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Impacts of disturbance on the terrestrial carbon budget of North America

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[1] Because it is an important regulator of terrestrial carbon cycling in North America, extensive research on natural and human disturbances has been carried out as part of the North American Carbon Program and the CarboNA project. A synthesis of various components of this research was carried out, and the results are presented in the papers contained in this special section. While the synthesis primarily focused on the impacts of fire, insects/disease, and harvesting on terrestrial carbon cycling in forests, several groups focused on impacts of disturbance on woody encroachment in western U.S. dry lands and on soil carbon present in northern high-latitude regions. Here, we present a summary of the results from these papers, along with the findings and recommendations from the disturbance synthesis.

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1. Introduction

[2] Recent studies have shown that ecosystems (both terrestrial and aquatic) and agricultural lands across North America serve as a net sink of atmospheric carbon ranging, the strength of this sink is highly uncertain averaging 2300 (±600) Tg C yr^{-1} circa 2000 to 2005 [*King et al.*, 2007]. The majority of this sink is associated with forests [*Pacala et al.*, 2001; *Goodale et al.*, 2002; *Pan et al.*, 2011; *King et al.*, 2012], wetlands [*Bridgham et al.*, 2006], and western U.S. shrublands experiencing woody encroachment [*Archer et al.*, 1995]. Although climate warming and increases in the atmospheric concentration of CO_2 have contributed to increases in ecosystem productivity, particularly forest growth, climate change has also been an important contributor to recent changes to natural disturbance regimes [*Gillett et al.*, 2004; *Taylor et al.*, 2006], which in turn, have likely altered the strength of these terrestrial carbon sinks. Examples of reduction of terrestrial carbon sinks by disturbances include the mountain pine beetle outbreak in British Columbia [*Kurz et al.*, 2008], deeper burning of organic soils in Alaskan black spruce forests [*Turetsky et al.*, 2011a], and a tundra fire on Alaska's North Slope [*Mack et al.*, 2011]. The large soil carbon stocks in boreal forests, peatlands, and tundra are also increasingly vulnerable because of thawing soils [*Schuur et al.*, 2009], the formation of thermokarst [*Jorgenson et al.*, 2010], and the burning of deep peat soils [*Turetsky et al.*, 2011b].

[3] To assess disturbance impacts on terrestrial carbon cycling, a synthesis activity was organized as part of the North American Carbon Program (NACP) and CarboNA project. Three objectives were addressed by ten working groups that carried out studies for this synthesis: (1) assess the capabilities to provide reliable information on the spatial and temporal extent of forest disturbances and their severity, (2) evaluate the current state of the science in understanding and quantifying the impacts of disturbance on carbon cycling in forests and processes controlling carbon cycling, and (3) review the current state of the science focused on quantifying and modeling the impacts of other (nonforest) disturbances on the terrestrial carbon budget of North America. Because most recent research has focused on the impacts of forest disturbances, the majority of the synthesis activity focused on this land cover type. However, because of their importance, working groups also focused on the impacts of disturbance on woody encroachment and northern high-latitude soils (Table 1).

Additional supporting information may be found in the online version of this article.

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Table 1. Summary of the Different Working Groups Working on Various Components of the Disturbance Synthesis, Including the Publications Resulting From Their Efforts

Working Group Number	Synthesis Focus	Reference
Objective 1: Quantifying Forest Disturbances		
1	Forest harvest and conversion	*Masek et al.* [2011]
2	Burned area	*Kasischke et al.* [2011]
3	Insects and disease	*Hicke et al.* [2012]
Objective 2: Assessing the Impacts of Forest Disturbance		
3	Impacts of insects and disease	*Hicke et al.* [2012]
4	Carbon emissions from fires	*French et al.* [2011]
5	Heterotrophic respiration	*Harmon et al.* [2011]
6	Carbon dioxide fluxes following disturbances	*Amiro et al.* [2010]
7	Integrated assessment of field observations	*Goetz et al.* [2012]
8	Modeling the impacts of forest disturbance on carbon cycling	*Liu et al.* [2011]
Objective 3: Assessing the Impacts of Nonforest Disturbances		
9	Woody encroachment	*Barger et al.* [2011]
10	High northern latitude soils	*Grosse et al.* [2011]

[4] Assessing the impacts of disturbance on the terrestrial carbon cycle requires not only methods that provide an assessment of how carbon source/sink relationships have changed in the past (diagnosis), but also models that predict how changes to disturbance regimes will affect the carbon cycle in the future (prognosis). The methods and models needed for both diagnosis and prognosis of the impacts of any disturbance on the carbon cycle are based on understanding and quantifying specific ecosystem processes and characteristics (Figure 1): (a) inputs on specific characteristics of different disturbance regimes, (b) the ability to quantify the impacts of disturbances on the abiotic (environmental) conditions that control ecosystem processes and combustion, (c) the ability to quantify combustion and the biological processes that result in changes to the amounts of carbon present in the different carbon pools within the ecosystem, and (d) an approach to document and quantify changes to the amounts of carbon transferred between different pools.

[5] Here, we present a summary of the findings of the NACP disturbance synthesis. Section 2 discusses the analysis and quantification of disturbance regimes. Section 3 discusses the impacts of disturbances on ecosystem processes that control carbon cycling. Section 4 discusses analysis of fluxes of carbon between terrestrial ecosystems and the atmosphere through measurements and modeling. Section 5 presents a summary of recommendations and identifies near-term opportunities and actions that could be taken to develop a clearer understanding of the impacts of disturbance on terrestrial carbon cycling in North America.

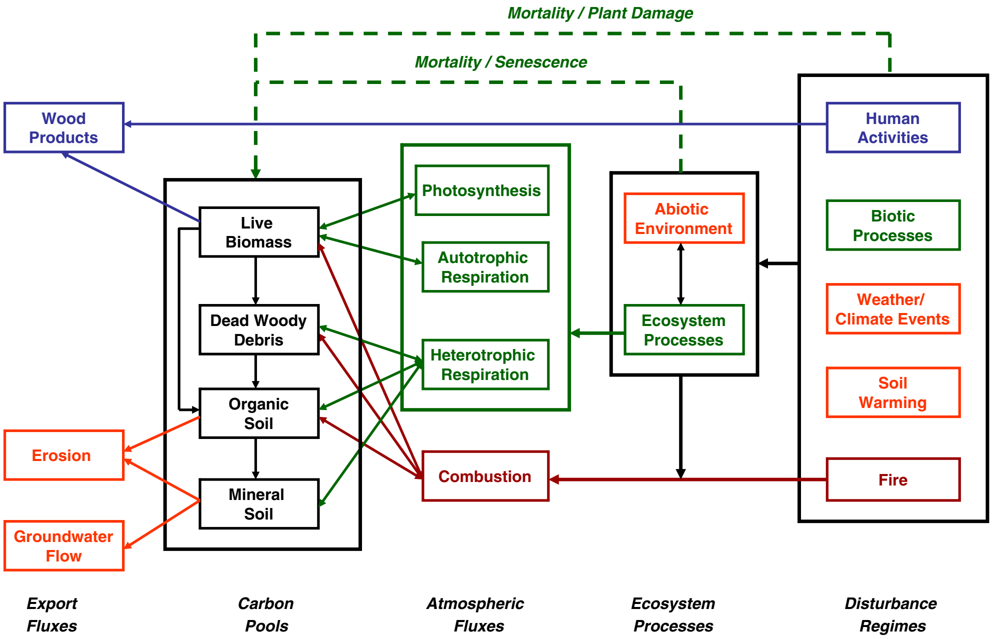

Figure 1. Schematic diagram of the relationship of disturbances to terrestrial carbon cycle, including key components (disturbance regimes, ecosystem processes, atmospheric fluxes, export fluxes) and the processes controlling carbon cycling.

2. Quantifying Disturbance Regimes

2.1. Disturbance Types

[6] For the purposes of the synthesis and this discussion, we define a disturbance after *White and Pickett* [1985] as being "any relatively discrete event that disrupts the structure of an ecosystem, community, or population, and changes resource availability or the physical environment." For the purposes of this discussion, decadal-scale climate events such as droughts are not considered to be a disturbance but a part of the natural variability terrestrial ecosystems naturally experience.

[7] Disturbances affecting terrestrial ecosystems can be organized into five broad categories, some of which are very specific and others encompass a number of physical and biological processes (Figure 1):

[8] 1. *Human activities* include processes that directly change the vegetation and/or site characteristics over the shorter term. Although much attention has been focused on forest harvest and forest clearing associated with conversion to other land uses [*Masek et al*., 2011], other human activities either directly or indirectly impact a site or region over the longer term via land management practices (fire suppression, grazing, infrastructure development, etc.) or through the introduction of invasive species [see, e.g., *Barger et al*., 2011]. The distinction between harvest (which does not change land use) and deforestation (which converts from forest to non-forest land use) is important for vegetation carbon accounting, and each process is treated uniquely under IPCC guidelines. For the purposes of this review, however, these two aspects of anthropogenic disturbance will be lumped under the common term "harvest."

[9] 2. *Biotic processes* include outbreaks of insects and diseases, as well as increased physiological stresses that result in large-scale forest dieback [*Hicke et al*., 2012]. Impacts of biotic disturbances can include defoliation, partial dieback of roots and branches on individual trees, heart rot, or whole-tree mortality. Biotic disturbances are often related to physiological stress from longer-term drought that either directly causes mortality or renders individual plants more susceptible to biotic disturbance agents [*Hicke et al*., 2012].

[10] 3. Short-term *weather and climate events* include those that directly result in vegetation damage and mortality and/or changes to ambient environmental conditions. These include wind events (tornadoes, hurricanes, and microbursts), ice and snow storms, storm surges in coastal regions, and floods.

[11] 4. *Soil warming* is a process that is important in all northern high-latitude regions, where in areas with permafrost, the transition from perennially frozen to thawed ground significantly increases the decomposability of soil organic matter and susceptibility to burning during fires [*Grosse et al*., 2011].

[12] 5. *Fires* result from ignitions from a variety of sources, including weather events (lightning strikes), land management activities, and other human activities [*Kasischke et al*., 2011]. Biomass burning during fires has a range of impacts. Direct impacts include consumption of aboveground and ground-layer biomass (both living and dead), releasing carbon to the atmosphere and causing plant mortality. Note that fire is a unique disturbance in that combustion represents one of the four major fluxes to the atmosphere from land surfaces [*French et al*., 2011] (Figure 1).

2.2. Disturbance Regime Characteristics

[13] A number of characteristics are used to describe and quantify disturbance regimes, including the frequency of disturbance, the seasonal timing of the disturbance, the length of time for a disturbance to occur, the size of individual disturbance events, disturbance intensity, disturbance severity, and residuals from disturbances [*Turner*, 2010].

2.2.1. Spatial and Temporal Characteristics of Disturbances

[14] Descriptors of the frequency of a disturbance depend on the spatial scale of impacts of that disturbance. When studying the impacts of individual disturbance events at the local or plot scale, the disturbance-free interval or time since the last disturbance is the measure of interest [*Johnstone*, 2006]. At landscape, regional, and larger scales, frequency is the preferred measure and is most often defined as the average or median number of disturbance events per unit time (e.g., events per year) [*Turner*, 2010]. The return interval represents the average time between disturbance events, whereas the rotation period is a measure of the average time it takes to disturb a specified area [*Turner*, 2010].

[15] Timing of the disturbance is important when seasonal or temporal variations in biotic and abiotic site characteristics control disturbance behavior, intensity and severity. Many biotic and abiotic characteristics of a site are tied to seasonal variation in weather conditions, which in turn, control seasonal patterns of plant growth and development, as well as ambient environmental conditions. For example, seasonal thawing of the active layer in high northern latitude regions governs the vulnerability of organic soils to burning during fires by controlling soil moisture, with deeper burning occurring during late-season fires [*Kasischke and Johnstone*, 2005; *Turetsky et al*., 2011a]. Measures of the seasonal timing of a disturbance are also scale dependent. At the plot or landscape scale, the day of the year or the season when the disturbance occurred at a site is an important characteristic for understanding the impacts of a specific disturbance event [*Turetsky et al*., 2011a]. For regional- and larger-scale studies, the total area disturbed or the fraction of the disturbed area that occurred during specific time periods is used as a measure [*Kasischke et al*., 2010].

[16] For both biotic and physical disturbances, the length of the disturbance event or the rate of growth of a disturbance feature is an important characteristic. Reduction in plant growth caused by insects and diseases (e.g., defoliation) represents a unique category of forest disturbance because this process often does not cause mortality, but only reduces photosynthesis and production of biomass over a limited period of time, typically from 1 to 5 years [*Hogg et al*., 2005; *Huang et al*., 2008]. Bark beetle outbreaks that kill trees often do so over the course of several years within a stand [*Amman and Baker*, 1972]. Thermokarst features can form over a number of years to decades, while more rapid thermo-erosion features may form over days to years; thus, an important characteristic is the area growth rate [*Jorgenson et al*., 2008].

[17] Size of disturbance events can be quantified in a variety of ways, including the area within the perimeter of discrete events such as fires, the average size of disturbance events within a region during a specified time period, or the fraction of a defined region that is affected by a disturbance in a specified time period [*Kasischke et al.*, 2002; *Turner*, 2010]. It should be noted that for some disturbances such as fires and deforestation resulting from clear-cutting, the size of the disturbance event is easy to discern and measure. For most other disturbances, the size of the disturbed area is more difficult to measure as the disturbance may only be affecting a portion of the landscape. For example, insects and diseases typically only attack certain species of trees [*Hicke et al.*, 2012]. In the case of weather disturbances, the impacts may be dependent on tree size (e.g., canopy versus understory trees) [*Duguay et al.*, 2001; *Manion et al.*, 2001; *Peterson*, 2007] or topographic position (e.g., is an area located on the windward or leeward slope relative to wind direction) [*Foster and Boose*, 1992; *McNab et al.*, 2004]. In these instances, determining the area impacted by a disturbance often requires mapping predisturbance vegetation cover and/or using topographic data. For thermokarst and thermo-erosion, usually only portions of the landscape are affected by rapid thawing of ice-rich permafrost depending on distribution of ground ice and strong hydrological feedbacks to thaw subsidence, whereas other areas of the same region remain unaffected [*Grosse et al.*, 2011].

2.2.2. Disturbance Intensity and Severity

[18] In assessing the impacts on terrestrial carbon cycling, there are two additional characteristics of disturbance regimes that are important—intensity and severity. Intensity represents a measure of the disturbance event itself, such as the measure of heat released during a fire per unit time [*Lentile et al.*, 2006], the strength of wind, amount of precipitation, the level of ice accumulation during weather/climate events [*Peterson*, 2007; *Negron-Juarez et al.*, 2010; *Proulx and Greene*, 2001], the type of harvest technique used (e.g., selective versus clear-cut logging), and the rate of infestation/infection by biotic agents [*Cooke and Roland*, 2003; *Nealis and Regniere*, 2004]. Disturbance severity is a function of disturbance intensity and system resistance and involves measures of the immediate effects the disturbance has on the biotic and abiotic characteristics of the impacted ecosystem [*Keeley*, 2009]. The approach selected for measuring severity depends upon the process affected by the disturbance [*Lentile et al.*, 2006; *Kasischke et al.*, 2008]. Table 2 presents examples of measurements used to quantify forest disturbance severity that affects the carbon budget.

2.3. Data Sets for Quantifying Disturbances

[19] A variety of contemporary (over the past half century) data sets focus on estimates of areas impacted by insects, fires, and forest harvesting that is recorded in land management records or information products derived from remotely sensed data [*Hicke et al.*, 2012; *Kasischke et al.*, 2011; *Masek et al.*, 2011], while longer-term assessments are based on quantification from proxies (such as tree rings and charcoal present in sediments) that provide information on disturbance frequency for specific tree species or regions (see discussion below). In contrast, there are little or no data on the extent of woody encroachment [*Barger et al.*, 2011], and data on the extent of the impacts of warming and thermokarst on high northern latitude soil carbon are even more limited. The large extent of thermokarst lakes and basins in high northern latitude permafrost regions is reasonably well known from local data sets on the current spatial distribution of these features and their formation history [*Hinkel et al.*, 2005; *Walter et al.*, 2007; *Jones et al.*, 2012]; however, these data sets largely reflect the paleorecord of thermokarst disturbances, while spatial data sets on active northern soil carbon disturbances for more recent periods are rare. For example, remote sensing-based local data sets on the number and dynamics of thaw slumps forming on permafrost slopes exist [*Lantuit and Pollard*, 2008; *Bowden et al.*, 2008; *Lacelle et al.*, 2010; *Lantz and Kokel* [2008].

[20] Data products or information sources available for assessing the spatial and temporal characteristics of disturbances are summarized in Table S1 in the Supporting Information. More detailed descriptions of these data sets are presented in the cited references, which also discuss the uncertainties and limitations associated with the different data

Table 2. Examples of Measures of Forest Disturbance Severity

	Forest Disturbance Class			
Severity Measure	Harvesting	Biotic	Weather/Climate Events	Fire
Tree removal rate[a] (stems/ha/yr)	X			
Slash (t/ha)	X			
Tree mortality rate[a] (stems/ha/yr)		X	X	X
Tree uprooting rate[a] (stems/ha)			X	
Canopy damage[a] (% or relative ranking)			X	X
Branch breakage rate[a] (branches/ha)			X	
Changes in dead woody debris (% or t/ha/yr)		X	X	X
Defoliation rate[a] (% or relative ranking per year)		X		
Canopy openness (%/year)		X	X	X
Change in radial growth[a] (% or mm/yr)		X	X	X
Change in basal area of live trees[a] (m^2/ha)		X	X	X
Fraction of biomass consumed[b]				X
Depth of burning of surface organic layer[c] (relative or absolute)				X
Residual organic layer depth[c]				X

[a] Includes both overstory and understory trees

[b] For different carbon pools or as a function of plant type (overstory tree, understory tree, woody shrubs, and herbaceous) or tree component (foliage, branches, bark, etc.)

[c] Also used as severity measures for tundra and peatlands

sets. A summary of the sources for the data sets presented in Table S1 is presented below:

[21] *Records compiled by land management agencies*. Land management agency records provide information on forest areas disturbed by harvest, forest conversion, and insects/disease as well as all areas (regardless of vegetation cover) disturbed by fire. For all disturbance types, data have been compiled in summary form for different political units at annual time scales. Information is available on an area impacted by major insect species and diseases for Canada and Alaska. For major insects and diseases, maps of the perimeters of areas affected are available. The most detailed information is available for fires, including databases for individual fire events that contain digital maps of fire perimeters, start and end time, and ignition source. More recently (since the mid-1990s), digital maps of areas affected by major insects and diseases have been generated.

[22] *Information derived through the analyses of satellite remote sensing data*. Disturbances to forests from harvesting/clearing, insects, and damage from weather-related events as well as to all vegetation types from fire are ideally suited for detection and mapping using satellite remote sensing data. Disturbances to land surfaces covered by living vegetation result in a dramatic decrease in surface reflectance in the near-infrared (IR) region of the electromagnetic spectrum (0.7 to 1.3 µm) and increases in the shortwave IR region (1.3 to 2.8 µm). Active fires are also detected through the use of thermal IR (8 to 14 µm) remote sensors. These changes have made it possible to develop a variety of approaches to map vegetation and forest disturbances using satellite remote sensing data, and in some cases to generate maps depicting disturbance severity. A variety of fire products derived from satellite remote sensing data are available for North America, including information on burned area, seasonality of fire activity, and fire severity (Table S1). Developing regional- to continental-scale data products on insect and disease damage from satellite remote sensing data is difficult for several reasons. First, because insects and diseases target specific tree species and because tree species respond differently to attack, changes in spectral signatures associated with damage are variable and complex. Second, damage has a variety of effects, ranging from partial defoliation to widespread mortality. Third, damage to canopy trees often results in increases in tree growth in understory vegetation, obscuring the signature of damage to canopy trees. In spite of these challenges, a number of approaches have been developed to map insect and disease impacts in specific regions [reviewed in *Hicke et al*., 2012]. While there are no standard remote sensing products to map damage from climate events, approaches have been developed for mapping the extent and impacts of hurricanes [*Chambers et al*., 2007; *Wang and Xu*, 2009] and tornadoes [*Yuan et al*., 2002; *Myint et al*., 2008].

[23] *Analysis of storm tracks and weather data*. A number of weather-related events cause damage to trees, which in turn impact carbon cycling in a number of ways. This damage includes breakage of branches from wind (hurricanes, tornadoes, microbursts) and excess snow/ice, breakage of tree boles during extremely high winds, and uprooting of trees. For many local- to regional-scale weather events, levels of damage have been quantified by integrating field observations with aerial surveys of canopy damage. For example, land management agencies in Ontario and Quebec produced forest damage maps from the 1998 ice storm that impacted large areas of the northeast U.S. and southeast Canada based on precipitation data [*Hopkin et al*., 2003]. Methods have been developed to estimate forest damage from large-scale, recurrent events such as hurricanes based on field-observed relationships between wind speed and rainfall and damage. *Zeng et al*. [2009] used the recorded tracks of hurricanes that made landfall in the southeastern U.S. along with the category level of these storm events to estimate damage and mortality from historical hurricanes. This information was used to estimate rates of mortality and creation of dead woody debris from hurricanes and carbon losses from increased heterotrophic respiration.

[24] *Analysis of paleodata*. Information on disturbance frequency is needed for assessing the longer-term impacts of disturbances on carbon cycling. For vegetation disturbances, this type of information can be derived from analyses of tree rings and charcoal present in soils and sediments. A review of the use of paleodata for forest disturbance frequency assessment is presented in the Supporting Information.

2.4. Forest Disturbed Area Trends

[25] Figure 2 presents the decadal average on forest disturbed area for Canada, Mexico, and the United States for the 1990s and the 2000s. The data for hurricanes are based on historical hurricane tracks provided by NOAA (http://csc.noaa.gov/hurricanes/). For fires, information is available over longer time periods for specific subregions of the U.S. and Canada [see *Kasischke et al*., 2011, Figure 4]. Data sets on areas affected by insects and disease are summarized in the Supporting Information. Because forest disturbance data for insects are not available for Mexico, it is not possible to directly compare the forest area disturbed for the three North American countries for all major disturbances.

[26] The uncertainties for estimates of disturbed areas have not been well studied and are a topic for additional research. Uncertainties have been estimated to be in the range of 20 to 40% for burned area [*Kasischke et al*., 2011]. Perhaps the most critical information needs are approaches to convert estimates of areas impacted by insects which depend not only on the agent for disturbance, but on the amount of host species present within the impacted area.

[27] Canada had the largest reported forest disturbance area over the past two decades, 20.6 million ha yr^{-1}, with 85% of this area being attributed to insects (see discussion on areas impacted by insects in the Supporting Information). The U.S. experienced 10.9 million ha yr^{-1} of forest disturbance over the past two decades, with the largest source being forest harvesting (45%). Mexico reported 1.3 million ha yr^{-1} of forest disturbance over the past two decades, with 82% associated with forest harvest.

[28] Overall, the level of forest disturbance remained constant between the 1990s and 2000s in Canada (20.6 million ha yr^{-1}). There were decreases in forest harvested (5%), burned area (58%), and areas impacted by forest defoliators (57%), but there was a large increase in areas infested by bark beetles (1632%).

[29] For the U.S. between the 1990s and 2000s, there was a 5% decrease in annual forest area harvested, a 65% increase in annual area burned, a 49% reduction in annual forest area

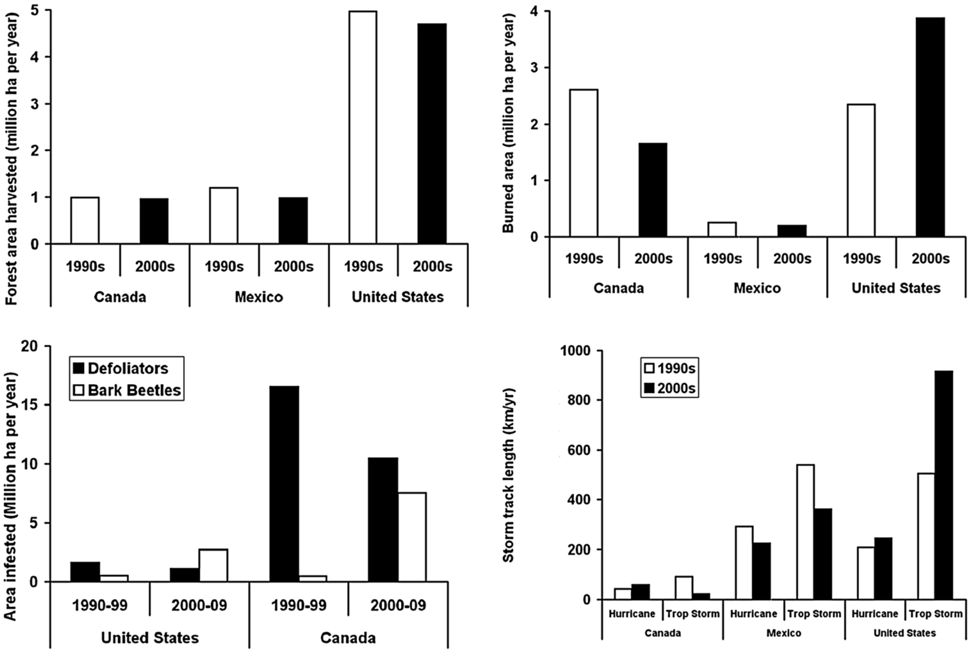

Figure 2. Areas disturbed in the 1990s and 2000s for Canada, Mexico, and the United States. Data include area estimates for harvest, fire, and major insect agents (conifer beetles and defoliators) and length of hurricane storm tracks over land. This last figure contains information on the length when the strength of the storm was at either hurricane level (sustained winds > 119 km h^{-1}) or tropical storm level (sustained wind > 63 km h^{-1}).

defoliated by insects, and a 527% increase in annual forest area experiencing mortality from bark beetles that infest conifer tree species. In addition, there was a 63% increase in the length of hurricane-related storm tracks over U.S. land areas. Overall, the area affected by fire and mortality from bark beetles increased by 3.4 million ha yr^{-1} from the 1990s to the 2000s, while the forest area defoliated decreased by 0.5 m ha yr^{-1}.

[30] For Mexico, there were small decreases in areas impacted by fire (0.1×0^6 ha yr^{-1}) and harvesting (0.23×10^6 ha yr^{-1}) disturbance types from the 1990s and 2000s, as well as a 30 to 50% decrease in the area affected by hurricanes and tropical storms, respectively.

3. Impacts of Disturbance on Ecosystem Processes and Carbon Cycling

[31] Disturbances have both direct and indirect impacts on ecosystems. Direct effects include changes to the physical and biological characteristics of the ecosystem, while indirect effects result in changes to the abiotic environment that in turn affect the biogeochemical processes that regulate carbon cycling. Direct effects include damage from disturbances to plants, trees, microbial communities, and dead organic matter (including mortality and direct removal through combustion). Indirect changes to the abiotic environment include changes to site microclimate (light, temperature, and precipitation distribution) from physical changes to tree and plant canopies, physically altering site geomorphology (e.g., permafrost thaw causes surface subsidence and reorganization of drainage systems), and changes to soil moisture and surface hydrology, site and ground temperature, and light conditions. The combination of direct and indirect impacts from disturbance often initiates feedback processes that may be self-reinforcing. These include secondary succession (following mortality or significant damage to individual trees), changing the growth rates of individuals within a forest stand, altering the amounts of dead woody debris, and thawing of near-surface permafrost. These combined effects change the biological processes that control photosynthesis, respiration (both aerobic and anaerobic), and methane oxidation—key processes that control exchanges of carbon between terrestrial ecosystems and the atmosphere (Figure 1).

[32] While encroachment of shrubs and trees into dry lands located in the western U.S. has been identified as a significant sink for atmospheric carbon, this conclusion is based on a limited number of studies (33) across a set of study sites that may not be representative of all ecoregions where it is occurring [*Barger et al.*, 2011]. The synthesis of data from these sites shows that there is a strong correlation between changes in aboveground net primary production (ANPP) with woody plant encroachment and mean annual precipitation (MAP), but that change in total biomass present at a site varies as a function of plant type, with shrub biomass being positively correlated to MAP and tree biomass being negatively correlated. Overall, the results show that compared to historic vegetation, there have been decreases in ANPP with woody encroachment in arid regions and increases in ANPP in semiarid and subhumid regions. Effects of woody plant encroachment on belowground carbon dynamics are more mixed and highly variable across plant functional types and biomes. Belowground carbon responses were unrelated to ANPP changes, but there was evidence that a combination of factors, including MAP and soil characteristics such as bulk density and texture, influenced belowground carbon change with woody plant encroachment.

Belowground carbon change was inversely related to MAP for tree or aborescent growth forms, but there was no clear relationship of changes in belowground carbon with shrub encroachment. Although *Barger et al*. [2011] concluded that the current evidence suggests that woody encroachment in western U.S. dry lands is a net carbon sink, they showed that in drier regions, woody encroachment may be carbon neutral or a net carbon source. Biome-level estimates of declines in ecosystem carbon in the most arid sites (e.g., Chihuahuan Desert) are largely driven by decreases in ANPP and to a lesser extent by belowground carbon changes. In these sites, highly productive grasslands are often replaced by less productive shrublands resulting in *ca*. 40% declines in ANPP [*Barger et al*., 2011] with small declines or no change in belowground carbon. Whereas longer-term climate change may be exerting a control on patterns of woody encroachment, land use and management practices that remove aboveground biomass may quickly and dramatically alter C gains associated with woody plant proliferation. In particular, fire management, drought, brush management, and grazing practices all have different impacts on carbon cycling. *Barger et al*. [2011] concluded that lack of historical data on land management practices combined with the paucity of research on the impacts of specific land management practices makes it difficult to quantify the strength of the carbon sink from woody encroachment, substantiating the large uncertainties assigned to this carbon sink by King *et al*. [2007].

[33] The large terrestrial soil carbon reservoir that exists in the Arctic and boreal regions of North America is not the result of strong inputs from the mostly low-productive vegetation in tundra or peatland regions, but rather a product of a combination of factors, including strong mechanisms of organic matter stabilization (low soil temperatures, permafrost aggradation, peat accumulation, cryoturbation, often anoxic soil regimes), weak destabilization (limited combustion due to water-saturated or frozen soils, reduced microbial activity), and low exports [*Grosse et al*., 2011]. Accumulation of dead organic matter in surface organic layers, burial of organic matter through cryoturbation, and the accumulation of dissolved organic carbon and dead organic matter in frozen soils over long time periods (centuries to millennia) cause a long-term carbon sink in permafrost regions [*Zimov et al*., 2006; *Tarnocai et al*., 2009]. While northern cryosphere regions are currently a net sink of carbon dioxide and a source for methane [*McGuire et al*., 2010], disturbances are an important factor in controlling soil carbon cycling in this region and therefore regulate the balance between net carbon sink and source [e.g., *Schuur et al*., 2008].

[34] *Grosse et al*. [2011] define two classes of disturbances that impact soil carbon cycling, both of which are controlled by variations in climate that influence temperature and water: press disturbances and pulse disturbances. *Press disturbances* are longer-term consequences of climate warming, including gradual soil thawing, changes to soil moisture, and the resulting changes to the biotic processes that control atmospheric fluxes. *Pulse disturbances* are changes to the land surface from thawing of ice-rich permafrost, including formation of thermokarst, changes to site drainage, thermal erosion, increased erosion of sites along rivers and coasts, and thaw slumping on slopes. Soil warming (a press disturbance) in Arctic and boreal regions is often associated with permafrost degradation, in particular the top-down thawing of permafrost. This warming and thawing deepens the active layer and thus changes potential rooting depth and soil moisture. The combined effects drive changes to the microbial and plant communities, affecting photosynthesis and respiration. Hydrologic changes to Arctic and boreal ecosystems are complex due to feedbacks with permafrost thaw and geomorphic change [e.g., *Jorgenson and Osterkamp*, 2005]. Some landscapes have experienced drying as a result of changes to the water balance (e.g., transpiration > precipitation) or as a result of loss of permafrost that increases site drainage (in areas with low-ice content permafrost on well-drained soils). Thawing areas with ice-rich permafrost can experience inundation. Changes in hydrologic state are important in controlling patterns of aerobic versus anaerobic decomposition [*Turetsky et al*., 2008; *Schuur et al*., 2009].

[35] The most important pulse disturbances that directly influence carbon cycling are fire and thermokarst formation. Lakes formed through thermokarst are an important source for methane in northern high latitudes [*Walter et al*., 2006] and are known to have influenced the atmospheric carbon pool during previous events of strong disturbance such as the warming during the last deglaciation [*Walter et al*., 2007]. The occurrence and severity of these pulse disturbances are closely linked to press disturbances, and changes to the abiotic environment control changes in ecosystem composition and exchanges of carbon with the atmosphere.

[36] An important direct result from disturbances is the transformation of large amounts of live woody biomass to dead woody biomass via damage to forest canopies or mortality of individual trees. *Harmon et al*. [2011] reviewed factors that control the fate of this disturbance-related carbon pool through processes that control the rates of heterotrophic respiration (R_H). While the basic factors controlling R_H are well known (e.g., temperature, moisture, the composition and quality of the dead woody material, consumption of woody material by macrovertebrates), the conditions regulating these factors in disturbed forests have not been systematically examined. Most importantly, these factors include the spatial/temporal distribution of different dead woody debris components (including small branches, large branches, and tree boles), which in turn controls the microclimate where the dead woody debris exists (which controls temperature and moisture) as well as access by macrovertebrates. Through various examples, *Harmon et al*. [2011] explored factors that can alter the temporal patterns of postdisturbance R_H from dead woody debris, including variations in the moisture content of dead woody material as controlled by the microenvironment where the material is located. They concluded that nonlinear temporal variations in R_H are likely to have profound impacts on the temporal patterns of carbon uptake and release following disturbance.

[37] Biotic disturbances from insects, diseases, and pathogens have a number of direct and indirect impacts on carbon cycling, as reviewed by *Hicke et al*. [2012]. While biotic disturbances that result in tree mortality have direct and indirect impacts that are similar to other stand-replacement disturbances, they can be more complex than other forest disturbances. First, as biotic disturbance agents often interact with other insects and pathogens, some biotic disturbances are the result of multiple biotic agents. Infestation by one

group of insects or pathogens may weaken a tree to become more vulnerable to infestations by other groups. Second, in the case of defoliating insects and some pathogens, the direct impacts are a reduction of net primary production over the length of the infestation. Third, at landscape and regional scales, outbreaks of insects and pathogens and their impacts often occur over multiple years, not in a single year.

[38] *Goetz et al.* [2012] review the most useful measurements for characterizing the carbon implications of different types of disturbance. They synthesize ways to improve model-data integration to capture changes in carbon pools and fluxes in the years following disturbance, and how the most relevant measurements and methods for capturing post-disturbance carbon balance differ between fire, insect, harvest, and wind disturbance. They show that coupled remote sensing-modeling approaches are particularly valuable, given the dynamic nature of disturbance and associated changes in vegetation state, but note that addressing several key areas of uncertainty would substantially advance disturbance research. These include characterizing disturbance severity, which has many linear and nonlinear effects, and capturing longer- and larger-scale disturbance dynamics, and how they interact. Both of these research foci involve legacies extending across a wide range of time scales; thus, incorporating field and satellite-based measurements into models will help refine research focused on capturing the magnitude and duration of those legacies.

4. Analyses of Carbon Fluxes Through Measurements and Modeling

[39] A wide variety of techniques and approaches have been developed to directly measure or estimate carbon fluxes between the earth's surface and atmosphere. Direct techniques include the use of chambers or eddy covariance flux towers to measure carbon exchange between surfaces and the atmosphere. Flux towers have been the technique of choice, providing an average flux measurement on the spatial scale of hundreds of meters to a few kilometers and a typical temporal scale of 30 min providing annual to multiyear records [e.g., *Baldocchi*, 2008]. Over the past two decades, a large number of towers have been deployed in forest stands globally to collect data to study factors controlling gross primary production, ecosystem respiration, and net ecosystem production. While the majority of these towers were deployed in mature forests, a number were also located in forests recovering from disturbance, including those impacted by fires, forest harvests, insect infestations, and storms [*Amiro et al.*, 2010]. Forest stands that were studied during the synthesis were located across the U.S. and Canada. The results of this synthesis showed that all the forest ecosystems studied had recovered from the impacts of disturbance in terms of switching from a net source of carbon following disturbances to a net sink by 20 years following a disturbance. More rapid recovery occurred in stands experiencing partial disturbance compared to those experiencing a stand-replacing disturbance [*Amiro et al.*, 2010]. Most of the change in carbon flux with forest age was driven by photosynthetic production, with heterotrophic respiration being nearly constant with age.

[40] While it is difficult to directly measure emissions from combustion that occurs during forest fires, approaches have been developed to estimate these emissions by combining information on burned area, fuel loads as a function of forest type, and combustion efficiency as a function of forest type and weather at the time of burning. Both *Kasischke et al.* [2011] and *French et al.* [2011] investigated factors influencing estimates of carbon emissions from wildland fires across North America. While a number of studies have estimated wildland fire emissions on a global scale, *Kasischke et al.* [2011] showed there were large differences between the satellite-based burned area estimates and those reported by land management agencies across North America. The satellite-burned area data set that best matched the burned areas reported by land managers was that being used by *van der Werf et al.* [2010] (developed by *Giglio et al.* [2010]) to estimate global biomass burning emissions. *French et al.* [2011] carried out a cross comparison of different approaches developed as part of the NACP to estimate emissions from wildland fires. This synthesis activity focused on using the same or very similar burned area data sets in order to provide the basis for comparison of different approaches. Emissions were estimated for five case studies from across western North America using six different approaches. The results from this synthesis activity showed how variations in fuel loads and approaches for varying consumption as a function of weather conditions influenced estimates of carbon consumed during fires [*French et al.*, 2011].

[41] Inventory-based methods are useful for assessing overall changes in forest carbon stocks [*Pan et al.*, 2011] if they include systematic and reliable methods for mapping of disturbances and accounting for the disturbance impacts on carbon pools (particularly biomass burned during fires). They can also provide critical information on longer-term mortality rates from the impacts of disturbances. Inventory-based methods are limited to estimating changes over relatively long time periods, e.g., years to decades, and thus cannot be used to assess seasonal variations in carbon exchange with the atmosphere. The forest growth models developed from inventory data do not provide the means to assess how forest carbon stocks vary as a function of temperature and precipitation, atmospheric concentrations of carbon dioxide, and variations in available nitrogen, all important factors regulating exchanges of carbon between forest ecosystems and the atmosphere. They are also limited in their ability to predict how forest carbon stocks are likely to change in the future (e.g., prognosis). Because of these limitations, process-based mechanistic models are needed.

[42] All models of impacts of disturbance on forest carbon cycling are similar in that they provide a means for quantifying how disturbances change the major carbon pools depicted in Figure 1 through changes to the abiotic environment, changes in vegetation dynamics (e.g., plant competition, succession, growth, and mortality), and changes in the size of carbon pools via the basic processes of photosynthesis, respiration, and combustion [*Botkin et al.*, 1972; *Parton et al.*, 1987; *Running and Gower*, 1991; *Pacala et al.*, 1996; *Hurtt et al.*, 1998; *Chen et al.*, 2003; *Mladenoff*, 2004]. Most models contain a number of different compartments within each of the primary carbon pools (e.g., the live biomass pool is typically divided into live leaves, branches, trunks, fine roots, and coarse roots and may treat trees, shrubs, and nonwoody plants separately). These models incorporate algorithms to account for the impacts of disturbances, including rates of mortality (state transition),

combustion of biomass by fires, mass transfers between carbon pools, and initiation of postdisturbance succession. A critical component of many models is incorporation of approaches that account for disturbance-caused changes to the abiotic environment, including changes to the microclimate (including light availability based on changes to stand structure) and the soil environment (temperature, moisture, and availability of macronutrients).

[43] Two basic types of models are used for forest carbon cycling—ecosystem demography (or forest gap models) and ecosystem compartment models [*Liu et al.*, 2011]. Demography models are based on dividing the landscape into small, homogeneous patches, where each individual patch is potentially occupied by the tree species present in a region [*Shugart et al.*, 1992; *Hurtt et al.*, 1998; *Bugmann*, 2001; *Norby et al.*, 2001]. Based upon the reproductive strategy of a tree species, the model determines the likelihood of seedling establishment after a disturbance (recruitment at a site). Once postdisturbance recruitment has occurred, the individual trees in each patch compete for resources and continue to grow until they cannot gain the needed resources to survive, or until a disturbance occurs, both resulting in mortality. The models keep track of changes in tree stand characteristics (density, height, diameter) as well as the amounts of biomass in different carbon pools and compartments.

[44] Ecosystem compartment models, with demographic processes abstracted and grouped, are computationally less expensive than the demographic models and therefore have been applied frequently to operate at large spatial scales, typically using a cell size that is greater than 1 km [*Parton et al.*, 1987; *Running and Gower*, 1991; *Chen et al.*, 2003; *Raich et al.*, 1991; *Liu et al.*, 2003]. While these models account for factors that cause variations in the distribution of major forest ecosystem types found in a region, and are designed to track changes in the same carbon pools and compartments as ecosystem demography models, they do not explicitly account for information on stand structure (stand height, density, etc.). Rather, they focus on approaches to account for the biotic and abiotic processes controlling the dynamics of carbon exchange between the atmosphere and forest ecosystems.

[45] *Liu et al.* [2011] identified some of the key uncertainties in the current ability to model the impacts of specific disturbances. For forest harvesting, challenges include modeling of selective harvesting and the impacts of harvesting on the soil environment. While approaches have been developed to account for the impacts of insects and diseases on carbon in specific regions [*Kurz et al.*, 2008; *Hicke et al.*, 2007; *Albani et al.*, 2010; *Edburg et al.*, 2011], *Liu et al.* [2011] noted that the impacts of insect/disease disturbances are not accounted for in most large-scale models because of the difficulty in consistently prescribing the impacts of a large number of insects and diseases on carbon cycling and the lack of adequate field observations for model validation. Understanding the factors controlling outbreaks of insects and diseases makes it difficult to predict the impacts of future insect/disease outbreaks on forest carbon cycling. As discussed in *French et al.* [2011], methods to predict carbon consumed during fires are well developed based on models developed from field-based observations. These methods provide the basis for improving forest carbon cycle models. The breadth of research on postfire recovery of forests across North America provides the information needed for further model development and validation. *Liu et al.* [2011] note, however, that changes to previously observed patterns of forest recovery are now occurring as a result of climate change, providing an impetus for further research. Finally, while the basic processes of how severe storms affect forest ecosystems are understood, the spatial data needed to quantify the extent of storm-damaged forests are limited, and additional field data are needed for model development and validation [*Liu et al.*, 2011].

[46] There are issues in modeling forest carbon cycling associated with the scale of the model input parameters. Spatial scales are limited not only by computational considerations, but also by the cell sizes of the input data sets. To address uncertainties associated with spatial scales, approaches need to be used that account for subcell heterogeneity in important driving factors [*Liu et al.*, 2011]. In addition, care must be taken in the approaches used to quantify the spatial patterns of disturbances, in particular, that the data used are collected at a high-enough frequency to capture the critical temporal characteristics of the disturbance event. *Liu et al.* [2011] also identify a critical set of issues related to the spin-up times needed to provide a realistic representation of the impacts of disturbance, in particular, the ecosystem carbon residence time and initial levels of carbon pools.

5. Recommendations and Opportunities for Near-Term Activities

5.1. Recommendations

[47] From research coordinated through NACP and CarboNA projects, considerable progress has been made on understanding how disturbances influence the terrestrial carbon budget of North America, especially for forest carbon dynamics. However, while much recent research has focused on the impacts of forest disturbances, less research has been carried out in other terrestrial biomes where disturbance plays an important role in carbon cycling. As a result, significant gaps still exist with assessments of disturbances affecting other parts of the carbon cycle, in particular, the soil carbon cycling in high northern latitude ecosystems and the impacts of woody encroachment in the western U.S. In addition, an emerging area requiring research is the impact of multiple disturbances on carbon cycling, for example, the impacts of fire and enhanced permafrost warming in tundra or the combined effects of insects and fire in western North American forests.

[48] Table 3 presents a summary of the recommendations presented by the different groups who carried out different components of the disturbance synthesis. More detailed discussion of these recommendations is presented in the individual papers. The information in Table 3 is organized into the following three categories: (1) develop geospatial data sets needed to document disturbances and their impacts, (2) understand and measure the impacts of disturbance on carbon cycling, and (3) model disturbances and their impacts on carbon cycling.

5.2. Near-Term Opportunities and Actions

[49] After reviewing the recommendations provided by the individual disturbance synthesis activities, we suggest that there are three areas where coordinated actions by the

Table 3. Summary of Recommendations From the Disturbance Synthesis Activities

Recommendation	Reference
Develop Geospatial Datasets Needed to Document Disturbances and Their Impacts	
Compile and catalogue all burned area data sets in a single site, and updating these data sets on an annual basis	*Kasischke et al.* [2011]
Develop a burned area product for the entire North America from Landsat TM/ETM+ data following the approach used in the U.S. Monitoring Trends in Burn Severity project	*Kasischke et al.* [2011]
Develop a gridded-map product across North America from forest inventory and harvest data	*Masek et al.* [2011]
Develop forest cover change maps for the entire North America based on processing of Landsat TM/ETM+ data	*Masek et al.* [2011]
Develop approaches to map areas affected by insects and diseases using remotely sensed data	*Hicke et al.* [2012]
Research on the uncertainties associated with the various data sets used to estimate disturbance area	*Kasischke et al.* [2011]
Develop approaches and data sets for assessing the extent of woody encroachment across the different ecoregions where it is occurring (including Arctic tundra)	*Barger et al.* [2011]
Validate approaches to use remotely sensed data to assess fire severity, particularly levels of fuel consumption	*Kasischke et al.* [2011]
Develop information products from remotely sensed data to monitor and assess the severity of impacts of insects and diseases, including defoliation	*Hicke et al.* [2012]
Develop approaches to use remotely sensed data for monitoring and quantifying forest degradation and partial harvest	*Masek et al.* [2011]
Develop approaches to use LIDAR and SAR data to map aboveground biomass in all ecosystem types	*French et al.* [2011]; *Grosse et al.* [2011]
Develop approaches to use remote sensing data to assess surface characteristics that regulate soil organic stocks in high-latitude ecosystems (soil moisture and surface water extent, surface temperature, macroscale changes in permafrost thaw, and active layer depth)	*Grosse et al.* [2011]
Develop a gridded database of weather variables that could be used for mapping dynamic vegetation fuel moisture	*French et al.* [2011]
Understand and Measure the Impacts of Disturbance on Carbon Cycling	
Research on factors controlling the heterogeneity of damage and mortality rates, and outbreak severity from forest insects and diseases	*Goetz et al.* [2012]; *Hicke et al.* [2012]
Research on the impacts of disturbance from fires, insects and disease, and damage from weather events on patterns of seedling establishment; growth of surviving tree, shrubs, and herbs; snag fall; changes in environmental conditions; and measures of heterotrophic respiration and net carbon flux	*Amiro et al.* [2010]; *Goetz et al.* [2012]; *Harmon et al.* [2011]; *Hicke et al.* [2012]
Assess the impacts of silvicultural management practices including postharvest treatments on forest ecosystems and carbon cycling	*Amiro et al.* [2010]; *Goetz et al.* [2012]
Research on factors controlling soil and substrate moisture and temperature as a function of disturbance severity in areas with complex terrains and permafrost	*Grosse et al.* [2011]; *Goetz et al.* [2012]; *Harmon et al.* [2011]
Research on factors controlling R_H of dead woody debris, including impacts of wood moisture and temperature on decomposition of woody material, factors controlling the rates of falling standing wood, factors controlling the moisture balance of aboveground dead biomass, and how variations in disturbance severity and ecosystem recovery after disturbance combine to influence the microclimates where decomposition of dead woody material is occurring	*Harmon et al.* [2011]; *Amiro et al.* [2010]
Research on factors controlling combustion during fires, particularly peatlands, tundra, subtropical and tropical forests, and shrublands under varying environment conditions that control fuel moisture	*French et al.* [2011]
Conduct systematic surveys of several ground-layer characteristics for improvement of understanding of carbon cycling in high northern latitude soils, including soil carbon quantity and quality in near-surface and deep permafrost-affected soils and properties of permafrost	*Grosse et al.* [2011]
Research in high northern latitude regions to understand controls on variations in soil organic carbon as a function of complex interactions that occur over space and time	*Grosse et al.* [2011]
Continuous collection of eddy covariance CO_2 flux measurements in disturbed and undisturbed sites (across all vegetation and disturbance types) to provide the ability for comparisons to the interannual variability caused by climate	*Amiro et al.* [2010]; *Grosse et al.* [2011]
Research on processes and factors controlling variations in fire regimes and insect and disease outbreaks to provide the foundation for further development of predictive models	*Goetz et al.* [2012]; *Hicke et al.* [2012]; *Kasischke et al.* [2011].
Modeling Disturbances and Their Impacts on Carbon Cycling	
Refine the way in which postdisturbance variations in biota and the physical microclimate are represented in carbon cycle models	*Liu et al.* [2011]; *Harmon et al.* [2011]
Incorporate the results from approaches developed using field observations for carbon consumption during fires into carbon cycle models, including the ability to incorporate seasonal variations in weather conditions that drive variations in fuel condition	*Liu et al.* [2011]; *French et al.* [2011]

(Continues)

Table 3. *(continued)*

Recommendation	Reference
For northern high-latitude ecosystems (both forested and nonforested), improve modeling of permafrost, including the ability to incorporate subgrid cell processes such as thermokarst and other pulse disturbances	
Incorporate permafrost carbon pools into earth system models	*Grosse et al.* [2011]
Develop generalized approaches to allow for extension of terrestrial carbon cycle models to consider nonforested terrestrial ecosystems such as tundra and shrublands	*Liu et al.* [2011]; *Barger et al.* [2011]; *Grosse et al.* [2011]
Construct and test predictive models of fire occurrence and spread, and insect and disease outbreaks as a function of variations in climate and include these models in carbon cycle models to allow for simulation of future impacts to carbon cycling by climate change	*Hicke et al.* [2012]; *Kasischke et al.* [2011]
Conduct sensitivity studies to assess the influence of different spatial and temporal scaling approaches on carbon cycling, as well as well as address the mismatches in spatial and temporal scales of model inputs	*Liu et al.* [2011]; *Grosse et al.* [2011]; *Goetz et al.* [2012]

government agencies responsible for managing the NACP and CarboNA can provide improved means for assessing the impacts of disturbance on North America's terrestrial carbon cycle.

5.2.1. Development of a Forest Disturbance Database

[50] In the near term, efforts could focus on the creation of an integrated forest disturbance database for the entire North American continent over the past two decades; this database could be updated on an annual basis over the next decade. This effort is critical for several reasons. First, although existing databases allow for examination of individual disturbance types, a specific geographic location can experience disturbances from multiple sources. Merging existing databases of different disturbance types into one integrated database will facilitate more complete understanding of the impacts of disturbances within a given location. Second, an integrated database would provide the means for the ongoing monitoring of trends in total forest disturbances over longer time periods. Third, it would provide the foundation needed to model the impacts of historical forest disturbances on carbon cycling as well as develop and validate prognostic models needed to assess how future variations in disturbance regimes will impact carbon cycling.

[51] Products already exist that map forest cover change using Landsat TM/ETM+ for the conterminous U.S. Fire perimeter maps in several different formats exist for Canada and the U.S. and could be generated for Mexico from existing archives of satellite remote sensing data. Maps of the locations of major insect outbreaks in the U.S. and Canada exist, and tracks of hurricanes (including varying levels of wind speed) exist. This effort could integrate maps and inventories for all disturbances, and thus would provide a database for assessment of the occurrence of multiple disturbances at the same site, as well as allow for comparison of different databases for the same disturbances (e.g., comparing maps of burned area from fire management agencies to those generated from analyses of remotely sensed data). Combining maps of disturbance location and severity with maps of forest inventory as recommended by *Masek et al.* [2011] would allow for the development of additional information products important for assessing impacts on carbon cycling, such as the amount of biomass in different compartments present in the disturbed area [e.g., *Ghimire et al.*, 2012]. Efforts are needed to translate disturbance area (for example, burned areas or areas affected by insects/diseases) into metrics more relevant for assessing carbon cycle impacts (such as area of canopy and/or understory mortality or area of defoliation severity). The database could also include a set of coefficients for different disturbance types that could be applied to provide a first-order estimate of the transfer of carbon between different pools (in the case of mortality and/or canopy damage) or the direct, immediate transfer of carbon to the atmosphere (in the case of fire). Increasing the frequency of forest inventories and associated field surveys is needed to assess the impacts of changing disturbance regimes by providing critical information on their impacts (e.g., tree mortality rates and amounts of dead woody debris).

5.2.2. Coordination of Research and Monitoring to Address Key Uncertainties on Disturbance Impacts

[52] As illustrated in the material presented here and in the papers that make up this special issue, the scientific community's understanding of how disturbance influences the carbon cycle has improved in the decade or so of research facilitated by the North American Carbon Program. An impressive amount of effort in the last few decades has been put toward understanding disturbance agents that influence the carbon cycle. However, to move forward to make the additional advances in meeting the goal of a full assessment of disturbance and carbon, a coordinated effort is needed.

[53] The greatest understanding of the impacts of disturbance on terrestrial carbon study will be achieved through coordinated, interdisciplinary research that occurs at long-term, replicated, postdisturbance chronosequences [*Goetz et al*., 2012; *Harmon et al*., 2011]. While disturbance research is already an important part of long-term research projects such as the National Science Foundation's Long Term Ecological Research (LTER) program [see, e.g., *Chapin et al*., 2010], there is a need to considerably expand such efforts to provide the opportunity to address the numerous research areas discussed in this section in a coordinated fashion. This could include funds for target of opportunity research when specific disturbance events occur within the same regions and ecosystems where existing LTER sites are located. In addition, across all terrestrial LTER sites, funding could be increased for research on factors regulating decomposition of dead woody material and carbon cycling in soils and for process studies in areas where novel patterns of postdisturbance ecosystem recovery are found. Unfortunately, many of the continuous carbon flux measurements

from eddy covariance towers at disturbance chronosequences have been terminated, and it is expensive to re-establish these sites and networks.

[54] While natural and human-caused disturbances across North America will continue to be one of the most important drivers of terrestrial ecosystem processes, the role of disturbance is not fully recognized within the grand challenges being used to drive the sampling design for the NSF National Ecology Observatory Network (NEON) [*Schimel et al.*, 2011]. As this program evolves, the importance of natural disturbance as a driver of ecosystem change should be recognized and used as a basis for deployment of relocatable sites that are part of the NEON design.

5.2.3. Establishing Pathways for Future Coordination

[55] Both the NACP and CarboNA programs need to provide clear and well-defined mechanisms for planning and carrying out coordinated research projects and for the continuous integration and synthesis of ongoing research activities that are addressing key goals and objectives. A mechanism needs to be developed to facilitate ongoing coordination of activities that are central to the goals and objectives of the NACP and CarboNA programs. While such coordination is provided to some degree through meetings of interagency working groups, science steering groups, and at periodic scientific meetings, coordination needs to be extended down to the level of the individual scientists who are conducting the research and monitoring activities that are sponsored through NACP and CarboNA.

[56] In particular, consideration should be given to the organization and support of working groups that could provide recommendations for coordinated research activities that would be funded by multiple agencies, carry out reviews and syntheses of ongoing research, and conduct intercomparisons using different carbon cycle models, including coordination of the development and integration of key data sets that are needed for modeling the impacts of disturbances. One model for synthesis of ongoing research and close interdisciplinary collaboration between researchers is NSF's research coordination network (RCN) program. One RCN that is currently underway is focused on carbon pools, processes, and fluxes associated with permafrost soils [*Schuur et al.*, 2011].

[57] A working group focused on terrestrial disturbances would include not only scientists from the research community, but also representatives from federal, state, provincial, and territorial land agencies who are involved managing land areas impacted by disturbance. Supporting such working groups would provide a means for the research and management communities to provide funding agencies with key recommendations for research gaps that need to be addressed for different countries who are part of CarboNA, as well as provide guidance to those agencies interested in a wider range of issues related to the impacts of climate change (such as the members of the U.S. Global Change Research Program).

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