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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 stocks 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 a useful  surrogate variable for analyses of  the impact of disturbance on forest carbon. 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 Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) project. 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, by analyzing the causes of disturbances from land management 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. 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. 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.

**Kay words:**

Forest age map, North American forests, disturbance legacy, forest carbon management, biogeochemistry models, atmospheric inversion

## 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 $yr^{-1}$ 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 U.S., 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 per year 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. 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). For example, disturbances affect the amount of carbon in coarse woody debris and the forest floor, causing these pools to shift between sources and sinks over time.

In this paper we present a forest age map of the U.S. 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 reflecting 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. The biological potential of afforestation, reforestation, and forest management 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 such 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. Data and Methods

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 (Table 1).

## 2.1. Approach for Canada

### 2.1.1. 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 dataset developed by Penner et al. (1997), which was the gridded data at 10 km resolution and originally compiled from Canada's Forest Inventory (CanFI) 1991 (1994 version) (Lowe et al. 1996). The data also include the forested area-fractions of age classes (0-20, 21-40, 41-60, 61-80, 81-100, 101-120, 121-140, 141-160 and older). Since the inventory data was outdated, we used more recent remote sensing data to update the age information (only about 55% of the total forest area of Canada is inventoried; unmanaged lands are not inventoried).

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 outlines of fires and associated attribute information, such as fire start date, year of fire, fire number, and final area burned.  The dataset includes 8,880 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 generally for 1959-1995.

### 2.1.2. 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.  The data from the VEGETATION sensor onboard the SPOT4 satellite were used in this study. The angular normalization scheme developed for AVHRR (Chen and Cihlar, 1997) was applied to VEGETATION 10-day 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. Co-registered with LFDB data, the relationship between the mean SWIR/NIR ratio in the summer and the number of years since the last burn (Amiro and Chen, 2003) was used to develop an algorithm for dating/mapping fire scar areas. The dating algorithms have accuracy of ±7 years for scar ages smaller than 25 years (Amiro and Chen, 2003). The satellite imagery from VEGETATION-SPOT were used to develop the fire scar maps of 25 years from 1973-1998, including the fire scars that were not included in LFDB.  The results show that the total disturbed area in any five-year period is within 10% variation of the total reported by Kurz and Apps (1995). The VEGETATION data were also used to extend the fire record of LFDB from 1995 to 2003 by detecting burned areas 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 (unmanaged forests without inventory data), but only included large fires over the period of 1959 to 1995. Remote sensing imagery was used to fill in the data gaps both in space and time. Annual forest burned area maps for years between 1973 and 2003 were constructed by the approaches described previously. 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. Therefore, these maps with fire scar dating were then used to replace the age data in the gridded inventory data. However, the older age classes (>25 years) in the inventory are unchanged because 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 x 10 km grid cell in the forest inventory was divided into 100 pixels at 1 km resolution. Pixels of different age classes were replaced by the fire polygons of known dates or by recent fire scars if detected by remote sensing. For the other areas, pixels were randomly assigned with ages ranging from 26 to 110 years, based on the area fractions in each age class reported in the inventories for the managed forests; while for the unmanaged forests in the far north, pixels were assigned the average age (75-120 years) depending on the disturbance occurrence interval in each ecoregion.

## 2.2. Approach for the US

### 2.2.1. FIA age information and disturbance data

Development of the age map for the US is based primarily on field sampling by the Forest Inventory and Analysis (FIA) Program, a continuous inventory and assessment of U.S. 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. Most forests of the U.S. are sampled, except for some remote areas where only partial inventories have been conducted, 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 (more than 150,000 sample locations), and mathematical models to estimate forest attributes such as biomass (Birdsey and Schreuder 1992). Stand age is estimated at sample plots by examining tree rings from cores of selected trees. Determination of stand age can be an inexact process because only one or a few trees, selected to represent the average age of the sample area, are cored. In this study, we also compiled forest regeneration areas for 1990-2000 from FIA database for the age-dating purpose.

### 2.2.2. Remote sensing and age distribution

The NASA Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Masek et al., 2008) applied remote sensing data, particularly Landsat TM/ETM data over the decades, to detect land disturbances and forest cover changes. LEDAPS produces disturbance maps at 28.5 m resolution for selected areas and at 500 m resolution for the whole of North America. It also provides the fraction of disturbed area within each 500 m pixel by summarizing the 28.5 m resolution information. In addition, the reflectance data for North America at 500 m resolution were also available for this analysis. We used atmospherically corrected 500 m North America surface reflectance mosaics from LEDAPS (1990 and 2000) to extract the disturbance information, through pair-wise comparison of reflectance data.  The disturbance indices (DIs), the ratios of the shortwave infrared (TM band 5) to near infrared (TM band 4) reflectance (Amiro and Chen, 1993), were developed for 1990 and 2000 and normalized. The DI is higher following disturbances, and then decreases as vegetation density increases towards the pre-disturbed status. The differences of normalized DIs (NDDIs) were used for detecting disturbances or forest regrowth (i.e. a positive value indicates disturbance), and making disturbance maps. The Monitoring Trends in Burning Severity (MTBS) data (hhp://mtbs.gov/index.html) were used as a reference to assess the accuracy of forest disturbance maps (He et al., 2010).  The MTBS is mapped at 30 m resolution using the differenced Normalized Burn Ratio (dNBR). The data from 4 states of the western US (California, Idaho, Oregon and Washington) were selected for accuracy assessment, composed of 1405 fire events (greater than 4 km$^2$) for 1987-2001.

The average stand age of FIA plots were used to develop the age map using  Voronoi polygons. Voronoi polygons show the entire area around a plot location that it is nearest to its location. These can be assumed to represent forest stands and their respective ages around each FIA plot. This method works well in high density areas where there is high spatial coverage of FIA plot locations (East Coast) and not as well when there is low spatial coverage of plot locations (Oklahoma). The polygon data were assigned to grid cells at 1 km resolution and then to adjusted to the 2003 USFS Forest Type map (Ruefenacht et al. 2008).  The disturbed area detected by the DI-based approach does not provide information about the timing of disturbance within the 10-year time window; however, the variation of NDDIs is generally related to disturbance time, being higher for newly disturbed areas. Assuming forest regrowth starts immediately after disturbance, we developed an algorithm to force total regenerated forest areas of the FIA statistics to relate to the total disturbed areas within each county (He et al., 2010). The NDDIs values of pixels in each county were sorted in descending order and a threshold NDDI was chosen based on the fractions of regenerated forest areas in two five-year groups (i.e. 1990-1995 and 1996-2000). The threshold NDDI was used to separate pixels of disturbed areas to two age groups of young forests (1-5, and 6-10 years) (He et al. 2010). Finally, the young forest ages were used to overlay and modify the inventory-based forest ages to produce the age map.

### 2.3. Uncertainty and major error sources of the age map

The major error sources and issues that users of the age map should be aware of are listed in table 1. The US map was based on high-density forest inventory data, but only incorporated the information of very recent disturbances (1990-2000). The Canadian map was based on older inventory data that was gridded at 10 km resolution and only covered managed forests (55% of total forests). However, historical fire polygon data (major disturbances for Canadian forests) over 4-5 decades provided valuable data sources, together with remote sensing, for detecting the perimeters and timing of disturbed forests.

Thus, the major error sources or inaccuracy for the Canadian age map are from older, inconsistent, and coarse resolution inventory data, incomplete data of unmanaged northern boreal forests, and problems related to the poor spatial resolution of the inventory data (it was necessary to randomly assign ages to the down-scaled 1 km pixels based on the fractions of age-classes in the 10 km grid cells). In addition, the remote sensing based approach also introduces errors in the algorithm dating (~ ±7 years) (Chen et al., 2003). For the US age map, errors could be derived from inaccurate determination of age at FIA sample plots, and from the use of average ages for uneven-aged stands when developing age polygons. For identifying the impact of recent disturbance on forest age pattern, the use of LEDAPS data included errors from inconsistency in acquisition dates for developing DIs for years from 1990 to 2000. Uncertainty can also be associated with a relatively arbitrary approach to algorithm dating by using the FIA data of forest regeneration to choose the spectral thresholds. In addition, land disturbances that occurred before 1990 that may affect the FIA-derived forest age patterns were not processed in this study, which may cause a certain degree of inaccuracy.

## 3. Age structure and disturbance legacy of North American forests

The forest age map (Fig. 1) developed in this study shows the pattern of 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 U.S. For example, 43% of forests in British Columbia are defined as old growth with ages between 120 and 250 years, 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 U.S. have a distribution of younger age classes because of intensive management and harvesting for wood products. To illustrate how forest age structures implicitly represent the land disturbance legacy from the past, we summarized the areas of age-map pixels to histograms by regions of the US and Canada (Fig. 3, 4, 5) and related the forest age distribution patterns with land-use and disturbance history to contrast the past human and natural causes.

### 3 .1 The U.S. 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 dominant middle-age brackets of 50-70, 40-70, and 40-60 respectively (Fig. 4). 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 years to 200 years or more as indicated by the oldest sampled forests (Fig.4). 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, roughly a decadal lag in shifting dominant forest age groups from the northeastern to the northern lakes and northern plains reflects 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. 4; Fedkiw 1989; MacCleery 1992). A lower representation of the age groups older than 80 years 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 years old or more in next four to five decades. There are also indications of shifting species composition from 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.

### 3.2 The U.S. 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 years, although some are as old as 180-200 years (Fig.4). Forests in the region are mostly composed of loblolly pine, slash pine, oak-pine, oak-hickory, 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 years old for more than 80% of the forested area (Fig.1). Few stands reach more than 80 years old (Fig.4). 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.

### 3.3 The U.S. 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). 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 years old and some even reach the 450 year mark. In the Rocky Mountain north region, forests ranging in age from 60-100 years are dominant, and then decline gradually with a long tail to the distribution (note that different scales were used in the age histograms). A large component of young trees (Fig.1, Fig. 4) displays a regeneration pattern in old forests that become susceptible to natural mortality and disturbances and often open large areas or gaps for regeneration. However, there is a small area of forests in age groups 20-60 years, the consequence of fire suppression for more than half a century, which reduced wildfires 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 year 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 years more (Fig 1, Fig 4). The dominant age groups are from 70-100 years. There are periodic evenly distributed age groups distinct from adjacent age groups, reflecting 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 years old compared with the northern region, which is expected for the southern forests with longer life-cycles and longer time taken for massive canopy openings to have new regeneration. 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.

### 3.4 The U.S. Pacific Northwest and Southwest regions

Forests in the Pacific Northwest and Southwest regions have the longest life spans of the U.S. though the distribution of age classes tends to younger ages than in the Rocky Mountains (Fig. 4). 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 years, while Pacific Southwest forests have trees up to 1000 years old (Fig.4). An abrupt decline of forest age groups older than 100 years reflects 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 years) vanished due to harvest and other disturbances. The area of old growth (generally, 200 years 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, 4), whereas the forests of the Pacific Southwest region were more often left for natural recovery from disturbances of a century ago and show a natural succession pattern associated with low occurrence of young forests (Fig 4), indicating that the forests in the region will take many decades to reach maturity.

### 3.5 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 (U.S. 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.5), and a high proportion of forests between 80-100 years. There are a few age groups with irregularly higher proportion of area intervened with flatly distributed age groups- the uneven pattern that suggests some large periodic disturbances such as fires that happened across the landscape .

### 3.6 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 years. However, the percentage is still much higher than that in the NE region (Fig 4, 5). 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 years old, on average 40 years older than the NE region, reflecting the early agriculture abundance but without such a heavy harvest of second forests in the early 20th century as occurred in the NE region. Forests in this region 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).

### 3.7 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 similar to that in the Atlantic Maritime region, but marked by less remaining trees older than 120 years (Fig 5). The succession pattern of forests is not as smooth as the maritime region with apparent traces of frequent natural disturbances, mostly in boreal forests in the north and northwest areas of the region with random disturbance patches and fire scars (Fig. 1). Most forests younger than 80 years are distributed relatively evenly across age classes except for 20-30 years old, regenerated after the last spruce-budworm outbreak that caused mortality of canopy trees (Williams and Birdsey 2003).

### 3.8 Canadian Prairie region

The northern part of the Prairie region is populated with dense, closed boreal forests dominated by white and black spruce and other coniferous types, and also has a transitional zone with mixtures of broad-leaved trees and a wide range 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), showing the traces of agricultural abandonment in the later 18th century (Sisk, 1998), but with much less density of recovered forests and greater components of young forests. There are more natural disturbances in the boreal forests, which has a natural fire return interval of about 75 to 100 years. Fires are the major cause of forest disturbances here because the region is dominated by coniferous trees and is also drier than other regions (Smoyer-Tomic et al., 2004). The dominant forest age groups are younger than 30 years to form the second wave of forest succession, and a relatively small area of forest is in the older age classes (Fig. 5).

### 3.9 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, trees younger than 40 years old, and trees between 80-120 years old (Fig. 5). Forest age structure in such a landscape is very much an indicator of periodic and highly variable fire disturbance cycles (Kurz and Apps 1999). However, for this region, the data are particularly poor. The lack of forests aged from 40-80 years indicates a lack of disturbance events for a long period, 1920-1960, which is unlikely. It is possible that this age cohort is missing because there is little data available for the region before 1959, and also because the average ages (75-120 years) were used to assign the pixels to age classes based on the disturbance occurrence intervals in each ecoregion (see Methods).

### 3.10 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 include old growth cedar and Sitka spruce, while the steep hill slopes are habitat to 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 years) 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 year to 20 year old, related to managed harvesting and reforestation in this most important timber industrial land of Canada. A high component of forests less than 20 years old is the result of combined effects, recent severe outbreaks of insects in the region (Kurz et al, 2007), harvesting, and regeneration of new plantations.

### 3.11 Summary of regional analysis

The above analyses based on characteristics of the forest age map and the current forest age distribution patterns in different regions of the US and Canada clearly show the dependence of current age structure on 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 area of current annual industrial timber harvest, and the burned area is even more widespread in bad fire years (Stocks et al., 2003). Just the opposite is true for the U.S. where the impact of timber harvest is several times that of the impact of natural disturbances.

## 4. 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 used for improving estimates of forest carbon stock and flux in North America, and can also be used as a 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.

### 4.1 Using the age map to analyze impacts of forest management on carbon sequestration

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 U.S. 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 derived from Smith et al. (2006) (both for afforestation and reforestation types (Fig. 6a, 6b). 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 (Figure 6a, 6b). 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). There is 25%-42% lower NEP (dependent on forest types) 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). In reforestation sites, post-disturbance NEP dynamics depend on disturbance types and slash treatment methods. However, our estimates of the reduced NEP reflect regional average patterns in this term and are not specific to either industrial forestry or areas prone to natural disturbances. As a result, annual NEP in the New England forests under the current age structure is between 60 and-76 Tg carbon which compares favorably with recent estimates of annual changes in carbon stocks from repeated inventories (U.S. 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 (Figure 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 a recent study, we used the age map to estimate spatial distribution of NEP at 250 m resolution for continental US forests and projected future NEP changes. The result highlighted the locations where NEP would decrease mostly due to forest aging, and potential management practices to maintain high NEP in the forested lands (Pan et al., 2010).

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 in practice over large regions, 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. A full assessment of management opportunities 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 results clearly show that after disturbances (referring to reforested sites) forests have reduced total NEP (Table 3) because of carbon losses in the earlier recovery stages. The age map combined with the mapped productivity provides 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.

### 4.2 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, 6b), 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).

### 4.3 Using the age map to improve land constraints on atmospheric inversion 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 (Colene 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 an 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 the inversion constraint are often obtained from ecosystems models validated at discrete sites using measurements such as eddy covariance (Deng et al., 2006; 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 to 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 (Figure 7) (Feng et al., 2010), 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. 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 mean annual air temperature at each pixel (He et al., 2010; 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 (Figure 1) and the mean annual air temperature (Feng et al., 2010). 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. The age factor map has been used to introduce *a priori* covariance as an additional constraint for an atmospheric inversion (Feng et al., 2010). The results show that at the sub-continental level, the inversed carbon fluxes are better correlated with the fluxes derived from the eddy covariance and MODIS when the age factor is used. 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.

## 5. Discussion and conclusion

Ground-based and spatially explicit forest age data provide valuable information for improving forest carbon estimates, evaluating disturbance impacts, and predicting forest carbon sequestration potential in the next few decades as forests naturally proceed to reach maturity or start new succession. . 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.

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. In addition, it is important to acknowledge the uncertainty and inaccuracy of the age map because of limitations of data sources and methodologies, particularly, inconsistency of age-related data between Canada and the US (Table 1). For instance, for the US, the disturbance information derived from remote sensing only covers 10 years (1990-2000), so the impact of disturbances that occurred before then could be missed in the age map if the inventory data does not pick up all disturbance effects. This can be particularly true for disturbance-prone regions in the western US where wildfires occur at a high frequency. In Canada, a big problem is for the massive area of northern boreal forests that have little ground-based inventory data to constrain the assignment of ages to pixels. Accordingly, the age map is only a metadata-based result, given the fact that the forest age is represented by a single value in a pixel of 1 km resolution that more likely contains a mix of ages. The map is most appropriate for large-scale studies and should be used very cautiously for geographic areas smaller than those described in this paper.

We have shown that age is a convenient indicator of forest development 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. However, 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). 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. 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.

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Table 1. Comparison of data and methods used to develop forest age maps for Canada and the U.S.

| **Data/ methods** | **Canada** | **The US** |
|---|---|---|
| Forest inventory data | National Forest Inventory (CanFI), collected mostly in late 1980's by provincial and territorial agencies (Penner et al., 1997). The inventory data were gridded to 10 km resolution with areal fractions of age classes in each grid (Chen et al., 2003). The data are only for managed forests (~55% of total forest) with exclusion of northern boreal forests. www.nrcan-rncan.gc.ca | National Forest Inventory Analysis (FIA), collected periodically (every 5-6 years, currently annual), at ~150,000 sample locations. FIA data include stand age with mostly one condition (even or average age), or 2-3 conditions of multiple ages (uneven-aged). Alaska has incomplete data. www.fia.fs.fed.us |
| Remote Sensing data | SPOT-VEGETATION, 10-d cloud-free synthesis data of June-August in 1998, for detecting fire scars from 1973-1998. The same data of 1999-2003 are used for new fire scar detection for the period. | NASA Landsat Ecosystem Disturbance Adaptive Procession System (LEDAPS). Disturbed areas between 1990 and 2000, 500 m pixels with fractions of disturbed areas summarized from mosaics at 28.5 m resolution. |
| Supplementary data | Canadian Large-Fire Data base (LFDB) covered 1959-1995, some areas back to 1945, with polygons (8,880) of fire scars larger than 200 ha, including outlines of fires and attributes of date, year, fire numbers, and area burned. | Monitoring Trend in Burn Severity (MTBS), with burning severity values (1-4) and fire perimeters. Four states in the western US were selected for this study, which include 1405 fire events in 1987-2001.<br>Areas of annual regenerations between 1990 and 2000 were compiled from FIA data |
| Methods of processing data | (1) Co-registered fire polygons (LFDB) and the remote sensing data to develop relationships between the reflectance ratio (SWIR/NIR) and the number of years since the last burn for 18 ecoregions. These relationships were used to develop a remote-sensing based fire-dating algorithm to map annual forest burned areas for 1973-2003, which include fire scars not covered by LFDB in terms of sizes, regions and years;<br>(2) At 1 km resolution, the fire polygons of known dates and recently detected annual burned maps were used to assign forest ages in the disturbed areas (including both managed and unmanaged forests), assuming age equals the number of years since the last burn;<br>(3) For managed forests without disturbances after 1973, forest ages were randomly assigned to 1 km pixels with ages | (1) Developed age polygons based on FIA plot stand ages and assigned to 1 km (or 250 m) grid cells;<br>(2) Used TM/ETM scenes from LEADAPS to develop reflectance ratios (SWIR/NIR), i.e. disturbance index (DI) , for 1990 and 2000. DIs were normalized and the differences (NDDIs) were used for detecting disturbances and making a disturbance map, which was validated using MTBS data;<br>(3) The FIA data of forest regeneration areas were forced to establish the relationship with the disturbed areas in each county; and used to find a threshold NDDI of for separating disturbances that occurred in 1991-1995 and 1996-2000;<br>(3) Converted the disturbance dating to an age map of young regeneration forests for age groups of 0-5 and 6-10 years; |

| | | |
|---|---|---|
| | of 26-110 years based on the fractions of age classes within related 10 km grid cells (because a younger forest supposedly fell to the disturbed area);<br>(4) For unmanaged forests in the far north, undisturbed areas are filled with the average age (75-120 years) depending on the disturbance occurrence interval in each ecoregion. | (4) Young forest ages were used to replace values of grid cells in the FIA-based age map. |
| Map resolutions | 1 km | 1 km and 250 m |
| Uncertainties and major error sources | Relatively high uncertainty; outdated, inconsistent and coarse resolution inventory data; poor and incomplete data of unmanaged north boreal forests; and errors introduced by remote sensing data and fire scar dating algorithm. | Relatively low uncertainty; biases of FIA stand age samples; averaging ages of uneven-aged forests in developing age polygons; inconsistency of acquisition dates from LEDAPS dataset for developing DIs for year 1990 and 2000; errors from the algorithm dating by using FIA data to set the thresholds. |
| Issues of concern for users | (1) Inconsistent inventory data collected from different years and outdated; (2) poor data of unmanaged northern boreal forests and inaccuracy of forest ages older than 50 years; and (3) remote-sensing based fire scar-dating algorithm can't separate disturbances of fires and insect outbreaks | (1) Metadata approach, ages of uneven-aged forests were averaged; and (2) landscape disturbances that occurred before 1990s were not processed in this study and the effects could be missed in the age map if the inventory data did not cover the disturbed areas-- this could be a particular problem for the western US. |
| Website of product | http://cdb.fs.usda.gov/content/dav/fs/RD/NRS/Science/NRS06/ResearchData/GIS_RemSens_Maps/AgeMap/ | |

Table 2. Area (1000 ha) by forest type and age class for the Northeast U.S.

| Age class | Aspen-birch | Maple-beech-birch | Oak-hickory | Oak-pine | Spruce-balsam fir | White-red-jack pine |
|---|---|---|---|---|---|---|
| 0-5 | 6,919 | 160,831 | 124,856 | 3,538 | 29,875 | 6,150 |
| 6-15 | 22,281 | 769,550 | 272,056 | 5,819 | 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 | 7,619 | 169,494 | 60,100 |
| 96-105 | 6,781 | 592,019 | 617,738 | 7,338 | 107,350 | 27,213 |
| 106-115 | 9,200 | 221,713 | 137,263 | 2,750 | 71,056 | 12,831 |
| 116-125 | 3,719 | 112,081 | 66,888 | 800 | 34,444 | 3,925 |
| >125 | 3,550 | 131,831 | 113,656 | 369 | 48,375 | 5,863 |
| Total | 416,426 | 18,351,507 | 14,073,982 | 260,247 | 3,027,732 | 1,081,164 |

Table 3a. Area-weighted average NEP (t×$10^3$/yr) by forest type for the Northeast U.S. (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 | 7,854 | 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 | 8,686 | 189,833 | 46,878 |
| 96-105 | 10,375 | 574,258 | 945,139 | 7,265 | 108,424 | 18,777 |
| 106-115 | 14,076 | 188,456 | 194,914 | 2,365 | 65,372 | 7,827 |
| 116-125 | 5,690 | 79,578 | 88,292 | 584 | 28,933 | 2,237 |
| >125 | 5,432 | 93,600 | 150,026 | 269 | 40,635 | 3,342 |
| Total | 1,525,713 | 34,891,161 | 32,164,847 | 514,829 | 5,514,014 | 1,395,199 |

Table 3b. Area-weighted average NEP (t×$10^3$/yr) by forest type for the Northeast U.S. (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 | -1,661 | -308,796 | -254,706 | -6,793 | -42,423 | 615 |
| 6-15 | 19,162 | 961,938 | 609,405 | 5,004 | 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 | 8,229 | 176,279 | 42,671 |
| 96-105 | 10,172 | 562,418 | 932,784 | 7,045 | 104,130 | 17,961 |
| 106-115 | 13,892 | 184,022 | 193,541 | 2,310 | 63,240 | 7,699 |
| 116-125 | 5,653 | 79,578 | 87,623 | 584 | 28,933 | 2,159 |
| >125 | 5,396 | 93600 | 148,889 | 269 | 40,635 | 3,225 |
| Total | 590,272 | 27,256,068 | 27,419,392 | 404,050 | 3,743,717 | 1,046,399 |

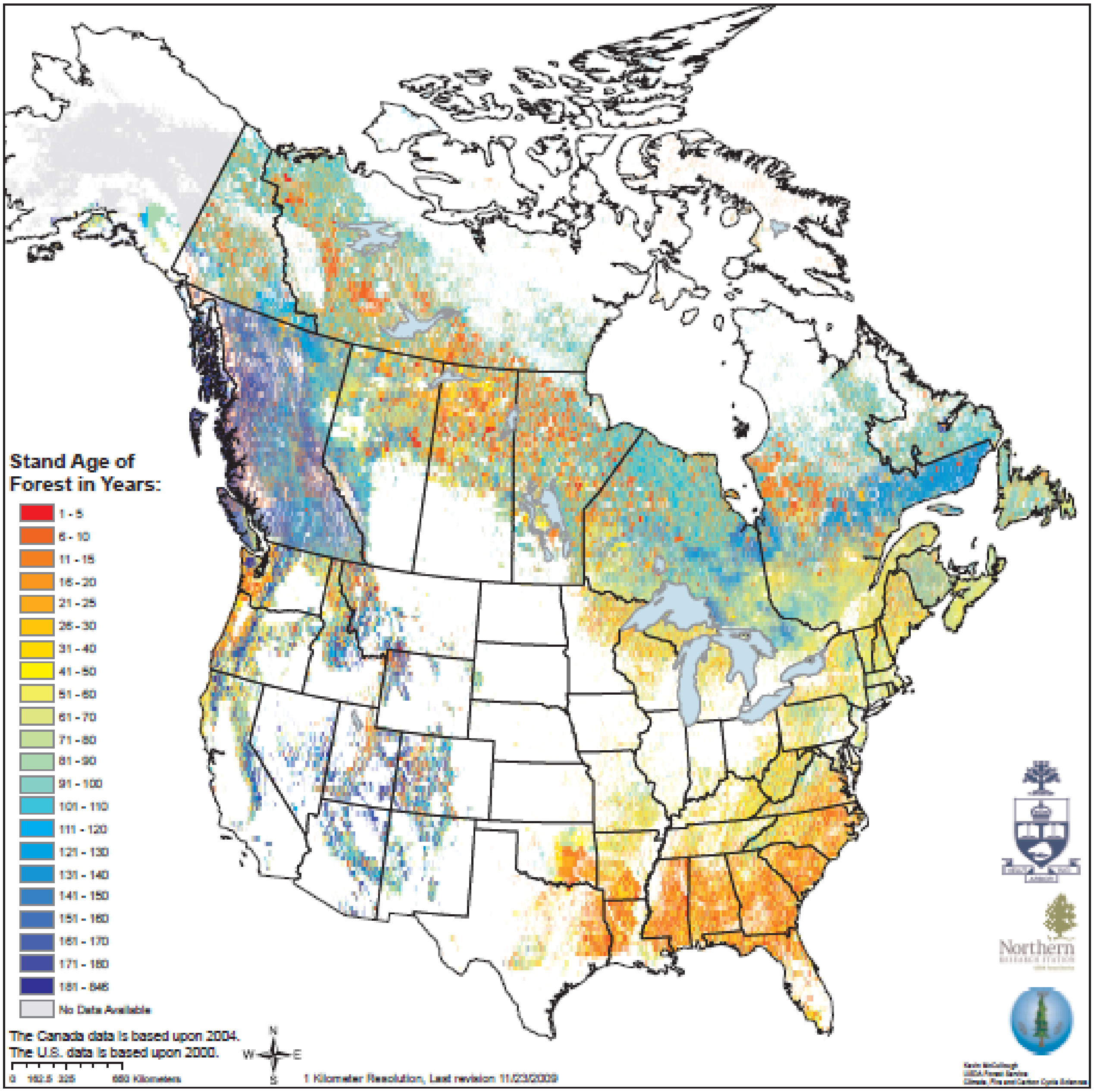

Figure 1. Forest age distribution in North America (excluding Alaska and Mexico), which was developed by combining forest inventory data (of US and Canada) with several remote sensing based disturbance data sources.

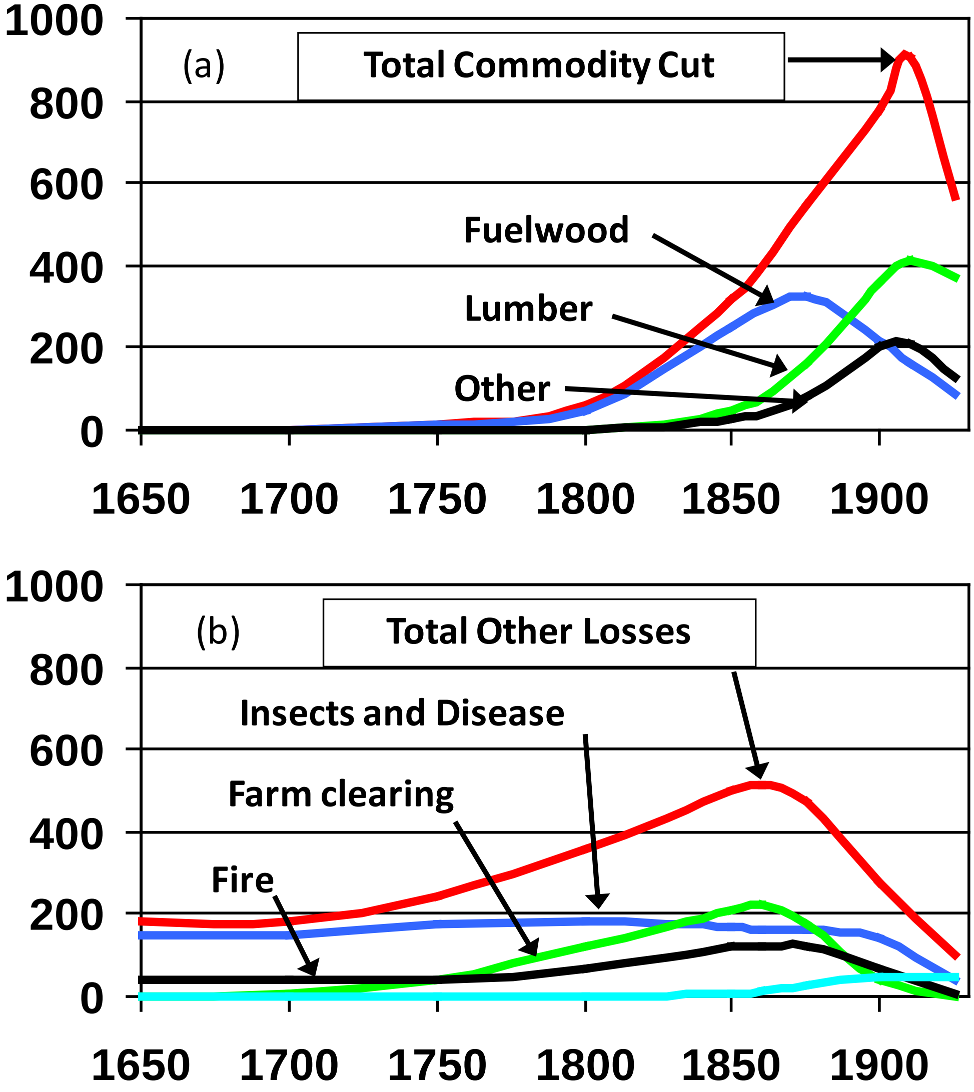

Figure 2. Impacts of disturbances on forests in the past: (a) Drain on the U.S. Sawtimber Stand, 1650-1925 (unit: billion board feet per decade); and (b) woody volume losses affected by other disturbances (based on the data from Birdsey et al., 2006).

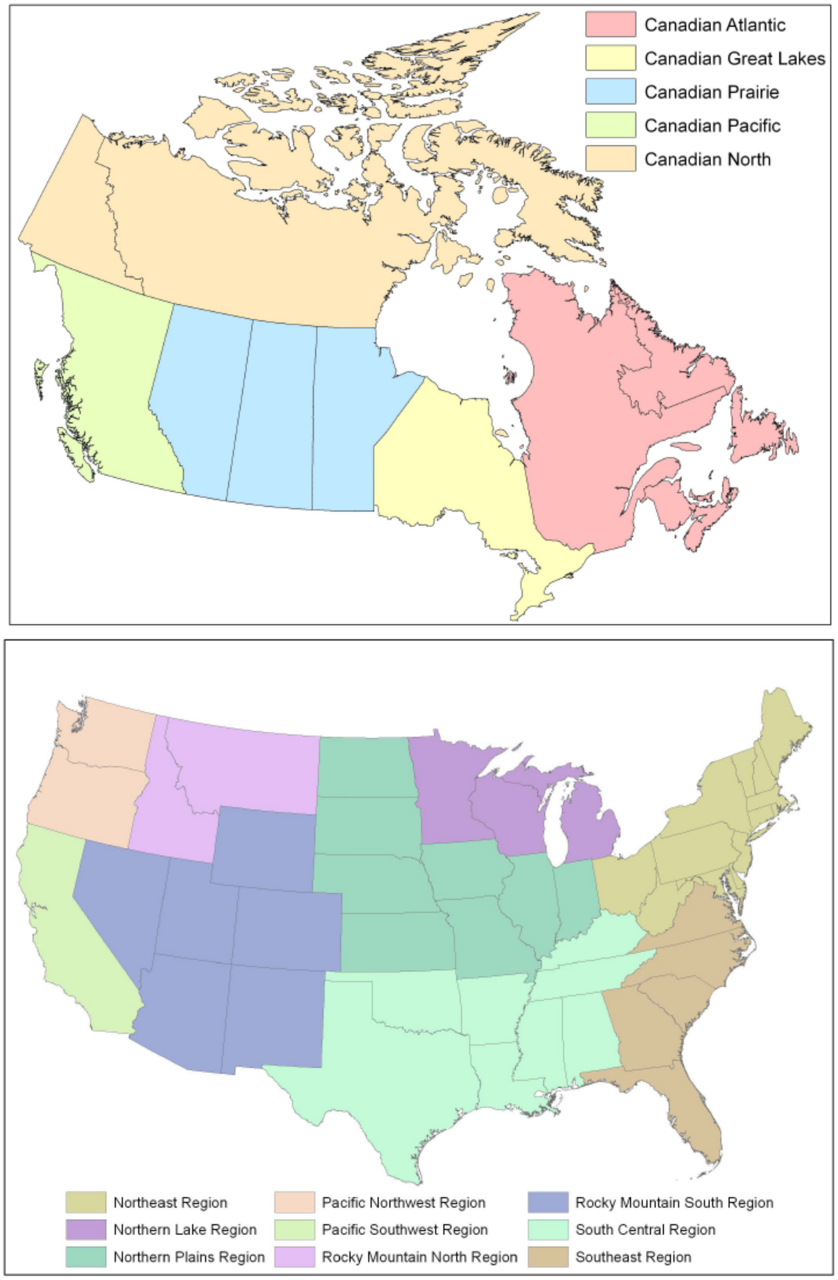

Figure 3. Forest regions in Canada and the United States (Alaska is not shown here)

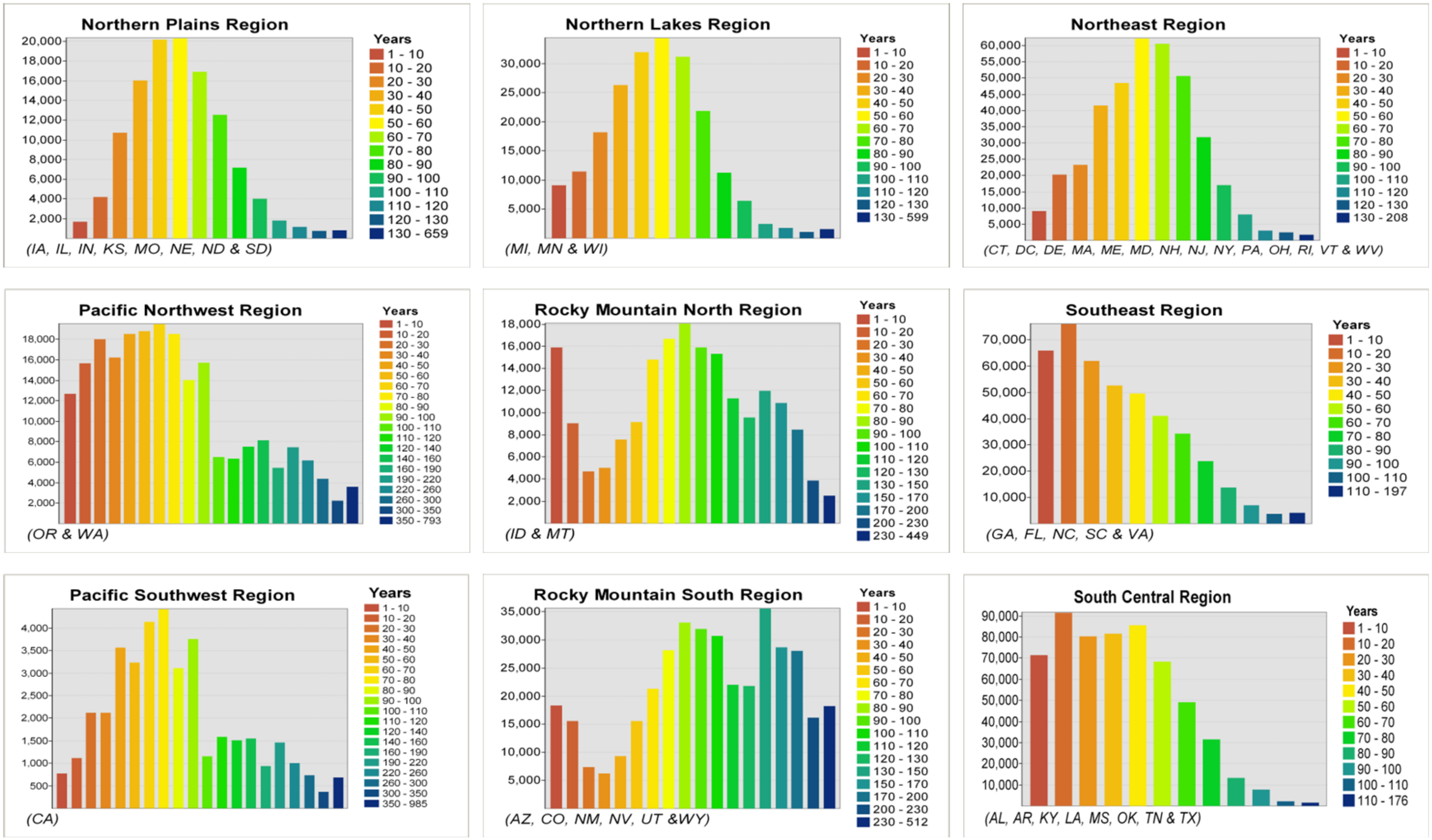

Figure 4. The forest age distributions in different regions of Continental US (the histograms are placed in this figure as much as possible corresponding to their geographical positions)

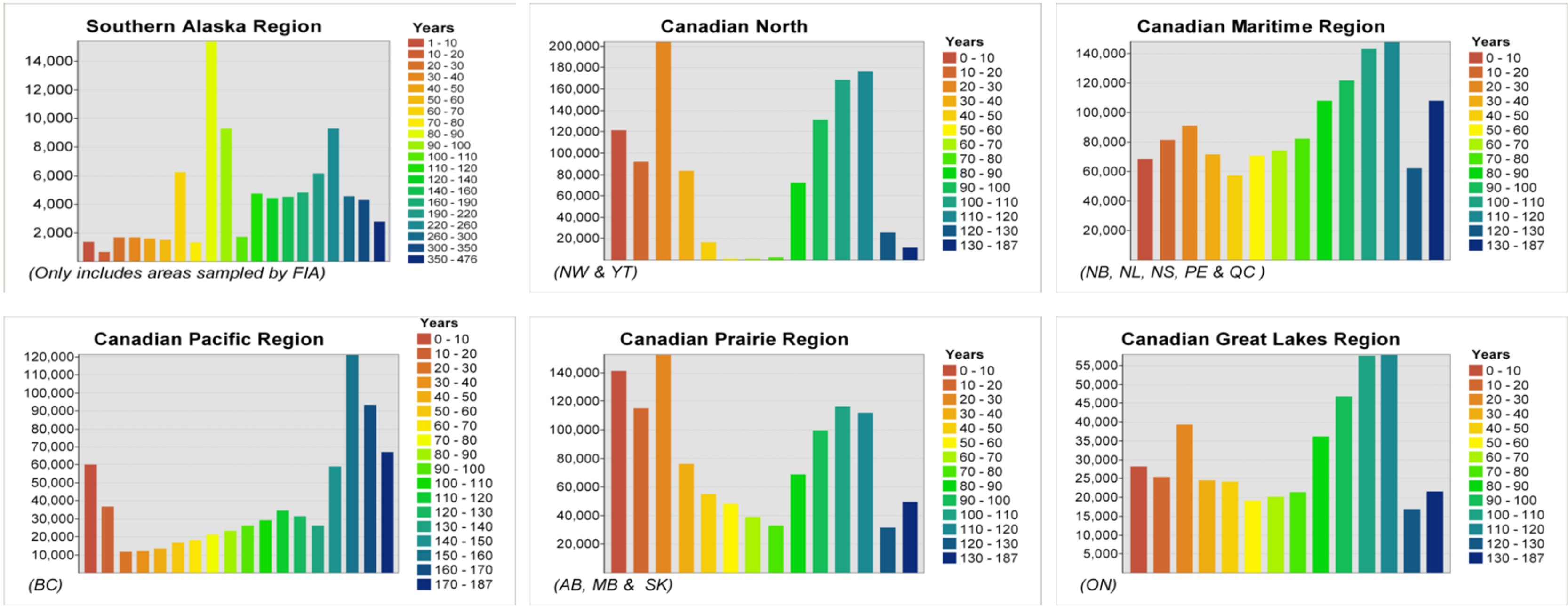

Figure 5. Forest age distributions of the Southern Alaska of the US and regions of Canada (the histograms are placed in this figure as much as possible corresponding to their geographical positions)

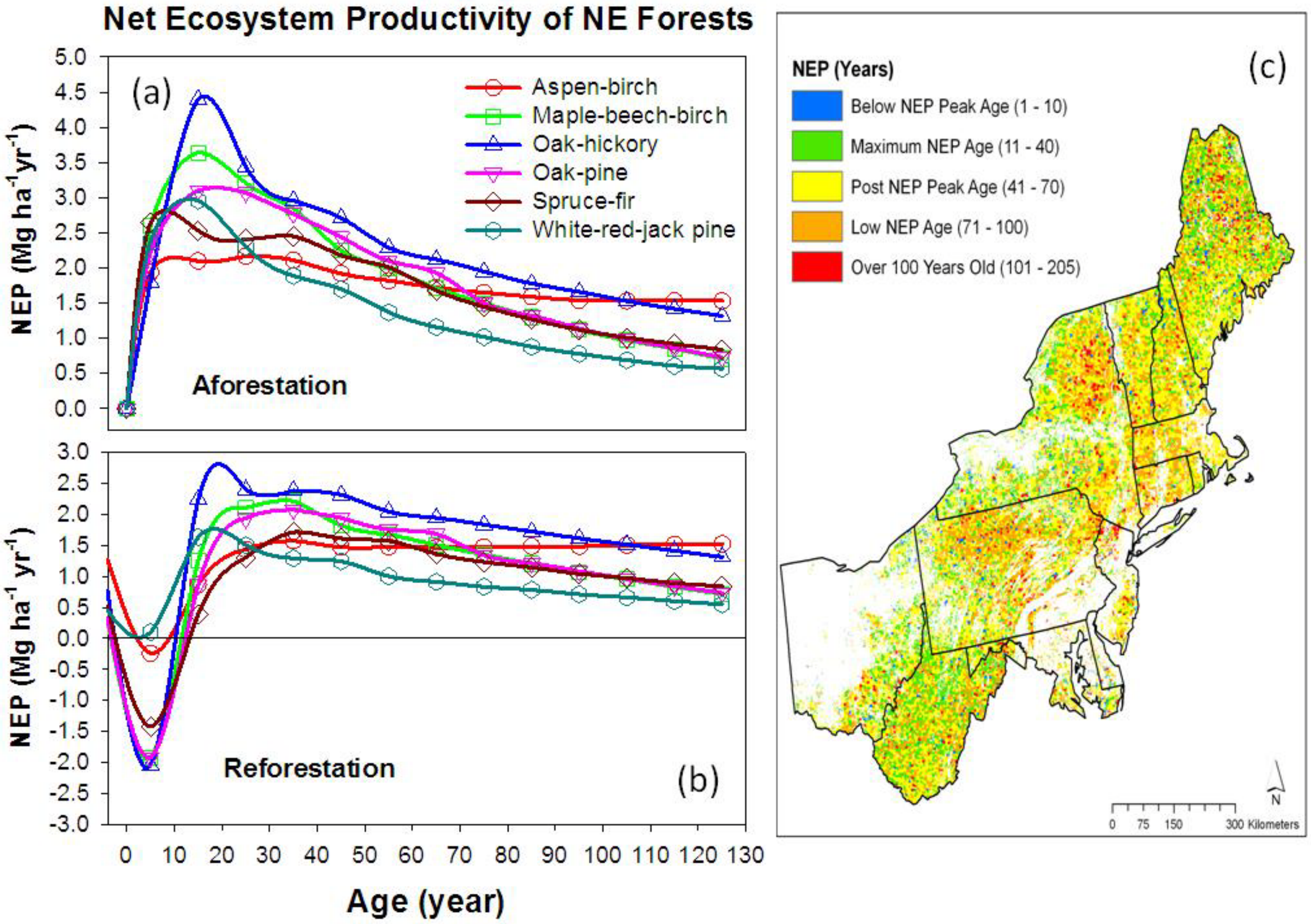

Figure 6. Mean annual net primary productivity of Northeast region forests based on forest inventory data: (a) from afforestation sites; (b) from deforestation sites, NEP loss from woody product is not counted in the initial year, and (c) Northeastern forests with different NEP levels related to age.

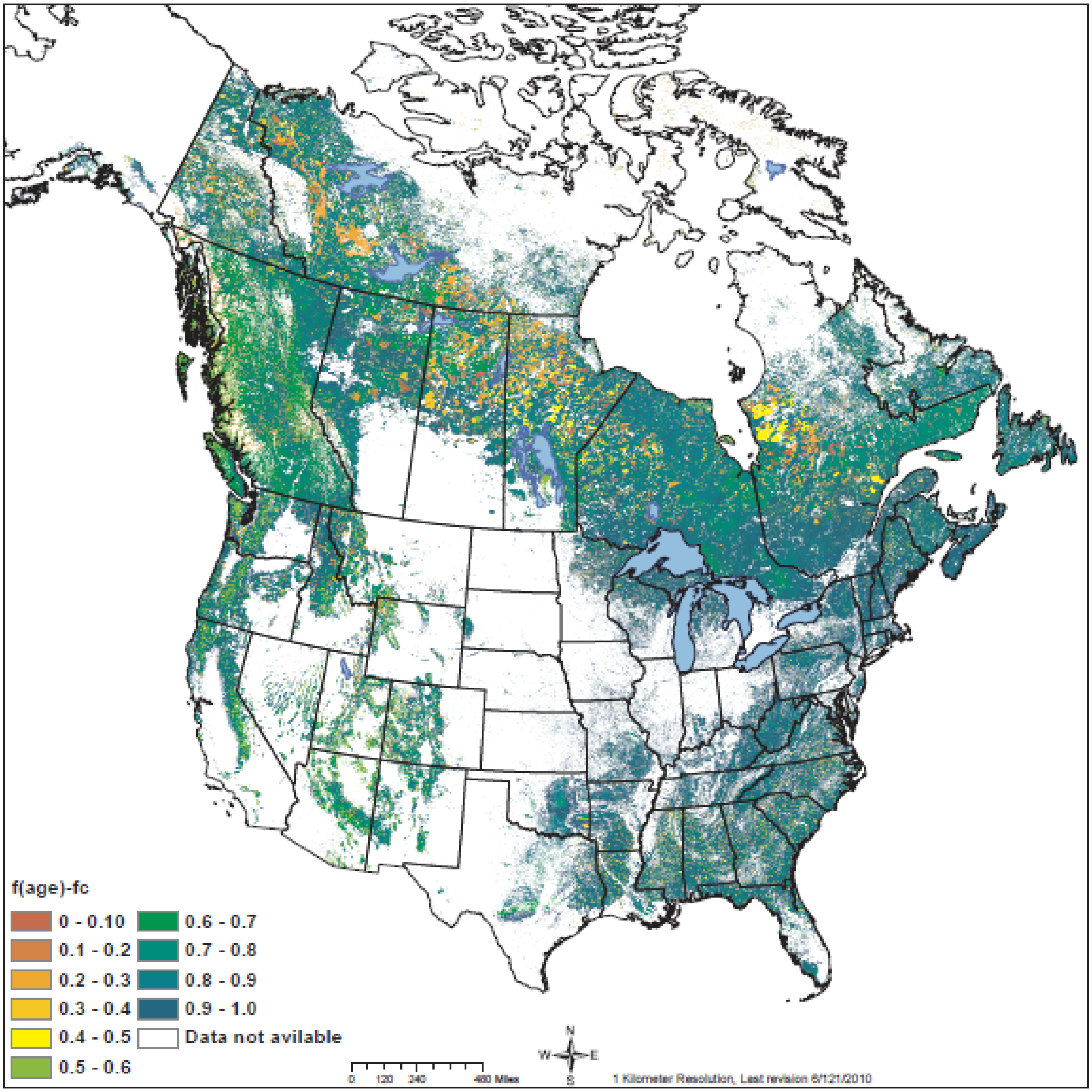

Figure 7. Forest age factor derived from the forest age map (Figure 1) useful for constraining atmospheric inverse modeling of the biosphere carbon flux.