Recent rates of forest harvest and conversion in North America

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[1] Incorporating ecological disturbance into biogeochemical models is critical for estimating current and future carbon stocks and fluxes. In particular, anthropogenic disturbances, such as forest conversion and wood harvest, strongly affect forest carbon dynamics within North America. This paper summarizes recent (2000–2008) rates of extraction, including both conversion and harvest, derived from national forest inventories for North America (the United States, Canada, and Mexico). During the 2000s, 6.1 million ha/yr were affected by harvest, another 1.0 million ha/yr were converted to other land uses through gross deforestation, and 0.4 million ha/yr were degraded. Thus about 1.0% of North America's forests experienced some form of anthropogenic disturbance each year. However, due to harvest recovery, afforestation, and reforestation, the total forest area on the continent has been roughly stable during the decade. On average, about 110 m^3 of roundwood volume was extracted per hectare harvested across the continent. Patterns of extraction vary among the three countries, with U.S. and Canadian activity dominated by partial and clear-cut harvest, respectively, and activity in Mexico dominated by conversion (deforestation) for agriculture. Temporal trends in harvest and clearing may be affected by economic variables, technology, and forest policy decisions. While overall rates of extraction appear fairly stable in all three countries since the 1980s, harvest within the United States has shifted toward the southern United States and away from the Pacific Northwest.

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1. Introduction

[2] Humans represent a primary disturbance agent in North American forests. Out of a total forest area of 734 million ha across Canada, the United States, and Mexico, we estimate that about 6.1 million ha are affected by harvest each year, while another 1.0 million ha are converted to other land uses through gross deforestation, and 0.4 million ha are degraded. In total, about 7.5 million ha (or 1.0% of forest area) are disturbed each year by direct human activity. While fire and insect damage remain the dominant disturbance mechanisms in Canada [*Wulder et al.*, 2007], stands growing in the United States or Mexico have a similar chance of being cleared or harvested as being affected by a "natural" disturbance event.

[3] From a carbon cycling perspective, wood extraction (including harvest, degradation, and conversion) releases carbon to the atmosphere through combustion, rapid decomposition of debris, emissions from disturbed soil, and the slow decay of leaves, wood, roots, and harvested wood products. Following disturbance, respiration typically exceeds primary productivity for 5–20 years [*Luyssaert et al.*, 2008] resulting in a net source of carbon to the atmosphere. Eventually, primary productivity dominates and the system becomes a carbon sink. Indeed, the legacy of forest clearing from the nineteenth and twentieth centuries continues to affect the overall carbon balance of the continent [*Houghton et al.*, 1999; *Birdsey et al.*, 2006; *Kurz and Apps*, 1999]. Much of the carbon sink of recent decades in the eastern United States can be attributed to the preponderance of young- and mid-aged regrowing forests recovering following agricultural abandonment [*Birdsey et al.*, 2006; *King et al.*, 2007].

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[4] A unique aspect of wood extraction is that, unlike "natural" disturbances, the rate of conversion and harvesting can be influenced by policy and economic incentives. Thus, as carbon sequestration emerges as a key management objective, both individual land owners and governments have the option to alter extraction rates and practices to maximize either standing biomass (i.e., stocks) or carbon uptake (i.e., fluxes), including accounting for carbon fluxes associated with timber use [e.g., *Schulze et al.*, 2000; *Tonn and Marland*, 2007; *Harmon et al.*, 2009; *Hennigar et al.*, 2008; *Raymer et al.*, 2009]. Critical to this carbon sequestration objective is reliable information on recent extraction rates at national and regional scales, as well as at the "management scale" of individual stands.

[5] Due to the economic importance of forestry our knowledge of timber extraction is increasingly well known and consistently characterized. Forest inventory and production data are gathered and reported regularly by the governments of Canada, the United States (U.S.), and Mexico. These reports are mandated or recommended for compliance with the United Nations Framework Convention on Climate Change (UNFCCC) and conform to Intergovernmental Panel on Climate Change (IPCC) best practices. However, there have been few attempts to synthesize available data into a continental view. The Food and Agriculture Organization (FAO) Forest Resources Assessment (FRA) has compiled data on forest conversion and timber extraction on a per-country basis for the globe [*FAO*, 2006]. Within the U.S. Global Change Research Program, the State of the Carbon Cycle Report (SOCCR, or Synthesis and Assessment Product 2.2) presented a brief overview of the forest carbon cycle and the impacts of forest management and disturbance across North America [*Birdsey et al.*, 2007; *King et al.*, 2007]. However, there is a major need to describe in greater detail current harvest and conversion information and its impact on forest carbon dynamics across the continent.

[6] The objective of this paper is to summarize available data on the rates of forest harvest, degradation, and conversion for the United States, Canada, and Mexico since the 1990s up to 2008. In particular we present rates of extractive forestry for all three countries using (to the greatest extent possible) common definitions and units, and present the data with as much geospatial detail as feasible. This paper expands on the FRA and SOCCR reporting by providing additional regional context for management activities, and gives a more detailed view of spatial and temporal patterns of harvest and clearing. We do not consider nonextractive forms of forest management, such as site preparation, fertilization, or fire suppression. While these management practices certainly affect the carbon balance of forests, they do not extract wood, and thus are outside the scope of this paper.

[7] We also confine our data sources to publicly available, operational government inventories and surveys. Considerable advances have been made on extracting disturbance information from remotely sensed data [*Cohen et al.*, 2002; *Goward et al.*, 2008; *Masek et al.*, 2008; *Mildrexler et al.*, 2009; *Pouliot et al.*, 2009; *Hansen et al.*, 2010]. However, these approaches generally have not separated different types of disturbance, and thus are not immediately suitable for characterizing extraction alone (see *Cohen et al.* [2002] as an exception). Further, the mean patch size of harvest events requires the use medium spatial resolution imagery (<100 m), at minimum, to consistently capture events and to reduce errors of omission. While larger harvesting events may be detected with lower spatial resolution imagery, the need for accurate spatial characterization is not supported with coarse-resolution imagery [*Wulder et al.*, 2008].

[8] It is critical to make a clear distinction between harvest and conversion from forest to other land uses [*IPCC*, 2000]. The UNFCCC and FAO define forestland in terms of real or expected land use. Thus, a recently harvested location temporarily lacking tree cover is still considered forestland. This definition accurately reflects the fact that carbon accumulation during postharvest recovery can compensate, over time, for the release of carbon from the harvested material itself. In contrast, the permanent conversion of forest to agriculture (deforestation) offers no compensatory sink of aboveground wood (Figure 1). Thus carbon dynamics associated with the harvest/regrowth cycle and deforestation are different, and the rates of each process need to be mapped separately. Difficulties emerge from a remote sensing perspective where land cover is well captured but land use characterization often requires inference or ancillary information [*Franklin and Wulder*, 2002]. Figure 2 indicates the nomenclature and classification of processes used in this paper, which also conform to UNFCCC definitions.

[9] In the sections below, we first review historical rates of forest clearing to document legacy effects on current carbon fluxes. We then present the most recent statistics on forest conversion (deforestation, reforestation, afforestation) and forest harvest for the United States, Canada, and Mexico. These data reveal geographic patterns of extraction associated with economic priorities, land ownership, and basic forest ecology. Finally, we offer a short discussion of the unique carbon consequences of forest management, and present recommendations for future research.

2. Historical Context

[10] Past rates of forest harvest and conversion affect not only past emissions of carbon to the atmosphere, but current and future fluxes as well. As a result of any disturbance, including harvest, some carbon may be released immediately through burning or fast decomposition while resistant material remaining on site will decompose over decades. In addition, a significant portion of harvested material may be stored as wood products over a longer term. Upon regrowth harvested areas will initially act as carbon sources for 1–2 decades, then function as carbon sinks for decades to centuries. One of the critical uncertainties for the observed accumulation of carbon in North American forests is the extent to which the observed accumulation results from regrowth (i.e., continued recovery from past clearing), as opposed to enhanced growth through, for example CO_2 fertilization, N deposition, or climate change. Two studies suggest that growth enhancement could either be negligible, or account for up to 35% of total observed growth over the last five decades [*Caspersen et al.*, 2000; *Pan et al.*, 2010]. The issue is critical because carbon sinks resulting entirely from regrowth are expected to decline when the forests reach an old age [e.g., *Hurtt et al.*, 2002] (but see *Hudiburg et al.* [2009] and *Luyssaert et al.* [2008]), while the fraction of the current sink due to enhanced growth from environmental change may be expected to continue or even accelerate in the

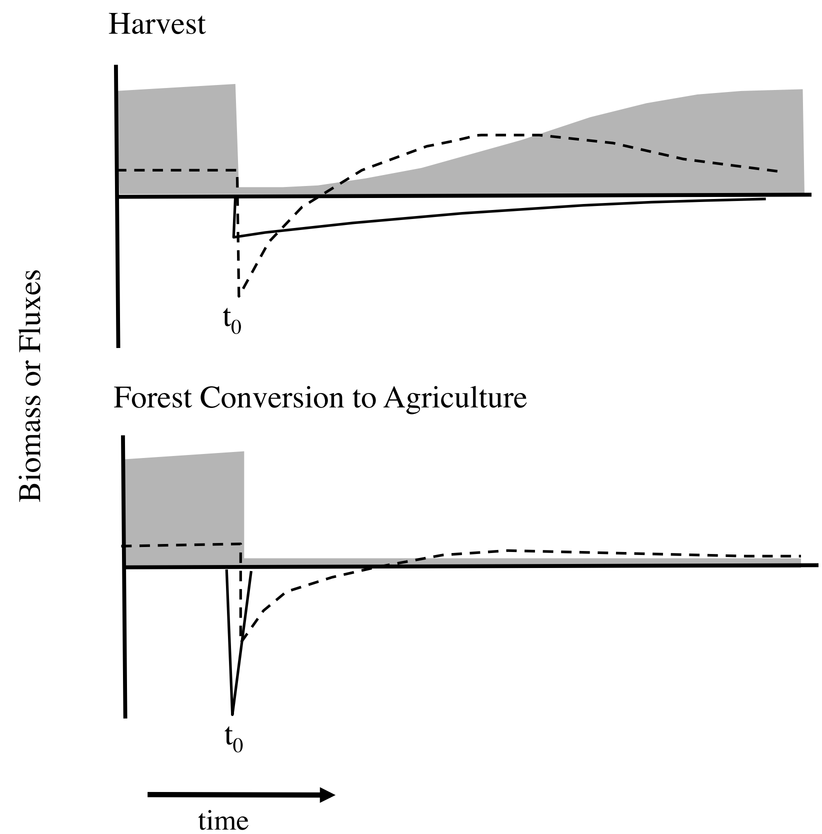

Figure 1. Schematic diagram showing hypothetical carbon dynamics associated with (top) harvest followed by recovery and (bottom) conversion of forest to agriculture, with disturbance occurring at time $t = t_0$. Grey area represents cumulative biomass through time, and dashed line represents net ecosystem productivity. Solid line represents wood product emissions (Figure 1, top) or fire emissions associated with clearing (Figure 1, bottom).

<table>
<tr><td rowspan="7">Wood Extraction</td><td rowspan="3">Forest Management</td><td rowspan="2">Harvest</td><td>Thinning/ Partial Harvest</td></tr>
<tr><td>Clearcut</td></tr>
<tr><td>Regrowth /Recovery</td><td></td></tr>
<tr><td rowspan="3">Forest Conversion</td><td>Deforestation: semi-permanent conversion of forestland to agricultural cropland, grassland, and settlements</td><td></td></tr>
<tr><td>Reforestation: Conversion of non-forest land use back to forest, for areas cleared within last 50 years</td><td></td></tr>
<tr><td>Afforestation: Conversion of non-forest land use to forest, for areas not historically forested</td><td></td></tr>
<tr><td>Forest Degradation: reduction in forest biomass through selective cutting, burning, etc.</td><td></td><td></td></tr>
</table>

Figure 2. Hierarchical terminology used in this paper to describe anthropogenic forest disturbance.

future. Regardless of whether we can separate regrowth from enhanced growth, it is important to recognize that some proportion of the carbon sink in forests today is a result of disturbances over the last several hundred years [*King et al.*, 2007]. Hence, past rates of conversion and harvest are, in one sense, as important as current and future rates.

[11] Past rates of forest harvest and conversion have been assembled for much of North America. Beginning in the 1600s eastern forests in the United States were cleared for crops and pasture. As westward expansion pushed into the Ohio Valley and Great Plains, relatively unprofitable farmland in New England began to be abandoned as early as the 1840s [*Williams*, 1989; *Foster and O'Keefe*, 2000; *Steyaert and Knox*, 2008]. This trend continued with several waves of agricultural abandonment emerging between the Civil War and Great Depression (1865–1940). At the same time, mechanized harvest of remaining old-growth forests in the Great Lakes region and southeastern United States began in earnest in the late-nineteenth century, spreading by the twentieth century to the Pacific coast [*Steyaert and Knox*, 2008]. The perception that the nation was "running out of timber" brought improved forest management and conservation practices during the 1920s and 1930s [*Williams*, 1989]. It also prompted the passage of the McSweeny/McNary Research Act of 1928, which mandated the Forest Service to "…make and keep current a comprehensive inventory and analysis of the present and prospective conditions and requirements of the renewable resources of the forest and rangelands of the United States." Although overall forested area increased in the eastern and southern United States during the twentieth century due to agricultural abandonment, this was offset to some extent by agricultural expansion in the western United States [*Ramankutty et al.*, 2010].

[12] For the United States, *Houghton et al.* [1999] and *Birdsey et al.* [2006] both calculated peak emissions around 1900, although the peak was somewhat earlier in the *Houghton et al.* [1999] analysis (~1880 versus ~1910). The magnitudes of the peaks varied substantially, however. Peak emissions were 0.35 PgC/yr in the work of *Houghton et al.* [1999] and nearly 0.8 PgC/yr in the work of *Birdsey et al.* [2006]. Both analyses showed carbon sinks at the end of the twentieth century, but, Houghton et al.'s analysis showed a maximum sink of 0.1 PgC/yr in the 1965–1980 period, while Birdsey et al.'s analysis showed a maximum of 0.25 PgC/yr around the period 1980–1990.

[13] Compared to the United States, a much smaller fraction of Canadian forests were converted to cropland, owing to lesser population pressure, the unsuitability of the boreal climate and soil conditions for agriculture, and different land ownership patterns. For instance, it has been reported that over 91% of Canada's original forest cover remains [*Bryant et al.*, 1997]. Even in the 1990s and into the 21st century, regions of Canada are expanding the area of resource extraction, agriculture and associated settlement infrastructure into largely undeveloped forest areas. Nevertheless, local areas of forest extraction developed during the nineteenth century. For example, contemporary reports suggest significant depletion of timber resources in the Maritimes by the 1820s, in part to satisfy the need for construction wood and shipbuilding timber in Great Britain [*Williams*, 2003]. The most northern reaches of Canada's forests largely function in a natural manner [*Wulder et al.*, 2007], with wildfire burning large tracts of land annually [*Amiro et al.*, 2001]. The north is characterized by low productivity forests and low population densities with large distances from markets further precluding initiation of industrial forest harvesting activities above those undertaken to support local communities. As one moves southward in Canada an increasing amount of harvesting activity occurs, with concentrations near urban centers and where forest productivity encourages suitable growth rates and desired timber qualities.

[14] The Mexican forest sector was not historically considered as an important economic driver for the country. Thus, commercial harvesting is mainly conducted in natural forests (about 60% are collectively owned by communities and "ejidos") and not forest plantations. It has been proposed that the low development of the Mexican forest sector is associated with: (1) an institutional and economic framework biased against the forest sector and forest owners, (2) pressure to convert forests to agriculture and pasturelands, and (3) inefficiency of the forest industry and inadequate forest management practices [*Masera et al.*, 1995]. Although industrial harvest activities have been modest, rates of deforestation have been relatively high for several decades. The causes of deforestation in Mexico have been largely influenced by government policies. For example, conversion of tropical forests to pasture resulted from an aggressive expansion of cattle ranching activities since the early 1940s. At the end of the 1970s there was a political movement that eliminated the concessions of large forested areas by private companies and promoted timber harvest by local communities and the ejidos. It has been estimated that highland and lowland tropical and subtropical forests, originally covered about 1 million km^2, half of the Mexican territory [*Rzedowski*, 2006]. By 1993 the losses of tropical rain forests, tropical dry forests, and tropical highland forests (pine, pine-oak, and cloud forests) were estimated as 32%, 45%, and 16% of this prehistoric area, respectively [*Rzedowski*, 2006].

[15] *Hurtt et al.* [2006] used a land use transition probability model to estimate global rates of land use change since 1700. The modeling suggested that North America (including Central America) experienced 122–144 10^3 km^2 yr^{-1} of gross land use change during the twentieth century, and 77–90 10^3 km^2 yr^{-1} change during the nineteenth century. In contrast, net land use change remained fairly constant at about 31–40 10^3 km^2 yr^{-1} during both epochs. The much larger values for gross change are consistent with emplacement of secondary forests due to agricultural abandonment and regrowth from harvest during the last 150 years.

3. Sources of Data for Recent Rates of Harvest and Conversion

[16] Each North American country has its own national forest inventory system, which, along with related spatial data sets, can be used to provide information about forest harvest and conversion. As indicated these national systems have been developed to meet national monitoring needs and to enable international reporting following established standards. This section briefly describes these data, but includes only those that are established as part of operational inventories or envisioned as long-term mapping programs (Table 1). Because each country had a unique historical approach to

Table 1. Description and URLs for Forest Inventory Data Available From the United States, Mexico, and Canada

Country	Resource	Description	URL
United States	Forest Inventory Data Online	FIA plot data	http://fiatools.fs.fed.us/fido/index.html
	FIA DataMart	FIA data summaries at the state level	http://199.128.173.17/fiadb4-downloads/datamart.html
	National Woodland Owner Survey	Census of forest owners (demographics, motivations, etc.)	http://www.fia.fs.fed.us/nwos/
	Timber Products Output Reports	Industrial and nonindustrial uses of roundwood	http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int1.php
	Carbon Online Estimator	Forest carbon characteristics for an area of interest	http://ncasi.uml.edu/COLE/index.html
	Spatial Data Services	Linking spatial data to plot data at specific locations	http://fia.fs.fed.us/tools-data/spatial/default.asp
	Biomass map	Timberland live tree biomass	http://fia.fs.fed.us/tools-data/maps/2007/descr/livebio.asp
	Forest type map	Forest types of the United States	http://www.fia.fs.fed.us/library/maps/
	National Land Cover Dataset (1992)	Land cover map of the United States, 1992	http://landcover.usgs.gov/natllandcover.php
	National Land Cover Dataset (2001)	Land cover map of the United States, 2001	http://www.mrlc.gov/nlcd.php
	National Resources Inventory	Statistical survey of land use, conditions and trends on non-Federal lands	http://www.nrcs.usda.gov/technical/NRI/index.html
Canada	Canada's National Forest Inventory (CanFI), 1981–2001	Forest inventory data from 1981 to 2001	https://nfi.nfis.org/history.php?lang=en
	National Forest Inventory (NFI) post-2001	Forest inventory data after 2001	https://nfi.nfis.org/home.php?lang=en
	Earth Observation for Sustainable Development	Land cover map of forest areas of Canada	http://cfs.nrcan.gc.ca/subsite/eosd/home
Mexico	National Forest Inventory 1992–1994	INFyS plot data	http://www.cnf.gob.mx:81/emapas/
	National Forest Inventory 2004–2007	INFyS plot data	http://www.cnf.gob.mx:81/emapas/ (registration required)
	Instituto Nacional de Estadistica y Geografia (INEGI)	Various national data bases and maps online, with socio-economic data and vegetation maps	http://galileo.inegi.org.mx/website/mexico/viewer.htm?sistema=1&s=geo&c=1160
	Comisión Nacional Para El Conocimiento Y Uso De La Biodiversidad	A variety of national and project maps, vegetation, biodiversity etc	http://www.conabio.gob.mx/informacion/gis/
	Secretaria de Medio Ambiente y Recursos Naturales (Semarnat)	Access to national data bases, maps and reports on environment and natural resources	http://www.semarnat.gob.mx/informacionambiental/Pages/index-sniarn.aspx
	GEO-Forest Carbon Tracking	Multi-institutional and multicountry effort to track carbon through remote sensing and ground data	http://www.geo-fct.org/national-demonstrators
	Harvest information	Harvest volume by state between 1997 and 2004	http://148.223.105.188:2222/gif/snif%5Fportal/secciones/demas/compendio2006/Reportes/D3_FORESTAL/D3_RFORESTAL03/D3_RFORESTA03_01.htm
	Deforestation statistics	Compiled from various sources	http://148.223.105.188:2222/gif/snif%5Fportal/secciones/demas/compendio2006/Reportes/D3_FORESTAL/D3_RFORESTA08/D3_RFORESTA08_01.htm

forest inventory and disturbance characterization, it is challenging to unify their presentation here. Consequently, we first provide a summary of each country's forest inventory and related data, and then follow this with a brief integration section discussing the value of these for characterizing forest change.

3.1. United States

[17] The forest inventory for the United States is known as the Forest Inventory and Analysis (FIA) Program within the U.S. Department of Agriculture (USDA) Forest Service (http://fia.fs.fed.us/). As a continuous forest survey, in operation for over 75 years, FIA collects data enabling reporting on status and trends of the nation's forests. Reported are basic information about forest area and location, statistics on species, size, and health of trees, total tree growth, mortality, and removals by harvest, wood production and utilization rates for various products, and forestland ownership. FIA protocols have evolved from a periodic survey to an annualized survey, with sample plots established at known locations, at a density of 1 per 2427 ha. After stratification of forest versus nonforest with remote sensing, forested plots are visited to collect the basic data described above. On a subsample of these plots, 1 per 38850 ha, expanded data are collected. More detailed information on FIA protocols can be found on the FIA web site (http://fia.fs.fed.us/library/fact-sheets/). It should be noted that the FIA sample does not cover large areas of interior Alaska, and that those areas are largely excluded from U.S. national forest carbon accounting [*U.S. Environmental Protection Agency* (*EPA*), 2009].

[18] FIA also conducts Timber Product Output (TPO) analysis, providing information about size and composition of wood used by milling industries by product, by species and by geographic location. Also included is information on logging utilization to determine residues left on site. Because TPO data are drawn from mill surveys rather than the field sample, harvest figures for Alaska are consistent with those for the rest of the country [e.g., *Halbrook et al.*, 2009]. The Carbon Online Estimator (COLE) permits summaries of carbon contents in forests for any area of the continental United States. FIA plot location information is confidential. However, through the Spatial Data Service Center, it is possible to receive extractions from other spatial data sets linked to the plot information for specific plots for correlative and modeling studies, but without the plot location information.

[19] A variety of maps of U.S. forest characteristics, indirectly related to forest harvest and conversion also are available (Table 1). FIA has produced both a forest type map and a forest biomass map for circa 2005 [*Ruefenacht et al.*, 2008; *Blackard et al.*, 2008]. The U.S. Geological Survey has produced National Land Cover Data sets (NLCD) for 1992 and 2001, with updates in process. NLCD data have finer spatial grain and a different thematic content than the FIA type map.

[20] The National Resources Inventory (NRI) is a statistical survey of land use and natural resource conditions and trends on non-Federal lands within the United States. It extends early survey data from the 1930s acquired by the National Resources Conservation Service. Beginning in 1977, NRI became a stratified multistage sample, collected at 5 year intervals. A variety of data attributes are collected, such as land use, cropping history, conservation practices, tillage residue, soil properties, and flooding propensity. *Nusser and Goebel* [1997] more fully describe the NRI design and data attributes. Currently the NRI provides a basis for reporting gross rates of deforestation and afforestation within the United States.

[21] Annual estimates of carbon stored in forests and harvested wood products, and rates of changes, are reported annually to the UNFCC by the U.S. Environmental Protection Agency. Estimates of forest carbon storage in the United States are based on the U.S. FIA database. Statistical estimates of forest area, species, and stand density are converted to ecosystem carbon estimates using standard procedures for estimating biomass, empirical ecosystem carbon models, models of the transformation and fate of carbon in harvested wood product. Estimation methods follow national and international accounting and reporting guidelines [*EPA*, 2009; *Skog*, 2008; *USDA*, 2008].

3.2. Canada

[22] In Canada, provincial, Federal, and territorial jurisdictions are responsible for forest management, resulting in public stewardship of over 93% of the nation's forest land. The federal government's role in forest inventory is mainly related to research and development, inventory of federally administered forests, and compilation and reporting of a national forest inventory. Each province or territory undertakes its own forest inventory and monitoring programs according to internal, increasingly national, standards and these inventory efforts are often restricted to forest land that is capable of producing a merchantable stand within a given period of time.

[23] Large regions in Canada are well characterized by these jurisdiction-based forest monitoring programs, typically undertaken to support forest management activities [*Leckie and Gillis*, 1995; *Gillis and Leckie*, 1995]. These provincial and territorial forest inventory programs operate to meet specific information needs, timing, and spatial coverage, among other considerations, that result in variability in the data collected when compared nationally. The Canadian national forest inventory has developed standards and definitions in conjunction with provincial and territorial forest management agencies, through the Canadian Council of Forest Ministers (now Resource Ministers), to enable the development of meaningful summaries of provincial and territorial data to form a national picture, and to augment provincial and territorial data where practical.

[24] Canada's earlier national forest inventory (CanFI) operated from 1981 to 2001, with data collected at 5 year intervals. CanFI was a computer-based system that converted the best available data from provincial and territorial inventories into a national classification scheme. While this data-compilation approach was cost effective, it was not found to be a satisfactory basis for monitoring change and was limited by differing jurisdictional standards, definitions, and data collection cycles.

[25] A new system, called the National Forest Inventory (NFI), was instituted in 2001 [*Gillis et al.*, 2005]. The NFI was designed to satisfy requirements for national and international reporting on forest statistics. The NFI is plot-based, consisting of permanent observation units on a 20 × 20 km national grid including both managed and unmanaged forests. A combination of ground plots, photo plot and remotely

sensed data are used to capture a set of basic attributes. At each plot location, a 2 km by 2 km photo plot is interpreted for land cover class, forest structure, species, age, height, and related variables [*Gillis et al.*, 2005]. Ground plots complement the photo plots with measurements on individual trees, and measurements of shrubs, woody debris, and soil characteristics. Ground plots are located at the centers of the photo plots, and consist of nested circles, transects, and soil pits.

[26] The Earth Observation for Sustainable Development (EOSD) project developed a land cover map for the forested areas of Canada [*Wulder et al.*, 2008] project (Table 1). Research programs, as a component of EOSD, are designed to develop techniques for change monitoring [*Walsworth and Leckie*, 2004; *Cranny et al.*, 2008; *Wulder et al.*, 2008] and biomass estimation [*Hall et al.*, 2006]. Inputs from EOSD are an important data source in the National Forest Carbon Accounting Framework and are being used to enhance the NFI, especially in northern ecosystems not typically monitored by provincial or territorial inventories [*Walsworth and Leckie*, 2004; *Wulder et al.*, 2004].

[27] Since 2006 the Deforestation Monitoring Group of Natural Resources Canada has annually reported deforestation estimates for 1970 through the current year [*Environment Canada*, 2006; *Leckie et al.*, 2006]. The approach is directed specifically at estimating permanent conversion of forest land to another land use and is based on mapping of deforestation on a stratified sample across the country (including both managed and unmanaged forests) using manual interpretation of Landsat imagery supported with other ancillary data. Mapping has been conducted for three time periods 1975–1990, 1990–2000, and 2000–2008, with interpolation and extrapolation performed to produce annual estimates. The concentration of the deforestation monitoring is focused on deforestation after 1990 and the sample is accordingly stronger in these periods. Deforestation data from this system are used for national reporting and carbon accounting and greenhouse gas emission estimates due to land conversion from forests [*Environment Canada*, 2006; *Leckie et al.*, 2006].

3.3. Mexico

[28] The forest inventory of Mexico, Inventario Nacional Forestal y de Suelos (INFyS), was established to assess and monitor the extent, status, and trends of Mexico's forests in a timely and accurate manner using consistent methods and protocols. This approach provides the flexibility for statewide and national reporting, and for integration into regional and global assessments. In total, there have been three completed forest inventories. The first, completed in 1985, concentrated on commercial forests and provided information in the form of statewide reports on standing volume of major timber species and area covered by the various forest types. The second inventory, 1992–1994, was based on about 16,000 1000 m^2 georeferenced plots, and included live vegetation measurements to calculate volume, biomass, and growth, litter observations, stump and harvest data, qualitative soil information, and notations of general ecological condition. The data are available on request (Table 1), except for the state of Quintana Roo. For the third inventory, 25,000 permanent plots were established between 2004 and 2007. These plots were systematically distributed across the nation's forests, and the same data as for the second inventory were collected (Table 1). The plots are on a systematic grid, with 5 km × 5 km to 20 km × 20 km spacing, depending on forest type and climate. From 2008 onward, the remeasurement of the permanent plots was initiated and all standing trees are tagged. In addition, starting in 2009, soil samples are collected for carbon content analysis to a depth of 60 cm, and quantitative measurements are made on dead organic matter and litter. In total, since the late 1960s, about 56,000 soil profiles have been established, of which about 23,000 can be used to estimate carbon content up to at least 100 cm. Every year about 20% of the permanent plots are remeasured systematically.

[29] A variety of land use maps and related information also exist for Mexico (Table 1). For example, INEGI (Instituto Nacional de Estadistica y Geografia) has available four national land use and land cover maps with similar classifications: 1970s–1980s, based on aerial photographs; and 1993, 2002, and 2007, based on satellite imagery. This is to be repeated every 5 years, and a national monitoring plan based on remote sensing is to capture annual change information. Mexico is one of the demonstrator countries of the GEO-Forest Carbon Tracking initiative. In support of this international initiative, modeling efforts are underway to relate the forest inventory data to satellite imagery. Recently there has also been a compilation of the Digital Atlas of Mexico (http://uniatmos.atmosfera.unam.mx/ACDM/) which satisfies the need to provide readily accessible climate information about Mexico.

3.4. Implications for Characterizing Forest Change

[30] All three countries of North America have increasingly sophisticated inventory programs designed to statistically characterize forest area and integrated forest characteristics such as live tree size and density by species. In addition, each inventory now contains carbon-relevant information on woody debris and soil properties. As these inventory systems have involved substantive design changes since their inception, it is difficult to use them to assess change directly. Rather, it has been necessary to difference bulk forest characterizations, such as forest area or volume, for different measurement cycles. In theory, it may be possible to characterize sampling and measurement errors for successive inventory for a given country, and to include those errors when reporting forest change, but this is rarely done. In addition, because forest changes associated with harvest and conversion are still relatively rare events over short periods of time, it is difficult to determine how well disturbance can be directly characterized by comparing successive inventories from changing sampling designs.

[31] Fortunately, inventory designs in North America appear to have stabilized, with current programs more statistically rigorous and probability based. This means successive inventory cycles will now involve revisiting the same field plots using consistent measurement protocols, greatly increasing the value of these data for characterizing forest change. However, given the relative rarity of forest change at any specific location across large areas, it will remain difficult to know how well forest change is captured by any specific sample design. A consideration to improve capacity for understanding how well sampled based estimates of change are capturing actual wide-area conditions could involve more spatially exhaustive remotely sensed data sets. Remotely

sensed data and maps depicting forest cover and disturbance/regrowth could be incorporated into estimates of forest change. The increasing variety of remotely sensed maps being developed for each country (Table 1) indicates that, eventually, maps of forest change supported by field plot/inventory data will be the norm. Currently no North American country has implemented this type of integrated forest change characterization as part of routine operations.

4. Recent Rates of Forest Conversion

[32] As noted in the Introduction, deforestation, afforestation, and reforestation are defined in accordance with UNFCCC guidelines (Figure 2). In general, nations report gross rates of deforestation, reforestation, and afforestation, as well as the net change in forest area. It should be noted, however, that natural increases in forest area (without human intervention) are not counted under UNFCCC carbon accounting, and thus may not be available.

4.1. United States

[33] Although the total area of forest land in the United States has been relatively stable for about a century [*Smith et al.*, 2009], there has been a significant loss of forest area to other land uses that has been balanced by additions of new forest land primarily from agriculture [*Birdsey and Lewis*, 2003]. The average annual gross deforestation between 1907 and 1997 was about 800,000 ha per year, or about 0.3% of the total area of forestland. In the 1990s, the annual gross loss of forestland was about 600,000 ha. Regionally, losses of forestland were greatest in the southeast and south central United States during the twentieth century. These two regions accounted for more than half of the forest loss between 1907 and 1997. The loss of forestland to other uses has been roughly equally split between cropland, pasture, and other nonforest uses primarily urban and suburban development. The latter category is particularly relevant since such losses tend to be irreversible.

[34] These historical conversion estimates are based primarily on statistical land surveys by FIA and NRI. Recent changes in the design of these surveys have disrupted the ability to estimate decadal-scale changes in land use or cover for the 2000s, although these sources of information are merged in the U.S. greenhouse gas inventory [*EPA*, 2009]. *EPA* [2009] estimated 600,000 ha per year of deforestation for the 2000s, offset by about 700,000 ha per year of afforestation, resulting in a net national increase of about 100,000 ha/yr forest area. In contrast, *Smith et al.* [2009] working from the FIA report a net increase of 339,000 ha per year in forest area during 1997–2007, equivalent to about 0.1%/yr of U.S. forest area. The greatest increases in forest area estimated from FIA data have been concentrated in the Rocky Mountain region and parts of the South (Figure 3). The 2009 NRI reported gross deforestation and afforestation rates on non-Federal land (conterminous United States only) of 355,000 ha/yr and 286,000 ha/yr, respectively, during 2002–2007 [*USDA*, 2009]. These NRI data thus suggest a slight net decrease of non-Federal forest area, although the decline is within the margin of error of the estimates. In addition, the NRI definition of forest cover requires 25% or greater tree cover, while the FIA uses a 10% cover threshold. Thus increases in sparse woody cover (Mesquite, Juniper, scrub oak) in the interior western United States may be reflected in the FIA data but not in the NRI. A recent satellite-derived data product known as the "Land-cover Change Retrofit Product" attempted to harmonize the 2001 and 1992 National Land Cover data, and provides an estimate of the net loss of forest land during this period of 62,000 km^2 or 690,000 ha/yr [*Fry et al.*, 2009]. This estimate seems unusually high compared with other sources of information. *Drummond and Loveland* [2010] used a sample of time series Landsat images to estimate a net loss of 141,000 ha/yr of forest cover in the eastern United States during 1973–2000, although their study used a land cover (rather than land use) definition. Thus a considerable portion of the forest cover loss they mapped probably derived from increasing harvest rates, rather than permanent conversion.

4.2. Canada

[35] Deforestation in Canada is estimated from the deforestation monitoring system described above [*Environment Canada*, 2006; *Leckie et al.*, 2006]. Gross deforestation rates were typically in the order of 60,000 ha/yr circa 1990, and decreased to 45,000 ha/yr in 2008, corresponding to about 0.02% of Canada's forest area. To meet UNFCCC and IPCC GPG requirements, Canada adopted a forest definition of 25% crown closure, capability of reaching 5 m at maturity and a minimum size requirement of 1 ha for deforestation. A minimum width of 20 m stem to stem is used for linear deforestation events. The losses were partly offset by afforestation rates of 6000–10,000 ha/yr through the 1990s and 2000s. Deforestation minus afforestation (according to UNFCCC definitions) amounts to a net loss of 35,000 ha/yr. However, considerable additional land area is reverting back to forest across Canada naturally. This additional area is not known, and lies outside the UNFCCC definition of afforestation.

[36] The annual trend of gross deforestation is fairly constant; however there can be spikes in national numbers caused by individual large events such as hydroelectric reservoir flooding and infrastructure development or regional spikes due to major highway construction. For example, development of the James Bay Project in northern Quebec resulted in a 25,000 ha spike in deforestation estimate due to loss of forest to flooding in 1994. Most industrial sectors do not show high annual or short-term fluctuations in deforestation levels, although the oil and gas sector does show the influence of petroleum market prices. Overall, there is a definite decrease in total deforestation rate from the 1990s to present. This is expected to continue in coming years, but at a lower rate of decrease.

[37] The agriculture sector is the largest source of forest conversion, accounting for approximately two-thirds of gross deforestation. Urban and industrial development is the next largest driver at approximately 17%, followed by forestry, almost all related to forestry roads, at approximately one-half that rate. These proportions fluctuate but in general are consistent from 1990 to 2008. Oil and gas, recreation (e.g., golf courses, ski slopes) and hydroelectric line corridors contribute small proportions of 2% or less each.

[38] The Boreal Plains ecozone spanning central Alberta, Saskatchewan, and Manitoba is the dominant location of deforestation over the 1990–2008 time period, contributing just under half the nation's deforestation for most years (while

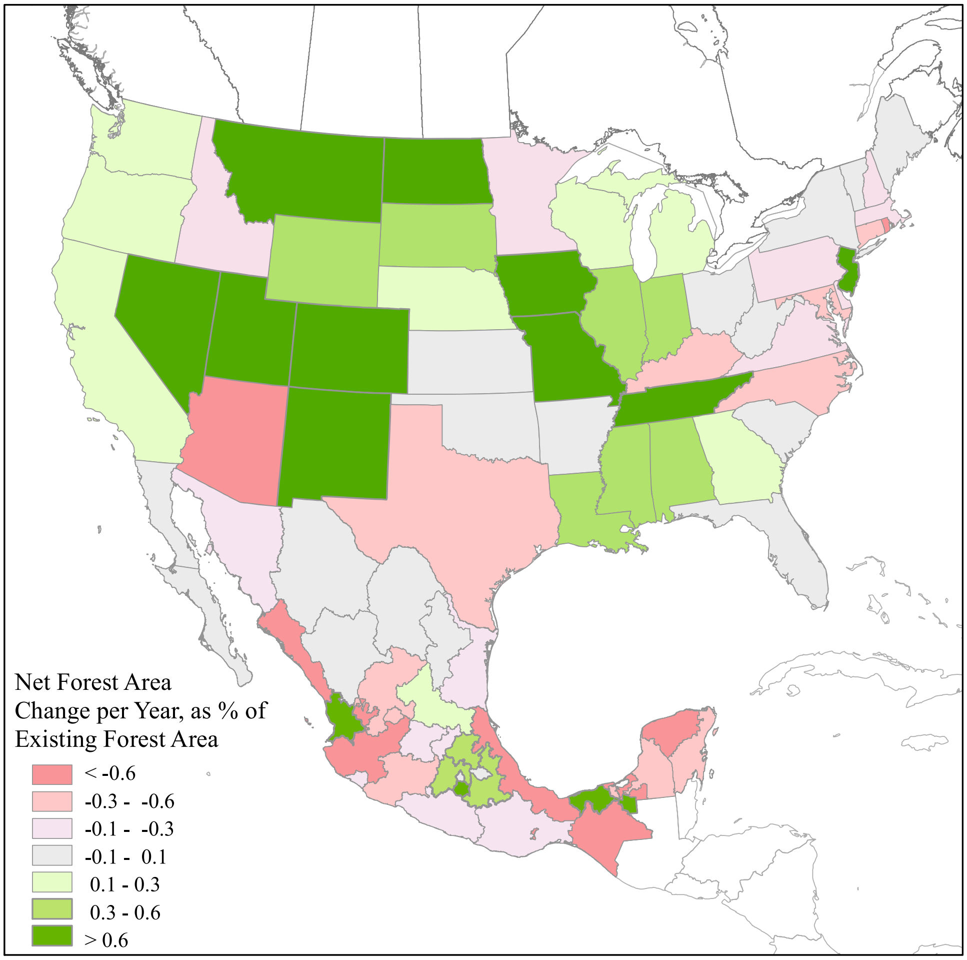

Figure 3. Net change in forest area for U.S. (1997–2007) and Mexican (2003–2007) states, expressed as a percentage of initial forest area. Note that color gradations are not even intervals. U.S. data from *Smith et al.* [2009]; Mexican data from INEGI (Table 3).

excluding hydroelectric developments). The prairie ecozone, which includes considerable prairie-fringe landscape, contributes another 13% of deforestation. Agricultural conversion in the overall prairie region (boreal plains and prairie ecozones) remains the single largest source of deforestation. In western Canada there is still some frontier development into largely undeveloped regions, emplacing new infrastructure of well pads, roads and pipelines for the oil and gas sector and roads for forestry. In contrast, the infrastructure for forestry in eastern Canada (including the Atlantic Maritime ecozone) is well established and there is very little additional deforestation due to new road building. In southern Ontario and Quebec (mixedwood plains ecozone), population growth results in deforestation due to urban expansion and related development such as gravel pits, industrial expansion and golf courses.

4.3. Mexico

[39] Land use and land use change are very dynamic in Mexico. Gross deforestation has been more or less constant during the 1990s and 2000s, averaging almost 600,000 ha/yr, or about 0.7% of the national forest area. Forest degradation was very high in the 1990s, mainly due to conversion to slash-and-burn agriculture in the tropics and uncontrolled harvesting and animal grazing in other parts of the country. The degradation process diminished somewhat during the 2000s, and natural regeneration of forests increased, particularly in the southern part of Mexico (Table 2). As a result, net loss of forest decreased during the last decade, compared to the 1980s and 1990s (Table 2).

[40] More than 50% of the forests are considered as degraded, according to the INEGI classification system. In these areas, broad-leaved primary forests have been replaced with secondary forests dominated by small trees and shrubs, whereas sparsely distributed pine and pine-oak trees are common in highland forests. Between the period 2002 and 2007, nearly 566,000 ha/yr have been deforested in

Table 2. Total Rates of Deforestation, Reforestation, Forest Degradation, and Recovery From Degradation for Mexico for Two Epochs (1993–2002, 2002–2007)[a]

	Deforestation	Reforestation	Degradation	Recovering
1993–2002	580,746	254,286	631,610	175,210
2002–2007	566,019	372,692	411,151	105,818

[a]All units are ha/yr. Data obtained from INEGI mapping; analysis courtesy of B. de Jong.

Table 3. Recent (2002–2007) Rates of Deforestation, Reforestation, Degradation, and Recovery for Mexico, by State[a]

State	Annual change 2002–2007 (ha/yr) Deforestation	Reforestation	Degradation	Recovering
Aguascalientes	716	289	1,036	401
Baja California	3,896	975	48,466	-
Baja California Sur	5,796	1,121	1,657	698
Campeche	37,282	21,168	3,867	3,278
Chiapas	60,276	31,262	27,209	4,091
Chihuahua	20,205	27,139	46,572	5,666
Coahuila	10,083	9,138	5,336	370
Colima	554	225	-	-
Distrito Federal	21	15	-	-
Durango	13,632	9,292	48,228	4,524
Guanajuato	6,280	4,071	362	121
Guerrero	71,191	64,068	74,466	11,786
Hidalgo	697	3,106	13	77
Jalisco	44,530	11,495	8,608	5,523
Michoacán	31,781	21,076	28,417	6,206
Morelos	1,977	4,518	708	27
México	7,188	9,263	9,384	1,737
Nayarit	15,500	25,677	22,802	27,197
Nuevo León	7,917	5,426	456	5,125
Oaxaca	42,514	25,538	24,544	8,102
Puebla	6,155	12,313	5,124	962
Querétaro	2,423	1,300	221	1,428
Quintana Roo	18,339	7,725	23,098	6,713
San Luis Potosí	7,287	9,101	2,370	1,461
Sinaloa	25,065	5,615	11,504	5,565
Sonora	28,722	4,222	9,629	46
Tabasco	12,565	14,014	1,151	217
Tamaulipas	17,311	12,070	583	953
Tlaxcala	11	49	5	-
Veracruz	23,015	16,205	667	996
Yucatán	33,030	11,566	1,591	148
Zacatecas	10,027	3,611	3,070	2,373
National (Rounded)	566,000	373,000	411,000	106,000

[a]All units are ha/yr. Data obtained from INEGI mapping; analysis courtesy of B. de Jong.

Mexico, with six states (Guerrero, Chiapas, Jalisco, Oaxaca, Campeche, and Yucatan) representing over 50% of this total (Table 3). Most of these states are dominated by tropical dry forest regimes. Of these, the states of Jalisco and Yucatan have proportionately lower reforestation rates (25 and 35% of the deforested area, respectively). In contrast, smaller states (i.e., Tlaxcala, Hidalgo) with relatively lower deforestation rates have a reforestation-to-deforestation ratio of nearly 4.5 (Table 3). Sustainable harvesting of these forests is possible, but would require large investments in forest restoration programs.

5. Recent Rates of Harvest

5.1. United States

[41] The best indicator of harvest in the United States is volume removed, since this parameter has been tracked by the U.S. FIA for decades in a relatively consistent manner. Among all owners, annual removals have increased from 402 million cubic meters in 1976 to 439 million cubic meters in 2006 (down slightly from1996), about a 10% increase [*Smith et al.*, 2009]. There has been a rather significant shift in removals by owner class during this period, with removals from national forests reduced to about 15% of the level in 1976, and corresponding increases in removals from private lands. The geographic pattern reflects both these ownership changes and a significant shift in timber production from the West to the South (Figure 4 and Table 4).

[42] Although removals are reported at the regional levels, additional geographic detail can be derived from the Timber Product Output (TPO) database (Figures 5 and 6). A caveat is that the TPO records timber production volume at mills, rather than harvest volume at the site of removal. In addition, for privacy reasons, if a single mill is operating in a county the production figure will be distributed across neighboring counties. The TPO data demonstrate the high intensity of timber production across the southeastern United States, as well as Maine, the northern Great Lakes, and the Pacific Northwest. Timber production throughout the Rockies and southern Pacific coast appears lower reflecting less productive forests in these drier regions, and the closing of most industrial wood processing facilities. Timber production is also somewhat lower in southern New England and the Ohio valley.

[43] The average annual area of forest harvested in the United States is about 4.4 million hectares, or 1.4% of the total area of U.S. forestland [*Smith et al.*, 2009]. More than half of this, 61% of the total harvest area, occurs by partial cutting methods. Timber stand improvement, which includes thinning, is practiced on more than 800,000 ha each year [*Birdsey and Lewis*, 2003]. Note that there may be some double counting between estimates of partial harvest and

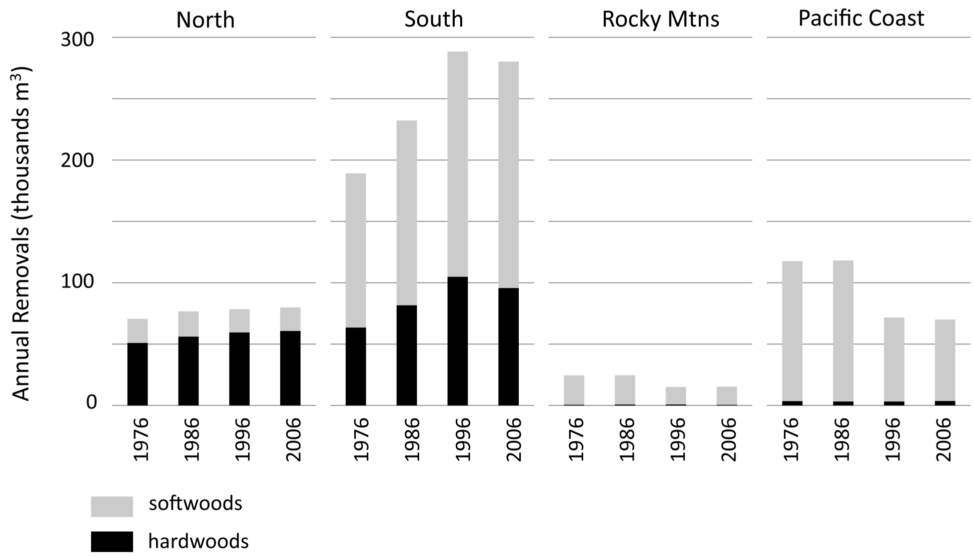

Figure 4. Annual removals from U.S. timber land, in thousands of cubic meters per year, by FIA region. Adapted from *Smith et al.* [2009, Figure 6a.3].

timber stand improvement. About 900,000 ha of harvested land is actively replanted each year. The remainder of the harvest area (3.5 million hectares) is assumed to regenerate naturally unless converted to another use.

5.2. Canada

[44] There is no single data set to spatially portray all harvest activity within Canada. With the development of the new plot-based NFI [*Gillis et al.*, 2005], following remeasurement there will be a consistent, national sample of harvest information. At present, jurisdictional depletions databases may be used to provide regional information. These are related to provincial and territorial inventories, forest management records, and inventory updates [*Gillis and Leckie*, 1995]. To aid with national carbon modeling, *Kurz et al.* [2009] developed capacity to simulate differing levels and types of disturbances to inform on a variety of science and policy relevant questions.

[45] Rates of harvest in Canada over the past 20 years have been typically 700,000 to near 1,000,000 ha per year (Figure 7). Recently (1998–2007) this rate has corresponded to a volume removed of 175 to 200 million cubic meters, about three-quarters of the total being conifers (Figure 5 and Table 4). This rate changes based on demand for wood products and general economic conditions. For example, from 2005 to 2007 volume harvested declined from approximately 200 million to 163 million cubic meters. The general stability of harvest rate is occasionally perturbed regionally or even at national totals by major events such as the recent mountain pine beetle (*Dendroctonus ponderosae*) outbreak in British Columbia which resulted in large amounts of salvage and preemptive harvest [*Kurz et al.*, 2008].

[46] The highest rates of harvest by area are found in Quebec, British Columbia, and Ontario. Harvest rates across most of the Canada have been relatively stable during the last thirty years, although the area of harvest increased steadily in Quebec during this period. However, by volume, British Columbia dominates timber extraction (62 million cubic meters compared to 23 million cubic meters in Quebec) due to the higher productivity of its forests.

5.3. Mexico

[47] Rates of harvest for industrial wood and paper production are relatively low in Mexico. Roundwood production typically varied from 6 to 9 million cubic meters during the 1998–2003 epoch, although reported values in 2004 dropped to just 4.1 million cubic meters. Greatest industrial production occurs in the northern Mexican states of Durango and Chihuahua, as well as in the highlands of the southwestern Pacific coast. Most harvest occurs via shelterwood silviculture or partial harvest removing up to ~40% of standing

Table 4. Volume of Roundwood Harvested by Country[a]

	Roundwood Harvest Volume (k m^3)
Canada (total)	141,484
Newfoundland	2,048
Prince Edward	404
Nova Scotia	5,249
New Brunswick	8,931
Quebec	23,718
Ontario	16,188
Manitoba	2,009
Saskatchewan	1,353
Alberta	19,736
British Columbia	61,805
Yukon Territory	19
Northwest Territories	24
United States (total)	599,261
North	134,859
South	344,140
Rockies	23,167
Pacific coast	94,591
Alaska	2,504
Mexico (total)	6,996

[a]Data for Canada record roundwood harvest volumes for 2008 (source: Canadian Forest Database); data for U.S. record total roundwood harvest including nongrowing stock sources for 2006 (source: *Smith et al.* [2009, Table 41]); data for Mexico record industrial roundwood production, including charcoal and fuel, for 2003 (source: INFyS).

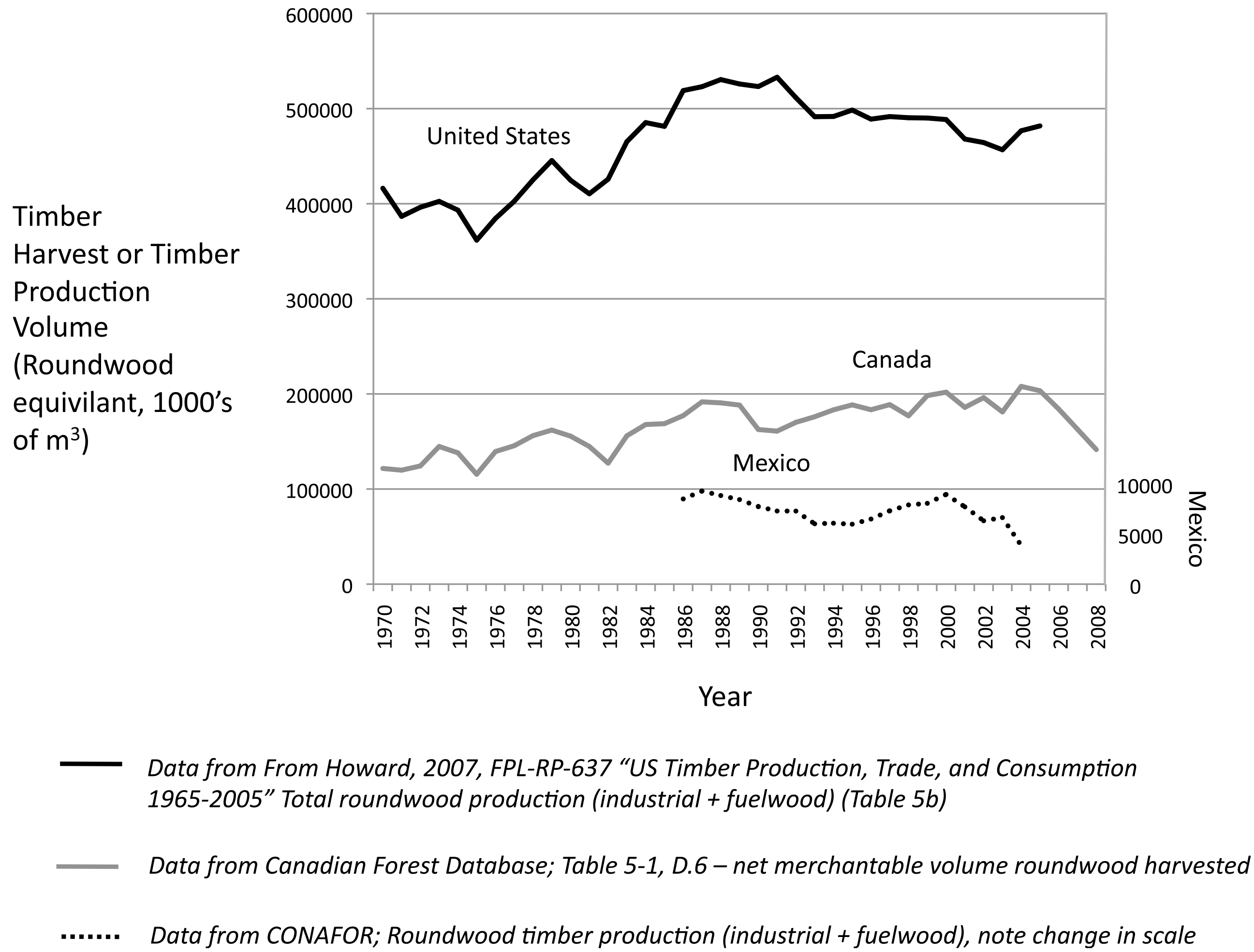

Figure 5. Recent rates of timber production or harvest for the United States, Canada, and Mexico.

volume. About 10% of Mexico's managed forest area (780,000 ha) experiences partial harvest each year, with about 8–10 m^3 of wood products being produced for each hectare of harvest.

6. North American Synthesis

6.1. Geographic Patterns and Drivers

[48] Patterns of forest extraction vary markedly among the United States, Canada, and Mexico (Tables 4 and 5 and Figures 5 and 8). U.S. forest dynamics are dominated by harvest, with some 1.4% of forest area affected by either partial or clear-cut harvest each year. The Unite States also exhibits significant but offsetting rates of deforestation and afforestation and thus overall forest area within the United States appears to be stable, or slightly increasing. In Canada, harvest only affects ~0.3% of forest area each year, although a greater proportion (~90% versus ~40% in the United States) occurs via clear-cut forestry. Forest conversion compared to harvest is relatively more important in Mexico. About 0.7% of Mexico's forestland is deforested each year, although this is offset by about 0.4% reforestation. Of the three nations, only Mexico is currently experiencing significant net loss land in forest use due to conversion. Although *Hansen et al.* [2010] recently reported large losses of forest cover for the United States and Canada (2.5 M ha/yr and 3.2 M ha/yr, respectively) derived from remote sensing data, these values represent gross forest cover loss (GLFC) due to conversion, harvest, and natural disturbances, rather than the net change in forest land use. An equivalent "anthropogenic GLFC" figure from Table 5 would combine clear-cut harvest loss and permanent deforestation (e.g., 2.07 M ha/yr, 0.93 M ha/yr, and 0.57 M ha/yr, respectively, for the United States, Canada, and Mexico, not including natural disturbances).

[49] While forest harvest occurs at different rates across a wide range of the continent's forest types and ownerships, forest conversion is largely concentrated at the boundary of existing nonforest uses. Agricultural expansion is the primary driver for high Mexican deforestation rates, as well as approximately half of the deforestation in Canada. Using systematically produced maps of deforestation, *Meneses* [2009] found that 82% of Mexico's forest conversion occurred within a 1.5 km buffer of known agricultural or animal production lands. The remainder of Canadian deforestation is attributed to urban development, hydroelectricity, resource extraction, and forest road development. In the United States, urban expansion is the primary driver of forest cover conversion, accounting for an estimated 0.4 million

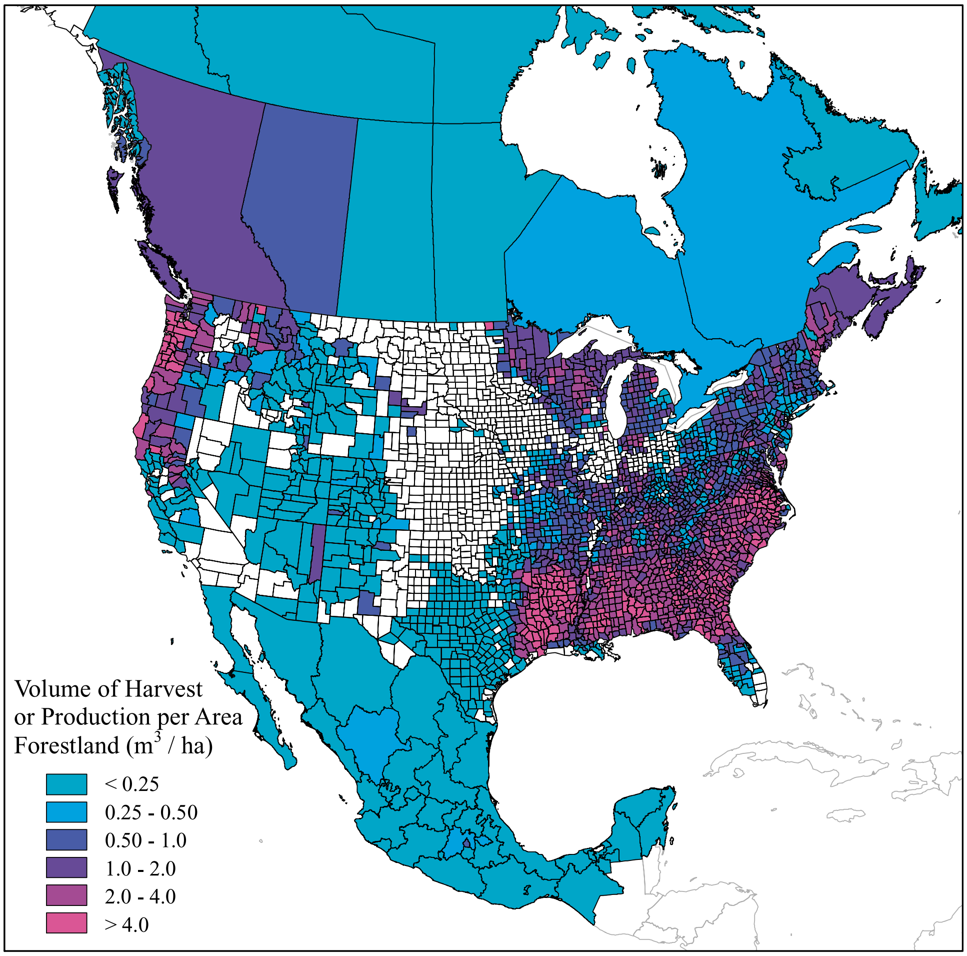

Figure 6. Geographic distribution of timber harvest and/or production across North America, expressed as volume harvest (or production) per unit forest area. Canada: volume of roundwood harvest, 2008, from Canadian Forest Database; United States: 2007 timber production volume from TPO; Mexico: 2003 timber production volume from INFyS. Note that timber harvest and timber production volumes are not directly comparable, and that color gradations are not even intervals.

hectares per year [*Alig et al.*, 2004], most of which occurs at the expanding edge of established developments.

[50] Biogeochemical models incorporating harvest require information on the amount of wood extracted (harvest intensity) in addition to the area affected by harvest. The Canadian CBM-CFS3 model includes information on harvest intensity as part of the disturbance matrix used for parameterization [*Kurz et al.*, 2009]. To provide comparable information across both the United States and Canada, we calculate the ratio of harvested roundwood volume to the area affected by harvest for individual Provinces and FIA regions (Figure 9). On average, about 110 m^3 of roundwood is extracted for every hectare harvested from the United States and Canada, but there is considerable variation about this average. Two factors affect this value for any given region: the merchantable biomass of timber on the landscape, and the fraction of this biomass removed during harvest (e.g., the degree of clear-cut versus partial harvest). The highest intensity of removals (~400 m^3/ha) is found in British Columbia where productive conifer stands are removed primarily through clear-cutting. In contrast, selective cutting of lower biomass stands in the northeastern United States result in relatively low harvest intensity (~50 m^3/ha). Characteristic values for Mexico are thought to be even lower (~10–20 m^3/ha) due to lower biomass and a preponderance of partial harvest.

[51] The geographic patterns observed in the inventory data reflect natural, economic, and historical drivers. In general, the highest rates of harvest are found in forests where high productivity and rapid growth justify investments in the infrastructure required to practice high-intensity forestry. Composition of a forest also affects harvest rate. In many highly productive forests in tropical Mexico, for example, only a few species are merchantable given local infrastructure. In these forests, removals are selective and highly dispersed [*Dickinson et al.*, 2001] and occur only when prices justify relatively high extraction costs.

[52] Ownership is an additional determinant of where and how harvests occur in North America, whether Federal, Provincial, private, or (as is common in Mexico) communal. Industrial forest owners usually have a responsibility to maximize profit in the short term, which often means frequent harvesting. In fact, industrial forests are sometimes harvested even before they reach peak growth rates because financial

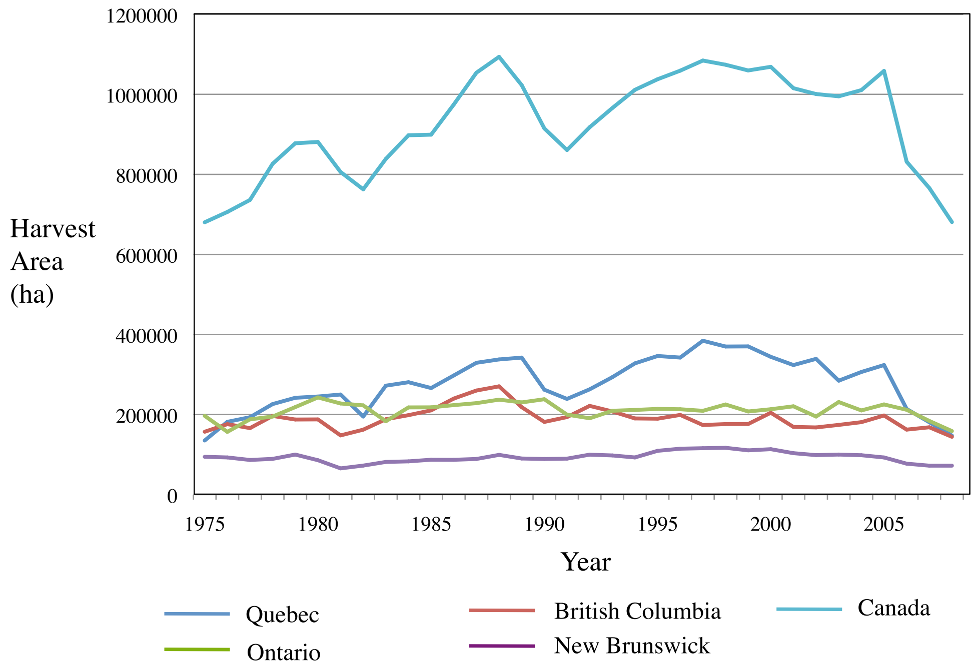

Figure 7. Annual area of harvest (ha) for Canada and the provinces of Quebec, Ontario, British Columbia, and New Brunswick for the period 1975–2008. Data from Canadian Forest Database.

concerns justify more immediate generation of revenue from forest assets. Private nonindustrial owners, who control a significant portion of U.S. forests, have much more varied management goals. While many such owners manage their land for timber production, many others cite recreation and conservation as preeminent management goals [*Butler*, 2008; *Rissman et al.*, 2007; *Wallace et al.*, 2008], resulting in lower rates of harvest. Similar variation exists in the management of forests on community-managed properties called "ejidos" in Mexico. While some communities choose not to harvest their forests, others hire forest operations contractors, while others cut and mill their own lumber [*Bray et al.*, 2005].

[53] Harvest rates on public forests are related to the goals of the specific entities charged with their management. Significant areas in all three countries have been designated as parks (from the local to the national level) and have almost no harvesting, although there is evidence of illegal logging in some protected areas in Mexico [*Honey-Rosés et al.*, 2009]. Federal land agencies, which control a majority of the forestland in the western United States, set their own harvest levels with input and direction from a variety of public and private stakeholders. The administrative designation of these lands, such as "wilderness" or "timberland," may be a predictor of federal harvest rates at the local level, although harvest levels are often changed as a result of litigation [*Thomas et al.*, 2006]. Harvest activities within Federal or Provincial forests in Canada provide an important source of local jobs and tax revenue.

[54] Considerable geographic variation also occurs in the style of harvest (silvicultural practice) across the continent. Since the 1970s, 80–90% of Canadian harvests have been clear-cuts [*Gillis and Leckie*, 1995; Canada Forest Database],

Table 5. Recent Rates of Forest Extraction by Area, for Mexico, the United States, and Canada[a]

	Mexico		United States		Canada	
	Area (ha/yr)	%FA	Area (ha/yr)	%FA	Area (ha/yr)	%FA
Deforestation	−566,019	−0.69	−355,000[b]	−0.12	−45,000	−0.02
Reforestation, afforestation	372,692	0.45	694,000[b]	0.09	10,000[c]	0.003
Net forest change	−193,327	−0.24	339,000[b]	−0.02	−35,000	−0.01
Clear-cut harvest			−1,721,000	−0.57	−878,461	−0.25
Partial harvest	−780,000	−0.95	−2,658,000	−0.87	−89,838	−0.03
Forest degradation	−411,151	−0.50				
Area planted			905,404	0.30	454,944	0.13

[a]For each nation, area of forest conversion and harvest activity is given in ha/yr as well as percent forest area (%FA) per year; negative values refer to loss of forest area or harvest. Mexico: forest conversion data taken from 2002 to 2007 epoch in Table 2 above; harvest data assumes ~10% harvest on managed forests each year; United States: forest conversion rates taken from *USDA* [2009] for 2002–2007 and *Smith et al.* [2009] for 1997–2007; harvest and planting areas for 2006 from *Smith et al.* [2009]. Canada: forest conversion data for 2008 from NRC Deforestation Monitoring Group; harvest area for 2008 from Canadian Forest Database.

[b]U.S. deforestation from NRI only includes data for non-Federal lands and uses a 25% tree cover threshold; *Smith et al.* [2009] reported 339,000 ha/yr net gain in forest area for 2002–2007 using FIA data (all lands, 10% cover threshold). Here the U.S. reforestation/afforestation value is calculated as the residual between the NRI deforestation and the *Smith et al.* [2009] net change.

[c]Includes only UNFCCC reported afforestation due to direct human intervention; does not include substantial additional natural reforestation.

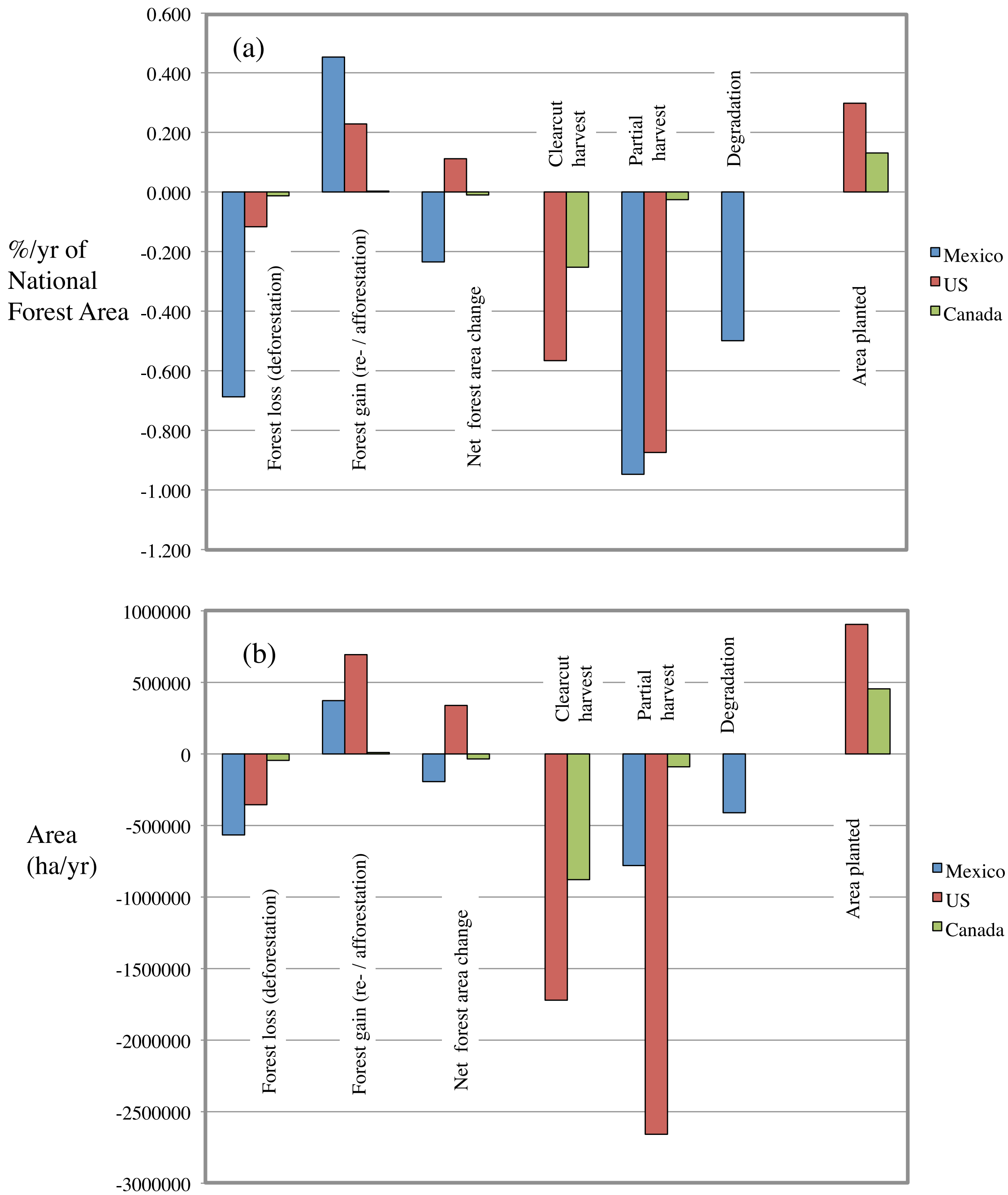

Figure 8. Comparison of rates of harvest and conversion for Mexico, United States, and Canada, given as (a) % forest area/yr, and (b) ha/yr. See Table 5 for explanation of data sources and variables.

while only ~40% of U.S. harvest occurs through clear-cutting [*Smith et al.*, 2009]. As noted, much of the forests present over Canada's northern boreal zone function largely by natural processes. Boreal forests are dominated by pioneer species that are resilient to disturbance (such as wild fire) and have a demonstrated ability to adapt to past climate changes. Clear-cut harvesting has been found to resemble natural disturbance. In areas where fire is the major natural stand-renewing process clear-cutting is typically used to emulate natural processes and is a common harvesting practice [*Perera et al.*, 2004]. In contrast, U.S. forests have generally been cut over at least once, road access is more readily available, and less intensive silvicultural practices are used (strip cuts, thinning, selective removal, etc.).

6.2. Temporal Dynamics and Drivers

[55] Overall, the forest area of North America has remained roughly stable due to the balance of deforestation, afforestation, and reforestation. At present, about 1.0% of North America's forest area is annually affected by anthropogenic disturbance, including harvest, deforestation, and degradation (Table 5). Despite the overall recent stability, several

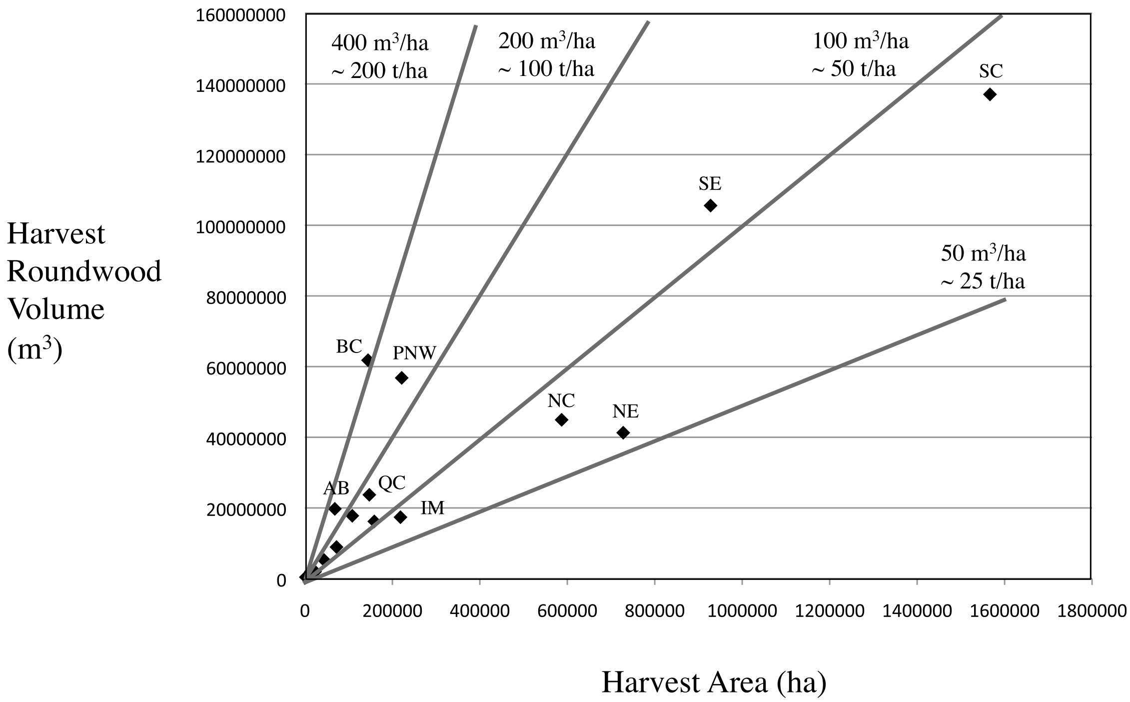

Figure 9. Harvest area and volume for U.S. regions and Canadian provinces. Lines indicate constant levels of "extraction intensity" (i.e., volume per unit area harvested). AB, Alberta; BC, British Columbia; QC, Quebec; PNW, Pacific Northwest; NC, north central; SE, southeast; SC, south central; NE, northeast; IM, intermountain. Rough conversion to roundwood biomass extracted is also shown (t/ha) assuming a constant specific gravity of 500 kg/m^3.

decade-scale trends are apparent from the inventory data and have been discussed above. Among them: a shift in harvest volume from the northwest to the southeast in the United States; stable harvest levels across Canada (with some regional fluctuation); low levels of industrial harvest in Mexico relative to the other two countries; stable deforestation rates in Mexico but rising reforestation rates, and slight declines in gross deforestation in both Canada and the United States.

[56] While the reasons for these trends are numerous and complex, it is possible to identify some factors that have influenced changes in harvest and deforestation rates across the continent. Since timber markets are increasingly global, macroeconomic forces can have somewhat synchronous effects on harvest rates in all three countries. Short-term drops in timber production have tended to follow economic crises (e.g., 1974, 1982, and 2008 in Figure 5) as demand for wood products slackened. Timber harvest is often tied to overall economic activity, and particularly to home construction, as producers respond to cyclical changes in commodity prices [*Howard and Westby*, 2007].

[57] Market forces also influence rates of forest conversion by influencing the relative value of competing land uses. In Mexico, for example, conversion of forest to pasture and other agricultural crops has been a major cause of deforestation, and the rate of deforestation has been sensitive to price of beef and other agricultural products [*Barbier and Burgess*, 1996]. As stated in section 4.2, deforestation due to petroleum exploration can fluctuate loosely with petroleum prices. A major recent driver of forest conversion in the United States and Canada has been suburban and exurban expansion [*Robinson et al.*, 2005; *Radeloff et al.*, 2005; *Sun et al.*, 2007], which in many cases creates economic incentive to convert forestland to more residential uses. However, strong land use regulations can mitigate this trend. In Oregon's Willamette Valley, for example, conversion of forest to residential uses slowed greatly following planning rules implemented during the 1970s and 1980s [*Lettman et al.*, 2002].

[58] Shifts in public policy have also affected the rate and method of harvests. In the Pacific Northwest of the United States, public controversy intensified in the 1980s over the harvest of older forests, as the value of their timber to local economies competed against their role as habitat for dependent endangered species [*Rapp*, 2008]. The Northwest Forest Plan, governing large areas of the region's federal forests, was enacted in 1994 to address multiple policy objectives, and has led to decreasing rates of harvest on federal lands [*Healey et al.*, 2008]. *Wear and Murray* [2004] analyzed the degree to which the harvest restrictions in the PNW were offset by market-driven compensatory harvesting in other areas of North America. They found that within the Pacific Northwest region, about 43% of the reduced harvest of the federal forests was replaced by increased harvest on private timberlands. Much, but not all, of the remaining decrease in federal harvesting was offset by increases in the southern United States and Canada [*Wear and Murray*, 2004]. Canada's large public forest ownership means that policy decisions there can have a large impact on the country's harvest rates. Illustrating this relationship are policies cited previously to aggressively salvage and preemptively harvest insect-threatened forests in British Columbia.

[59] Changes in land use policy also affect rates of forest conversion. Mexican forest and agrarian policies have likely reduced net deforestation rates in that country. Mexican federal and state governments have in place a large reforestation program of approximately 210,000 ha/yr (Comisión Nacional Forestal (CONAFOR), Metas del Programa Nacional de Reforestación, http://www.ambiente.gob.ec/paginas_espanol/4ecuador/docs/PlanForestacion.pdf, 2002), although initial results indicate the success of governmental reforestation projects may be limited by low seedling survivorship [*Sheinbaum and Masera*, 2000; *Secretaria del Medio Ambiente y Recursos Naturales*, 2000]. There have also been significant local efforts to eliminate land use change in "permanent forest areas" in Mexico (see *Merino* [1997], cited by *Bray et al.* [2003]) [see also *Dalle et al.*, 2006]. Further, in the case of a few increasingly sophisticated community forest enterprises, recent higher rates of sustainable harvests and lower rates of forest conversion have been encouraged by the government particularly since 1997 legislation [*Bray et al.*, 2003]. In the United States, the USDA Conservation Reserve Program (CRP) and Environmental Quality Incentives Program (EQIP) compensate farmers to "retire" environmentally sensitive farmland to more ecologically benign land uses (http://www.ers.usda.gov/Briefing/ConservationPolicy/Retirement.htm). While soil and water quality are primary criteria for the programs, carbon sequestration of the proposed change is a minor consideration. The majority of CRP projects are located in the highly agricultural central United States, an area which generally shows positive change in forest area (Figure 3).

[60] Advances in the processing industry have also affected harvest patterns. For example, the development of oriented strand board (OSB, composed of layers of shredded wood, compressed and bound together with wax and resin) has allowed fast growing species like aspen or poplar to be used in solid wood products that previously required mature, higher-quality logs. Production of OSB has risen steadily over the last 30 years, creating a market for rapidly harvested wood products [*Wear et al.*, 2007]. Along with the development of high-capacity mills that can process smaller logs, this trend has cooccurred with shifts in harvest to regions and ownerships where intensive management favors shorter rotations. While the reasons behind reported national trends are complex, factors related to markets, policy, and technology are likely to continue to drive changes in continental rates of harvest and conversion.

7. General Carbon Consequences of Harvest and Conversion

[61] All countries that are party to the UNFCCC are required to provide national inventories of emissions and removals of greenhouse gases due to human activities. The agriculture, forestry, and other land use (AFOLU) sector is the second largest emitter of greenhouse gases, but the single largest source of uncertainty [*IPCC*, 2007]. Here we review the general carbon consequences of harvest and conversion activities.

7.1. The Emissions of Carbon From Disturbance

[62] Globally, terrestrial ecosystems store approximately 2000 PgC, about 60% of which is contained in forest vegetation and soils [*Winjum et al.*, 1992]. The emissions of carbon from disturbance vary geographically due to variation in the amount of predisturbance biomass on the landscape, which in turn is caused by the diversity of vegetation types, climate regimes, and disturbance history. For example, tropical forests have a mean density between 195 and 95 MgC ha^{-1}, while temperate and boreal forests of 135 and 41 MgC ha^{-1}, respectively [*Houghton et al.*, 2009; *Luyssaert et al.*, 2007]. When accounting for carbon stored in both vegetation and soils, forests in Canada could have densities nearly 500 MgC ha^{-1}, while those in the continental United States average 170 MgC ha^{-1}[*Dixon et al.*, 1994]. Few studies are available to estimate the total carbon stored in the tropical forests of Mexico but estimates range between 279 MgC ha^{-1} in tropical wet forests [*Hughes et al.*, 1999] to 121 MgC ha^{-1} in tropical dry forests [*Vargas et al.*, 2008].

[63] Some of the carbon held in forests is released to the atmosphere with disturbance. Deforestation in the tropics, for example, is often accomplished through biomass burning, which represents a near-instantaneous carbon release to the atmosphere [*Eastmond and Faust*, 2006; *Kauffman et al.*, 2003; *Román-Cuesta et al.*, 2004]. Although "standing dead" snags can persist on the landscape following forest fires on wild land [*Vargas et al.*, 2008], ecosystems will gradually lose carbon to the atmosphere as the snags decompose over decades. In addition, burning associated with agricultural conversion typically combusts a greater portion of the live biomass compared to wildfire [*Kauffman et al.*, 2003].

[64] Forest degradation also causes a release of carbon, although not necessarily from the forest itself. Much of the wood extracted from intact forests in Mexico (e.g., forest degradation in Tables 1 and 2) is used locally for fuel wood, and thus combusted within a short time after extraction. Note that this local use of fuel wood is not included in the industrial timber production statistics shown in Table 3. The FAO reported ~38 million m^{3}of fuel wood were produced per year from Mexican forests during 2000–2005, which far exceeds the ~7 million m^3 of industrial production shown in Table 3 [*FAO*, 2006]. Carbon emissions from fuel wood use were estimated by *Ghilardi et al.* [2007] to have been 1.3 TgC/yr.

[65] In contrast to forest conversion, harvest is unique among disturbance phenomena in that much of the dead wood is moved off-site to be used for wood and paper products. In the United States, about 65% of wood carbon is removed at the time of harvest [*Turner et al.*, 1995], and the remainder stays on site as debris. Some products have long lifetimes [*Eriksson et al.*, 2007]. The decay rate of wood products depends on their use, and is typically given as a characteristic half-life for the particular product pool. Half-life values range from 2 to 3 years for paper products to ~20 years for particleboard to 70–100 years for new residential wood construction [*Penman et al.*, 2003; *Skog and Nicholson*, 2000; *U.S. Department of Energy*, 2006]. About two-thirds of discarded wood and one-third of discarded paper in the United States go into landfills, where anaerobic decay processes can result in long residence times [*Skog*, 2008].

7.2. The Uptake of Carbon During Recovery

[66] Forest conversion results in a permanent loss of carbon from land, unless the land is subsequently returned to forest. On the other hand, afforestation causes a carbon sink as woody biomass accumulates on the site. In contrast to both of

these one-directional fluxes, forested land that is harvested (or degraded) and then allowed to regenerate produces, first, a large and short-lived CO_2 source, followed, second, by a small and long-lived CO_2 sink (Figure 1). Forests can remain an annual net source of CO_2 to the atmosphere for 5–20 years before becoming a net sink [*Law et al.*, 2001], with shorter crossover times in warmer and wetter climates [*Luyssaert et al.*, 2008] and in areas where the conversion process is rapid and more complete [*Morton et al.*, 2008]. Depending on the disturbance the change in net carbon uptake (net of opposing fluxes from photosynthesis and respiration) can be dominated by changes in productivity [*Law et al.*, 2001, 2003] or a combination of productivity and heterotrophic respiration. For example, in the Pacific Northwest, changes in net carbon uptake through succession are primarily dominated by changes in productivity, while with decomposition, soil carbon storage reaches an asymptote 150–200 years after stand-replacing disturbance [*Campbell et al.*, 2009; *Sun et al.*, 2004].

[67] Because of differences in carbon pool densities, climatic conditions, and management strategies, the recovery of forests can be quite different across vegetation types and ecoregions in North America [*Turner et al.*, 2007]. First, harvested stands may either be replanted and managed, or allowed to regrow naturally. Planting and applying fertilizers will tend to increase site productivity compared to unmanaged, naturally regenerating stands. Forest inventory data indicate that about half of clear-cut stands are actively planted following harvest in both the United States and Canada (Table 5).

[68] In addition, nutrients, including nitrogen, have been identified as a global limitation for net primary productivity [*LeBauer and Treseder*, 2008], and the fate of soil nutrients after harvest are different between temperate and tropical forests [*Attiwill*, 1994]. In boreal forests one can expect higher retention of nutrients and lower organic matter decomposition rates due to temperature constraints. In contrast, biomass and nutrients in tropical and subtropical forests are rapidly lost after disturbances [*Ostertag et al.*, 2003]. Therefore, recovery and decomposition rates in boreal and temperate regions are mainly limited by temperature and precipitation whereas in tropical regions by soil physical properties and nutrient availability [*Attiwill*, 1994].

[69] All three nations considered in this study have opportunities to increase carbon storage within the forest sector. In Mexico, forest regeneration through agroforestry and forest management may be useful solutions to increase land-based carbon storage, but economic incentives and management practices may be different than those from the United States or Canada [*de Jong et al.*, 2000]. It is feasible to consider maintaining or optimizing the regrowth forest sink through a combination of forest management (limited harvest) while sequestering harvested wood in long-term storage or long-lived products [*Tonn and Marland*, 2007]. In theory, timber use would result in net sequestration across the entire forest sector if the net productivity from regrowing stands were greater than emissions from derived wood products. However, recent studies have suggested that carbon emissions during manufacturing can equal to 25–50% of the harvested amount, and it can take centuries to reach the total carbon stores of the primary forest [*Mitchell et al.*, 2009; *Hudiburg et al.*, 2009; *Sun et al.*, 2004]. In addition, other aspects of forest sector operations need to be included in a "whole carbon" accounting framework, including fuel emissions associated with the transport and manufacture of timber and wood, as well as sequestration associated with substituting wood for concrete as a construction material.

8. Future Directions and Research Needs

[70] This paper has presented recent data on conversion and harvest rates for North American forests. The increasing richness of these data reflects the ongoing efforts of national forest inventory programs to characterize forest stocks and their changes to meet international reporting requirements. While the original goal of inventory programs was primarily to estimate merchantable timber for resource planning, evaluating the sources and sinks of forest carbon has become increasingly important. This evolution is reflected in both the architecture of the inventories (e.g., the uniform plot locations associated with the post-2000 FIA and the Canadian NFI), as well as the development of carbon-specific modeling tools such as the USGS Carbon Online Estimator (COLE, P. Van Deusen and L. S. Heath, COLE web applications suite, National Council for Air and Stream Improvement and USDA Forest Service Northern Research Station, Lowell, Massachusetts, available at http://ncasi.uml.edu/COLE/) and the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3 [*Kurz et al.*, 2009]).

[71] By their nature, the forest inventory data are based on a representative sample of the landscape. Thus, while appropriate for constructing national and subnational estimates of forest dynamics, forest inventories are not generally suitable on their own for mapping at the local scale. As local forest management becomes a means to accomplish national carbon sequestration goals, additional geospatial information is required to support carbon monitoring, reporting, and verification at the management scale of individual tracts (10–1000 ha). Cap-and-trade systems by which individual landowners could be paid for carbon credits typify the need for precise geospatial information on aboveground and belowground stocks and stock changes. In addition, national forest inventories have not been consistent about releasing gridded, map products derived from existing data. Such products, especially if coordinated across national boundaries, would provide a substantial benefit to the ecological science community.

[72] Remote sensing offers a promising alternative approach to management-scale mapping of forest disturbance, including harvest [*Cohen et al.*, 2002; *Goward et al.*, 2008; *Masek et al.*, 2008; *Huang et al.*, 2010] and tropical forest conversion [*Skole and Tucker*, 1993; *Achard et al.*, 2002; *Hansen et al.*, 2008]. Both Landsat-scale optical data and synthetic aperture radar (SAR) can record forest clearing and, given sufficient annual to biennial temporal resolution, partial harvest, thinning, and degradation [*Asner et al.*, 2005; *Huang et al.*, 2010]. In some cases, however, these studies have not separated the type of disturbance, nor have they always clearly separated forest conversion from harvest [*Kurz*, 2010]. Doing so requires either an independent assessment of land use (as opposed to cover), or a retrospective analysis of the fate of disturbed patches. Lidar data are increasingly available for localized areas and beginning to be acquired multiple times over the same locations

[*McRoberts et al.*, 2010]. Although they lack the temporal richness of Landsat data, lidar data can be used to provide detailed forest structure information at multiple points in time that can inform change analyses with Landsat and radar data sets; particularly changes associated with partial harvest and regrowth.

[73] Further research is needed to carefully reconcile remotely sensed estimates of forest dynamics with attributes recorded regionally by forest inventory data. Because inventory data are collected at intervals of 5–10 or more years, it is difficult to directly infer annual changes in carbon stocks and fluxes with inventory data, particularly at more local scales. By linking plot measurements of carbon stocks at 5–10 year intervals with annual disturbance and regrowth information available from Landsat data, and forest growth models, we could better utilize the plot data to infer annual stocks and fluxes.

[74] The majority of current anthropogenic greenhouse gas emissions regulated under the UNFCCC are in the form of CO_2, and almost 20% of the emissions are from deforestation [*IPCC*, 2007]. Uncertainties associated with net CO_2 emissions from agriculture, forestry, and other land uses are comparable in magnitude to the estimated emissions themselves [*IPCC*, 2007]. To address emissions targets, it will be critical to reduce uncertainty associated with land use activities and apply consistent monitoring and reporting methods globally. The U.S. National Research Council (NRC) [*NRC*, 2010] recommended integrating inventories, flux data, remote sensing estimates of disturbance and land cover change, and production of global maps of land use and land cover change every two years using a combination of moderate resolution data (Landsat-type) and high resolution satellite imagery (e.g., to quantify selective removals). In atmospheric inversions, it is often assumed that disturbance is randomly distributed in time and space, affects only a small portion of the land surface area (1–2%/yr), and therefore, with the exception of vast tropical forest disturbance, it has little effect on atmospheric CO_2. This assumption can be evaluated with improvements recommended by the NRC.

[75] Forest degradation and partial harvest are also important within North America, as well as globally. Although the two processes should not be confused, and have different effects on productivity, both degradation and partial harvest extract wood and affect carbon cycling. About 60% of U.S. harvest occurs through partial harvest, and forest degradation is widespread in Mexico (Table 2). Remote-sensing based estimates of harvest often ignore selective harvest, but *Asner et al.* [2005] estimated the extraction of 27–50 million cubic meters of wood in the Brazilian Amazon using Landsat observations to identify degraded areas. Subkilometer-scale remote sensing observations combined with time series analysis and high-resolution data are necessary for accurate assessments of degradation, small-scale deforestation, and partial harvest. Landsat-based tools for doing this are in rapid development, and include abilities to monitor forest change associated with a host of anthropogenic and natural disturbances, as well as regrowth [*Kennedy et al.*, 2007; *Huang et al.*, 2010]. Moreover, within the context of the UNFCCC Reducing Emissions from Deforestation and forest Degradation (REDD) initiative, integrated strategies for comprehensively monitoring forests are under development and being implemented [*GOFC-GOLD*, 2009].

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