detail as to their planted forests. We used this dataset to analyse the proportion of planted forests intended for production vs protection use on the 2015 top 20 planted forest countries (see Section 2.1) identified.

2.4. Outlook analysis: climate, population pressure, and forest health

An aim of this paper was to present an outlook for planted forests that relates to the two key global drivers – climate and population change. Another aspect that is hard to extract from the FRA dataset is forest health status but one that is very important to consider.

Population data are well covered in the FRA dataset and we analysed various planted forests variables in relation to population trends. However climate trends are not covered in the FRA dataset. To evaluate the impact of climate on the planted forest outlook we utilised two sources on information: 1. The IPCC 5th Assessment report (IPCC, 2014); and 2. The Germanwatch climate risk index (Kreft and Eckstein, 2013).

The IPCC 5th Assessment report outlines climate related drivers e.g. warming trends, drying trends, extreme precipitation; and associated key risks e.g. drought, storm and flood damage, decreased crop production. We mapped these drivers and risks to the FAO subregions.

The Germanwatch risk index is developed from historic data analyses regarding the extent to which countries have been affected by the impacts of weather-related loss events (storms, floods, heat waves, etc.). The 2014 index is based on data from 1993 to 2012. It provides a country level index which we compiled to give a population weighted average for each of the FAO subregions. It serves to provide an indication of past impacts that may be extrapolated to the future where these climate impacts will remain the same or worsen under climate change. The subregional range was from 40 (highest risk) to 111 (lowest risk).

Forest health data in the FRA dataset shows area affected by the 10 most important extensive pest and disease impacts/outbreaks for each country. We summed the total area affected and calculated percentage of total forest area affected and averaged this by region. Only 76 countries reported this variable so values must be taken as only indicative. Additionally, and as for other variables, this does not relate to planted forests *per se* but could provide a perspective on current forest health impacts by country and region. To augment these data we considered published studies to develop the regional outlook for health risk.

Utilising the forest area, population, climate and health information we developed a subregional outlook from a three class (low, medium and high) ranking of current forest areas (planted and natural), population and population density; and changes in population and natural and planted forest area between 1990 and 2015. This information was then considered in relation to the climate drivers and risks, and forest health state, and an outlook statement developed. This outlook was developed in terms of level of future challenge facing planted forests. These outlook statements were subject to review by planted forest experts in the new IUFRO task force "Sustainable Planted Forests for a Greener Future" (http://www.iufro.org/science/task-forces/-planted-forests/).

3. Results

3.1. Total forest trends (1990–2015)

Total forest area decreased between 1990 and 2015 from 4.12 to 3.99 billion hectares. The Tropics and Subtropics both decreased in area while Boreal and Temperate increased (Table 1).

Changes in total forest cover varied regionally (Table 2). Central America, East Africa, North Africa, Oceania, South America, Southern and Southeast Asia, and West and Central Africa decreased while the Caribbean, East Asia, Europe, North America, and West and Central Asia increased. Overall percentage of land covered by forest decreased from 31.85% to 30.85%.

While total forest area declined, forest productivity increased over the period from an average 4.10 m^3 ha^{-1} yr^{-1} to 5.26 m^3 ha^{-1} yr^{-1} with the changes varying by climate domain and region. Temperate zone productivity increased the most (1.91 m^3 ha^{-1} yr^{-1}) with the boreal zone also increasing slightly. These data should be taken as indicative as only 45% of countries surveyed provided data for this variable.

3.2. Planted forest trends

3.2.1. Planted forest area

Global planted forest area increased from 1990 to 2015 from 167.5 million ha to 277.9 million ha with the increase varying by region and climate domain. Annualised rates of increase in area were highest in the 1990–2000 period (2.0%) and the 2000–2005 period (2.7%) but dropped in 2005–2010 (1.9%) and further in 2010–2015 to 1.2%. This drop may be of concern given that a study by WWF and IIASA have suggested that a rate of increase of 2.4% is needed to meet future demands and supply all of the world's timber and fibre and thus offset deforestation impacts on wood supply (WWF and IIASA, 2012).

Of the 277.9 million ha of planted forests in 2015 56% are in the temperate zone, 15% boreal, 20% tropical, and 9% subtropical (Fig. 1). All zones showed an increase in area, with the largest increase in area in the temperate zone (93.4–154.4 million ha) followed by tropical, boreal, and subtropical (Fig. 2).

Overall East Asia and Europe had the largest areas of planted forests, followed by North America and Southern and Southeast Asia (Fig. 3). All regions, except Central America, showed an increase in planted forest area over the period with the greatest absolute increases in these top four regions followed by South America. Central America showed a very slight decrease between 1990 and 2015, probably within the margin of error. The trend of a slowing of expansion rate (annualised% change in area) noted globally was also apparent at the subregional level (Table 3). Most regions showed a peak in annualised percent change in either 2000–2005 or 2005–2010 followed by a decrease in expansion rate in 2010–2015. The only exception was East Africa where the

Table 1
Change in total forest area by climate domain from 1990 to 2015.

Year	Forest area by climate domain (Million ha)				
	Boreal	Temperate	Subtropics	Tropics	Total
1990	1219.3	618.0	325.4	1965.5	4128.3
2000	1219.8	640.9	324.8	1870.1	4055.6
2005	1218.9	659.2	323.9	1830.8	4032.7
2010	1224.9	673.4	319.6	1797.8	4015.7
2015	1224.5	684.5	320.1	1770.2	3999.1

Table 2
Change in total forest area by FAO sub region from 1990 to 2015.

Year	Forest area by subregion (Million ha)											
	Central America	Caribbean	East Asia	East Africa	Europe	North Africa	North America	Oceania	South America	South and Southeast Asia	West and Central Africa	West and Central Asia
1990	27.0	5.0	209.2	319.8	994.3	39.4	720.5	176.8	930.8	319.6	346.6	39.3
2000	23.4	5.9	226.8	300.3	1002.3	37.7	719.2	177.6	890.8	298.6	332.4	40.5
2005	22.2	6.3	241.8	291.7	1004.1	37.2	719.4	176.5	868.6	296.6	325.7	42.4
2010	21.0	6.7	250.5	282.5	1013.6	37.1	722.5	172.0	852.1	296.0	318.7	42.9
2015	20.3	7.2	257.0	274.9	1015.5	36.2	723.2	173.5	842.0	292.8	313.0	43.5

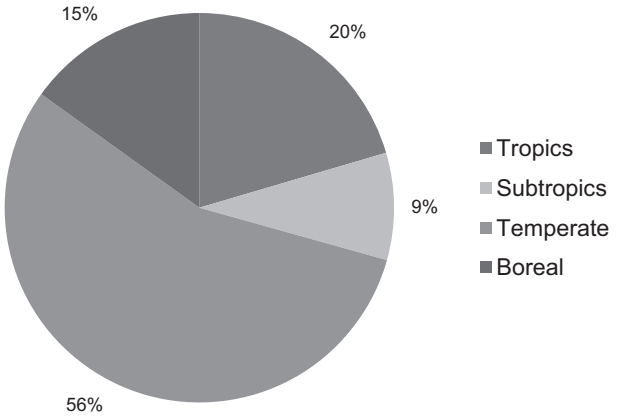

Fig. 1. Percentage of total planted forest area in 2015 by climate domain.

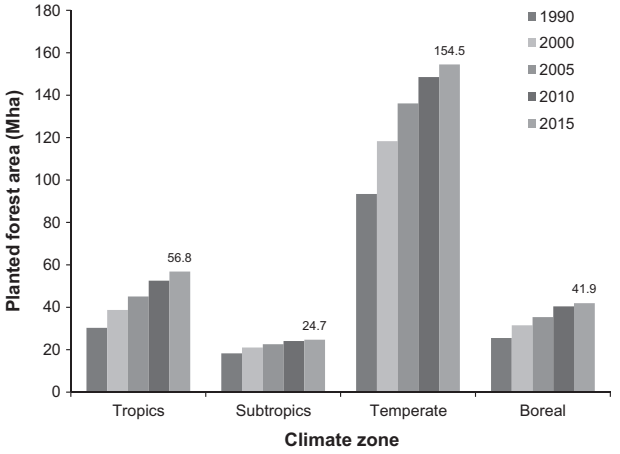

Fig. 2. Trends in planted forest area 1990–2015 by climate domain.

percentage change increased in each five year period peaking at 2.65% in the 2010–2015 period.

3.2.2. Planted forest contribution to global forest area

Deforestation is a major concern globally, and total forest area has decreased over the 1990–2015 period (Table 1). Planted forests play a role in offsetting the pressure and negative impacts on natural forests. Analysis of total global area and the relationship between natural and planted forest area shows that the decrease in natural forest area is offset by the increase in planted forest area to an increasing degree with time. Planted forests increased from 4.1% to 7.0% of the total forest area over the period, or 1.29% to 2.14% of total land area[1] (Fig. 4). Also of interest was the species

[1] Based on land area from UN Statistics Division.

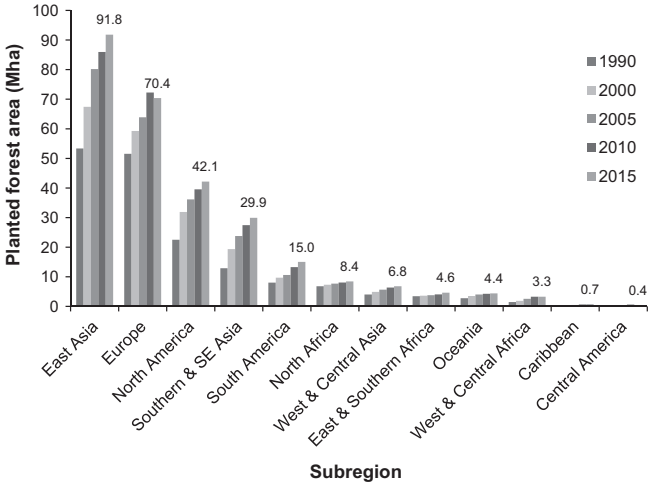

Fig. 3. Changes in Planted Forest Area by FAO subregion 1990–2015.

composition of the planted forests, with only between 18% and 19% of the planted forests comprising exotic or introduced species. The high proportion of native species in planted forests is not well appreciated by those opponents of planted forests who cite as a major concern the use of introduced species.

When considering the distribution regionally we can see that South America, Oceania, and East and Southern Africa are the regions dominated by plantings of introduced species with 88%, 75% and 65% of plantings with introduced species respectively (Fig. 5). North America, West and Central Asia, and Europe are at the other end of the spectrum with 1%, 3% and 8% of the area planted in introduced species.

3.2.3. Country level trends

For country-level data, planted forest area for the top 20 countries is shown in Fig. 6. These top 20 countries accounted for 85% of planted forest area and were distributed across most regions bar Central America, the Caribbean, and West, Central, East and Southern Africa. In 2015, China had by far the largest planted forest area at 91.8 million ha followed by the USA (26.4), the Russian Federation (19.8) and Canada (15.8).

None of the 20 countries showed a decrease in planted forest area though Japan and Germany were static over the period. China showed by far the largest absolute increase in area (37.0 million ha) followed by Canada (11.2), the USA (8.4) and Russia (7.2). The next tier were India and Sweden (6.3), Brazil (2.8) and Finland (2.4). Data for Indonesia were missing for 1990 but this country also appears to be of this second tier order of increase.

These countries also exhibited the slowdown in expansion rate noted at the global and regional level (Table 3). Generally, the period 2000–05 had the most rapid increase in planted forest area with the rate slowing in 2005–10 and slowing again in 2010–15, although for some countries the peak was between 2005 and

Table 3
Annualised rate of change in planted forest area (%) (shaded cells are peak values).

Country	Area planted by 2015	1990-2000	2000-2005	2005-2010	2010-2015	change from peak rate
	Million ha	Annualised % change				
Chile	3.0	1.3	1.3	2.9	5.0	0.0
Germany	5.2	0.1	-0.5	0.0	0.0	-0.1-
Japan	10.2	0.0	0.0	-0.1	0.0	0.0
Ukraine	4.8	0.3	0.1	0.1	0.2	-0.1
Sudan	6.1	0.4	0.8	0.3	0.6	-0.2
New Zealand	2.0	2.9	0.5	-0.2	0.0	-2.9
Sweden	13.7	2.9	2.4	2.5	1.8	-1.1
United States	26.3	2.3	1.6	0.9	0.6	-1.7
Turkey	3.3	2.7	2.3	5.3	3.6	-1.7
Russia	19.8	2.0	2.0	2.9	0.2	-2.7
Canada	15.7	7.4	4.6	3.6	2.5	-2.1
Thailand	3.9	1.5	2.1	3.0	0.0	-3.0
Spain	2.9	2.1	0.4	2.5	0.2	-2.3
Brazil	7.7	0.4	1.7	4.4	2.1	-2.3
China	78.9	2.6	4.3	1.7	1.6	-2.7
Finland	6.7	1.2	3.6	2.8	0.0	-3.6
India	12.0	2.3	5.8	3.3	1.6	-4.2
Australia	2.0	1.4	6.7	3.2	1.2	-5.5
Indonesia	4.9		7.0	0.6	0.6	-6.4
Vietnam	3.6	7.8	5.7	7.1	-0.9	-8.7
Rest of world	44.1	1.8	1.4	1.3	1.5	-0.3
Total	277.9	2.0	2.7	1.9	1.2	-1.5

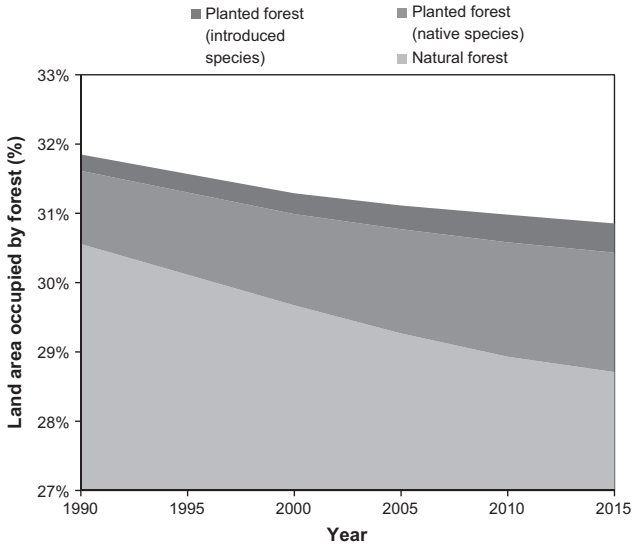

Fig. 4. Proportion of total forest cover made up of natural and planted forests and changes with time.

2010. The decline in planting rate was common across most countries with only 3 of the 20 countries (Chile, Sudan, and Ukraine) planting at a greater rate in the last 5 years (2010–2015) than in the 5 previous years.

3.3. Forest timber production [Roundwood supply]

3.3.1. Area trends

Statistics and trends in forest area as presented previously are important, however the production from these forests is the ultimate measure of their use. Roundwood (industrial roundwood) supply is the major production variable to be considered here. Table 4 summarises the results from this analysis. Globally in 2012 46.3% of industrial roundwood comes from planted forests. One interesting result was that in the tropics and subtropics, 65% of production is from planted forest, but this reduces to 45% for temperate and only 14% for the boreal zone. The lower values for boreal and temperate zones could reflect that planted forests in these cooler areas may be too young to produce much wood. However, given the large areas of planted forest especially in the temperate zone (15% of total forest area) there appears to be potential for much greater production in the future from these forests. Also, the rate of increase in planted area across all regions

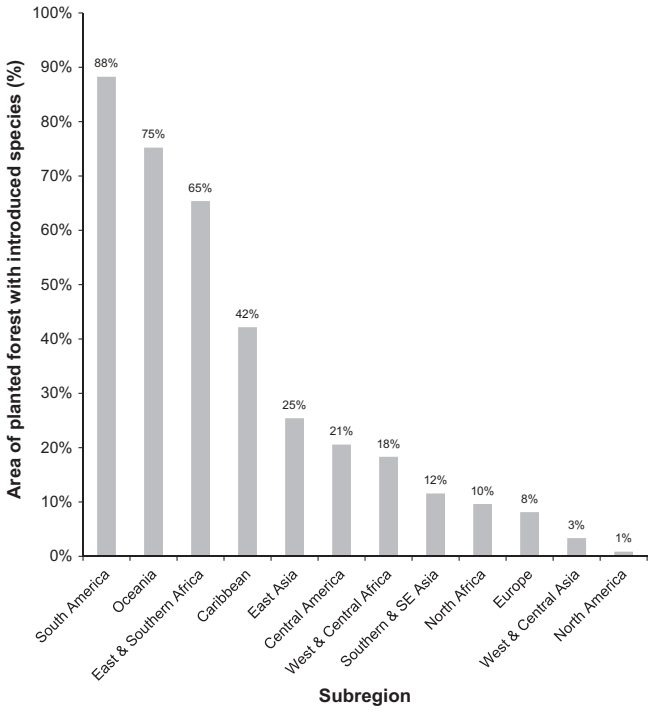

Fig. 5. Proportion of planted forests with introduced species by FAO subregion.

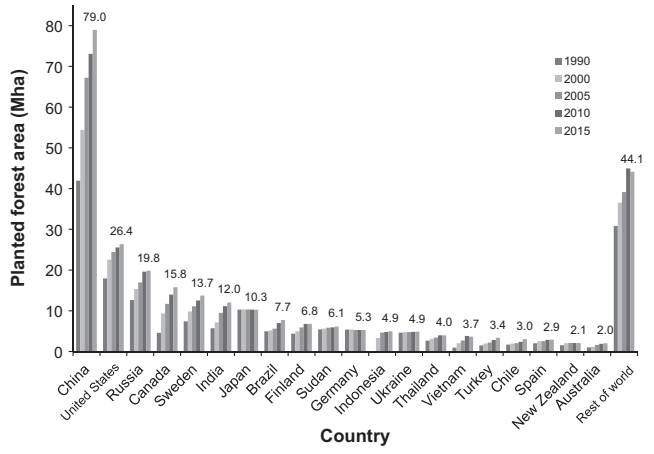

Fig. 6. Planted forest area and trends (1990–2015) for the top 20 countries by planted forest area.

must be reflected by a corresponding increase in wood production in future decades. This all points to a greater proportion of wood being supplied from planted forests in the future. Already in 2012, almost as much (46.3%) industrial wood comes from planted than natural forest when fuel wood is excluded from the analysis.

An analysis of the data by region indicated that the production of industrial roundwood in planted forests in 2012 was close to 200 million m^3 in South America (193 million m^3), followed by Asia (151 million m^3) and North and Central America (104 million m^3). Oceania, Europe and Africa produced considerably less, ranging from 26 million to 47 million m^3. Productivity and percentage roundwood sourced from planted forests was highest in South America (24.0 $m^3\ ha^{-1}\ yr^{-1}$; 92.4%) and Oceania followed by East and Southern Africa and Southern, Southeast, and East Asia. These regions host countries with highly developed intensively managed tree plantations and fast growing exotic species. Other regions probably contain a higher proportion of less intensively managed planted forests.

In 2012, 20 countries (Fig. 7) together produced 87 percent of the global industrial roundwood production from planted forests, totalling about 675 million m^3. The country mix and rankings of these top 20 countries differs from the top 20 area rankings (Fig. 6) reflecting opportunities for large increases in production in countries such as China where area is high and production currently relatively low.

3.3.2. Temporal trends in roundwood supply 1990–2015

The FRA 2015 dataset showed an overall increase in roundwood production from 1990 to 2015 though data was sparse. The time-series data on the industrial roundwood production from 17 countries reported in the Jürgensen et al. (2014) study showed that for many countries in Latin America and Asia (Chile, Brazil, China, Indonesia, Malaysia, Myanmar, Thailand, Uruguay and Vietnam), the production had increased considerably since 2000; while in Argentina, Australia, New Zealand and the United States of America, production had been increasing at a considerably slower pace. In European countries (Portugal, Spain, and Turkey) and in South Africa, the trend in industrial roundwood production had basically been stagnant since 2000, with some noticeable ups and downs during this period.

3.4. Population, climate and forest health trends

3.4.1. Population

Over the period 1990 to 2015 global population increased from just over 5bn to just over 7bn an annualised rate of increase of 1.46%. Highest 2015 population densities were in Southern and Southeast Asia, Caribbean and East Asia (Table 5). All regions show increasing population but rate of population increase varies regionally. Southern and Southeast Asia, Western and Central Africa, and East Asia showed the largest rate of increase with Europe the lowest rate. Comparing annualised population growth rate with annualised change in planted forest area showed that globally the rates are similar, but regionally these vary. Europe for example, had minimal population growth, but a 37% increase in planted forest area while Central America has shown a 45% increase in population with only a 17% increase in planted forest area. Southern and Southeast Asia by contrast shows large increases in both population and planted forest area. We used these relationships to infer pressure on future supply of timber regionally – high pressure where annualised population growth rate was greater than annualised forest area increase and vice versa for low pressure.

3.4.2. Climate

The regional analysis of the Germanwatch climate risk index showed a range of risk indices across regions and also across climate zones (Table 5). Highest risk regions (lowest scores) were Central America, the Caribbean, East Asia, and Southern and Southeast Asia; and lowest risk regions Western and Central Africa, Western and Central Asia, North Africa, and Eastern and Southern Africa. In terms of planted forest regions this suggests that Eastern Asia and Southern and Southeast Asia with large and increasing areas of planted forests are most at risk. This analysis gives a retrospective view and future risk distributions may change.

The IPCCC AR5 findings suggest that all regions will be affected by climate change and that there may well be effects on planted forests. IPCC AR5 projections (IPCC, 2014) for climate change suggest increased risks and impacts globally, both from direct climatic events such as storms, but also indirectly from increased risks from fire, pests and diseases, or spread of invasive species. As most

Table 4
Planted forest roundwood production in 2012 by region and climate domain adapted from Jürgensen et al., 2014.

	Total forest area 2015 (Million ha)	Planted forest area 2015 (Million ha)	Annualised% change in planted forest area 1990–2015	Planted forest industrial roundwood 2012 (1000 m^3)	Planted forest % of total industrial roundwood	2012 Planted forest roundwood productivity index based on 1990 area (m^3 ha^{-1} yr^{-1})
World	3999.1	277.9	2.0	770,200	46.3	4.6
Tropical	1770.1	56.8	2.5	255,300	63.7	8.4
Subtropical	320.0	24.7	1.2	69,600	64.7	3.8
Temperate	1031.5	154.4	2.0	410,100	45.2	4.4
Boreal	877.3	41.9	2.0	35,200	13.9	1.4
South America	842.0	15.0	2.5	193,000	89.8	24.0
Oceania	173.5	4.3	1.9	47,500	84.0	17.2
East and Southern Africa	274.8	4.6	1.2	20,700	64.7	6.0
Caribbean	7.1	0.7	2.4	300	24.7	0.7
East Asia	257.0	91.8	2.2	78,700	46.9	1.5
Central America	86.2	0.4	0.6	1600	18.0	4.3
West and Central Africa	313.0	3.2	3.2	5100	14.1	3.5
Southern and SE Asia	292.8	29.9	3.4	82,700	52.0	6.4
North Africa	36.2	8.4	0.9	400	15.7	0.1
Europe	1015.4	70.4	1.3	166,200	33.4	3.2
West and Central Asia	43.5	6.7	2.1	3900	19.1	1.0
North America	657.1	42.1	2.5	170,100	36.0	7.6

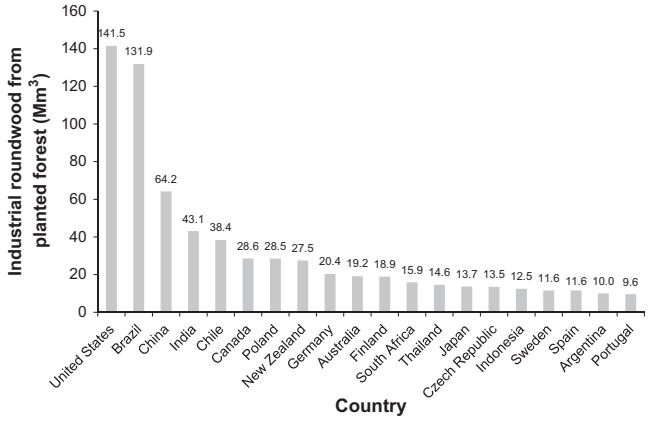

Fig. 7. The world's top 20 producers of industrial roundwood from planted forests in 2012.

terrestrial ecosystems, planted forests are vulnerable to climate change projected even under low to medium-range warming scenarios (RCP[2]2.6 to RCP6.0) as defined in IPCC AR5; in the second half of the 21st century, climate change is projected to be a powerful stressor specially under high-warming scenarios such as RCP6.0 and RCP8.5 (Settele et al., 2014). Increases in the frequency or intensity of disturbances such as droughts, wind storms, fires and pest outbreaks have been detected in many parts of the world where planted forests are located and in some cases are attributed to climate change (medium confidence in IPCC AR5). Also, the establishment, spread and survival of populations of invasive species have increased (IPCCAR5), mainly due to increased dispersal opportunities or to increased disturbances rather than climate change.

The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products, but might induce an increased demand on wood supply from planted forests. Decreased production from planted forests is expected in already dry forest regions where increasing water deficit is projected such as the south-western part of Europe, USA or Africa. Extreme drought conditions will also decrease yields in areas not water limited. Under all future climate projections, a range of climate change-related factors (extreme events and disturbances, changes in precipitation, increased temperatures and CO_2) will continue to exacerbate the establishment and spread of pests, vectors and pathogens, and negatively impact production systems such as planted forests (Robinet and Roques, 2010). Globally, biomass and soil carbon stocks in forest ecosystems are currently increasing but are vulnerable to loss to the atmosphere as a result of rising temperatures, droughts, and fires projected in the 21st century. Measurements of increased tree growth over the last several decades, a large sink for carbon, are consistent with this (Settele et al., 2014), but confounding factors such as N deposition, increasing area of productive planted forests, and forest management practices make attribution of these trends to climate change difficult.

[2] RCPs (Representative Concentration Pathways) are identified with the radiative forcing by 2100; four main RCPs scenarios have been used in AR5 (8.5, 6.0, 4.5, and 2.6 W m^{-2}).

3.4.3. Forest health

Only 76 countries supplied data for this variable covering a total forest area of 2.8 billion hectares or 30% of global forests. Averaged across the 76 countries, 8.5% of forest area was affected by pest and disease outbreaks. The percentage area affected was highly variable and ranged from very close to zero to 82%. Average percent area affected varied regionally (Table 5) from a minimum of 0.37% in Western and Central Africa to 12.04% in Europe. Trend data were not available, but it seems that the total area affected has increased from previous FRA surveys – total area affected in 2015 was 141 million ha, as compared to 68 million ha in 2005 (FRA 2005/thematic study/chapter4).

4. Discussion

4.1. Outlook

The FRA 2015 data analysed in this study suggest that in planted forests, a new timber resource is continuing to be created and that it will contribute significantly not only to future wood and energy supplies but can also meet a range of wider social and environmental benefits (ecosystem services). Planted forests are likely to continue to supply an increasing proportion of the world's wood requirements; the trend is supported by this new dataset. The ability of planted forests to increase supply will depend on global and

Table 5
Summary of forest, population trends, and climate impacts and risks by FAO sub-region.

Subregion	Population density 2015 (n/km^2)	% Change since 1990 Natural Forest	% Change since 1990 Planted Forest	% Change since 1990 Population	IPCC key risks	IPCC climate related drivers	Climate Risk Index	% Forest area affected by outbreaks	Outlook
South and Southeast Asia	276	−14	132	49	Drought, decreased crop productivity, storm and flood damage, drought	Warming trend, drying trend, extreme temperatures, extreme precipitation, cyclones	40	1.2	High population density, rapid population increase, large natural forest loss, but large planted forest expansion though rate slowing, climate impacts high. Population pressure and climate impacts likely to put pressure on further planted forest area. Focus on increasing productivity from existing resource, adaptation to extreme climate impacts
Europe	33	0	37	2	Storm and flood damage, decreased crop production, wildfires	Warming trend, drying trend, extreme temperatures, extreme precipitation	59	12	Medium density but stable population, stable natural forest, low planted forest expansion, medium climate impacts and high disease impacts. Focus on climate adaptation and forest health management to maintain status
Caribbean	188	40	79	25	Storm and flood damage, decreased crop production	Warming trend, drying trend, extreme temperatures, extreme precipitation	44	2.1	High population density, increased area of natural forest, medium increase in planted forest area, low population growth, high climate impacts and medium disease. Focus on adaptation to extreme climate impacts
Eastern Asia	137	6	72	16	Drought, decreased crop productivity, storm and flood damage, drought	Warming trend, drying trend, extreme temperatures, extreme precipitation, cyclones	49	8.7	High population density, low population growth, low increase in natural forest area and medium increase in planted forest area, climate impacts high and medium level of health impacts. Focus on adaptation to extreme climate impacts
Western and Central Asia	40	4	70	63	Drought, decreased crop productivity, storm and flood damage, drought	Warming trend, drying trend, extreme temperatures, extreme precipitation, cyclones	98	11.4	Medium population density, high population growth, low increase in natural forest, medium growth in planted forest area, low climate impacts, high health impacts. Focus on increasing production from existing planted forests and adaptation to extreme climate impacts
East and Southern Africa	43	−15	35	35	Drought, decreased crop productivity, flood damage, increased pest and disease impacts	Warming trend, drying trend, extreme temperatures, extreme precipitation	84	1.7	Medium population density, medium population growth, high loss of natural forest, low increase in planted forest, medium climate and health impacts. Focus on expanding planted forest area and adaptation to drought and health risks
Oceania	5	−3	58	46	Storm and flood damage	Warming trend, cyclones, extreme precipitation	59	2.0	Low population density and growth, low loss in natural forests, medium increase in planted forests, medium levels of climate and health impacts. Focus on adaptation to extreme climate impacts
Central America	68	−11	17	45	Storm and flood damage, decreased crop production	Warming trend, drying trend, extreme temperatures, extreme precipitation	50	0.4	High population density and growth, high loss of natural forest, low planted forest increase, high climate impacts, low health impacts. Focus on increasing planted forest area, adaptation to extreme climate impacts
Western and Central Africa	47	−10	122	94	Drought, decreased crop productivity, flood damage, increased pest and disease impacts	Warming trend, drying trend, extreme temperatures, extreme precipitation	111	0.4	Medium population density, high population growth, medium natural forest loss, high planted forest increase, low climate and health impacts. Focus on increasing planted forest area and adaptation to drought
Northern Africa	25	−15	24	63	Drought, decreased crop productivity, flood damage, increased pest and disease impacts	Warming trend, drying trend, extreme temperatures, extreme precipitation	105	12.1	Low population density, high population growth, high loss of natural forest, low increase in planted forest area, low climate impacts, high health impacts, dependence on fuel wood. Focus on increasing planted forest area, adaptation to drought, forest health management
South America	24	−10	87	39	Storm and flood damage, decreased crop production	Warming trend, drying trend, extreme temperatures, extreme precipitation	78	1.2	Low population density, medium population growth, medium loss of natural forest, high increase in planted forest area, low climate and health impacts. Focus on increasing planted forest area, adaptation to extreme climate impacts
North America	18	−2	87	27	Wildfires, storm and flood damage	Warming trend, drying trend, extreme temperatures, extreme precipitation, cyclones	50	11.2	Low population density, low population growth, stable natural forest, high increase in planted forests, medium climate impacts, high health impacts. Focus on health management and adaptation to extreme climate impacts

country policies, the sustainable forest management and trade requirements, and the development of supply chains and markets (Freer-Smith and Carnus, 2008). The FRA dataset has allowed us to develop a global and regional picture of the extent and trends in a number of planted forests variables over the period 1990 to 2015. Overall planted forests are playing a very significant role in 2015. While deforestation has continued to occur, the area of planted forests has increased to 277 million hectares (now making up 6.95% of forest area) and this has slowed deforestation. While expansion has continued over the period, the rate of that expansion has dropped in the decade from 2005 to 2015. So while general signals concerning the state of planted forests are good – increase in area, roundwood supply approaching that from natural forests – there are some potential concerns regarding the ability to meet future demands, but also some opportunities. Outlook statements developed for the FAO sub regions based on past changes in planted forest area, population growth, and climate and forest health risks to identify key issues for the future are summarised in Table 5. Overall, we suggest that climate impacts, especially from extreme climatic events will affect planted forests in the future and that forest health impacts can be expected to increase. Expansion of planted forest area will be at a slower rate than previously and this may put pressure on roundwood supply; however there will be a lag between increase in area and supply so this may not be a real concern over time.

Regionally there are variations in the outlook for planted forests. The two most stable regions are Europe and North America. Both these regions have well established and relatively stable, or increasing, areas of planted forests. They also have stable natural forest areas, and populations are either stable or only growing slowly. The main issues for these two regions will be climate change, adaptation to extreme events and managing forest health impacts. By contrast Asia – South and Southeastern, Western and Central, and to a lesser degree Eastern – has a high and increasing population pressure, recent rapid expansion of planted forest area and relatively low roundwood production from these new forests and high climate impacts and risk index. These regions will probably face a number of challenges both from population pressure slowing any future increase in planted forest area and from some very significant impacts from extreme climate events. To respond to these pressures, focus on enhancing productivity from existing forests and developing robust climate adaptation strategies is likely to be a high priority. The dominant risk to South America, including the planted forest powerhouses of Brazil and Chile, appears to be climate impacts. Africa has a major issue with continuing loss of natural forest area, population growth and only low to moderate increase in planted forest areas. This suggests that focus will need to be on expanding planted forest areas, but that this will have to take into account the high risk of future droughts and also pests and diseases on the success of these new forests. Other smaller regions – Oceania, the Caribbean, Central America – will face their main challenges around the impacts of extreme climate events.

4.2. Challenges and opportunities facing planted forests

The challenges facing planted forests will come from population growth and climate impacts, but also other issues such as Governance (Cubbage et al., 2014) which can affect forest investment and management. The noted decrease in expansion rate of planted forest area, while unexplained here, is of concern. Competition for land is likely to be a major factor affecting future expansion. The UN is projecting that an increase in food production of 60% will be required by 2050 (UN 2013). A more recent study (Ray et al., 2013) suggests it will not be possible to meet this target by boosting crop yields on existing land. This will lead to competition for forest land, both natural and planted, and requires forestry and farming practices that produce more with less land and water. Regions with the highest population pressure (mainly Asia) will have the highest level of competition and future expansion may not be an option or may be very difficult.

The focus may then move to intensification of management and increasing productivity in existing forests. Well managed planted forests usually have higher yields of wood than natural, unmanaged forests, with commercial plantations in the tropics having annual growth rates of 10–30 $m^3\ ha^{-1}$ compared to 1–5 $m^3\ ha^{-1}$ for natural forests (Evans and Turnbull, 2004). Annual growth rates could not be assessed for planted forests within the FRA 2015 data set, but the planted forests thematic study (Del Lungo et al., 2006) gives a more comprehensive picture that complements Evans and Turnbull. There are a number of examples of improvements in planted forest productivity in the literature, often related to genetic improvement, e.g., Bouffier et al. (2008). Brazil has shown a steady increase in productivity; in the 1970s, the average yield was 13 $m^3\ ha^{-1}\ yr^{-1}$, and it currently exceeds 40 $m^3\ ha^{-1}\ yr^{-1}$ (Gonçalves et al., 2013; IBA, 2015). New Zealand can demonstrate a 25% improvement in productivity through use of improved genotypes in its radiata pine forests (Kimberley et al., 2015). Intensification is a feature of many national research programmes, e.g., www.gcff.nz.

It is clear from this study and from the associated literature that pest (including insects and pathogens) problems are giving rise to increasing levels of loss in planted forests. This includes both those that are established based on native and non-native species. Native species in planted forests are often very seriously damaged by native pests but they are also subject to increasing problems due to accidental introductions of non-native organisms. Plantations of non-native, or introduced, species such as Eucalyptus, Pinus and Acacia have typically been relatively free of pest problems during the early years of establishment due to a separation from their natural enemies (Wingfield et al., 2008, 2010). In all areas studied, this situation has changed dramatically as pests are accidentally introduced, but also where native organisms have adapted the ability to infect/infest trees (Wingfield, 2003; Wingfield et al., 2010). Given the dramatic increases in the movement of pests globally, largely driven by anthropogenic factors (Liebhold et al., 2012; Santini et al., 2013), forest health will be an increasingly important constraint to forest productivity although the application of modern breeding and other technologies can offset losses (Wingfield et al., 2012). The impacts of future climate related events remain poorly understood although there is good evidence for increased pest problems in some situations (Sturrock et al., 2011). These will require increased emphasis on forest health management and also adaptation strategies to deal with a changing climate. Investment in forest health research is globally significant and organisations such as IUFRO (www.iufro.org) are coordinating major global initiatives on forest health including for example newly established task forces on these topics.

One of the most important challenges to the further expansion of planted forests and indeed the on-going management of existing forests is that of societal expectations. In the past there was serious concern about conversion of natural forest systems to plantations and thus a strong negative perception of planted forests. However, with the development of independent third party audit certification schemes such as FSC (www.fsc.org) and PEFC (www.pefc.org) in the 2000s this perception is changing. These schemes disallow conversion of natural forests to plantations, and together with the development of WWF's New Generation Plantations platform and its concept of well-managed and designed, inclusive and profitable plantations (NGP, 2014), the negative views of planted forests will most likely change. Acceptability does appear to be increasing with a more positive view from bodies such as FSC

where plantations are now fully integrated into global standards (Maunder 2014 pers comm). This will make it easier to develop new forests in the future. Community involvement and dialogue between forestry companies and stakeholders is becoming increasingly important. Initiatives such as The Forests Dialogue (The Forests Dialogue, 2015), convenes exchanges between forestry companies and civil society organisations, provides an ongoing, multi-stakeholder dialogue focused on developing mutual trust, a shared understanding, and collaborative solutions to sustainable forest management across a range of topics such as "Intensively Managed Planted Forests (IMPF)", and "Food, Fuel, Fibre and Forests (4F's)".

Increasingly, planted forests will need to be recognised within the wider community for the range of values provided, not just the timber. While this analysis has shown that the predominant use of planted forests by the top 20 countries was for 'production', planted forests are established and managed for a wide range of objectives not solely for intensive wood production. Historically trees and woodlands have been planted for landscape, protection (against snow avalanche, landslip and soil erosion), hunting and other socio economic objectives. In the East Asian region for example the protection which planted forests provide against soil erosion and flooding have been important drivers of woodland creation. In China alone, the Natural Forest Protection Program (NFPP) and the Conversion of Cropland to Forest Program (CCPF), triggered mainly by the flooding disaster of 1998, have generated afforestation area of more than 32.5 million hectares.

In Europe and North America the increasing areas of planted forests are likely to have even broader explanations. The Millennium Ecosystem Assessment and subsequent research and policy initiatives have been informed by the ecosystem services concept. This categorises the benefits/services of ecosystems as: Supporting Services such as primary production, soil formation, nutrient and water cycling which provide the basic infrastructure of life; Provisioning Services which are the goods such as food, fuel and fibre; Regulating Services such as climate and hazard regulation (prevention of erosion, carbon storage, water regulation, avalanche protection, etc.); and Cultural Services such as recreational use, benefits to health and spiritual well-being. The important policy development has been the recognition that as populations increase, there will be a need to manage rural and urban landscapes so as to benefit from the full range of services which woodland and trees can provide. Relative to other land-uses, and particularly when compared to food production, the benefits from planted forests especially their protection functions are often uncosted and may be enjoyed by stakeholders other than those who own the land (Boyd et al., 2013). It has become recognised that land-use policies focussed solely on say agriculture or wood production, give lower overall benefits relative to policies which consider the full range of ecosystem services (Bateman et al., 2013). The drivers for establishment of new forests in the future may therefore be through new opportunities from voluntary carbon offset accreditation schemes or on a wider scale through the FCCC REDD + scheme rather than just timber alone.

In this study we have shown that planted forests will continue to be a major source of timber and other forest products that on an area basis far outweigh production from natural forests. A recent paper (Buongiorno and Zhu, 2014) noted that planted forests reduced harvesting from natural forests globally by 26% and had significant ecological benefits. We have also shown that in some regions, expansion rates of planted forests are decreasing and that climate impacts and population pressures on land availability will have an impact on planted forests in the future. We suggest these pressures can be managed by development of more intensive management regimes in existing forests, improved forest health management techniques, and the development of adaptation strategies to mitigate climate change impacts. Additionally the increasing involvement of communities with planted forest issues and the development of socially based programmes such as forest certification and New Generation Plantations will aid in future management of existing forests and development of new ones.

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References

Bateman, I.J., Harwood, A.R., Mace, G.M., Watson, R.T., Abson, D.J., Andrews, B., Binner, A., Crowe, A., Day, B.H., Dugdale, S., Fezzi, C., Foden, J., Hadley, D., Haines-Young, R., Hulme, M., Kontoleon, A., Lovett, A.A., Munday, P., Pascual, U., Paterson, J., Perino, G., Sen, A., Siriwardena, G., Van Soest, D., Termansen, M., 2013. Bringing ecosystem services into economic decision-making: land use in the United Kingdom. Science 341 (6141), 45–50.

Bouffier, L., Rozenberg, P., Raffin, A., Kremer, A., 2008. Wood density variability in successive breeding populations of maritime pine. Canadian J. Forest Res. 38 (8), 2148–2158.

Boyd, I.L., Freer-Smith, P.H., Gilligan, C.A., Godfray, H.C.J., 2013. The consequence of tree pests and diseases for ecosystem services. Science 342 (6160).

Buongiorno, J., Zhu, S., 2014. Assessing the impact of planted forests on the global forest economy. NZ J. Forest Sci. 44 (Suppl 1), S2.

Carle, J., Holmgren, P., 2008. Wood from planted forests: a global outlook 2005–2030. Forest Prod. J. 58, 6–18.

Cubbage, F., Mac Donagh, P., Balmelli, G., Morales Olmos, V., Bussoni, A., Rubilar, R., De La Torre, R., Lord, R., Huang, J., Afonso Hoeflich, V., Murara, M., Kanieski, B., Hall, P., Yao, R., Adams, P., Kotze, H., Monges, E., Hernandez Perez, C., Wikle, J., Abt, R., Gonzalez, R., Carrero, O., 2014. Global timber investments and trends, 2005–2011. NZ J. Forest. Sci. 44 (Suppl 1), S7.

Del Lungo, Ball, J., Carle, J., 2006. Global planted forests thematic study: results and analysis FAO. Planted Forests and Trees Working Paper 35b , p. 38.

Evans, J., 2009. Planted forests: uses, impacts and sustainability. Rome: CAB International and Food and Agriculture Organization of the United Nations (FAO).

Evans, J., Turnbull, J.W., 2004. Plantation forestry in the tropics: the role, silviculture and use of planted forests for industrial, social, environmental and agroforestry purposes, OUP Oxford.

Food and Agriculture Organization of the United Nations (FAO), 2010. Global Forest Resources Assessment 2010. <http://www.fao.org/docrep/013/i1757e/i1757e.pdf>.

FAO, 2012. FRA 2015 Terms and Definitions. Forest Resources Assessment Working Paper 180, p. 31.

Freer-Smith, P., Carnus, J.M., 2008. The sustainable management and protection of forests: analysis of the current position globally. Ambio 37 (4), 254–262.

Gonçalves, J.L.M., Alvares, C.A., Higa, A.H., Silva, L.D., Alfenas, A.C., Stahl, J., de Barros Ferraz, S.F., de Paula Lima, W., Brancalion, P.H.S., Hubner, A., Bouillet, J.D., Laclau, J., Nouvellon, Y., Epron, D., 2013. Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. For. Ecol. Manage. 301, 6–27.

IBA, 2015. Brazilian Tree Industry 2015: a report of the Brazilian Tree Industry, Brasilia, p. 62. <http://www.iba.org/images/shared/iba_2015.pdf>.

International Congress on Planted Forests (ICPF), 2013. Planted forests are a vital resource for future green economies. Summary report of the 3rd International Congress on Planted Forests. <http://www.fao.org/forestry/37902-083cc16479b4b28d8d4873338b79bef41.pdf>.

IPCC, 2014. Summary for Policy Makers. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, p. 32.

Jürgensen, C., Kollert, W., Lebedys, A., 2014. Assessment of industrial roundwood production from planted forests. <http://www.fao.org/3/a-i3384e.pdf>.

Kimberley, M.O., Moore, J., Dungey, H., 2015. Quantification of realised genetic gain in radiata pine and its incorporation into growth and yield modelling systems. Can. J. For. Res. (accepted for publication).

Kreft, S., Eckstein, D., 2013. Global Climate Risk Index 2014. Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2012 and 1993 to 2012. Germanwatch e.V, p. 28. <http://www.germanwatch.org/en/cri>.

Liebhold, A.M., Brockerhoff, E.G., Garrett, L.J., Parke, J.L., Britton, K.O., 2012. Live plant imports: the major pathway for forest insect and pathogen invasions of the US. Front. Ecol. Environ. 10, 135–143.

New Generation Plantations (NGP), 2014. New generation plantations: review 2014. <http://newgenerationplantations.org/multimedia/file/12b486cb-ea24-11e3-9f9e-005056986313>.

Paquette, A., Messier, C., 2009. The role of plantations in managing the world's forests in the Anthropocene. Front. Ecol. Environ. 8 (1), 27–34.
Pawson, S.M., Brin, A., Brockerhoff, E.G., Lamb, D., Payn, T.W., Paquette, A., Parrotta, J.A., 2013. Plantation forests, climate change and biodiversity. Biodivers. Conserv. 22 (5), 1203–1227.
Payn, T., Carnus, J., Freer-Smith, P., Orazio, C., Nabuurs, G.-J., 2014. Third international congress on planted forests: planted forests on the globe – renewable resources for the future. NZ J. Forest. Sci. 44 (Suppl 1), S1.
Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield trends are insufficient to double global crop production by 2050. PLoS ONE 8 (6), e66428. http://dx.doi.org/10.1371/journal.pone.0066428.
Robinet, C., Roques, A., 2010. Direct impacts of recent climate warming on insect populations. Integrat. Zool. 5, 132–142.
Santini, Ghelardini, A.L., De Pace, C., Desprez-Loustau, M.L., Capretti, P., Chandelier, A., Cech, T., Chira, D., Diamandis, S., Gaitniekis, T., Hantula, J., Holdenrieder, O., Jankovsky, L., Jung, T., Jurc, D., Kirisits, T., Kunca, A., Lygis, V., Malecka, M., Marcais, B., Schmitz, S., Schumacher, J., Solheim, H., Solla, A., Szabò, I., Tsopelas, P., Vannini, A., Vettraino, A.M., Webber, J., Woodward, S., Stenlid, J., 2013. Biogeographical patterns and determinants of invasion by forest pathogens in Europe. New Phytol. 197, 238–250.
Settele, J., Scholes, R., Betts, R., Bunn, S.E., Leadley, P., Nepstad, D., Overpeck, J.T., Taboada, M.A., 2014. Terrestrial and inland water systems. In: Field, C.B., Barros, V.R., Dokken, D.J., et al. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271–359.
Sturrock, R.N., Frankel, S.J., Brown, A.V., Hennon, P.E., Kliejunas, J.T., Lewis, K.J., Worrall, J.J., Woods, A.J., 2011. Climate change and forest diseases. Plant. Pathol. 60, 133–149.
The Forests Dialogue, 2015. The Forests Dialogue: Overview. <http://theforestsdialogue.org/about>.
Vira, B., Wildburger, C., Mansourian, S., 2015. Forests, trees and landscapes for food security and nutrition. A global assessment report. IUFRO World Ser. 33, 1–172.
Wingfield, M.J., 2003. Increasing threat of diseases to exotic plantation forests in the Southern Hemisphere: lessons from Cryphonectria canker. Australas. Plant Pathol. 32, 133–139.
Wingfield, M.J., Slippers, B., Hurley, B.P., Coutinho, T.A., Wingfield, B.D., Roux, J., 2008. Eucalypt pests and diseases: growing threats to plantation productivity. Southern Forests 70, 139–144.
Wingfield, M.J., Slippers, B., Wingfield, B.D., 2010. Novel associations between pathogens, insects and tree species threaten world forests. New Zealand J. Forest Sci. 40, S95–S103.
Wingfield, M.J., Roux, J., Slippers, B., Hurley, B.P., Garnas, J., Myburg, A.A., Wingfield, B.D., 2012. Established and new technologies reduce increasing pest and pathogen threats to Eucalypt plantations. Forest Ecol. Manage. 301, 1–10. http://dx.doi.org/10.1016/j.foreco.2012.09.002.
WWF, IIASA, 2012. Living Forests Report. Gland, Switzerland.