Forest sector carbon management, measurement and verification, and discussion of policy related to climate change

Article in Carbon Management · April 2014
DOI: 10.4155/CMT.10.40

Beverly E Law
Oregon State University

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Carbon Management (2011) 2(1), 73–84

Beverly Elizabeth Law†[1] & Mark E Harmon[1]

The objective of this review is to give ecologists, land managers and policy makers a better understanding of important issues related to forest sector carbon management, measurement and verification, as well as policy related to mitigation and the adaptation of forests to climate change. The focus is on carbon sequestration processes; appropriate measurements for international, regional and local scale assessment of net ecosystem carbon balance; and life cycle analysis, with special attention given to the concept of substitution of fossil fuels with bioenergy from forests. Given the slow dynamic of forest carbon, life cycle analysis needs to account for pre-existing forest conditions, since carbon neutrality (i.e., net ecosystem carbon balance of forests is zero) can take at least a century to achieve in many cases. The substitution of wood for more energy-intensive materials has probably been overestimated compared with cases in which additionality, permanence and saturation of wood building stores are considered. GHG emission policies will need to account for emissions associated with bioenergy, which is currently not considered internationally. Thus, GHG emissions resulting from substitution for fossil fuels will have to be more accurately represented if their true impact is to be understood.

CO_2 accounts for the majority of anthropogenic GHG emissions covered by the UN Framework Convention on Climate Change (UNFCCC), where approximately 74% are due to fossil fuel emissions and approximately 20% from **deforestation** and forest **degradation** [1]. Currently, approximately half the annual increase in CO_2 emissions accumulates in the atmosphere and half is taken up by natural **sinks** in the ocean and on land. Forests are an important component of the global carbon cycle because of the large amount of carbon stored in live and dead woody biomass as well as soil organic matter. Land-use change from forest to other uses releases carbon to the atmosphere. Thus, reducing deforestation and forest degradation, and increasing forest carbon sequestration by **afforestation**, reforestation, or increasing carbon stored per area (i.e., carbon density) via management are priorities for GHG reduction strategies. For example, carbon density can be increased by lengthening harvest rotations over a business-as-usual period (see below). To determine whether GHG targets are met, there is a need to improve the accuracy of estimates of forest carbon budgets by using scientifically based measurement approaches that account for uncertainty. This article reviews forest carbon dynamics, and important emerging issues related to forest **sector** carbon management, measurement and **verification**, as well as policy related to mitigation and adaptation of forests to climate change. Examples are provided from the US, European and Amazonian tropical forests.

Carbon sequestration

Biologically, forests take up CO_2 from the atmosphere through the process of photosynthesis, and release it in the growth and maintenance of living cells in plants (autotrophic respiration) and by respiration from microbial decomposition of dead plant material and soil organic matter (heterotrophic respiration). The net of uptake and release is net ecosystem production (NEP). Mathematically, NEP is the difference between net primary productivity (NPP; the annual net carbon

[1]Department of Forest Ecosystems & Society, 328 Richardson Hall, Oregon State University, Corvallis, OR 97331, USA
†Author for correspondence: Tel: +1 541 737 6111; Fax: +1 541 737 1393; E-mail: bev.law@oregonstate.edu

10.4155/CMT.10.40

ISSN 1758-3004

Key terms

Deforestation: Conversion of forestland to agricultural cropland, grassland and settlements.

Degradation: Decrease in carbon stocks through selective harvest or burning.

Sink: Any process, activity or mechanism that removes a GHG, an aerosol or a precursor of a GHG or aerosol from the atmosphere. Removals of GHGs by a sink are conventionally shown as negative emissions.

Afforestation: Conversion of other land categories to forest.

Sector: An emission-producing segment of the economy. The Intergovernmental Panel on Climate Change currently specifies four sectors for GHG reporting: energy; industrial processes and product use; agriculture, forestry, and other land use; and waste.

Verification: An independent examination of monitoring data to help establish whether or not a country's actual emissions are consistent with its obligations under a climate treaty.

uptake, which is the net of photosynthesis and autotrophic respiration) and heterotrophic respiration. Both NEP and the size of the live and dead carbon pools including those in soil are highly sensitive to forest management activities as well as natural disturbances. For carbon accounting purposes, net biome production (NBP; NEP minus harvest removals and fire emissions) [2,3] plus net storage in long-term products, is compared with fossil fuel emissions in units of **CO_2 equivalence** [101]. An alternative to NBP is net ecosystem carbon balance (NECB) [4], which also considers NEP and the losses due to harvest and fire as well as other losses and gains (e.g., dissolved organic carbon, erosion and volatile organic carbon).

A forest-stand that is disturbed and then allowed to regenerate produces a large CO_2 **source** for 5–50 years (depending on growth rates and amount of woody debris left after disturbance) followed by a long-term CO_2 sink [5,6], with the shorter time-frames in warmer and wetter climates. After clear-cut harvest, the stand is a net emitter of CO_2 because the forest regrowth is far outweighed by heterotrophic respiration from the soil and woody debris left on the site after harvest (Figure 1); for example, a semi-arid ponderosa pine forest-stand after harvest remains a source to the atmosphere for approximately 15–20 years, after which it slowly transitions to a net sink [7].

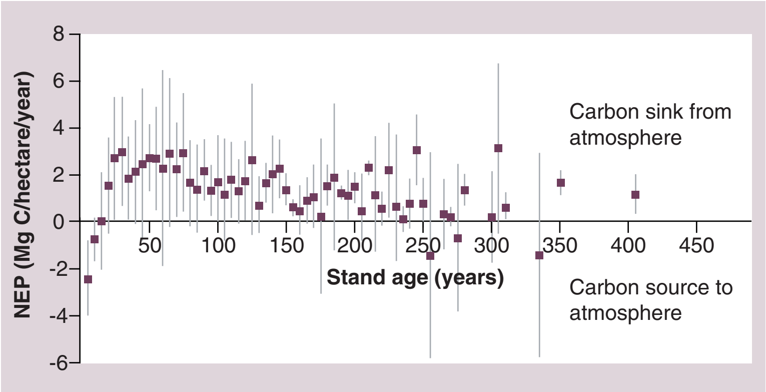

Figure 1. Changes in net ecosystem production after a disturbance that kills all live vegetation, showing source and sink phases over time. The analysis is based on inventory data from the West Cascades ecoregion in Oregon, and ancillary data from 200 plots for computing heterotrophic respiration. It includes different forest types, soil conditions and disturbance histories. Thus, it does not represent a timeseries of one forest type and productivity class. It includes plots that had been partially disturbed (thinning, harvest on subplots, windthrow), as indicated by the large standard deviation (gray lines), and represents the range of conditions on the landscape.
NEP: Net ecosystem production.

Management effects on forest carbon sinks include deforestation, forest degradation and afforestation, as well as management practices that increase the overall density of carbon on a given area of land. 'Deforestation' is the conversion of forestland to agricultural cropland, grassland and settlements [8]. One can increase input by enhancing NPP, reduce losses by decreasing decomposition rates (with likely impacts on fertility), or reduce losses associated with harvests by lengthening the time between harvests [9,10] or removing less each harvest [11].

Deforestation can cause a large net emission of CO_2 because of decomposition of dead wood and short-lived wood products, and burning to facilitate clearing. Globally, deforestation and forest degradation in the tropics are major contributors to CO_2 emissions. Although degradation related to thinning of forests is thought to have minimum impact on carbon, a study in the Brazilian Amazon indicated that observed selective harvest would lead to a gross annual flux of approximately 0.1 billion metric tons of carbon to the atmosphere; the logged area was equivalent to 60–120% of previously reported deforestation area [12]. This value increases the estimated annual anthropogenic flux of carbon from Amazon forests by up to 25% over carbon losses from deforestation alone.

Owing to the global importance of deforestation and forest degradation, recent climate change negotiations requested a mechanism for reducing these sources of CO_2 to be operational by 2013 [13]. Compared with other methods to reduce **anthropogenic emissions** of CO_2, reducing deforestation and forest degradation is relatively straightforward with a minimum of new technologies involved (although developing policies that avoid perverse incentives has proven challenging). Many of these changes in management would also provide the benefit of protecting biodiversity and aiding natural adaptation to climate change by enhancing connectivity of forest land for species to migrate to a more favorable climate.

Given that vast areas of forest have been cleared, an appealing step is to afforest lands that once held forests. However, there are challenges to increasing forest area by afforestation. First, the area has to be suitable for growing forests in terms of water and nutrient availability. If irrigation is required, it will conflict with other needs for water, and can be further complicated by predicted changes in hydrologic regimes with climate change.

If nitrogen fertilization is required, this is a potential source of nitrous oxide (N_2O) to the atmosphere, which is another long-lived GHG (delays in mitigation are costly), albeit with less total **radiative forcing** than CO_2 (CO_2 is 1.66 W m^{-2}, N_2O is 0.16 W m^{-2}) [14]. In some cases, forest had been converted to agricultural land decades or centuries ago, such as in the midwest and southeast USA. These areas may be suitable for afforestation, but removal of productive agricultural lands may result in clearing of forests elsewhere.

There are current proposals to protect forest carbon by removal of fuel to reduce the amount of carbon emitted by wildfires [15]. Ideally, such harvests would change forest structure such that the expected fire severity would result in survival of at least 80% of the dominant and codominant trees under 80% fire weather conditions likely to occur, otherwise known as the '80–80' rule [16]. To achieve this goal, it has been suggested that management needs to reduce above-ground biomass (and thus carbon density) by as much as 40–50% [17,18]. This is a significant reduction in live biomass and, if implemented, would result in a net emission of CO_2 to the atmosphere from forests for two reasons. First, the amount of carbon removed to change fire behavior is often far larger than that saved by changing fire behavior [19]. Second, more area in a forested landscape has to be harvested than will ultimately burn over the period of effectiveness of the thinning treatment, leading to a greater loss of carbon via fuel treatment [20]. Other factors may also be involved when assessing relative effects of fire prevention and fire loss on forest carbon, such as indirect effects of fire prevention on soil productivity, but the two key points above are the major issues in this assessment.

Carbon density can be increased by using longer rotations or reducing the amount harvested each time to allow forests to accumulate more carbon (similar to avoiding deforestation) [9–11]. This can potentially result in hundreds of additional years of forest carbon accumulation; for example, in the Pacific northwest USA, an analysis of inventory and remote sensing data indicated that the current carbon storage on forest land is half of the potential, and it could increase by 15% over the next several decades if allowed to grow and accumulate carbon [10]. The potential increase was greatest on private lands because of the younger age classes that currently exist in private ownership. Increasing on-site carbon stores may be of interest to private landowners if subsidies are provided for avoiding or delaying harvest. Over a large area, increasing carbon density could be challenging because of land ownership considerations, as well as conditional use on federal lands; for example, the Bureau of Land Management has a large land base in the western USA, yet the current law is that the agency is required to provide income to local communities and this is carried out through harvest taxes. Removal of Bureau of Land Management forest land from consideration for carbon sequestration can have a significant impact on the ability to meet those economic goals. In such cases, federal or state policies will need to be changed to meet forest carbon sequestration goals. Increasing rotation lengths could shift harvesting elsewhere; however, this could be countered by using harvested carbon more efficiently and/or increasing the longevity of wood buildings and other wood products. It would also depend on the magnitude of increase in rotation lengths and how long the transition takes.

In addition to changing the interval and intensity of harvest, forest carbon density could be enhanced by increasing NPP or decreasing decomposition-related losses. While thinning is commonly proposed to increase forest productivity, this increases the amount of carbon harvested but does not increase the amount of carbon being removed by photosynthesis (i.e., ecosystem production). Planting species or varieties with high growth rates will increase NPP, but will probably conflict with biodiversity goals [13]. As stated above, fertilization can also increase NPP, but the consequences for other GHGs (i.e., N_2O and CH_4) have to be considered since they will counter benefits from NPP gains [14]. While decreasing decomposition losses would temporarily increase NEP, the accumulation of dead material would cause greater losses via fire and ultimately lead to decreased soil fertility and, thus, decreased NPP.

Appropriate measurements for management & policy

Carbon stores and net fluxes to and from the atmosphere will have to be measured at multiple spatial scales ranging from international to local. Inventories, remote sensing and modeling will probably play a role in each, as will estimates of uncertainty. The consequences for overestimating carbon sequestration with respect to climate protection are greater than those of underestimation. Thus, discounting estimates to account for associated uncertainties will have a lower consequence than using mean estimates. In addition, estimates at

Key terms

CO_2 equivalence: The amount of CO_2 emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a well-mixed GHG. It is a standard metric for comparing emissions of different GHGs, but does not imply exact equivalence of the corresponding climate change responses. The 100-year global warming potential is used to calculate CO_2 equivalents.

Source: Any process, activity, or mechanism that releases a GHG, an aerosol, or a precursor of a GHG or aerosol into the atmosphere. Certain activities, such as forestry, can be both a source and a sink of GHG emissions.

Anthropogenic emissions: Emissions of GHGs, precursors of GHGs and aerosols resulting from human activities. Since it is difficult to separate anthropogenic and natural components of emissions and removals from land use, the UN Framework Convention on Climate Change considers emissions and removals on managed lands as anthropogenic.

Radiative forcing: A measure of the tendency of a GHG to change the climate. It multiplies the increased abundance of the gas caused by anthropogenic emissions and the gas's potency as a greenhouse agent.

Key term

Substitution: The substituted use of materials with lower energy costs for those with higher energy costs that have greater GHG emissions. Energy costs include those associated with transport, manufacturing, installation and maintenance.

all scales will need to be verified by independent bodies for policy and treaty agreements [14].

Inventories of existing carbon stores will need to occur at all scales. Eventually some carbon stores will be directly inventoried using remote sensing (e.g., light detection and ranging [LIDAR] estimates of above-ground biomass), but many significant stores such as soil stores will require on-site measurements. Methods of remotely estimating biomass and change at required accuracies of approximately 25% at scales of 100 m or more are still under development, especially in the tropics [21]. Inventories of some forest sector pools such as wood products and **substitution** offsets may not be possible at the local scale (i.e., a specific parcel of forest land), since the movement of wood-based materials is difficult to estimate even at a national scale. It will not be possible to track the fate of every harvested tree back to the land from which it was harvested. This makes accounting of wood products different than accounting for forest carbon. In the latter case, one can actually inventory the carbon on a specific forest area. However, inventory of wood products, is only feasible at a larger scale.

Inventories of stocks can be used to calibrate models or directly in a change in stocks approach. The latter is equivalent to NECB and can be measured directly as the change in organic carbon stock in live and dead vegetation, and soil over a measurement interval. This change in stock approach approximates NBP and/or NECB as it accounts for losses due to harvest and fire. Other losses and gains (e.g., dissolved organic carbon), while part of NECB, are usually assumed to be negligible in application.

Remote sensing methods, with some exceptions, such as LIDAR, will be best used to determine the area of forest, rates of clearing and other forms of disturbance. These data can be combined with either inventories or models to scale up local results. Remote sensing can also be used to assess whether management targets such as afforestation or slowing deforestation are being met or whether planned changes in management such as increases in harvest intervals or reductions in harvest intensity (i.e., amount taken per area) have been implemented. Remote sensing can be used to guide inventory sampling or to scale-up results, thus increasing efficiency.

Projections of impacts of changes in forest practices at all levels will involve the use of models. Changes in management should be based on practices proven to increase forest sector-related carbon stores or carbon offsets. However, these projections will still need to be validated as changes in climate, disturbance and other factors potentially reduce, or in some cases increase, the gains that actually occur. Models will also be important tools to estimate the interannual variability of carbon uptake and release, particularly if climate changes to the degree that consistent trends begin to occur.

International & national

International agreements to limit future GHG emissions will rely on the ability of each country to estimate emissions accurately and to monitor and verify changes over time (Figure 2). Independent estimates will be necessary to confirm national or state estimates. International programs recommend a basic level for producing national estimates of forest carbon by integrating Landsat-type remote sensing data and inventories, essentially multiplying carbon densities from inventories by the land area in that forest condition and type (Figure 2). The change in stocks approach will be all that is possible in some countries. Ground-based inventories require spatially representative sampling and repeat visits to permanent plots. To reduce uncertainty, measurements should include annual growth from tree cores rather than diameters (except for species without growth rings), changes in dead material (e.g., tree stems, branches, bark, stumps and surface litter), and adequate sampling of changes in soil carbon between two measurement periods (e.g., 5-year intervals). Detailed methods for measurements are provided in Global Terrestrial Observing System-Terrestrial Carbon Observations (GTOS-TCO) protocols [22]. Improvements in quality of estimates and efficiency can be made by relying more heavily on satellite remote sensing of vegetation characteristics (to which carbon densities and emissions factors are applied), and would have variable sampling intensity based on ecosystem characteristics.

Currently, the UNFCCC uses guidelines developed by the IPCC [8]. The IPCC Good Practice Guide requires spatially explicit tracking of forest area change and estimation of forest carbon stock change or emission factors (carbon per hectare) [102,103]. The Guide provides 'Tiers' for different capabilities, where Tier 1 uses default data, Tier 2 requires *in situ* national level data (from forest inventories), and Tier 3 uses measurements of carbon stock changes for carbon pools that are spatially explicit. International policies and compensation mechanisms for implementing post-Kyoto agreements in developing countries are still under discussion by the UNFCCC. However, draft methodology refers to the need to establish national monitoring systems that use an appropriate combination of remote sensing and ground-based forest carbon inventory approaches. Countries that aim to adopt UNFCCC guidelines are expected to develop a roadmap for the establishment of a system for monitoring, reporting and verification (MRV), to participate in emissions reporting and to benefit from credits. Broader application of Tier 3 should reduce uncertainties in a broad sense, since some countries do not even have resources for inventories. However, the expanded methods described here and by the National Research Council could be adopted by the UNFCCC to reduce uncertainties to acceptable levels and for independent verification [14,22].

Since deforestation is the second largest source of anthropogenic CO_2, and mitigation by conservation and planting are likely to be important, satellite monitoring of forest cover, age and disturbance (e.g., fire, clear felling, thinning and insects) will be critical. Satellite imagery can be used to determine areas that have been affected by deforestation, disturbance, forest degradation and afforestation. The current total annual change in forest area has an uncertainty of 10–25% in northern forests and up to 100% in tropical forests [14]. Uncertainties in annual net emissions from these activities are high, ranging from 25 to 100%, because of uncertainties in values used to translate area into CO_2 emissions and sinks. A goal in the next 5–7 years is to reduce these uncertainties to less than 10% [14].

A comparison of moderate resolution images at two points in time, or time-series analysis can detect changes in forest cover. Landsat-type sensors are most appropriate in that the spatial resolution is approximately 30 × 30 m. Trajectory-based image analysis, which is currently used across the Pacific northwest region of the USA, has advantages over traditional approaches in that it can detect forest thinning and trends such as progressive change from one land cover type to another, spreading mortality and slow regrowth of forests over time [23]. It can also detect a wide range of disturbance and recovery phenomena that were previously too ambiguous, capturing types of degradation with accuracies two- to five-times higher than previous change detection methods. Combining trajectory-based image analysis and high-resolution data improves the accuracy of regional estimates of terrestrial carbon fluxes and enables identification of the type of forest degradation (e.g., thinning vs mortality from insects or diseases) [23].

Subtle disturbances have potentially large cumulative impacts on carbon cycling at the regional scale (e.g., large-scale mortality of boreal forests from insect attack) [24]. Landsat data are also being used in time-series analysis across North America to identify forest areas subject to stand-replacing harvest and wildfire with a repeat interval of 2 years [25]. An assessment over southeastern and northern USA national forests indicated overall accuracy of 80%. Most of the omissions were partial disturbances, such as thinning and storm damage, although some clearing harvests may not be detectable with temporal intervals of 2 years or more in areas of rapid forest regrowth [26]. This type of approach has the potential to be applied globally.

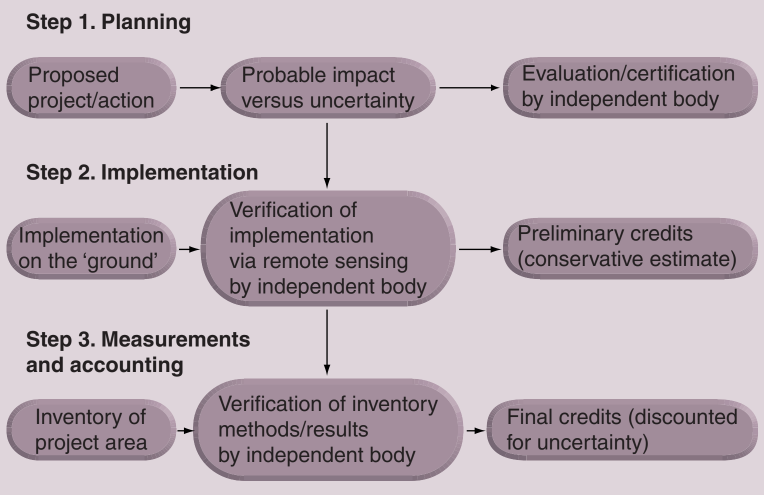

Figure 2. Planning and implementation of forest carbon projects, and measurement activities to verify GHG emissions reductions at local, national and international scales.

At the national scale, the most effective method for detecting areas of selective harvest is to apply high spatial and temporal resolution remote-sensing approaches to areas suspected of thinning, such as those determined by detection of landings along roads. For example, an automated image analysis approach was applied to annual Landsat data along with pattern recognition techniques for detecting selective logging [12]. The analysis required initial ground-based spectroscopic characterization of surface features and tree species canopy spectra from a spaceborne hyperspectral sensor (Hyperion). The authors found an overall uncertainty of up to 14% in total logged area, based on seasonal Landsat data, atmospheric modeling, detection of forest canopy openings, surface debris and bare soil exposed by forest disturbances.

For developed countries (e.g., European program on Integrated Carbon Observation System [ICOS]) and independent assessments, an improvement on the combination of satellite forest characteristics data and inventories is the integration of observation and modeling frameworks for producing annual estimates of carbon fluxes and live and dead carbon pools [27]. The observations include inventories and remote sensing data as noted above, as well as eddy covariance sites for model calibration [28]. There are approximately 100 eddy covariance sites in the Americas and 500 sites worldwide. The eddy covariance tower measures instantaneous exchange of CO_2 and other gases between the atmosphere and land surface for areas ranging from a hectare to a few square kilometers, depending on tower and canopy height. Fluxes are computed half-hourly and summed annually to provide an estimate of the net amount of CO_2 absorbed or released by the forest. The calibrated models use this combination of observations to produce maps of NEP. Using such integrated frameworks can produce estimates of carbon pools and fluxes for some countries with uncertainties of approximately 30% [29]. The uncertainties can be reduced by using improved observations of disturbance, land cover and land-use change, and data assimilation methods in the modeling framework [14,28]. This framework takes into account variation from year to year due to changing weather and other factors, which aids separation of anthropogenic from other causes.

Forest carbon at small scales

Estimates of carbon increases due to changes in management at small or local scales will probably initially be made using models that range from site-specific to very general. If general models are used, for example, look-up tables (e.g., carbon density for a specific class of forest type, age and site fertility), the subsequent estimates of carbon increases will need to be fairly accurate to account for site-to-site variation and management effects or discounting of estimates will be necessary. Methods used to project carbon increases (or decreases) will need to be certified by independent bodies if carbon credits are to be traded or sold (Figure 2). Regardless of the model used, verification of forest carbon projects (e.g., offsets) requires measurements at the scale of a forest-stand, forest land-owner or landscape with multiple small owners. The change in stocks method will probably be the most economical to use in these situations, but distinguishing management influences from those of climate change are challenging to discern because of weather and climate change-related effects on carbon uptake and release. An approach to identifying management effects on forest carbon uptake is to compare measurements against baseline carbon fluxes on similar lands without recent management [30]. If forestry offset projects are to be implemented successfully, there need to be accounting rules that are effective in preventing cheating. These rules must be conservative with respect to the amount of carbon credited, balance economic costs versus carbon gains and will only credit carbon that has a high probability of being physically present [30].

Life cycle analysis

Life cycle analysis (LCA) of forest carbon removals considers forestry-related sinks and sources of carbon to and from the atmosphere and the associated impact on total fossil fuel emissions (FFE). LCA often emphasizes either the products' chain or on-site changes, but rarely covers both on-site and off-site carbon tracking in depth. Most LCA studies rely heavily on wood product substitution for GHG benefits, and these have been grossly overestimated, with many ambiguous assertions that gloss over forest carbon dynamics; for example:

- Biofuel emissions are assumed to be zero because they are balanced by net growth, yet this would depend on the state of the preceding forest system – they could be positive, neutral or negative;
- Old forests are assumed to always be carbon sources, while young forests are always assumed to be carbon sinks, contrary to forest carbon dynamics findings;
- Dead wood and soil carbon stores are either not included or assumed to be constant;
- In one LCA, dead wood is not present in older forests, contrary to findings in the extensive ecological literature;
- The wood product pool is assumed to be an increasing carbon stock over time.

To account for net carbon benefits and when carbon neutrality is achieved, LCA must consider pre-existing conditions of the forest system for all carbon pools, including dead wood and soil, and not just focus on live carbon. Establishment of carbon neutrality of all forest pools can take decades to centuries depending on the initial conditions and the new management system [31].

International treaties and domestic legislation account for bioenergy incorrectly by treating all bioenergy as causing a 100% reduction in emissions regardless of the source of the biomass [32]. This error is perpetuated by exempting CO_2 emissions from bioenergy usage from national emissions limits. Most renewable energy standards for electric utilities have the same effect because bioenergy is viewed as a renewable energy source even when the biomass harvest increases GHG emissions from the ecosystem [33,34].

A direct approach to estimating CO_2 emissions to the atmosphere (FCO_2) is:

FCO_2 = NEP - fire emissions - harvest and trade emissions - processing FF emissions - wood decomposition 1 - wood decomposition 2 + FF substitution

(Equation 1)

Following the sequence from forest to product, this breaks down to:

FCO_2 = (NEP - fire emissions - harvest removals from land) + harvest additions to product chain + import of US grown wood - export of US grown wood - harvest and trade FFE - processing FFE - decomposition emission 1 - biofuel stock from land + biofuel stock addition to product pool - decomposition emission 2 + FF substitution.

(Equation 2)

Harvest and trade FFE and processing FFE include refining and transport costs [35]. The terms in parentheses are the net ecosystem carbon balance mentioned earlier, assuming dissolved organic carbon, dissolved inorganic carbon and volatile organic carbon losses from the forest system are negligible. Decomposition emission 1 and 2 are emissions from wood waste at the processing facility (Equation 1) or from biomass burned for energy (Equation 2). Biomass combustion replaces fossil fuel emissions with its own emissions of CO_2, and emissions will be higher per unit energy produced because of the inherently lower energy content of bioenergy and energy losses associated with transformation into other fuel forms (i.e., solid to liquid fuel) [33]. This equation is a modification of an approach that did not adequately represent the land-based net ecosystem carbon balance [36]. The FORCARB2 model used in [37] calculates forest carbon stock changes from inventory data at two points in time (all predicted from volume changes in above-ground live-tree biomass) and identifies it as 'net sequestration', but this neglects changes in key pools such as soil and dead wood carbon, as well as below-ground root growth. Equation 1 is a more process-based approach [3,4]. The factors we believe should be considered in LCA are shown in Figure 3.

Conversion of natural areas or mature forests to bioenergy production has a larger loss of carbon than management on low-quality or degraded land. Converting rainforests, peatlands, savannas or grasslands to produce food-crop-based biofuels in Brazil, Southeast Asia and the USA creates a biofuel carbon debt by releasing 17–420-times more CO_2 than the annual GHG reductions that biofuels would provide by displacing fossil fuels [33].

Thinning of forests for bioenergy production has the short-term potential to counteract GHG reduction goals. A modeling study evaluated the impact of a global bioenergy program and found that related indirect land use will be responsible for substantially more carbon loss – up to two-times that of current conditions [34] – indicating that one cannot automatically assume near-term carbon benefits. Furthermore, because of predicted increases in fertilizer use to meet forest growth requirements, nitrous oxide emissions will be more important than carbon losses in terms of global warming potential [34].

Some clarifications are required here regarding replacement of fossil fuel with bioenergy production from forests. First, to determine whether there is a net benefit, the amount of carbon stored in forests needs to be correctly estimated. Carbon storage in forests includes live and dead wood (including stumps and roots) as well as soil carbon. If the forests are allowed to grow, they can continue to accumulate live carbon for hundreds of years as observed in inventory data from Pacific northwest US forests [8]. Second, above-ground dead wood in these forests accounts for approximately 15–20% of total wood biomass in mature and old forests, yet it is often assumed to be zero in carbon models used for estimating forest carbon storage. Thus, carbon can potentially accumulate in forests far beyond the timeframe of GHG reduction targets and to higher levels than often assumed.

Once carbon enters the forest system, management can determine to some degree where it goes. However, with the exception of enhancing NPP, management cannot influence how much carbon enters the forest system. To the extent that management can direct carbon into longer lived pools, it can increase the stores of carbon in the forest sector. Harvest of carbon is one proposed strategy to increase carbon stores. However, harvesting carbon will increase the losses from the forest itself and to increase the overall forest sector carbon store, the lifespan of wood products carbon (including manufacturing losses) would have to exceed that of the forest. Under current practices this is unlikely to be the case. A substantial fraction (25–65%) of harvested carbon is lost to the atmosphere during manufacturing and construction depending on the product type and manufacturing method [37]. The average lifespan

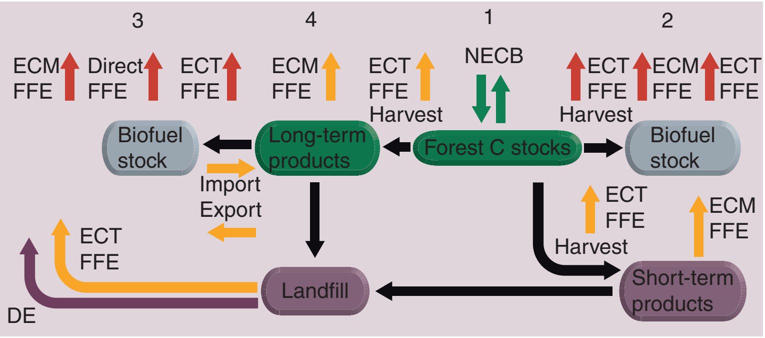

Figure 3. Forest carbon life cycle analysis. Black arrows indicate flows from one location to another. NECB (green arrows) is net primary production minus carbon losses from harvest debris on site, fire emissions and other factors assumed to be negligible (e.g., dissolved organic carbon and volatile organic carbon). Wood can be harvested directly for bioenergy production (2) or indirectly as a by-product of manufacturing (3, 4). FFEs result from ECM and ECT (orange arrows). The wood products chain is from domestic forests only; emissions from exports are accounted for by virtual processing in the country of origin, and imports are accounted for by the country of origin. Emissions sources from imports and exports in the US are less than 1% (assumed negligible). At the end of life, wood and pulp and paper products decompose in landfills or are reused and delay decomposition, resulting in DE (methane). Bioenergy production (gray ovals) produces FFEs to transport and convert biomass for ethanol production (manufacturing emission) and results in direct emission from biomass burning (red arrows). The net of bioenergy minus associated FFE is substitution.
DE: Decomposition emissions; ECM: Energy consumption in manufacturing; ECTs: Energy consumption in transportation; FFE: Fossil fuel emission; NECB: Net ecosystem carbon balance.

of wood buildings is 80 years in the USA, which is determined as the time at which half the wood is no longer in use and either decomposes, burns or, to a lesser extent, is recycled. However, many forest trees have the potential to live hundreds of years (e.g. 800 years in the Pacific northwest USA). Mortality rates of trees are generally low, averaging less than 2% of live mass per year in mature and old forests [39]; for example, in Oregon, mortality rates average 0.35–1.25% in forests that are older than 200 years in the Coast Range and Blue Mountains, respectively [8]. Moreover, the average longevity of dead wood and soil carbon is comparable to that of live trees [39]. When the loss of carbon associated with wood products manufacturing is factored in, it is highly unlikely that harvesting carbon and placing it into wood products will increase carbon stores in the overall forest sector. This explains why in all analyses conducted to date, wood products stores never form the majority of total forest sector stores [11,40–42].

Substitution of more energy-intensive building materials with a less energy intensive one can, in theory, result in a fossil fuel offset; for example, when wood replaces a construction material with higher emissions (e.g., concrete or steel), the fossil CO_2 emission avoided by choosing wood is credited as an offset. Thus, harvest of forest carbon and placement into buildings can impact the overall carbon balance of the forest sector [33,42]. However, several additional factors need to be considered. First, changes in the carbon stores of the forest ecosystem have to be considered relative to a base case that includes a lower level of harvests. As noted above, decreasing the interval between harvests, or increasing harvest intensity will lower the carbon store in the forest [9–11,31]; the question is whether stores in forest products combined with substitution offsets surpass losses from shorter rotations. Since the forest has a maximum carrying capacity, just the growth in carbon stores and offsets would seem to eventually exceed old forest carbon, although it could take centuries to happen, even using the most generous substitution effects. With more realistic substitution effects, it may never happen. In some cases, the amount of live and dead biomass in unharvested forests was grossly underestimated [42] leading to an overestimation of the relative benefits of substitution. Second, in substitution effects calculations, it is often tacitly assumed that wood that is removed from forests and used in long-term wood products, specifically buildings, continues to accumulate infinitely over time. While building carbon stores have increased in many areas (e.g., the USA), this is largely because more forest area is being harvested and not because the harvest-related stores per harvest area are increasing. The trend that is being used as evidence of increasing building stores is based on the fact that because a greater area has been harvested, the total store has increased. This is not the same thing as the increase associated with a particular area of forest. A fixed per area basis is how substitution effects have largely been evaluated in the past, so arguing on an expanding area basis is inappropriate. The reason that wood products saturate is that housing and other wood products have a finite lifespan and are eventually replaced [43]. Although there can be some reuse of wood, essentially assuming an infinite lifespan or 100% reuse of wood products is completely unrealistic. Carbon is always lost as wood products are used or disposed of, which means release of CO_2 to the atmosphere. Since long-term storage in forest products saturates over time (i.e., eventually does not increase), the effect of substituting wood for fossil fuel energy is also likely to saturate. Third, in most cases, the substitution offset was calculated based on the assumption that each time a house is to be built, the preference is for nonwood materials. This results in an estimate of the maximum substitution effect possible, but does not account for actual preferences for building materials. Granted, preferences vary by region and over time, but without accounting for these one cannot possibly estimate realistic substitution benefits. Fourth, current substitution accounting appears to violate a key principle of carbon offsets, namely permanence. In fact the ever-increasing substitution offset presented in these analyses appears to depend on impermanence of wooden buildings. Fifth, most, if not all, current analyses of substitution effects ignore the effects of additionality and whether wooden buildings are initially present. Given that many forests have already been harvested to produce wood products, replacing wooden buildings with more wooden buildings results in no additional substitution effect. Finally, these studies assume that it is a permanent benefit to GHG removal from the atmosphere. That is, they assume there is a continual increase in the carbon credit, and maintenance of a sustainable productive forest dedicated to providing substitutes for nonwood fuels and materials [44].

These caveats all suggest that while there is likely to be some building material substitution effect that is valid, it is far lower than generally estimated and as subject to saturation as other forest-related carbon pools. In summary, the substitution effect appears to have been grossly overestimated. Substitution is an offset, not a store. Offsets depend on the use of appropriate accounting rules. Until rules such as permanence, additionality and leakage are followed, the values being presented in many analyses are not credible.

Adaptation, other ecosystem services & ecosystem sustainability

Vulnerability to climate change can be exacerbated by the presence of other stresses. Nonclimate stresses can increase vulnerability to climate change by reducing resilience and can also reduce adaptive capacity because of resource deployment to competing needs; for example, current stresses on forests include human-caused wildfires as access to forests increases, and land-use change in addition to drought stress. Vulnerable regions face multiple stresses that affect exposure and sensitivity as well as capacity to adapt.

Managing forest carbon should also consider other ecosystem values and services, and ecosystem sustainability in the face of climate change, allowing for natural adaptation to climate change. Indeed, in some forest ecosystems, carbon may not be the primary focus of management or the primary ecosystem service provided by forests.

The IPCC states that [45]:

- Approximately 20–30% of known plant and animal species are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5–2.5°C;
- Types of changes observed in plants include range shifts (latitude, elevation) and changes in growing season length, and threatened systems include those with physical barriers to migration (e.g., mountain ecosystems);
- Nonclimate stresses can increase vulnerability to climate change by reducing resilience and adaptive capacity.

The climate projection for North America is characterized by a variety of different patterns of precipitation, with increasing precipitation at high latitudes and a sharp decrease in precipitation across the southwest. Drought-affected areas will probably increase in extent. Warming in western mountains of the USA is projected to cause decreased snowpack, more winter flooding and reduced summer flows. This has implications for forest ecosystem sustainability and shifts in vegetation distribution that must be considered in carbon-management scenarios. Managing for carbon sequestration in forests can be pursued on lands compatible with preserving biodiversity over large areas. Careful planning and evaluation are needed to avoid practices that impact biodiversity with little to no net decrease in atmospheric CO_2 [13].

Future perspective

Decisions to limit GHGs are being made within states, nationally and internationally. Mitigation and adaptation actions applied to forests will need to include more thorough carbon accounting through LCA of forest carbon stocks and fluxes, and energy use and emissions resulting from the removal of wood from forests for products and bioenergy production. GHG emission policies will need to account for emissions from bioenergy, which is currently assumed to be zero internationally. Thus, GHG emissions resulting from substitution for fossil fuels will have to be more accurately represented.

Future considerations in reducing anthropogenic GHG emissions go beyond carbon accounting. Climate mitigation policies do not account for the effects of changes in the land surface on sensible and latent heat flux, and albedo, and the distribution of energy in the climate system. Although this is important for understanding how we can reduce anthropogenic effects on the climate system, it presents challenges for policies for mitigating climate change [46]. Research has shown that changes in the energy balance after forest-stand replacing disturbance (e.g., insects, harvest and fire) can either enhance or offset carbon sources and sinks when examining the effect of both factors on net radiative forcing [47]. Others have shown that fragmentation of the landscape can cause changes in rainfall patterns locally and globally [48,49]; for example, land surface changes over 10 × 10 km can cause changes in local rainfall patterns. The spatial scale of a disturbance that would result in a global impact depends on where the disturbance occurs (e.g., climate or carbon storage). Climate model simulations with disturbed areas over

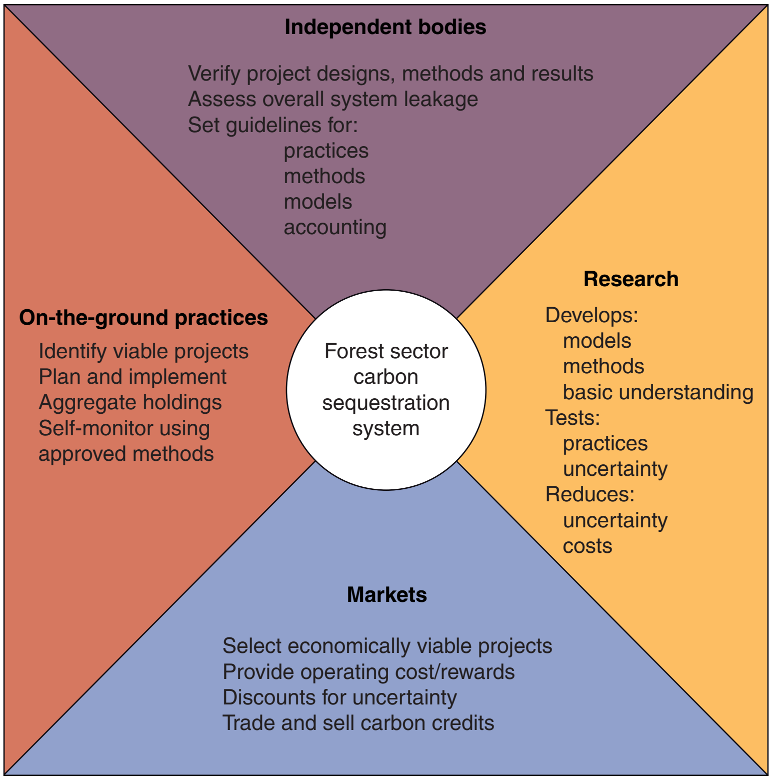

Figure 4. Elements of a fully functioning forest sector carbon sequestration system and the roles of each component.

hundreds of square kilometers have the potential to lead to global impacts [50]. Climate model sensitivity to such disturbances over larger areas needs to be tested at regional and global scales.

An envisioned forest carbon sector sequestration system is illustrated in Figure 4. The research component needs to develop models and methods, test effectiveness of practices and reduce uncertainty. Other system components include important features of practices and markets. In addition, the role of independent bodies is to set guidelines for practices and methods, verify project designs, and assess the effectiveness of the carbon sequestration system, including potential trans-boundary leakage [51].

Research will lead to improved methods for accounting for GHG emissions, and implementation of these methods will need to occur within the next 5–7 years for tracking improvements in atmospheric GHGs to meet treaty and policy obligations.

Financial & competing interests disclosure

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties. No writing assistance was utilized in the production of this manuscript.

Executive summary

Carbon sequestration

- Deforestation and forest degradation (thinning) are the second largest source of anthropogenic GHG emissions.
- Thinning forests to reduce potential carbon losses due to wildfire is in direct conflict with carbon sequestration goals, and, if implemented, would result in a net emission of CO_2 to the atmosphere because the amount of carbon removed to change fire behavior is often far larger than that saved by changing fire behavior, and more area has to be harvested than will ultimately burn over the period of effectiveness of the thinning treatment.
- Forest carbon density could be enhanced by changing the interval and intensity of harvest, increasing net primary productivity or decreasing decomposition-related losses.

Measurements for management & policy

- Scientific advancements in monitoring carbon sources and sinks are expected to become operational within 5–7 years for treaty and policy verification.
- Capabilities of some countries will be limited to expansion of change in carbon stock estimates by including previously unmeasured pools (soil carbon, dead material), and improving emissions factors.
- Deforestation is the second largest source of anthropogenic CO_2, therefore, mitigation by conservation and planting are likely to be important; satellite monitoring of forest cover, age and disturbance (e.g., fire, clear felling, thinning and insects) will be critical.

Life cycle analysis (including substitution, proposed considerations)

- Carbon can potentially accumulate in forests far beyond the timeframe of GHG reduction targets.
- When the loss of carbon associated with wood products manufacturing is factored in, it is highly unlikely that harvesting carbon and placing it into wood products will increase carbon stores in the overall forest sector. This explains why in all analyses conducted to-date, wood products stores never form the majority of total forest sector stores.
- Carbon is always lost as wood products are used or disposed, which means release of CO_2 to the atmosphere. Since long-term storage in forest products saturates over time (i.e., eventually does not increase), the effect of substituting wood for fossil fuel energy also saturates.
- To determine if there is a net substitution benefit, the amount of carbon stored in forests needs to be correctly estimated.
- Substitution of more energy-intensive building materials with less energy-intensive materials can, in theory, result in a fossil fuel offset, but important considerations suggest that the substitution effect is substantially lower than estimated, and is subject to saturation.

Adaptation & other ecosystem services: ecosystem sustainability

- Managing forest carbon should consider other ecosystem values and services, and ecosystem sustainability in the face of climate change, allowing for natural adaptation to climate change (e.g., landscape connectivity for migration and minimizing impacts of management on species ability to survive in a new climate).

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