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Age structure and disturbance legacy of North American forests

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Abstract

Most forests of the world are recovering from a past disturbance. It is well known that forest disturbances profoundly affect carbon stock and fluxes in forest ecosystems, yet it has been a great challenge to assess disturbance impacts in estimates of forest carbon budgets. Net sequestration or loss of CO_2 by forests after disturbance follows a predictable pattern with forest recovery. Forest age, which is related to time since disturbance, is the most available surrogate variable for various forest carbon analyses that concern the impact of disturbance. In this study, we compiled the first continental forest age map of North America by combining forest inventory data, historical fire data, optical satellite data and the dataset from NASA's LEDAPS project. Mexico and interior Alaska are excluded from this initial map due to unavailability of all required data sets, but work is underway to develop some different methodology for these areas. We discuss the significance of disturbance legacy from the past, as represented by current forest age structure in different regions of the US and Canada, tracking back disturbances caused by human and nature over centuries and at various scales. We also show how such information can be used with inventory data for analyzing carbon management opportunities, and other modeling applications. By combining geographic information about forest age with estimated C dynamics by forest type, it is possible to conduct a simple but powerful analysis of the net CO_2 uptake by forests, and the potential for increasing (or decreasing) this rate as a result of direct human intervention in the disturbance/age status. The forest age map may also help address the recent concern that the terrestrial C sink from forest regrowth in North America may saturate in the next few decades. Finally, we describe how the forest age data can be used in large-scale carbon modeling, both for land-based biogeochemistry models and atmosphere-based inversion models, in order to improve the spatial accuracy of carbon cycle simulations.

1 Introduction

Most forests of the world are recovering from a past disturbance. According to the most recent global forest resources assessment, 36% of the world's 4 billion ha of forest are classified as primary forest, i.e., showing no significant human impact (FAO 2005). The same report estimates 104 million ha/yr of the world's forests, or 3% of the total area, are disturbed each year by fire, pests, and weather, though this is a significant underestimate of the disturbance rate because of incomplete reporting by countries. For the US, it is estimated that about half of the forest area, or 152 million ha, is disturbed each decade, but this estimate covers a wide range of disturbance types including timber harvesting and grazing which affect more area than natural disturbances (Birdsey and Lewis, 2003). In Canada, wildfires were the largest disturbance type in the 20th century, affecting an average of 2.6 million ha/yr in the last two decades (Stocks et al., 2002; Weber and Flannigan, 1997). Insect pests are also significant and likely to increase in the future according to model simulations (Kurz et al., 2008).

The net sequestration or loss of CO_2 by forests after disturbance follows a predictable pattern determined by age, site, climate, and other factors (Pregitzer and Euskirchen, 2004). Typically, regenerating forests grow at an accelerating rate that reaches a peak at about the time the canopy closes, followed by a declining rate of increase that may last for centuries. However, as the forest floor and soil release carbon continuously, disturbances may cause large variations from sources to sinks of carbon with time. A recent review of data from old-growth forests concluded that they may continue to sequester atmospheric CO_2 indefinitely (Luyssaert et al., 2008), with continued increases in soil C as a likely long-term repository (Zhou et al., 2006). Disturbance affects all of the ecosystem carbon pools, and the rate of their recovery to pre-disturbance levels is different between C pools and geographically (Bradford et al., 2008; Pregitzer and Euskirchen 2004).

In this paper we present a forest age map of the US and Canada, describe our approaches to develop this map, and discuss how such a map may be used with inventory data for analyzing carbon management opportunities and for other modeling applications. Forest age, implicitly bearing the past disturbance legacy, is a simple and direct surrogate for the time since disturbance and may be used in various forest carbon analyses that concern the impact of disturbances. By combining geographic information about forest age with estimated C dynamics by forest type, it is possible to conduct a simple but powerful analysis of the net CO_2 uptake by forests, and the potential for increasing (or decreasing) this rate as a result of direct human intervention in the disturbance/age status. We consider broad categories of forest management activities, those described in the most recent IPCC assessment including afforestation, reducing deforestation, and forest management (Nabuurs et al., 2007). The biological potential of each class of activity to offset fossil fuel emissions may be estimated with knowledge of the area available for the activity and estimated changes in ecosystem C by age. This kind of analysis is regionally and globally significant with respect to managing the carbon cycle. According to the latest IPCC report, the potential of global forestry mitigation measures may be as high as 13.8 Pg CO_2/yr at carbon prices of 100 $/t CO_2 (Nabuurs et al., 2007). We also briefly described how age information can be applied in large-scale carbon modeling, using both land-based biogeochemistry models and atmosphere-based inversion models for improving the accuracy of simulated carbon dynamics.

2 Age structure and disturbance legacy of North American forests

To generate the age map, we integrated remote sensing data with the age information from forest inventories, disturbance datasets, and land-use/land cover change data. Because Canada and the US have different systems and approaches to collect and manage forest and land data, different approaches were used to produce spatial forest age information for these two countries (see Data and methods). The forest age map (Fig. 1) developed in this study demonstrates forest age structure in temperate and boreal areas of North America. Although the approaches to develop forest age maps in Canada and the US are not exactly the same, the map results show consistent and smooth patterns across the boundaries between these two countries. Natural and human forces over the last two centuries together have shaped the age structure of forests in the US (Fig. 2) and Canada today (Birdsey et al., 2006; Kurz and Apps, 1999). Due to geographical features, land-use history, harvesting, and disturbance regimes, Canada in general has older forests than the US. For example, 43% of forests in British Columbia are defined as old growth with ages between 120 and 250 yr, but there are large patches of younger forests (41%) in the early stages of recovery from wildfire and harvesting (BC Ministry of Forests, 2003). In contrast, forests in the Southeastern US have a distribution of younger age classes because of intensive management and harvesting for wood products. To illustrate how forest age structures implicitly represent land disturbance legacy from the past, we relate the forest age distribution patterns in different regions of the US and Canada (Figs. 3–5) with land-use and disturbance history because they provide diverse pictures for contrasting the past human and natural causes.

2.1 The US Northeast, Northern Lakes and Northern Plains regions

Forest age classes in the US Northeast, Northern Lake, and Northern Plains regions appear to have distributions with the majority of areas falling into the middle age brackets of 50–70, 40–70, and 40–60, respectively (Fig. 4 inset). Forest types in these regions are composed of northern hardwood and coniferous types including maple-beech-birch, aspen-birch, elm-ash-cottonwood, oak-hickory, spruce-balsam fir, white-red-jack pine, and mixed oak-pine forests. The average life-span of forests in these regions is approximately 130–200 yr or more as indicated by the oldest sampled forests (Fig. 4 inset). From the eastern coast towards the north-central inlands, species composition gradually changes from more maple-beech-birch, oak-hickory, and oak-pine to more aspen-birch and spruce-fir because of climate factors. However, a decadal lag in shifting dominant forest age groups from the northeastern to the northern lakes and northern plains reflects vividly the natural recovery of forests from westward agricultural clearing and abandonment and the pattern of forest harvest in the regions in the early 20th century (Fig. 1; Fedkiw, 1989; MacCleery, 1992). A lower representation of the age groups older than 80 yr may indicate an increased mortality rate, but more likely reflects the heavy harvest in the early 20th century (compared to the Canadian Atlantic Maritime region). Forests in these regions have potential to reach dominant ages of 100–120 yr old or more in next four to five decades. There are also indications of shifting species composition from spruce-fir and white-red-jack pine types to deciduous maple-beech-birch and oak-hickory types (Birdsey and Lewis, 2003) as a result of natural succession. Lower representation of young forests is typical for middle-aged forests that are not mature enough to create gaps for the next wave of regeneration.

2.2 The US Southeast and South Central regions

Forests in the Southeast and South Central regions are dominated by young growth and have shorter average life-span of approximately 80–100 yr, although some are as old as 180–200 yr (Fig. 4 inset). Forests in the region are mostly composed of loblolly pine, slash pine, oak-pine, oak-cum-cypress, and elm-ash-cottonwood, with slightly more deciduous types than coniferous types in the southeast region and much more deciduous types towards the south central region. In the first half of the 20th century much of the Southern forest was cutover and frequently burned (Larson, 1960). Afterwards, large areas of the southeast and south central regions were converted to short-rotation pine plantations, mostly loblolly-shortleaf pine. These plantations are routinely harvested and replanted, which results in relatively evenly-distributed age groups less than 60 yr old for more than 80% of the forested area (Fig. 1). Few stands reach more than 80 yr old (Fig. 4 inset). Areas that are not in plantation forestry are still harvested frequently; therefore other forest types are also maintained in a relatively young age pattern. In short, the southeast and south central forest age patterns strongly reflect the impacts of industrial forestry and plantation practice.

2.3 The US Rocky Mountain north and south regions

Forests in the Rocky Mountain regions (north and south) have totally different age structure patterns compared with the Eastern US (Fig. 4 inset). The forests are dominated by Douglas fir, fir-spruce, mountain hemlock, Lodgepole pine, and Ponderosa pine. These mountain types of forests generally have much longer life-spans than the forests in the East. Many are up to 200 yr old and some even reach the 450 yr mark. In the Rocky Mountain north region, forests ranging from 60–100 yr old are dominant, and then decline gradually with a long tail (note that different scales were used in the age histograms). A large component of young trees (Fig. 1, Fig. 4 inset) displays a regeneration pattern of old forests that are susceptible to natural mortality and disturbances, which open large areas or gaps for regeneration. However, the area of forests in age groups 20–60 yr are small, likely as the consequence of fire suppression for more than half a century, which reduced natural disturbances and maintained dense stand structure that resulted in low understory recruitment (Donnegan et al., 2001; Gallant et al., 2003; Keeling et al., 2006). A high peak of age groups in the 60–100 yr classes reflects the more usual stand-replacing disturbances that occurred before fire suppression. In the Rocky Mountain south region, forests tend to be older than in the northern region, with much higher components of old-growth forests and a longer life-span of 50 yr more (Fig. 1, Fig. 4 inset). The dominant age groups are of 70–100 yr. There are periodic evenly distributed age groups distinct from adjacent age groups, which may reflect periods of disturbances from fires or insects that left only forest fragments, and periods of logging as the region was settled. There is less forest area below 20 yr old compared with the northern region likely due to longer life-cycles of the southern forests and longer time taken for massive canopy openings. Because of the less accessible geography and recent lack of forest harvesting, a large component of intact old forests has survived. In general, the forest age structure of the Rocky Mountain regions reflect less human impacts compared with natural disturbance and succession.

2.4 The US Pacific Northwest and Southwest regions

Forests in the Pacific Northwest and Southwest regions have the longest life spans of the US though the distribution of age classes tends to younger ages than in the Rocky Mountains (Fig. 4 inset). Forest types in the Pacific West are similar to those in the Rocky Mountain regions, though with more local types such as western oak, Hemlock-Sitka spruce and Alder-maple. In the Pacific Northwest, trees can live up to 800 yr, while Pacific Southwest forests have trees to 1000 yr (Fig. 4 inset). An abrupt decline of forest age groups older than 100 yr may reflect pervasive harvest in late 19th century (Birdsey et al., 2006) during the westward expansion. In the Pacific West, more than a half of old forest areas (more than 100 yr) vanished due to harvest and other disturbances. The area of old growth (generally, 200 yr old or more) in 1992 was estimated to be about 10 million acres (Bolsinger and Waddell, 1993), whereas in 1920 there was an estimated 40 million acres of “virgin forest” (Greeley, 1920). There is a distinct contrast in the age pattern of young forests between Pacific Southwest and Northwest regions. The Pacific Northwest region has much higher components of young forests due to more intensive regeneration of harvested lands for industrial forests (Fig. 1, Fig. 4 inset), whereas the forests of the Pacific Southwest region seem to be left unperturbed for natural recovery from disturbances of a century ago and show a natural succession pattern associated with low occurrence of young forests (Fig. 4 inset), indicating the forests in the region will take many decades to reach maturity.

2.5 The US Southern Alaska region

Inventory-based forest age information in Alaska is quite limited except for the Southeastern Alaska region. The forest age structure in the region is largely defined by natural disturbances and harvesting in the Tongass National Forest, the largest in the nation (US Forest Service, 2005). The forest longevity is comparable to the Rocky Mountain regions, with species composed of spruce-fir, Hemlock-Sitka Spruce, Fir-Spruce-Mountain Hemlock forests, and a small amount of aspen-birch. There are more old-growth forests than young forests (Fig. 4 inset), and a high proportion of forests between 80–100 yr. There are a few age groups with irregularly higher proportion of area intervened with flatly distributed age groups- the uneven pattern that may suggest some large periodic disturbances such as fires that happened across the landscape (Fig. 1).

2.6 Canadian Maritime region

Forests in Canada are generally much less affected by human-induced disturbances. The forest age structure in the Canadian Atlantic Maritime region, compared to adjacent Northeast US (NE), fully reflects such a difference. After centuries of farming in this region, few remaining forests are older than 120 yr. However, the percentage is still much higher than that in the NE region (Fig. 5 vs. Fig. 4 inset). Forest types and life-spans in this region are similar to the NE region though there are more boreal white and black spruce forests in the northern areas. The region is densely forested with second- and third-growth forests. The dominant forest age groups are from 80–120 yr old, on average 40 yr older than the NE region, reflecting the early agriculture abundance but without such a heavy harvest of second forests in early 20th century as occurred in the NE region. Forests also demonstrate a perfect natural successional pattern and the next wave of forest regeneration following various natural disturbances that affected mostly the boreal old growth forests located in the northern areas (Fig. 1; Kurz and Apps, 1999; Williams and Birdsey, 2003).

2.7 Canadian Great Lakes region

This region is characterized by high coverage of forests and transitional coniferous boreal forests to broad-leaved deciduous forests. Forest types are similar to the US Northern Lakes region and the NE region. The forest age structure is basically similar to that in the Atlantic Maritime region, but marked by less remaining trees older than 120 yr (Fig. 5 inset), perhaps due to amiable climate and conditions for earlier agriculture that caused more harvesting. The succession pattern of forests is less smooth than the maritime region with apparent traces of frequent natural disturbances, mostly in boreal forests in the north and northwest areas of the region (Fig. 1) with random disturbance patches and fire scars. Most forests younger than 80 yr are distributed relatively evenly across age classes except for 20–30 yr old, likely the result of the last spruce-budworm outbreak (Williams and Birdsey, 2003).

2.8 Canadian Prairie region

The northern part of the Prairie region is populated with dense, closed boreal forests dominated by white and black spruces and other coniferous types and also has a transitional zone with mixtures of broad-leaved trees and a wide ranging of trembling aspen that thins out into open and almost treeless Prairie in the south. The forest age structure bears some similarities to forests in the Great Lakes region (Fig. 5 inset), showing the traces of agricultural abandonment in later 18th century (Sisk, 1998), but with much less density of recovered forests and greater components of young forests. It is very likely that more natural disturbances occurred in the boreal forests, which has a natural fire return interval of about 75–100 yr. Fires are the major cause of forest disturbances here because the region is dominated by coniferous trees and is also drier than other regions (Fig. 1). The dominant forest age groups are younger than 30 yr to form the second wave of forest succession, and a relatively small area of forest is in the older age classes.

2.9 Canadian North region

The forests in this region represent the northern component of the Canadian boreal forest belt. A colder climate and shorter growing season nurture more spruce and larch, which dominate the landscape. Along the northern edge the forest thins into open lichen-woodland with trees growing farther apart and smaller in size as the forest stretches towards the treeless tundra. The forest age structure in the region is broken into two cohorts, i.e. trees younger than 40 yr old, and trees between 80–120 yr old (Fig. 5 inset, Fig. 1). Such a pattern perhaps reflects severe growth conditions and the strong influence of natural disturbances that are critical for stimulating forest resurgence in the region. Forest age structure in such a landscape is very much an indicator of periodic and highly variable fire disturbance cycles (Kurz and Apps, 1999).

2.10 Canadian Pacific region

This region is characterized by the temperate rainforest, which is adapted to the steep cliffs and rugged coastlines of this area. The region has higher rainfall and fewer fires than other regions in Canada. As a result, trees in the temperate rainforest are often much older than those found in the boreal forest (Fig. 1). Forests in the lower seaward slopes of the Coast Mountains and extending to the coastal islands support old growth cedar and Sitka spruce, while the steep hill slopes are home to ancient western hemlock, balsam, red cedar and spruce. In the areas between the Rockies and the Central Plateau including several valleys, forest types resemble the coastal region, characterized by Douglas fir, western white pine, western larch, Lodgepole and ponderosa pine, and trembling aspen. Engelmann spruce and alpine fir are found in the subalpine region. The forest age structure shows a great amount of old-growth forests (>150 yr) still remaining in the region (Fig. 5 inset). However, harvests between later 19th and early 20th centuries replaced old-growth forests with younger trees. Since then, forest age classes smoothly decline from 120 yr to 20 yr old, related to managed harvesting and reforestation in this most important timber industrial land of Canada. A high component of forests less than 20 yr old may be the result of combined effects, recent severe outbreaks of insects in the region (Kurz et al., 2007), harvest and new plantations.

2.11 Summary of regional analysis

The above analyses based on characteristics of the forest age map and the current forest age structure in different regions of the US and Canada clearly show the dependence of current forest-age structure on forest disturbances of the past, both by natural and human activities. The information is remarkably consistent with our knowledge about the land-use history and forest past in North America since European colonists arrived in North America (Sisk, 1998). Forest ages certainly carry the disturbance legacy and are excellent surrogates for addressing disturbance impacts on forests. Our analysis shows that forests in the US bear much deeper and broader human footprints than in Canada, that most forests in the US were disturbed in the last two centuries, except some inaccessible areas in the Rocky Mountains and Alaska, and that some old-growth remains in the Pacific Northwest and Southwest. In Canada, industrial timber harvest is quite intensive in some areas of boreal and temperate rainforests. However, because of Canada's immense forest lands and frequent and wide-spread natural disturbances, particularly wildfires, forested lands are distinctly marked by natural disturbances with the exception of the Pacific Region. On average in Canada, the annual burned area is more than three times the current annual industrial timber harvest, and even more in bad fire years (Stocks et al., 2003). Just the opposite is true for the US where the impact of timber harvest is several times that of the impact of natural disturbances.

3 Application of forest age map in forest carbon studies

Because forest disturbance and regrowth profoundly affect forest capacity for sequestering and storing carbon, our continent-wide spatial data of forest age distribution can be critical for improving estimates of forest carbon stock and flux in North America, and can also be used as reference for assessing the future forest carbon balance and potential, regardless of whether the estimation approach is empirical or model based.

Though there are many possible applications of this valuable information to forest carbon studies, here we describe a few potential uses to provoke further ideas.

3.1 Using the age map to analyze carbon-favorable forest management opportunities

Estimates of current carbon stocks and changes in carbon stocks at the landscape scale may be simply made by combining the age map with standard estimates of ecosystem carbon for different forest types and regions (Smith et al., 2006). Here we present an example of this kind of applications for the Northeastern US. From the age map, we estimate the area by forest type and age (Table 1) and then multiply the estimated area in each cell of the table by the corresponding estimate of NEP from Smith et al. (Table 2a and b, Fig. 6a and b), both for afforestation and reforestation types. Results suggest that, on average, NEP is 1.35–2.19 t/ha/yr in afforestation sites, and 0.88–1.57 t/ha/yr in reforestation sites with some variation by forest type (Table 2a and b). These estimates compare reasonably well with measured NEP at flux towers at the Harvard Forest in Massachusetts and the Howland Forest in Maine (Barford et al., 2001; Hollinger et al., 2004). It also shows 25%–42% lower NEP on reforestation sites that follow harvest or other disturbances because of the loss of carbon from forest floor and soils, which is different from afforested sites where soil carbon typically increases to recover depleted pools from previous agriculture use (e.g., Post and Kwon, 2000). As a result, annual carbon accumulation in the New England forests under the current age structure is between 30–38 Tg carbon (using 0.5 as the carbon conversion), which compares favorably with recent estimates of changes in carbon stocks from repeated inventories (US Department of Agriculture, 2008). In total, the carbon accumulation from reforestation sites is about 20% lower than afforestation sites; however we did not count carbon in harvested wood from the reforestation sites, which could largely compensate for the lower carbon accumulation in reforestation sites.

Forest age can be a good indicator of management opportunity. When compared with a standard growth curve, forest age can indicate whether the stand is aggrading or degrading, giving the land manager an indication of the kind of treatments that can be applied if the manager is interested in changing the rate of carbon sequestration or increasing the stock of carbon on a landscape. Continuing the previous example for New England, we show the deviation from maximum NEP for each forest grid cell of the Northeast and indicate whether this deviation is because the forest is younger or older than the age of maximum NEP (Fig. 6c). If the manager is interested in maximizing NEP, it may be determined that forests younger than the age of maximum NEP could be left alone because carbon sequestration will increase without any intervention, and that forests older than the age of maximum NEP may be considered for thinning to reduce stand density to an effectively younger age. If the manager is interested in increasing the stock of carbon on a landscape, the map may be used to identify forests that are already at high stocking levels and would require protection from disturbance, and to identify forest areas that could be left to grow older. In practice, and as shown by the regional age distributions described in the previous section, some combination of maximizing NEP and maximizing C stocks is likely to emerge as the best strategy, considering that forests are not only managed for carbon but also for many other purposes such as timber production and recreation. Note that in this simple exercise we are not recommending a specific approach to increase carbon sequestration or carbon stocks. In reality this kind of analysis is much more complicated and needs to consider factors such as emissions and retention of C in harvested wood, the energy inputs for stand treatments, and impacts on soil C, to name a few. Our analysis clearly shows that after disturbances, forests have reduced total carbon accumulation particularly if dead trees are left to decompose. Consideration of these factors over the full life cycle of a stand will provide a more comprehensive and credible recommendation, such as valuing the carbon credits for old-growth forests (Luyssaert et al., 2008). Nonetheless, the age map combined with the mapped productivity does provide a first-level spatial analysis of the state of the forest system, which may then be expanded to a full carbon accounting and management recommendations.

3.2 Using the age map to improve carbon estimation by terrestrial models

Process-based biogeochemical models are important tools to estimate terrestrial carbon budgets (Sitch et al., 2008). A very unique function of such "mechanistic" models is the ability in a diagnostic sense to interpret temporal and spatial patterns of forest C dynamics and partition the effects of various climatic drivers and different environmental variables, which are not always identifiable by experimental and observation approaches (Pan et al., 2009). Therefore, terrestrial carbon models can serve as powerful methods to integrate and expand our knowledge of complex interactive effects of multiple environmental changes on forest carbon dynamics. Terrestrial carbon models are continuously improving by reducing uncertainty in estimation and prediction, and by improving input data layers, model formulas and parameters (Pan et al., 2006).

Currently, many land-based terrestrial carbon models are not capable of reflecting the impact of land disturbances because spatially-explicit historical data at landscape scales is lacking. Therefore, most models represent ecosystem dynamics at equilibrium conditions (Canadell et al., 2007a). However, with the availability of spatial forest age data and its ability to simply represent historical disturbance legacy, we can improve terrestrial biogeochemistry models through certain modifications, including the use of age cohorts and incorporation of forest growth curves (Fig. 6a,b), making the models capable of simulating forest regrowth dynamics as the consequences of the impact of land-use, human and natural disturbances (Pan et al., 2002), even if they may not able to separate direct and indirect effects. In a Canada-wide forest carbon cycle study using a mechanistic ecosystem model with consideration of both disturbance (mostly fire) and lack of disturbance (climate, CO_2 and nitrogen) effects, a forest age map compiled from forest inventory, large fire polygons and remote sensing played a central role in estimating the direct carbon emission during the fire and regrowth after the disturbance (Chen et al., 2003). The improved terrestrial carbon models can also use the current forest age map to project the forest age structure over the next few decades following natural succession, and predict forest potential carbon sequestration capacity in the near future, for better understanding of the role of forests in the entire global carbon cycle and addressing the recent concern about the possibility of terrestrial carbon sink saturation in the next few decades (Canadell et al., 2007b).

3.3 Using the age map to improve land constraints on atmospheric inverse models

Several recent publications show a full analysis of the global carbon cycle with comprehensive consideration of carbon fluxes or stock changes in the atmosphere, ocean, and land (Le Quéré et al., 2009; Canadell et al., 2007b). In such analyses, the carbon exchange between the ocean and land surfaces with the atmosphere is estimated based on global transport inversion using observations of CO_2 concentration in the atmosphere (Peters et al., 2007). Usually, inverse models are not well constrained because of insufficient number of CO_2 observation sites in the global monitoring network. Simulated carbon fluxes from lands and oceans with additional consideration of other surface observations are needed to provide constraints to the inverse modeling to obtain meaningful results. However, such inverse modeling could suffer great uncertainty from small-scale structure of the fluxes due to spatial heterogeneity, particularly for the regions lacking observations such as the tropical areas (Stephens et al., 2007).

One way to improve the inversion estimates is to provide better land-surface flux constraints. The a priori carbon flux fields from lands used for inversion constraint are often obtained from ecosystems models validated at discrete sites using measurements such as eddy covariance (Deng et al., 2007; Peters et al., 2007). None of these surface flux fields used for constraining the inversions has so far considered the forest carbon dynamics associated with forest age. The flux tower data have shown the obvious relationship between net ecosystem productivity (NEP) and forest stand age, indicating that the carbon flux over forests is closely related to forest age (Chen et al., 2003; Law et al., 2003). In order to capture the large scale regional patterns of the carbon flux associated with the disturbance and regrowth cycle and estimate the first order effect of forest age on NPP and therefore NEP, the continent-wide forest age map is used for developing a forest age factor map (Fig. 7), in which the age factor was calculated as a scalar based on a generalized NPP-age relationship (Chen et al., 2003). The generalized NPP-age relationship has a similar temporal pattern to those shown in NEP curves (Fig. 6b), when the heterotrophic respiration is assumed to be constant. Therefore, it can be derived from the NEP curves by shifting the curves upward with a constant to allow NPP to start with a zero value in the initial year. The relationship is normalized against the maximum NPP value, so that the normalized NPP varies between zero and one. In the generalized NPP-age relationship, the age at which the maximum NPP occurs depends on the climatological mean annual air temperature at each pixel (Chen et al., 2003), considering the fact that forests grow faster and reach the maximum NPP earlier under warmer climates. Other factors, such as precipitation, soil and topography, may influence the magnitude of NPP but are assumed to have no influence on the timing of the maximum NPP occurrence.

Figure 7 shows the distribution of the age factor (normalized NPP value) at the continental scale determined by the age map (Fig. 1) and the mean annual air temperature. Low values (warm tone, i.e. yellow to red) indicate low productivity relative to its own life cycle either due to young or very old ages, where NPP is most likely smaller than the heterotrophic respiration (NEP<0). High values (cold tone, i.e. green to blue) suggests high productivity, where NPP is most likely greater than heterotrophic respiration (NEP>0). The fact that the overall distribution over the continent has a cold tone suggests that the forest age structure in North America is in favor of carbon sinks. In addition to this simple diagnosis of the age effect at this large scale, this age factor map may be particularly useful for adjusting the neutral biosphere flux (annual NEP=0) simulated by land models, to be used as an additional constraint for atmospheric inversion. As reliable CO_2 concentration observation stations are still quite sparse and carbon fluxes from forests in various regions in the North America are quickly mixed by the atmosphere, the relative differences among the regions caused by their different age structures could help improve the spatial resolution of the atmospheric inversion. However, this utility is yet to be tested.

4 Discussion and conclusion

Ground-based and spatially explicit forest age data provide valuable information for improving forest carbon estimates, evaluating the disturbance impact, and predicting forest carbon sequestration potential in the next few decades as forests naturally proceed to reach maturity or start rebirth after old forests are disturbed or complete their life cycle. However, there are limitations of an age map for characterizing succession and carbon sequestration. Assigning an age to a forest is an inexact process. Trees in many if not most forests have different ages, so the assigned age is typically an average age unless there is a very distinct disturbance and regeneration activity such as a clear-cut followed by a plantation establishment (Bradford et al., 2008). Forests undisturbed for long periods of time tend to develop an uneven-aged stand structure as canopy gaps become filled with younger trees (Luyssaert et al., 2008). Many natural disturbances do not kill all of the trees in a forest stand, so the regenerating trees are often growing amongst a residual number of older trees. And natural regeneration may be a slow process such that the new trees may span a range of ages over several decades (Pregitzer and Euskirchen, 2004). Because of the nature of these disturbance and regeneration processes, there is a difference between age and time since disturbance (Bradford et al., 2008). In many cases, an observed tree age may be a poor predictor of time since disturbance, and depending on how this information is used in models, estimates of carbon stocks or fluxes may have significant errors. Nonetheless, we have shown that age is a convenient indicator of successional status after disturbance, can be easily related to ability of forests to sequester and store carbon, and can support improvements in analysis and modeling techniques. In addition, age is not the only factor affecting carbon stocks and rate of C uptake. Climate, atmospheric CO_2, air pollution, N deposition, fertilization, and other factors may be significant (Canadell et al., 2007a; Pan et al., 2009). However, the data from forest inventories that underlie the carbon stock and NEP curves used in this analysis reflects the aggregate effect of these factors over the region of interest. Therefore, results may be accurate even if the effects of all of the contributing factors are not individually estimated.

Tree age data are not available everywhere in North America. Some regions are not very well covered by forest inventories, such as interior Alaska and the northern part of Canada. And in tropical hardwood forests such as those in parts of Mexico, trees do not have visible growth rings which are typically used to assign ages during inventories. Finally, forest age maps may be used in conjunction with remote sensing data for driving predictive models of forest dynamics. Although signals from optical remote sensors tend to saturate at the time of tree crown closure, lidar and radar sensors can extend the data to older age classes and higher biomass densities. Models driven by remote sensing, such as CASA (Potter et al., 1993), may benefit from good characterization of forest age in terms of improving the accuracy of gridded estimated of productivity and carbon stocks.

Appendix A

Data and methods

A1 Approach for Canada

A1.1 Inventory and disturbance data

In Canada, the national forest inventory (CanFI) is compiled about every five years by aggregating provincial and territorial forest management inventories (www.nrcan-rncan.gc.ca). Stand-level data provided by the provincial and territorial management agencies are converted to a national classification scheme and then aggregated to ecological and political classifications. The data used for this study were derived from the Canadian forest biomass inventory of Penner et al. (1997), which was originally compiled from Canada's Forest Inventory (CanFI) 1991 (1994 version) (Lowe et al., 1996). The gridded data of biomass were obtained by allocating the 10 km cell data proportionately to the 1 km pixels on a land-cover class map. An inland water mask was overlaid on this 1 km grid to exclude all pixels known to be dominantly water covered (about 10% of the Canadian land surface). However, since the available inventory data are outdated, we had to use the remote sensing data to update the age information upon the baseline of inventory data in 1991 (see description in the next paragraph).

Then the historical fire data, based on the Canadian Large-Fire Data Base (LFDB), were compiled from datasets maintained by provincial, territorial and federal agencies (Amiro et al., 2001). The dataset provides polygons mapped in a Geographical Information System (GIS), which delineates the outline of the fire and attribute information, such as fire start date, year of fire, fire number, and final area burned. It includes 8880 polygons of fire scars larger than 200 ha distributed across much of the boreal and taiga ecozones, going back as far as 1945 in some areas (Stocks et al., 2003). The LFDB includes fire records for the 1959–1995 period. These fire polygons were co-registered with remote sensing images and used to estimate the forest stand age in pixels that overlap with the polygons. The datasets were also used to develop the remote sensing algorithm to detect and date fire scars that were not included in LFDB.

A1.2 Remote sensing and age distribution

Satellite imagery was used to supplement data from inventory and LFDB to complete a Canada-wide forest stand age map in 2003. Satellite imagery is useful for extending the fire record from 1995 to 2003 and discovering fire scars that are not included in the LFDB. Fire scar maps for the 25 yr prior to 1998 were produced using data from the VEGETATION sensor onboard the SPOT4 satellite. The angular normalization scheme developed for AVHRR (Chen and Cihlar, 1997) was applied to VEGETATION 10-d cloud-free synthesis data from June to August 1998. Ratios of shortwave infrared (SWIR) to NIR in these 9 images, named as the disturbance index (DI), were averaged for each pixel to produce a single ratio image for the mid-summer. The averaging process was necessary as SWIR signals are sensitive to rainfall events. The relationship found by Amiro and Chen (2003) between the mean SWIR/NIR ratio in the summer and the number of years since the last burn was used to develop an algorithm for mapping the fire scar areas of the individual years between 1973 and 1998. The dating algorithms have accuracy of ±7 yr for scar ages smaller than 25 yr (Amiro and Chen, 2003), and the total disturbed area in any five-year period is within 10% variation of the total reported by Kurz and Apps (1995). From 1999 to 2003, VEGETATION data were used to detect fire scars annually.

A map of forest stand age for 2003 was created using the combined information from forest inventory, fire polygon data and remote sensing. Fire polygons in the LFDB provided data for the northern boreal regions, but only included large fires in the period from 1959 to 1995. Remote sensing imagery was used to fill in the data gaps both in space and time. Annual forest burned area maps in the years between 1973 and 1998 were constructed using the fire scar dating algorithm developed by Amiro and Chen (2003), and the same maps between 1999 and 2003 were derived through annual fire scar detection. These maps were then used to replace the age data in the gridded inventory data while the older age classes in the inventory are unchanged, i.e., we assumed that the inventory age-class data were correct for all grid cells that were not disturbed after 1973. In the combination of these three types of data, a 10×10 km grid cell in the forest inventory was divided into 100 pixels at 1 km resolution. Pixels of different age classes were randomly distributed within the grid cell and were replaced by fire polygons of known dates or by recent fire scars if detected by remote sensing. For simplicity, forest regrowth is assumed to start immediately after disturbance, so the age of forest in a burned area is assumed to equal the time since the date the fire scar was detected by remote sensing. For non-commercial forests, areas with fire scars younger than 25 yr were considered to be reliable, and the other areas randomly assigned an age in the range from 26 to 110 yr, based on the area fractions in each age class reported for the inventoried regions. The future work of this study will develop new regression analyses using the LEDAPS data (see description in the next paragraph) against the Large Fire Polygon database (18 ecoregions, 1959–1995), as refinement to the results of Amiro and Chen (2003).

A2 Approach for the US

A2.1 FIA age information and disturbance data

Development of the age map for the US mostly relied on the Forest Inventory and Analysis (FIA) data. The USDA Forest Service FIA Program conducts a continuous inventory and assessment of US forests (Bechtold and Patterson, 2005). This national inventory provides periodic estimates of area, timber volume, tree biomass, growth, mortality, and harvest of wood products (Smith et al., 2001). The inventory also characterizes important forest attributes such as forest type, tree density, and stand age. The forest inventory data is the basis for reporting statistics about carbon in US forests (Birdsey and Heath, 1995; US EPA, 2005). Continuous geographic coverage is a problem in remote areas where past inventories have been incomplete, most importantly Alaska. Alaska is currently being inventoried and comparable data will be available within a decade.

The FIA estimates are based on tree measurements from a very large statistical sample of US forests (more than 150 000 sample locations), and mathematical models to estimate forest attributes such as biomass (Birdsey and Schreuder, 1992). The FIA age information reflects disturbances over the past 100 yr or more. However, FIA data are statistically based point samples within geographical units as small as counties. Stand age is estimated at sample plots by examining tree rings from cores. Therefore, it can be an inexact process because only one or a few trees selected to represent the average age of the sample area are cored. We compiled estimates of age-class distributions for forest types within the county or "super-county" (i.e. the combination of several small counties). The county or super-county have sufficient size to contain an adequate number of FIA sample points for constructing estimates of age-class distributions by forest type, including estimation of the sampling error. The FIA summarized age-class distribution were allocated to individual pixels by the remote-sensing based disturbance classifications including timing and areas to cast a current spatial pattern of forest ages in the US. This approach avoids the inaccuracy of using individual point estimates of age classes.

A2.2 Remote sensing and age distribution

The relationship between age-class and spectral/structural properties from remote sensing is interpolated from points to 1-km pixels, primarily for the younger age classes since these remotely sensed signals saturate at an early stand age (He et al., 2010). Disturbance (wildfire, insect-induced mortality, harvest) modifies forest age structure (Kurz and Apps, 1996). Satellite remote sensing acquired in the recent decades can be processed to retrieve the needed disturbance information to supplement (update and spatialize) forest age data in FIA. The LEDAPS (Landsat Ecosystem Disturbance Adaptive Processing System, Masek et al., 2008) has produced useful data for this purpose. In LEDAPS, historical Landsat data in two years, 1990 and 2000, are processed to extract the disturbance information, through pair-wise comparison of reflectance data. LEDAPS produces disturbance maps at 28.5 m resolution for selected areas and at 500 m resolution for the whole of North America. In addition, the reflectance data for North America at 500 m resolution are also available for this analysis.

We used atmospherically corrected 500 m North America surface reflectance mosaics of LEDAPS (1990 and 2000) to produce a disturbance index (DI), which consists of the ratio of the shortwave infrared (TM band 5) to near infrared (TM band 4) reflectance (Amiro and Chen, 1993). Large fire and insect disturbance areas (>100 ha) derived from different sources (such as FIA, Landfire, Fire maps, defoliation maps) during the 1975–2000 period in different ecoregions (~20) were selected to develop correlations and thresholds between DI and the time since disturbance for each ecoregion for fire, insect, harvesting and afforestation separately (He et al., 2010). As mentioned earlier, DI can be used for dating fire scars for up to 25 yr, with an error of about 7 yr (Amiro and Chen, 2003), but the longer the dating period, the larger is the dating error. When dating between the two remote sensing years (1990 and 2000) and within 10–25 yr before 1990, the error was much less than 5 yr. Assuming forest regrowth starts immediately after disturbance, time since disturbance was taken as the forest age. However, we quantified the delay of regrowth after disturbance using FIA data where possible. Because the variation of DI with time since disturbance depends mostly on the rate of regrowth after disturbance, separation of the statistical analysis by ecoregion is necessary. This approach limited the available data for regression analysis for each region. We therefore used the results of annual Landsat data cube analysis to develop reliable relationships between DI and the time since disturbance. This DI based approach was also used to determine if a 500 m pixel has been disturbed over the 10 yr period, i.e. for mapping disturbed area at this moderate resolution.

The LEDAPS product also provides the fraction of disturbed area within each 500 m pixel through summarizing the 28.5 m resolution information. It provides more reliable disturbed area estimation than the DI-based approach described above, but it does not provide the information of the timing of disturbance within the 10 yr time window. We therefore used this product to check against the disturbance detection using DI for possible refinement of the algorithm and for error assessment. The rate of regrowth provided in this product is also related to the variation of DI with time, and was used for dating error assessment. After all, we used the disturbance-dating results and the area fraction of disturbance at 500 m resolution with FIA disturbance data to develop a forest age map for young forests established between 1990 and 2000. This product then was used to overlay and modify the inventory-based US forest age map in 2000 at 1 km. The FIA age data and indicators of disturbance in the period of 1990–2000 provide an additional control on the errors in dating and mapping disturbance. We took the age distribution and indicators of disturbance in FIA data as the truth, and used remote sensing data (LEDAPS and its derivatives) to spatialize the information with each 1-km grid, creating a pseudo 500 m resolution forest age map, which may represent the best forest age spatial information by integrating the major information sources currently available.

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Table 1. Area (1000 ha) by forest type and age class for the Northeast US.

Age class	Aspen-birch	Maple-beech-birch	Oak-hickory	Oak-pine	Spruce-balsam fir	White-red-jack pine
0–5	6919	160 831	124 856	3538	29 875	6150
6–15	22 281	769 550	272 056	5819	232 631	20 731
16–25	36 838	923 075	982 156	10 950	316 119	27 775
26–35	42 019	1401 188	789 894	14 738	274 350	70 763
36–45	61 769	2 198 769	2 311 050	43 075	301 919	140 375
46–55	55 281	2 609 775	1 404 206	43 775	358 263	188 044
56–65	64 006	3 176 638	3 176 706	58 119	376 831	239 156
66–75	51 475	2 755 381	1 456 706	28 519	389 419	171 313
76–85	34 200	2 106 606	2 030 619	32 838	317 606	106 925
86–95	18 388	1 192 050	590 188	7619	169 494	60 100
96–105	6781	592 019	617 738	7338	107 350	27 213
106–115	9200	221 713	137 263	2750	71 056	12 831
116–125	3719	112 081	66 888	800	34 444	3925
>125	3550	131 831	113 656	369	48 375	5863
Total	416 426	18 351 507	14 073 982	260 247	3 027 732	1 081 164

Table 2a. Net ecosystem production (tC/ha/yr) by forest type and age class for the Northeast US (calculated from afforestation tables in Smith et al., 2006)[a].

Age class	Aspen-birch	Maple-beech-birch	Oak-hickory	Oak-pine	Spruce-balsam fir	White-red-jack pine
0–5	1.94	2.60	1.80	2.22	2.64	2.38
6–15	2.10	3.64	4.40	3.10	2.53	2.96
16–25	2.17	3.21	3.44	3.07	2.41	2.30
26–35	2.11	2.85	2.96	2.77	2.45	1.89
36–45	1.92	2.25	2.71	2.44	2.18	1.70
46–55	1.82	1.99	2.29	2.10	2.01	1.37
56–65	1.72	1.71	2.12	1.93	1.68	1.16
66–75	1.65	1.50	1.95	1.50	1.45	1.02
76–85	1.59	1.30	1.78	1.32	1.27	0.88
86–95	1.54	1.12	1.66	1.14	1.12	0.78
96–105	1.53	0.97	1.53	0.99	1.01	0.69
106–115	1.53	0.85	1.42	0.86	0.92	0.61
116–125	1.53	0.71	1.32	0.73	0.84	0.57
>125	1.53	0.71	1.32	0.73	0.84	0.57
Mean	1.76	1.82	2.19	1.78	1.67	1.35

[a] For simplicity, we used the afforestation and reforestation tables (see Table 2b), respectively even though the actual area is a mix of afforestation and reforestation (with afforestation representing the dominant prior land use in the Northeast).

Table 2b. Net ecosystem production (tC/ha/yr) by forest type and age class for the Northeast US (calculated from reforestation tables in Smith et al., 2006).

Age class	Aspen-birch	Maple-beech-birch	Oak-hickory	Oak-pine	Spruce-balsam fir	White-red-jack pine
0–5	−0.24	−1.92	−2.04	−1.92	−1.42	0.1
6–15	0.86	1.25	2.24	0.86	0.39	1.63
16–25	1.43	2.1	2.39	1.93	1.3	1.5
26–35	1.57	2.21	2.38	2.07	1.71	1.29
36–45	1.47	1.82	2.31	1.94	1.61	1.24
46–55	1.47	1.67	2.04	1.75	1.57	1.00
56–65	1.46	1.5	1.94	1.68	1.36	0.91
66–75	1.47	1.35	1.83	1.34	1.23	0.83
76–85	1.48	1.2	1.72	1.21	1.14	0.78
86–95	1.48	1.07	1.61	1.08	1.04	0.71
96–105	1.5	0.95	1.51	0.96	0.97	0.66
106–115	1.51	0.83	1.41	0.84	0.89	0.6
116–125	1.52	0.71	1.31	0.73	0.84	0.55
>125	1.52	0.71	1.31	0.73	0.84	0.55
Mean	1.32	1.10	1.57	1.09	0.96	0.88

Table 3a. Area-weighted average NEP ($t \times 10^3$/yr) by forest type for the Northeast US (based on NEP of afforestation sites).

Age class	Aspen-birch	Maple-beech-birch	Oak-hickory	Oak-pine	Spruce-balsam fir	White-red-jack pine
0–5	13 423	418 161	224 741	7854	78 870	14 637
6–15	46 790	2 801 162	1 197 046	18 039	588 556	61 364
16–25	79 939	2 963 071	3 378 617	33 617	761 847	63 883
26–35	88 660	3 993 386	2 338 086	40 824	672 158	133 742
36–45	118 597	4 947 230	6 262 946	105 103	658 183	238 638
46–55	100 611	5 193 452	3 215 632	91 928	720 109	257 620
56–65	110 090	5 432 051	6 734 617	112 170	633 076	277 421
66–75	849 334	4 133 072	2 840 577	42 779	564 658	174 739
76–85	54 378	2 738 588	3 614 502	43 346	403 360	94 094
86–95	28 318	1 335 096	979 712	8686	189 833	46 878
96–105	10 375	574 258	945 139	7265	108 424	18 777
106–115	14 076	188 456	194 914	2365	65 372	7827
116–125	5690	79 578	88 292	584	28 933	2237
>125	5432	93 600	150 026	269	40 635	3342
Total	1 525 713	34 891 161	32 164 847	514 829	5 514 014	1 395 199

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 3b. Area-weighted average NEP ($t \times 10^3$/yr) by forest type for the Northeast US (based on NEP of reforestation sites).

Age class	Aspen-birch	Maple-beech-birch	Oak-hickory	Oak-pine	Spruce-balsam fir	White-red-jack pine
0–5	−1661	−308 796	−254 706	−6793	−42 423	615
6–15	19 162	961 938	609 405	5004	90 726	33 792
16–25	52 678	1 938 458	2 347 353	21 134	410 955	41 663
26–35	65 970	3 096 625	1 879 948	30 508	469 139	91 284
36–45	90 800	4 001 760	5 338 526	83 566	486 090	174 065
46–55	81 263	4 358 324	2 864 580	76 606	562 473	188 044
56–65	93 449	4 764 957	6 162 810	97 640	512 490	217 632
66–75	75 668	3 719 764	2 665 772	38 216	478 985	142 190
76–85	50 616	2 527 927	3 492 665	39 734	362 071	83 402
86–95	27 214	1 275 494	950 203	8229	176 279	42 671
96–105	10 172	562 418	932 784	7045	104 130	17 961
106–115	13 892	184 022	193 541	2310	63 240	7699
116–125	5653	79 578	87 623	584	28 933	2159
>125	5396	93 600	148 889	269	40 635	3225
Total	590 272	27 256 068	27 419 392	404 050	3 743 717	1 046 399

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

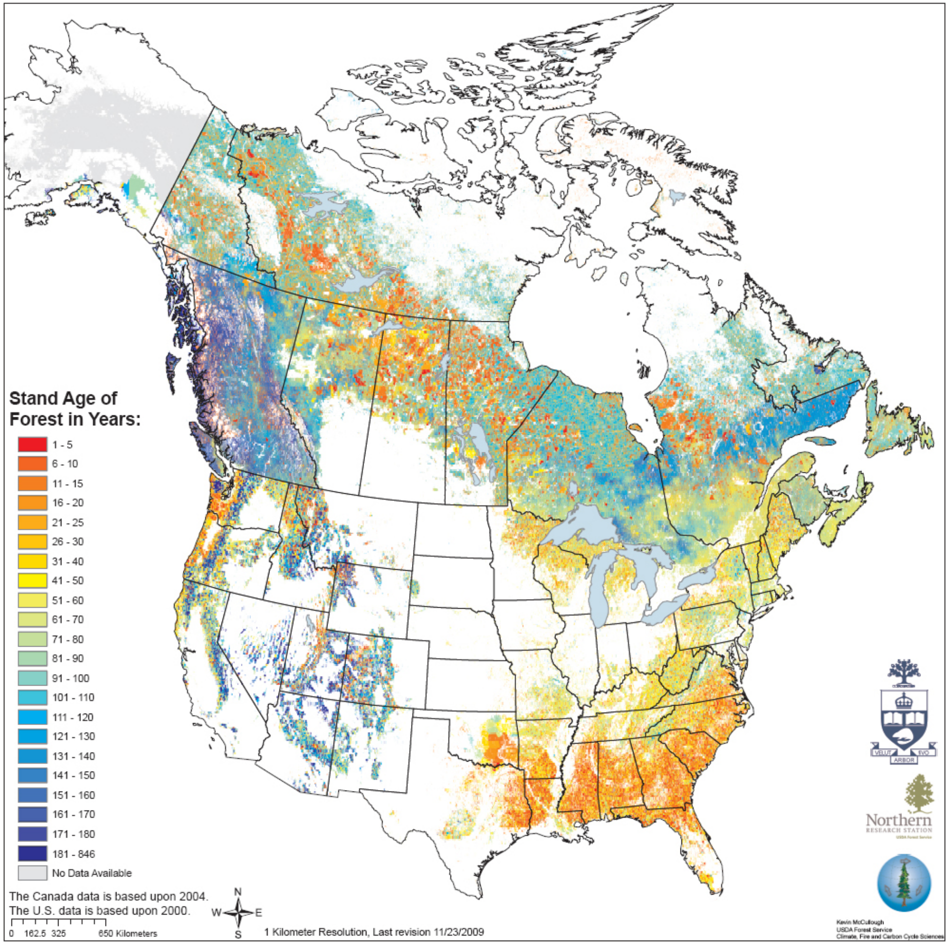

Fig. 1. Forest age distribution in North America (excluding Alaska and Mexico), which was developed by combining forest inventory data (of US and Canada) with several remote sensing based disturbance data sources.

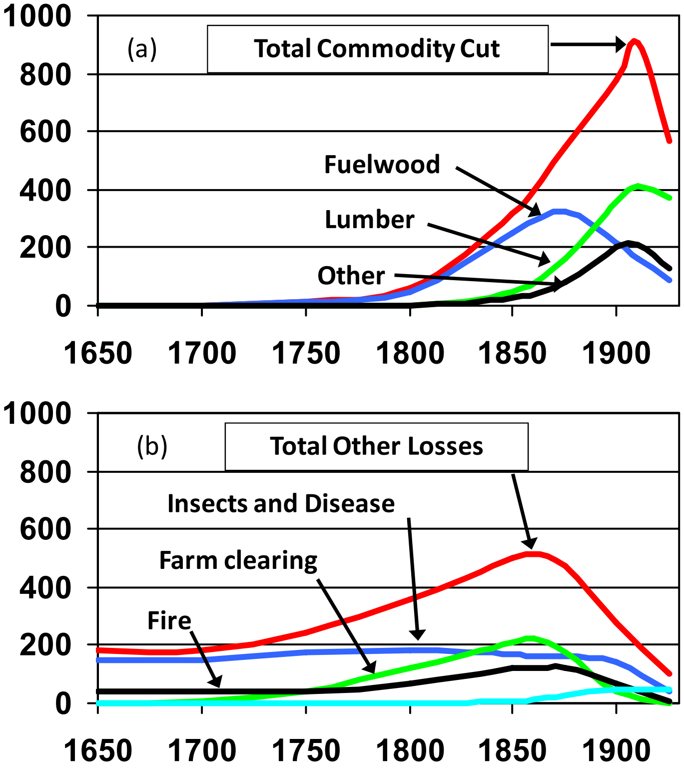

Fig. 2. Impacts of disturbances on forests in the past: **(a)** drain on the US Sawtimber Stand, 1650–1925 (unit: billion board feet per decade); and **(b)** woody volume losses affected by other disturbances (based on the data from Birdsey et al., 2006).

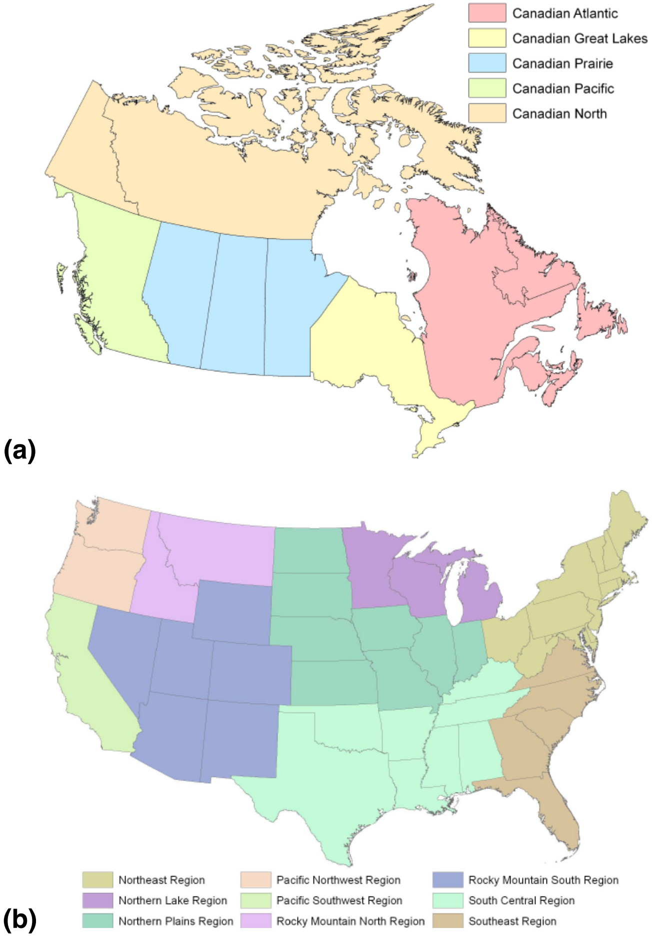

Fig. 3. Forest regions in **(a)** Canada and **(b)** the United States (Alaska is not shown here).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀ ▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

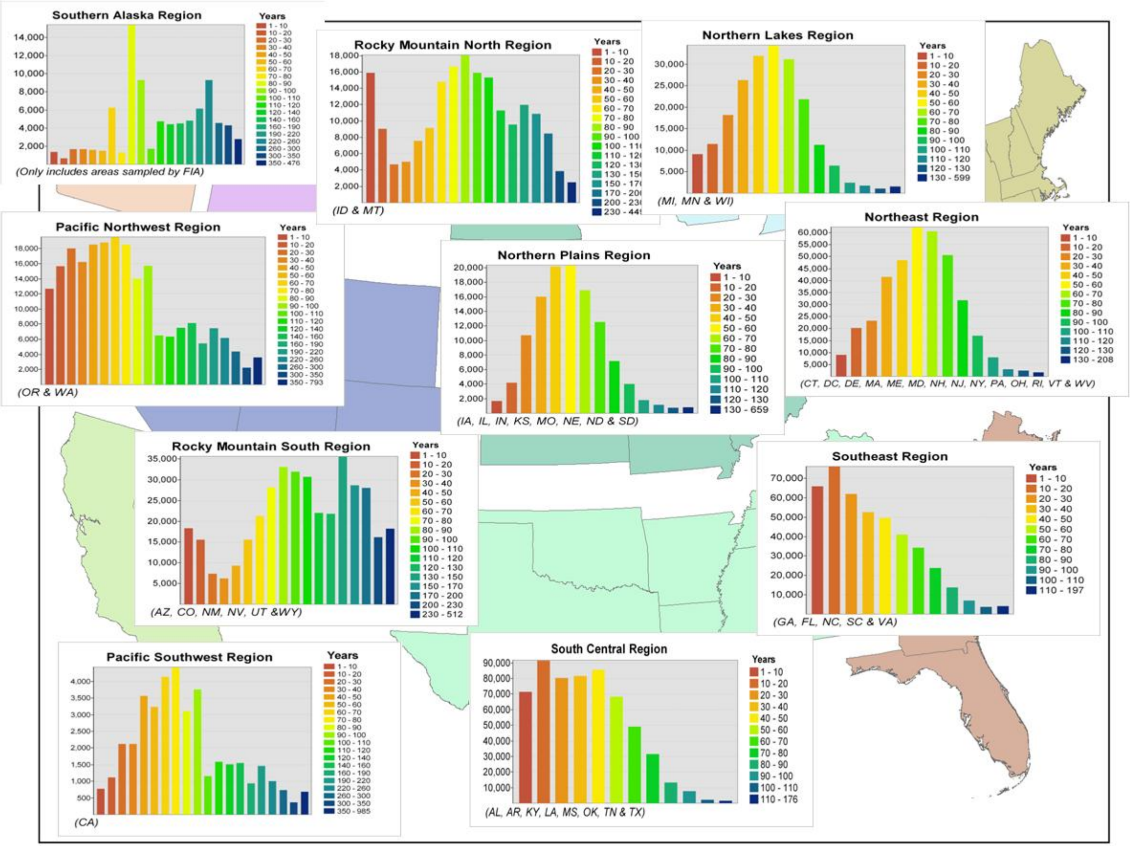

Fig. 4. The US forest age structures in different regions.

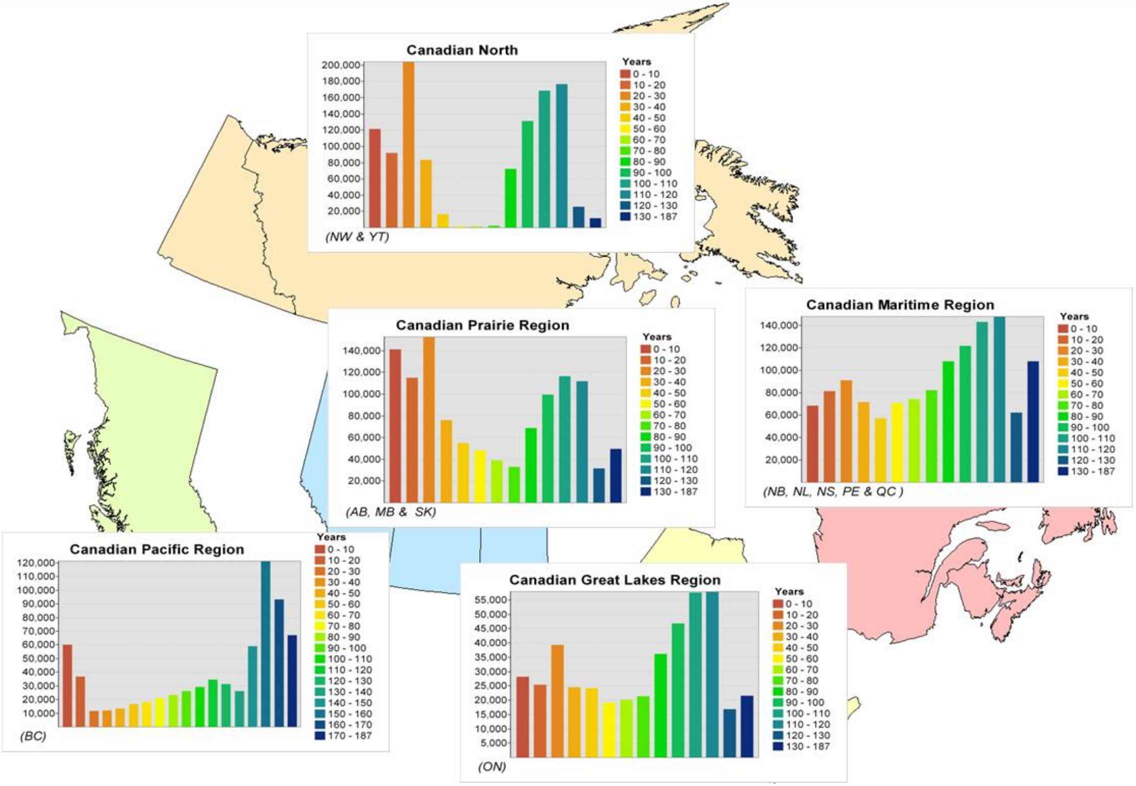

Fig. 5. Canadian forest age structures in different regions.

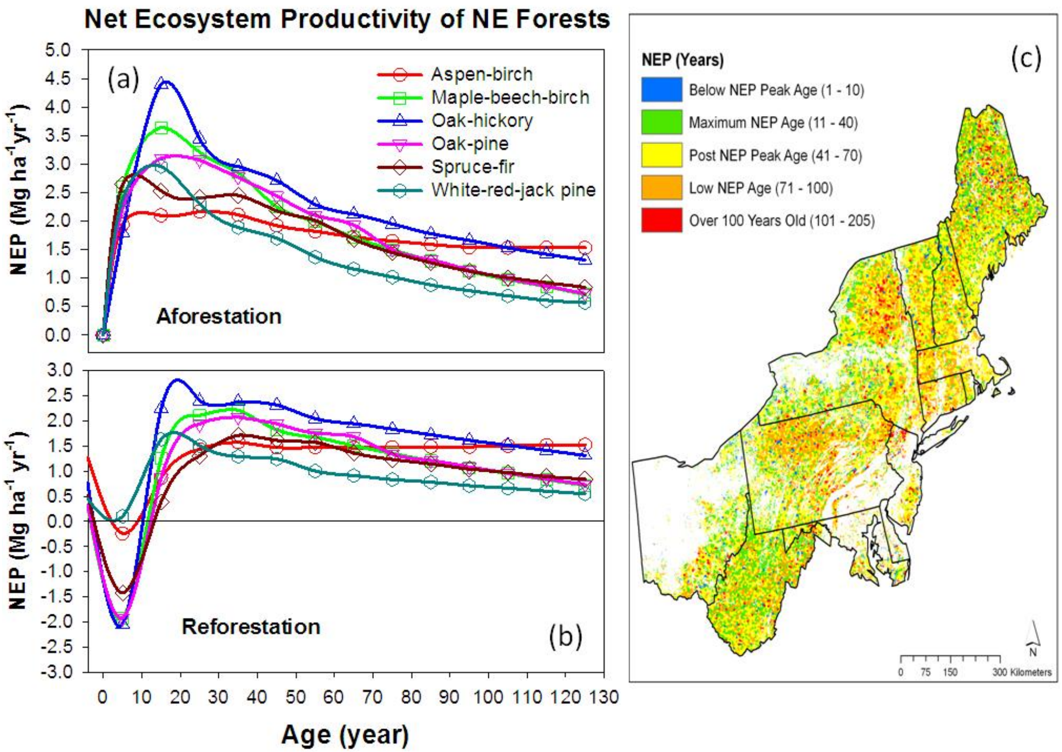

Fig. 6. Mean annual net primary productivity of Northeast region forests based on forest inventory data: **(a)** from afforestation sites; **(b)** from deforestation sites, NEP loss from woody product is not counted in the initial year, and **(c)** NE forests with different NEP levels related to age.

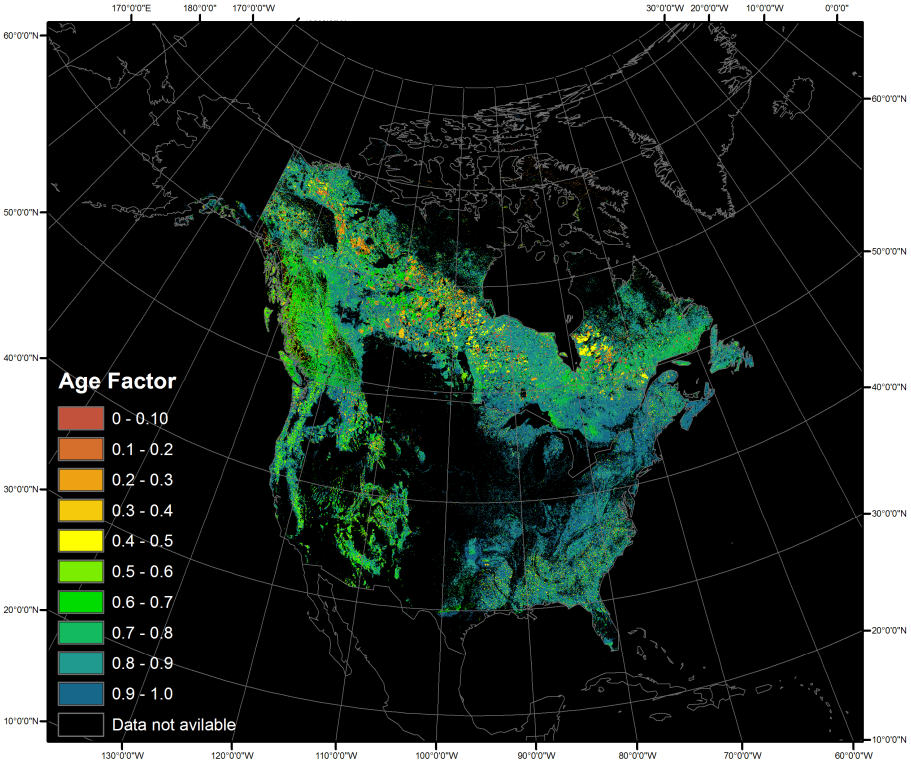

Fig. 7. Forest age factor derived from the forest age map (Fig. 1) useful for constraining atmospheric inverse modeling of the biosphere carbon flux.