Impacts of disturbance on the terrestrial carbon budget of North America.

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Objectives:

- This paper is a synthesis of extensive research on natural and human disturbance disturbances carried out as part of the North American Carbon Program and the CarbonNA project.
- The primary focus is on the impacts of fire, insects/disease, and harvesting on terrestrial carbon cycling in forests, but also includes information on impacts on disturbance on woody encroachment in western U.S. dry lands and on soil carbon present in northern high-latitude regions.
- Three objectives were addressed by ten working groups:
  - Assess the capabilities to provide reliable information on the spatial and temporal extent of the forest disturbances and their severity.
  - 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.
  - Review the current state of the science focused on quantifying and modeling the impacts of other (non forest) disturbances on the terrestrial carbon budget of North America.

New Science:

- The purpose of this study was not to derive new science, but to synthesize research carried out as part of the North American Carbon Program and the CarbonNA project.
- This synthesis resulted in a number of findings on the current state of research in forest disturbance, as well as identified many recommendations and opportunities for the future.
- To quantify disturbances, a variety of contemporary (last 50 years) data sets are available via land management records or information products based on remotely sense data; longer term assessments are based on quantification from proxies (such as tree rings).
- There are little or no data on the extent of woody encroachment; data on the extent of the impacts of warming and thermokarst on high northern latitude soil carbon are even more limited; and spatial data on active northern soil carbon disturbances for recent periods are rare.
- It was found that, overall, the level of forest disturbance remained constant between the 1990s and 2000s in Canada, with 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%).
- 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 defoliated by insects and a 527% increase in annual forest area experiencing mortality from bark beetles that infest conifer tree species. There was also a 63% increase in the length of hurricane-related storm tracks over the U.S. land areas.
- The synthesis of data from the western U.S. show that there is a strong correlation between changes in aboveground net primary production with woody plant encroachment and mean annual precipitation, but that change in total biomass present at a site varies as a function of plant type.
- Given the various land management practices and paucity of historical data available, it is difficult to quantify the strength of the carbon sink from woody encroachment in the western U.S.
- Some of the key uncertainties in current models to measure the impacts of certain disturbances include: modeling selective harvest and soil impact, accounting for impact of disease and infestations, post-fire recovery; impacts of climate change and the spatial data needed to quantify the extent of storm-damaged forest.
- There are also issues in modeling forest carbon cycling associated with the scale of model input parameters.
- Much research has focused on impacts of forest disturbance, but less research has been carried out in other terrestrial biomes where disturbance plays an important role in carbon cycling.

- Significant gaps still exist with assessments of disturbances affecting other parts of the carbon cycle, especially the soil carbon cycling in high northern latitude ecosystems and the impacts of woody encroachment in the western U.S..
- An emerging area requiring research is the impact of multiple disturbances of carbon cycling, such as impacts of fire and enhance permafrost warmings in tundra or the combined effects of insects and fire in western North American forests.

Significance:

- Disturbance, both human and natural, is one of the most important drivers of terrestrial carbon cycling in North America.
- Multiple recommendations for future, critical work has been brought forward by this synthesis effort, and are listed in the table below.
- Three broad categories of recommendations are: 1.develop geospatial data sets needed to document disturbances and their impacts, 2. understand and measure the impacts of disturbance of carbon cycling, and 3. model disturbances and their impacts on carbon cycling.
- In the near term, the government agencies responsible for managing the NACP and CarbonNA can provide improved means for assessing the impacts of disturbance on North Americas terrestrial carbon cycle by 1) developing an integrated forest disturbance database for North America for the last two decades, 2) facilitating the coordination of research and monitoring to address key uncertainties on disturbance impacts, and 3) the establishment of pathways for future coordination, including the creation of working groups that include a broad group of scientists, land managers and agency representation.
- Despite the importance of disturbance as a driver 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); disturbance should be recognized and used as a basis for deployment of relocatable sites that are part of the NEON design.

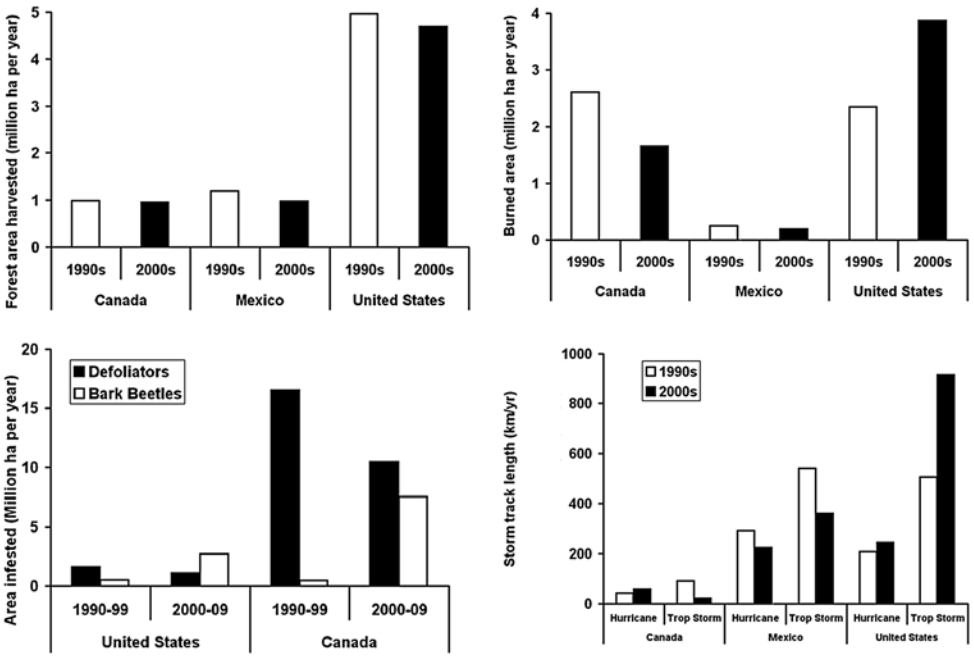

Figure 2. Areas disturbed in the 1990s and 2000s for Canada, Mexico, and the United States. Data include area estimates for harvest, fire, and major insect agents (conifer beetles and defoliators) and length of hurricane storm tracks over land. This last figure contains information on the length when the strength of the storm was at either

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]