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Review and synthesis

Trends in management of the world's forests and impacts on carbon stocks ☆,☆☆

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ABSTRACT

Global forests are increasingly affected by land-use change, fragmentation, changing management objectives, and degradation. In this paper we broadly characterize trends in global forest area by intensity of management, and provide an overview of changes in global carbon stocks associated with managed forests. We discuss different interpretations of "management" and highlight some important accounting and analysis issues. The area of global forests has declined by 3% since 1990 but the area of planted forest has increased in all regions of the world and now accounts for almost 7% of global forest land. The area of primary forest, which is typically defined as lacking direct human influence, is about 34% of all forest land according to country reports, but the area is declining especially in South America and Africa because of human-caused habitat fragmentation and degradation. Concurrently, the area of naturally regenerated forest that is not classified as primary forest has declined. As a result of increasing management intensity, the area of unmanaged forest, typically defined as land lacking protected status or a management plan, dropped significantly since 1990 and now comprises only 21% of global forests. There have been significant increases in areas of forest used for non-wood forest products such as protection of soil and water, conservation of biodiversity, and provision of social services. Globally, timber production has been relatively stable since 1990, but increasing areas of forest used for non-wood forest products indicates that harvesting is taking place on a smaller proportion of the total forest area. Based on trends in the area of managed forest and regional studies, it is clear that historical and current forest management has been a very significant determining factor of current carbon stocks. Established forests currently offset about 30% of global emissions of CO_2 from fossil fuel use, and there are mitigation opportunities involving forests that could increase the gross terrestrial C uptake from roughly 4.0 to 6.2 Pg C annually. However, our results suggest that a diversifying use of forest land may have significant consequences for maintaining or increasing the current rate of terrestrial carbon sequestration. In the future, indirect human influences such as increasing atmospheric CO_2 and climate change, along with the direct effects of land management and projected increasing demand for wood biofuel, are likely to become increasingly important elements that influence land management strategies and the role of forests in the global carbon cycle.

Contents

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1. Introduction

Global forests are increasingly affected by land-use change, fragmentation, changing management objectives, and degradation. At the same time all forests, no matter how remote, are responding to changes in atmospheric composition especially increasing concentration of CO_2 and climate change. How these concurrent factors will affect future forests is a critical question not only for the sustainability of the many traditional services provided by forests such as timber production and watershed protection, but also for the continuation of the role of forests in removing emitted CO_2 from use of fossil fuels. If the global carbon sink in established forests that currently absorbs about 30% of fossil fuel CO_2 emissions (Pan et al., 2011a) is reduced or eliminated, global efforts to mitigate climate change will require even more emissions reductions than currently envisioned (IPCC, 2014). Because the concept of forest management takes on different meanings around the world in different contexts, and because changes in forest management are often considered to be a significant component of climate change mitigation, the purpose of this paper is to highlight some of the different interpretations of forest management and reveal some of the major trends in forest management that are likely to affect the many services of forests in the future. We broadly characterize global forest area by intensity of management, and provide an overview of changes in global carbon stocks associated with managed forests. We highlight some of the important accounting and analysis issues associated with assessments of managed forests and carbon stocks. We conclude with comments about accounting for the full impacts of forest management on the concentration of CO_2 in the atmosphere, taking consideration of harvested wood and associated indirect effects such as substitution of wood for other material.

"Managed forest" may take on different meanings in different contexts, but generally refers to forests that have been directly impacted by human activities, excluding deforestation which is distinguished from forest management since it is a change in land use according to the most commonly used definition (Foley et al., 2005). In some contexts, a forest may be defined as managed even without obvious direct human impacts, for example, areas that have been set aside or protected by administrative statute.

Forest management is related to goals defined by the landowner or responsible management entity, and there are typically specific management practices that support the defined goals. Tree plantations and natural forests managed for wood products are obvious examples of "managed forests", and for these examples, applied practices leading to the goal of producing timber may include thinning, harvesting, and regeneration treatments. Forests with other management objectives may not be considered managed since the direct influence of human activity is minimal. For example, a wilderness area is by some definitions managed for its biodiversity values, but direct human impacts may be limited to maintenance of hiking trails and low-impact camping sites. Indirect human impacts such as increasing atmospheric CO_2 and climate change may significantly affect forests no matter how remote, even if the cause of these effects originates elsewhere.

To help frame the concept of managed forests, Table 1 includes some common forest classification terms arranged in an approximate hierarchy of management intensity. In this paper we focus on the forest land classifications, but also give some consideration to those forests or areas with tree cover that may not meet some definitions of forest, and are often classified as areas with "trees

Table 1
Land management classifications and definitions of key terms, roughly organized by intensity of management from lowest to highest. Categories are not all mutually exclusive.

Classification	Description
Land classifications	
Wildland	Land with little to no evidence of direct human impact as evidenced by occurrence of population density, land transformation, accessibility, and infrastructure (Sanderson et al., 2002)
Intact land	An unbroken expanse of natural ecosystems showing no signs of significant human activity, and large enough that all native biodiversity, including viable populations of wide-ranging species, could be maintained (adapted from Potopov et al. (2008))
Protected areas	Areas especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means (FAO, 2010). Direct human impacts may be allowed by administrative statute
Forest land[a] classifications	
Primary forest	Naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed (FAO, 2010)
Protected forest	Forest area within formally established protected areas, regardless of the purpose for which the protected areas were established (FAO, 2010)
Unmanaged natural forest	Forest land without protected status that does not have a documented management plan. Some areas may be actively managed or there may be direct human impacts such as occasional tree harvesting
Managed natural forest	Forest area that has a long-term (ten years or more) documented management plan, aiming at defined management goals, which is periodically revised (FAO, 2010). Excludes forest plantations and managed forests without a documented management plan
Planted forest	Forest predominantly composed of trees established through planting and/or deliberate seeding (FAO, 2010). Plantation forests may be used for timber production or other purposes such as erosion control
Land with trees outside forests	
Other wooded land	Land not classified as "forest", spanning more than 0.5 hectares; with trees higher than 5 m and a canopy cover of 5–10%, or trees able to reach these thresholds *in situ*; or with a combined cover of shrubs, bushes and trees above 10%. It does not include land that is predominantly under agricultural or urban land use (FAO, 2010)
Agroforestry	A collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence (Lundgren and Raintree, 1982)
Settlements	All developed land with trees, including transportation infrastructure and human settlements of any size, unless already included under other categories (IPCC, 2003)

[a] Land spanning more than 0.5 hectares with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds *in situ*. Forest lands that are temporarily treeless because of harvest or disturbance are included. Forest does not include land that is predominantly under agricultural or urban land use, even though such land may have some tree cover. Tree plantations are included (FAO, 2010).

outside forests". For the most part, statistics presented in this paper reflect the areas of forests as defined by the United Nations Food and Agriculture Organization (FAO).

When compiling statistics about forest area, the highly ambiguous difference between land cover and land use should be kept in mind (Erb et al., 2007). Generally, field-based observations such as those traditionally generated from forest inventories or land mapping describe land use classes such as timber plantation or unmanaged forest, and distinguish these classes from land that has a primary non-forest use such as a residential development, even if trees are present in the landscape. Recently, remote sensing has been widely used to monitor land cover and land cover changes, and classifications of land cover are commonly based on both vegetation types and land-use types such as deciduous forests, grasslands or agricultural lands. The common term "land-cover change" may describe a land-use change or may only describe a temporary condition. For example, changes in land cover may be associated with conversion of land from one class to another (e.g. deforestation for agriculture), or may be associated with management practices within a land class such as harvest followed by regeneration. Subtle differences in use of terminology can cause confusion and misinterpretation of results. This paper focuses on land use rather than land cover using the inventory-based definition of FAO, because of the need to describe forests as impacted by various human activities, even though some of the information reported may represent changes in land cover and be fully or partially derived from remote sensing.

Inconsistent use and interpretation of terminology has had a confounding effect on global carbon cycle analyses, especially with respect to separating the direct human-induced effects of land use and management on the carbon cycle from the indirect effects of environmental changes such as climate change and increasing atmospheric CO_2. Houghton (2013) argues that this distinction is critically important because of climate-change policies that seek to attribute CO_2 reductions from land management primarily to the direct effects of the management activity, separate from reductions that happen naturally or as an indirect result of human actions. Pongratz et al. (2014) developed a comprehensive framework for partitioning the global land-use and land-cover change carbon flux into components so that estimates from various studies can be compared. They found at least nine definitions that differed significantly with respect to treatment of carbon emissions and sinks, and how vegetation regrowth is accounted. These studies set an appropriate context for this paper, which delves deeper into the direct effects of management on land use and carbon, and highlights how pervasive such effects have been and will continue to be in the future.

2. Methods

Estimates of managed forest areas reported here come from several different sources of information: remote sensing, field inventories, bookkeeping studies, models, and country reports. Most of this information is readily available from international organizations such as FAO and the Intergovernmental Panel on Climate Change (IPCC). The methodologies are described in Birdsey et al. (2013) and Pan et al. (2013), and briefly summarized here. The main elements of current monitoring systems such as Landsat satellites and traditional forest inventories will continue to be the backbone of many forest monitoring systems around the world for many years, although new remote sensing and modeling technologies are increasingly being deployed in operational forest monitoring.

2.1. Remote sensing

Aerial photographs have been used for more than 80 years in forest inventories to estimate the proportion of land classified as forest in a given sampling area, and as a first-phase sample in a double sampling strategy (Gregoire, 1993). In more recent decades the Landsat satellites have provided a time series of remotely-sensed digital images that are widely used for establishing historical baselines and for current monitoring of deforestation, forest degradation, and natural disturbances; and when associated with field observations or models, for estimating changes in biomass and carbon stocks. The MODIS satellite has also had a long history of operational deployment, providing useful information about forest biomass, productivity, and disturbances over large regions at coarse spatial resolution (Running et al., 2004; Wang et al., 2010). Remote sensing approaches typically represent land cover and land-cover change, not land use or land-use change, although these terms are often used interchangeably. Both terms can be associated with land management, but it is usually difficult to separate human and natural causes of observed changes using remote sensing images without combining the images with other information, and it may be difficult to determine whether an observed change in land cover indicates a permanent change in land use or a temporary change in land cover without an associated change in land use. A remote sensing approach is often combined with field sampling in national forest inventories to more effectively identify causes of change and to improve overall monitoring efficiency.

2.2. National forest inventories and field sampling

National forest inventories based on field sampling have been used for more than a century for assessing timber supplies and monitoring forest changes, and can be the foundation of forest carbon monitoring, either as an initial inventory of carbon stocks from which changes can be estimated using remote sensing or modeling, or as a direct estimate of stock-change from repeated inventories. National forest inventories are particularly suitable for monitoring the vital elements of forest dynamics (growth, harvest, mortality) and for estimating biomass of trees and forests, and when combined with remote sensing, can provide statistics with quantifiable error estimates about managed forest uses. Forest inventories involve systematic or random selection of sampling locations in areas as large as countries; field measurements of tree parameters such as species, diameter and height; and the development of allometric equations estimating a variable of interest that is difficult to directly measure (e.g., timber volume or biomass) (Pearson et al., 2007). Most of the global statistics on forest biomass and other forest attributes reported by FAO are based on national forest inventories (FAO, 2010).

2.3. Bookkeeping

Houghton et al. (2012) used a bookkeeping approach comprised of information about changes in forest area from nationally-aggregated land-use statistics, satellite data on land cover, and satellite data on wildfires; and vegetation response curves to define per-hectare changes in carbon density as a result of land management. The bookkeeping model sums the per-hectare changes in carbon density over all areas that have observed change in management; in this way, global estimates as reported in Houghton et al. (2012) are a good approximation of both the area and carbon density changes that result from direct human activities. Estimated changes in terrestrial carbon stocks that do not result from the bookkeeping approach may be attributed to indirect human factors such as CO_2 fertilization and N deposition, and natural disturbances such as hurricanes or fires in areas without evidence of land-use changes (if the bookkeeping approach does not specifically include these factors).

2.4. Model estimates

A variety of ecosystem and accounting models are used to quantify forest carbon dynamics through the synthesis and integration of data representing different spatial and temporal scales, from detailed plot-level measurements to national scale remote sensing products (Kurz et al., 2009; Lemay and Kurz, 2008; Wuldur et al., 2008). Models are often the best tools available to create and compare future scenarios to examine the effects of different activities or events (e.g. management, land-use change, natural disturbances). In this paper, models are the sources of most estimates about changes in carbon pools that result from land management activities and are also used to infer the causes of observed changes in carbon stocks especially those causes that are difficult to directly observe such as CO_2 fertilization and N deposition.

2.5. Country reports

The UN organizations FAO and IPCC rely on country reports, often based on national forest inventories but sometimes based on very incomplete data, for compiling regional and global statistics (FAO, 2010 and earlier reports; FAOSTAT, 2009; Ciais et al., 2013). FAO currently provides two data sets useful for estimating land use and changes in land use. FAOSTAT (2009) reports areas in croplands, pastures, forests, and other lands, and the periodic FAO Forest Resource Assessments report details about forests alone. Periodic IPCC Assessments report summary statistics about the global carbon cycle including the role of terrestrial ecosystems, based on both country reports and other approaches described above, including estimates of terrestrial ecosystem carbon calculated as a residual of observations of emissions, atmosphere, and oceans (Ciais et al., 2013; Le Quéré et al. 2014). Global analyses that rely on reporting by individual countries are more accurate for some countries than others and may include significant inconsistencies and ambiguities (Grainger, 2008).

2.6. Combining information from different sources

From the forest inventory perspective, and as defined by FAO, forest land may include areas that are temporarily treeless as a result of harvesting or natural disturbance. This same land may be classified in a non-forest category from remote sensing of land cover, and in a forest category from an inventory of forest land. The opposite is also true -- the FAO forest definition does not include land that is predominantly agricultural or urban, even if such land has some tree cover. Failing to account for these differences can have a significant effect on the resulting estimates.

3. Results

3.1. Global forest area and management trends

According to statistics compiled periodically by FAO (2010), the area of global forests has declined by 3% since 1990 but the area of planted forests has increased in all regions of the world and now accounts for almost 7% of global forest land (Table 2). The FAO statistics also indicate that the area of primary forest is about 34% of all forest land, and has been declining since 2000 especially in South America and Africa. Conversion of natural forest to plantations and other human activities have reduced the area of both primary forests and naturally regenerated forests that are not classified as primary forest.

There have been significant changes in the management status of global forests over the last 20 years (Table 3). The area of forest within protected areas has increased by about 36% considering data from countries that have consistently reported over the period. The total area of protected forests in 2010 is 460 million ha if counting all countries that reported for that year in the most recent global FAO statistics (FAO, 2010). Likewise, the area of forest with a documented management plan increased by 18% based only on countries that consistently reported over the period, although the total area of forest with a management plan is closer to 1631 million ha. As a result of this increase in management intensity of global forests, the area of unmanaged forest dropped significantly over the 20 years, by about 35%, and now comprises only 21% of global forests.

Not all areas of planted forests and forests with a management plan are managed intensively for timber products. FAO (2010) estimates that 30% of the world's forests are used primarily for production of both wood and non-wood forest products, and that the area of forest land primarily used for forest products has declined slightly as more forests are designated for other uses or multiple uses. Since the global production of industrial roundwood and fuelwood was nearly stable between 1990 and 2005 at about 3.2 billion m^3 per year, there is a corresponding trend towards concentrating timber production on smaller areas of forest land as production of non-wood forest products increases. This trend may be changing since 2005 because of increasing interest in using wood for biofuel (FAO, 2009).

There are significant regional and national differences in the relative areas of forest protection and management intensities. For example, the Americas have a relatively higher proportion of forests in protected areas (10–17%) compared with Europe which has less than 5% of forest areas protected. Similarly, Russia reports that all of its forest area is covered by a management plan even though it is questionable whether all of the forest areas, especially in remote regions, are directly affected by human activities. Many other countries and regions, especially in Africa, report a much smaller percentage of forest area under management.

Table 2
Area of global forest land by land class.[a]

Forest land class	1990	2000	2010
	(1000 ha)		
Primary	1,352,216	1,392,869	1,358,864
Other naturally regenerated[b]	2,644,851	2,477,680	2,410,195
Planted forest	171,332	214,619	264,001
Total forest land	4,168,399	4,085,168	4,033,060

[a] From FAO (2010).
[b] Calculated as residual quantity from estimates of other classes and total forest; may be managed or unmanaged.

Table 3
Status and trends in management of global forests.[a]

Forest management class	1990	2000	2010
	(1000 ha)		
Trend in area of forest within protected areas[b]	266,482	296,874	360,715
Trend in area of forest with a management plan[c]	1,305,000	1,390,000	1,545,000
Trend in unmanaged natural forest[d]	1,339,851	1,087,680	865,195

[a] From FAO (2010).
[b] Includes data from countries that consistently reported for all 3 periods (FAO, 2010). The complete estimate for 2010 is 460,032 accounting for all countries that reported in 2010.
[c] Includes data from countries that consistently reported for all 3 periods (FAO, 2010). The complete estimate for 2010 is 1,630,589 accounting for all countries that reported in 2010.
[d] Calculated as difference between "other naturally regenerated forest" (Table 2) and trend in area of forest with a management plan (this table). Does not include primary forest.

At the opposite extreme from management for production of services, the area of primary forest that is defined as having no visible indications of direct human activity has also remained large but is declining according to FAO statistics. Only a few large areas are considered truly "wild", that is, lacking evidence of high population density, land transformation, accessibility, and infrastructure (Sanderson et al., 2002). Wild areas with predominant forest cover include portions of the boreal forests of Canada and Russia, and areas of tropical broadleaf forests of the Amazon Basin and Central Africa. Tropical deforestation and forest degradation occur at the boundaries of primary forests that are more accessible by human activities, and there is increasing concern about the future area of primary forests. A satellite-based analysis by Haddad et al. (2015) revealed that 70% of global forest area is within one km of the forest/nonforest boundary and therefore subject to fragmentation in the future, including some areas that are currently considered primary. Furthermore, in addition to direct human influence, indirect human influence is evident everywhere on the planet due to changing atmospheric composition especially increasing CO_2 concentration, N deposition, and climate change.

In addition to forests that are managed primarily for timber production, there has been a significant increase in areas of forest used for non-wood forest products. These include protection of soil and water, conservation of biodiversity, and provision of social services.

3.2. Changes in global forest carbon stocks and relation to land and forest management

Management intensity may have significant direct and indirect impacts on carbon stocks. Intensively managed forests can more efficiently grow timber and remove CO_2 from the atmosphere, yet carbon stocks of intensively managed forests tend to be less than primary forests (McKinley et al., 2011). Over time, carbon sequestered in harvested wood products becomes increasingly significant for forests that are managed on harvest rotations for timber products (Fig. 1; Perez-Garcia, 2005). Spatial and temporal scales are critical for analyzing carbon impacts of management. Generally, analyses at landscape or larger spatial scales, and for longer periods of time, give a more comprehensive picture of impacts (Fig. 2; McKinley et al., 2011).

As many authors have noted, estimation of changes in terrestrial carbon and attribution to causes is extremely challenging (e.g. Houghton et al., 2012; Le Quéré et al., 2014; Pan et al., 2011a). The most obvious and well-quantified effect of land management on the carbon cycle is that land-use and land-cover change (intended to reflect elements of both land-use change and land management) has accounted for net emissions of about 1.0 Pg C to the atmosphere each year from 2000 to 2009 (Houghton et al., 2012). This net estimate has been partitioned into gross sinks and sources, including estimation of the immediate effects during the reporting period of harvest, deforestation, forest degradation, and forest regeneration; and the legacy effects of decomposition and forest regrowth from these activities that were carried out before 2000 (Houghton et al., 2012; Pongratz et al., 2014). After accounting for the net effects of land-use and land-cover change, fossil fuel emissions, plus estimated changes in atmospheric CO_2 concentration and CO_2 uptake by the oceans, the remainder of the terrestrial C flux is often calculated as the "residual" needed to balance the global C budget, about 2.4 Pg C annually from 2000 to 2009 (Le Quéré et al., 2014). Following this logic of attribution, the entire 2.4 Pg C terrestrial sink is then attributed to CO_2 fertilization, N deposition, and climate change as reported in Le Quéré et al. (2014).

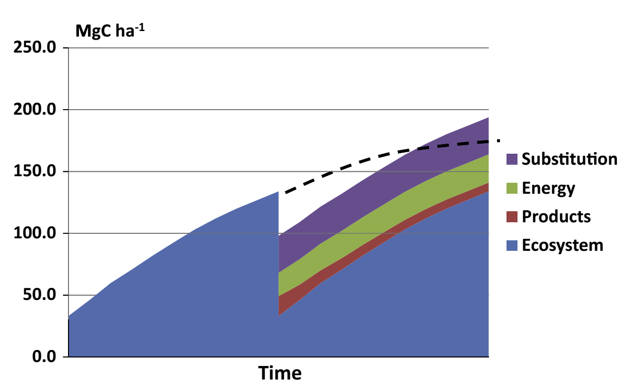

Fig. 1. Hypothetical example of carbon stored in a managed forest ecosystem, harvested wood products, burned for energy, and retained because of substitution for concrete and fossil fuel energy, compared with carbon stored in an unmanaged forest (dotted line). The managed forest has been replanted or afforested, harvested, and regenerated again. This example highlights full accounting for carbon in harvested wood products plus substitution of wood for fossil fuels and other products that require fossil energy to manufacture, and indicates that over time, a managed forest may have greater carbon benefits than an unmanaged forest.

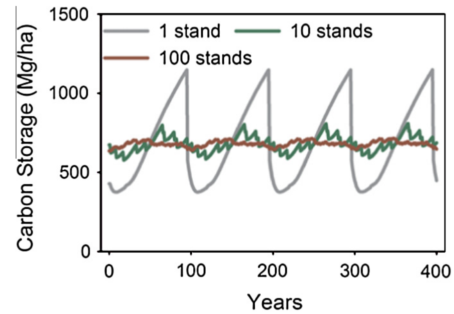

Fig. 2. The impacts of management actions on carbon storage at different spatial and temporal scales (adapted from McKinley et al. (2011)).

Pan et al. (2011a) estimated the residual terrestrial C sink based on a compilation of information from global forest inventories. They attributed most of the residual terrestrial land sink to "established" forests (forests remaining forests, excluding deforestation and afforestation of tropical forests), and attributed little or no net change to the effects of non-forest terrestrial land uses such as cropland, savanna, and pasture, which may individually be sources or sinks but their aggregate contribution to the land sink was not considered significant. In the Pan et al. (2011a) analysis, carbon in established forests was affected by multiple factors including management, natural disturbance, atmospheric composition, and climate change. Therefore, we suggest that the residual terrestrial carbon sink includes some effects of land management and natural disturbance that were not considered by Houghton et al. (2012) or Le Quéré et al. (2014) to be part of the land-use and land-cover change budget, as recently described by Erb et al. (2013). For example, there have been significant improvements in the productivity of industrial forest plantations (Stanturf et al., 2003), and many forest areas recovering from previous deforestation and non-forest uses are currently at relatively high productive ages (Pan et al., 2011b). Unfortunately, it is difficult if not impossible at the current time to separate the total residual terrestrial C sink at the global scale into the net effect of forest management and other factors such as CO_2 fertilization, N deposition, and natural disturbance. However, a recent study by Schimel et al. (2014) that reconciles global estimates from many different sources including Pan et al. (2011a), estimates that up to 60% of the global terrestrial C sink is attributed to increasing atmospheric CO_2.

Lacking availability of a global quantitative analysis that separates the relative contribution of all factors affecting forest carbon stocks, we assume that the lower bound on the net effect of land-use change and forest management during 2000–2009 is equal to that reported by Houghton et al. (2012) of −1.0 Pg C per year (i.e. a source), and the upper bound is equal to the entire estimated residual terrestrial sink for the same period, or +2.4 Pg C per year (Le Quéré et al., 2014). Based on expert analysis of the various reported estimates and modeling studies (many not reported here), the true estimate of the effect of forest management using the broad management definition of FAO could be roughly half-way between these two extremes, or about +0.7 Pg C annually, which is also about half of the total sink in temperate and boreal forests (Pan et al., 2011a). If this preliminary estimate of management impacts were directly associated with the area of global forest having a management plan as defined by FAO, the average gain in C on these lands would be very close to 0.4 tons C per hectare of managed forest per year. This estimate includes only the direct human-induced effects of management of established forests, excluding all other factors.

4. Discussion and conclusions

The FAO estimates of forest area, based on forest inventories and country reports, are different than similar estimates based on remote sensing. For example, Erb et al. (2007) using spatially explicit estimates of forest area based on land cover, indicated that FAO estimates based on land use are 94% of the land-cover based estimates. FAO has also used a satellite-based land-cover approach to complement the inventory approach, and these independent results show a slightly smaller global forest area that is 96% of the inventory-based approach (D'Annunzio et al., 2014). These differences are due to inherent contrasts in land use vs. land cover indicators. Estimates based on tree cover may include land with trees that does not meet the inventory-based definition of forest because the observed tree cover may be below the percentage threshold used for classifying forest from an inventory perspective, or there may be another more dominant land use that has significant tree cover, such as commonly observed on urban or developed land. On the other hand, a land-use indicator usually includes lands that are temporarily without trees (e.g., recently harvested but not regenerated) as forest land, whereas these areas can be classified as a nonforest land type based on cover because they lack observable tree cover.

Although the total global area of forest land has declined by a few percent since 1990, some categories of forest have been stable or increasing (Tables 2 and 3). The area of protected forest has increased, and management intensity of forest land has increased significantly, with substantial gains in the areas of planted forests and forests with a management plan. As a consequence, the trend in unmanaged natural forest has been sharply downward. Although not quantified at the global scale in this paper, it is highly likely that the area of land with trees outside forests has increased as urban and developed lands have grown (Guo et al., 2014), and as some formerly dry woodlands not satisfying the definition of forest have greened up (Brandt et al., 2015; Piao et al., 2015).

Globally, timber production has been relatively stable since 1990, but increasing areas of forest used for non-wood forest products indicates that harvesting is taking place on a smaller proportion of the total forest area, while harvesting for biofuel has increased recently. The indirect effect of concentrating timber production on a smaller land base is to reduce harvesting on other forest areas where carbon stocks may increase significantly in the absence of harvest. However, these areas are then subject to higher carbon losses from natural disturbances (including drought) as has become evident in the Western U.S. and elsewhere (Allen et al., 2010; Hicke et al., 2012). Overall, our results suggest a diversifying use of forest land that may have significant consequences for terrestrial carbon sequestration.

The important issue of interpreting the causes of the residual carbon sink is confused by different interpretations of the term "management". Estimates from Houghton et al. (2012) and related reports interpret management as primarily the result of timber harvest, a consequence of their methodology which is based in part on historical statistics about timber removals; whereas, in Pan et al. (2011a) and in FAO statistics, forest management is a much broader concept involving multiple uses of forests with varying levels of direct human impact. However, in addition to this inconsistency, it is still a somewhat intractable problem to separate out the effects of management, disturbance, and non-disturbance factors at the global scale although some notable efforts have been made at the regional scale (Bellassen et al., 2011; Hudiberg et al., 2013; Pan et al., 2009; Zhang et al., 2012). If the recent study by Schimel et al. (2014) establishes a credible upper bound on the effect of CO_2 fertilization, which is 60% of the terrestrial C sink (~1.4 Gt C yr^{-1}), given our estimate of 0.7 Gt C yr^{-1} as the consequence of forest management impacts, we may attribute the rest of the terrestrial C sink (~0.3 Gt C yr^{-1}) to the effects of climate, N deposition, natural disturbances, and growth/expansion of other terrestrial ecosystems such as shrublands.

An important historical consequence of the increasing intensity of global land management has been the long-term reduction of terrestrial carbon stocks as land has been converted to crops, pasture, and settlements for human life support (Pan et al., 2013). This has led to consideration in climate mitigation policies of the potential to increase carbon stocks on lands with lower stocks than expected compared with lands such as highly stocked old-growth forests that have experienced relatively less disturbance. Although much of the world's forest land has been permanently converted to other uses such as food production and therefore is not likely to revert back to forest, and other areas of forest are needed for fiber production and other social uses, within these categories are areas of land where tree stocking and carbon density could be increased without negative effects on provision of other services. Pan et al. (2013) compared current biomass and potential biomass of the world's biomes, indicating that global forests today contain about half of the biomass that would be present without human use of the land for food, fiber, and other nonforest uses. How much of the potential increase in C stocks could be realized as part of a mitigation program depends on economic and social constraints, since increasing C stocks is not the only management goal for forests or other land. It is also possible to increase the productivity of existing managed forests to sequester C at a faster rate, and to store additional C in harvested wood products (Bellassen and Luyssaert, 2014). In one of the most comprehensive global analyses, the IPCC (Nabuurs et al., 2007) calculated that the global mitigation potential for forestry activities could sequester an additional 3.8 Pg C annually from afforestation, reduced deforestation, and improved forest management at a carbon cost of \$50–100 per ton of CO_2. Since about 1.6 Pg C of the estimated 3.8 Pg C would be from reduced deforestation, such an effort could increase the gross C uptake by forests reported in Pan et al. (2011a) from roughly 4.0 to 6.2 Pg C annually, potentially the maximum limit of carbon sequestration by global forest ecosystems we may expect.

There are important C accounting considerations regarding forests that are managed for timber production. Perhaps the most important is the need to account for the C that is removed from the forest in harvest operations and retained in wood product pools or discarded in landfills, since this C is not immediately returned to the atmosphere. A related consideration is the substitution effect, that is, the effect on atmospheric CO_2 from using wood instead of other materials (for example, in building construction). If a substitution effect can be documented, then a life cycle analysis can be performed to determine the energy consumption, emissions, and sequestration throughout the full cycle of growing, harvesting, and processing wood compared with the life cycle of alternate materials (Perez-Garcia et al., 2005). Another analysis issue of increasing interest is complete accounting for the biophysical effects of land management on climate, which go beyond C to account for surface albedo and evapotranspiration which have direct effects on climate. Many studies have looked at these effects with respect to land-use and land-cover change, but few have considered the impact of changes in management within a land-use category. Luyssaert et al. (2014) found that biophysical changes within a land class may have an effect of similar magnitude to that of changes in land class, and therefore the biophysical should receive increasing emphasis as more knowledge is gained. Finally, it is critical to consider the appropriate temporal and spatial scales for any assessment of C impacts of land management, since the results will be highly dependent on the time frame and geographic extent of the analysis (McKinley et al., 2011).

This paper addresses an issue of global significance, the past and future impacts of intensifying land use and management that have enabled humans to benefit from land resources (Foley et al., 2005). We found clear indicators of continued increases in land management intensity. We estimate an overall enhanced carbon sink in managed forests although it is difficult to attribute the effect clearly to management or other environmental factors. However, no land area of the earth lacks significant indirect human influence from atmospheric and climate changes. In the future, these indirect influences along with the direct effects of land management are likely to become increasingly important elements to consider in developing land management strategies.

References

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., et al., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259, 660–668.

Bellassen, V., Luyssaert, S., 2014. Carbon sequestration: managing forests in uncertain times. Nature 506, 153–155.

Bellassen, V., Viovy, N., Luyssaert, S., Le Maire, G., Schelhaas, M., et al., 2011. Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000. Glob. Change Biol. 17, 3274–3292.

Birdsey, R., Angeles-Perez, G., Kurz, W., Lister, A., Olguin, M., Pan, Y., Wayson, C., Wilson, B., Johnson, K., 2013. Approaches to monitoring changes in carbon stocks for REDD+. Carbon Manage. 4 (5), 519–537.

Brandt, M., Mbow, C., Diouf, A.A., Verger, A., Samimi, C., Fensholt, R., 2015. Ground- and satellite-based evidence of the biophysical mechanisms behind the greening Sahel. Glob. Change Biol. http://dx.doi.org/10.1111/gcb.12807.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S., Thornton, P., 2013. Carbon and other biogeochemical cycles. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

D'Annunzio, R., Lindquist, E., MacDiken, K., 2014. Global Forest Land-Use Change from 1990 to 2010: An Update to a Global Remote Sensing Survey of Forests. 6p. <http://foris.fao.org/static/data/fra2010/RSS2010update.pdf>.

Erb, K.-H., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., Haberl, H., 2007. A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. J. Land Use Sci. 2 (3), 191–224.

Erb, K.-H., Kastner, T., Luyssaert, S., Houghton, R.A., Kuemmerle, T., Olofsson, P., Haberl, H., 2013. Bias in the attribution of forest carbon sinks. Nat. Clim. Change 3 (10), 854–856.

Food and Agriculture Organization, 2009. State of the World's Forests, 2009. Rome, Italy, 168p.

Food and Agriculture Organization, 2010. Global Forest Resources Assessment 2010. Forestry Paper 163. Rome, Italy.

FAOSTAT, 2009. <http://faostat.fao.org/site/377/default.aspx#ancor>.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin III, S.F., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, C.I., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574. http://dx.doi.org/10.1126/science.1111772.

Grainger, A., 2008. Difficulties in tracking the long-term trend of tropical forest area. Proc. Natl. Acad. Sci. 105, 818–823.

Gregoire, T.G., 1993. Roots of forest inventory in North America. In: Proceedings National Convention: A-1 Inventory Working Group, Society of American Foresters. Bethesda, MD.

Guo, Z.D., Hu, H.F., Pan, Y., Birdsey, R.A., Fang, J.Y., 2014. Increasing biomass carbon stocks in trees outside forests in China over the last three decades. Biogeosciences 11 (15), 4115–4122.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R.M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.M., Levey, D.J., Margules, C.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.-X., Townshend, J.R., 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci. Adv. 1 (2). http://dx.doi.org/10.1126/sciadv.1500052.

Hicke, J.A., Allen, C.D., Desai, A.R., Dietze, M.C., Hall, R.J., Hogg, E.H., et al., 2012. Effects of biotic disturbances on forest carbon cycling in the United States and Canada. Glob. Change Biol. 18, 7–34.

Houghton, R.A., 2013. Keeping management effects separate from environmental effects in terrestrial carbon accounting. Glob. Change Biol. 19, 2609–2612.

Houghton, R.A., House, J.I., Pongratz, J., van derWerf, G.R., De-Fries, R.S., Hansen, M.C., Le Quéré, C., Ramankutty, N., 2012. Carbon emissions from land use and land-cover change. Biogeosciences 9, 5125–5142. http://dx.doi.org/10.5194/bg-9-5125-2012.

Hudiberg, T.W., Luyssaert, S., Thornton, P.E., Law, B.E., 2013. Interactive effects of environmental change and management strategies on regional forest carbon emissions. Environ. Sci. Technol. 47 (22), 13132–13140.

Intergovernmental Panel on Climate Change, 2003. Good Practice Guidance for Land Use, Land-Use Change, and Forestry. IGES, Japan. <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html>.

Intergovernmental Panel on Climate Change, 2014. Climate change 2014: synthesis report. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, p. 51.

Kurz, W.A., Dymond, C.C., White, T.M., et al., 2009. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Model. 220 (4), 480–504.

Le Quéré, C., Peters, G.P., Andres, R.J., Andrew, R.M., Boden, T.A., Ciais, P., Friedlingstein, P., Houghton, R.A., Marland, G., Moriarty, R., Sitch, S., Tans, P., Arneth, A., Arvanitis, A., Bakker, D.C.E., Bopp, L., Canadell, J.G., Chini, L.P., Doney, S.C., Harper, A., Harris, I., House, J.I., Jain, A.K., Jones, S.D., Kato, E., Keeling, R.F., Klein Goldewijk, K., Körtzinger, A., Koven, C., Lefèvre, N., Maignan, F., Omar, A., Ono, T., Park, G.-H., Pfeil, B., Poulter, B., Raupach, M.R., Regnier, P., Rödenbeck, C., Saito, S., Schwinger, J., Segschneider, J., Stocker, B.D., Takahashi, T., Tilbrook, B., van Heuven, S., Viovy, N., Wanninkhof, R., Wiltshire, A., Zaehle, S., 2014. Global carbon budget 2013. Earth Syst. Sci. Data 6, 235–263. http://dx.doi.org/10.5194/essd-6-235-2014.

Lemay, V.M., Kurz, A.W., 2008. Estimating carbon stocks and stock changes in forests: linking models and data across scales. In: Bravo, F., Lemay, V., Jandl, R., Gadow, K.V. (Eds.), Managing Forest Ecosystems: The Challenge of Climate Change. Springer, New York, pp. 63–81.

Lundgren, B.O., Raintree, J.B., 1982. Sustained agroforestry. In: Nestel, B. (Ed.), Agricultural Research for Development: Potentials and Challenges in Asia. ISNAR, The Hague, Netherlands, pp. 37–49.

Luyssaert, S., Jammet, M., Stoy, P.C., Estel, S., Pongratz, J., Ceschia, E., Churkina, G., Don, A., Erb, K.H., Ferlicoq, M., Gielen, B., Grünwald, T., Houghton, R.A., Klumpp, K., Knohl, A., Kolb, T., Kuemmerle, T., Laurila, T., Lohila, A., Loustau, D., McGrath, M.J., Meyfroidt, P., Moors, E.J., Naudts, K., Novick, K., Otto, J., Pilegaard, K., Pio, C.A., Rambal, S., Rebmann, C., Ryder, J., Suyker, A.E., Varlagin, A., Wattenbach, M., Dolman, A.J., 2014. Land management and land cover change have impacts of similar magnitude on surface temperature. Nat. Clim. Change 4, 389–393.

McKinley, D.C., Ryan, M.G., Birdsey, R.A., Giardina, C.P., Harmon, M.E., Heath, L.S., Houghton, R.A., Jackson, R.B., Morrison, J.F., 2011. A synthesis of current knowledge on forests and carbon storage in the United States. Ecol. Appl. 21 (6), 1902–1924.

Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, J., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanz Sanchez, M.J., Zhang, X., 2007. Forestry. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Pan, Y., Birdsey, R., Hom, J., McCullough, K., 2009. Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. Mid-Atlantic temperate forests. For. Ecol. Manage. 259 (2), 151–164.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., 2011a. A large and persistent carbon sink in the world's forests. Science 333 (6045), 988–993, doi:1201609.

Pan, Y., Chen, J.M., Birdsey, R., McCullough, K., He, L., Deng, F., 2011b. Age structure and disturbance legacy of North American forests. Biogeosciences 8 (3), 715–732.

Pan, Y., Birdsey, R.A., Phillips, O.L., Jackson, R.B., 2013. The structure, distribution, and biomass of the world's forests. Annu. Rev. Ecol. Evol. Syst. 44, 593–622.

Pearson, T.R.H., Brown, S.L., Birdsey. R.A., 2007. Measurement guidelines for the sequestration of forest carbon. Newtown Square, PA: USDA Forest Service General Technical Report NRS-18.

Perez-Garcia, J., Lippke, B., Comnick, J., Manriquez, C., 2005. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood Fiber Sci. 37, 140–148.

Piao, S., Yin, G., Tan, J., Cheng, L., Huang, M., Li, Y., Liu, R., Mao, J., Myneni, R.B., Peng, S., Poulter, B., Shi, X., Xiao, Z., Zeng, N., Zeng, Z., Wang, Y., 2015. Detection and attribution of vegetation greening trend in China over the last 30 years. Glob. Change Biol.

Pongratz, J., Reick, C.H., Houghton, R.A., House, J.I., 2014. Terminology as a key uncertainty in net land use and land cover change carbon flux estimates. Earth Syst. Dynam. 5, 177–195.

Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., Aksenov, D., Egorov, A., Yesipova, A., Glushkov, I., Karpachevskiy, M., Kostikova, A., Manisha, A., Tsybikova, E., Zhuravleva, I., 2008. Mapping the world's intact forest landscapes by remote sensing. Ecol. Soc. 13 (2), 51.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M.S., Reeves, M., Hashimoto, H., 2004. A continuous satellite-derived measure of global terrestrial primary production. Bioscience 54 (6), 547–560.

Sanderson, E.W., Jaiteh, M., Levy, M.A., Redford, K.H., Wannebo, A.V., Woolmer, G., 2002. The human footprint and the last of the wild. BioScience 52 (10), 891–904.

Schimel, D., Britton, B.S., Fisher, J.B., 2014. Effect of increasing CO_2 on the terrestrial carbon cycle. PNAS 112 (2), 436–441.

Stanturf, J.A., Kellison, R.C., Broerman, F.S., Jones, F.B., 2003. Productivity of Southern pine plantations – where are we and how did we get here? J. For. 101, 26–31.

Wang, F., Eurico, J., 2010. Potential of MODIS EVI in identifying hurricane disturbance to coastal vegetation in the northern Gulf of Mexico. Rem. Sens. 2, 1–18.

Wulder, M.A., White, J.C., Fournier, R.A., et al., 2008. Spatially explicit large area biomass estimation: three approaches using forest inventory and remotely sensed imagery in a GIS. Sensors 8, 529–560.

Zhang, F., Chen, J.M., Pan, Y., Birdsey, R.A., Shen, S., Ju, W., He, L., 2012. Attributing carbon changes in conterminous U.S. forests to disturbance and non-disturbance factors from 1901 to 2010. J. Geophys. Res. 117 (G02021), 1–18.