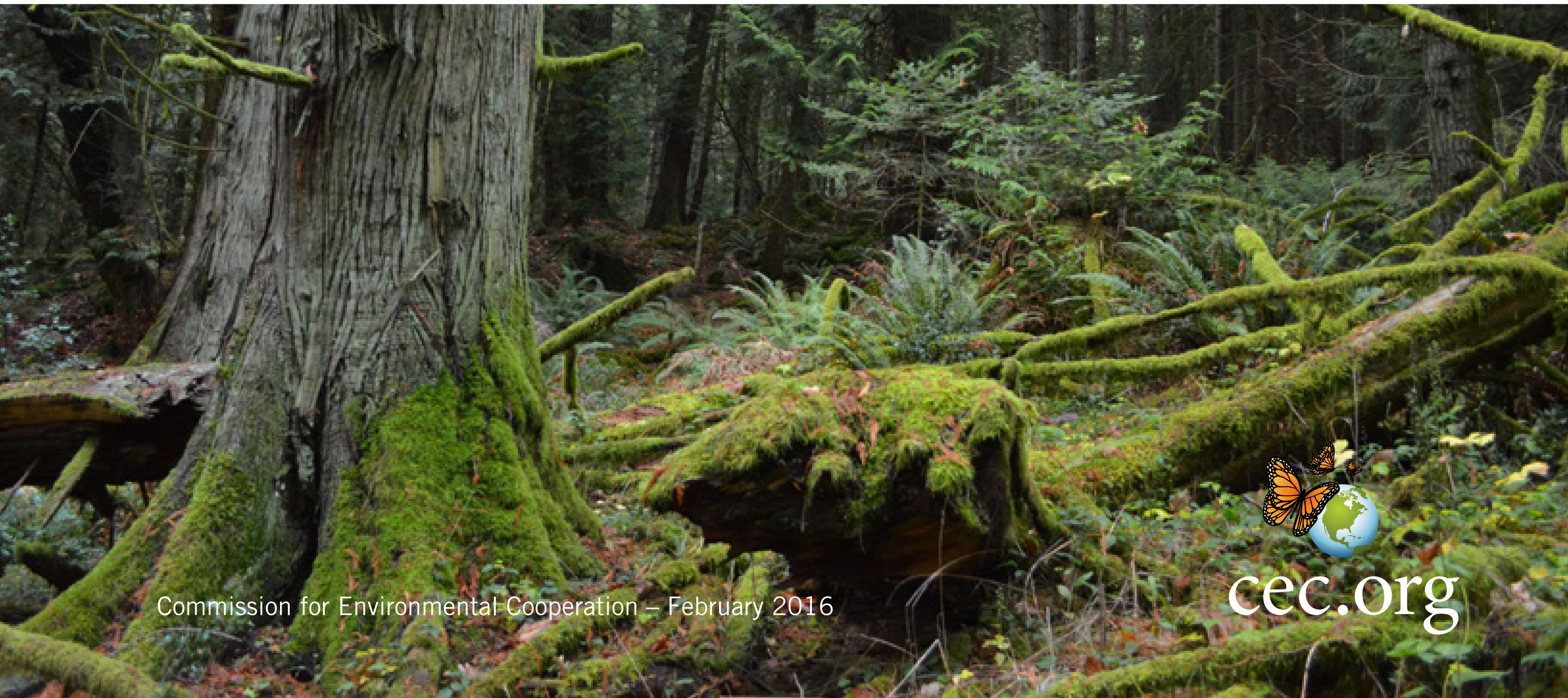
Integrated Modeling
and Assessment of North American

Forest Carbon Dynamics:

Tools for monitoring, reporting and projecting forest greenhouse gas emissions and removals



Commission for Environmental Cooperation – February 2016

cec.org

Please cite as:

> W.A. Kurz, R.A. Birdsey, V.S. Mascorro, D. Greenberg, Z. Dai, M. Olguín, and R. Colditz. 2016. *Integrated Modeling and Assessment of North American Forest Carbon Dynamics: Tools for monitoring, reporting and projecting forest greenhouse gas emissions and removals. (Summary Report)* Montreal, Canada: Commission for Environmental Cooperation. 24 pp.

This report was prepared by W.A. Kurz, R.A. Birdsey, V.S. Mascorro, D. Greenberg, Z. Dai, M. Olguín, and R. Colditz for the Secretariat of the Commission for Environmental Cooperation. The information contained herein is the responsibility of the authors and does not necessarily reflect the views of the CEC, or the governments of Canada, Mexico or the United States of America.

Publication Details

Publication type: Project report
Publication date: February 2016
Original language: English
Review and quality assurance procedures:
Final Party review: January 2016
QA250
Project: Operational Plan 2013–2014/ Integrated Modeling and Assessment of North American Forest Carbon Dynamics and Climate Change Mitigation Options

Disponible en español Disponible en français

For more information:

Commission for Environmental Cooperation
393, rue St-Jacques Ouest, bureau 200
Montreal (Quebec)
H2Y 1N9 Canada
t 514.350.4300 f 514.350.4314
info@cec.org / www.cec.org

Integrated Modeling
and Assessment of North American

Forest Carbon Dynamics:

Tools for monitoring, reporting and projecting forest greenhouse gas emissions and removals

---

W.A. Kurz, R.A. Birdsey, V.S. Mascorro, D. Greenberg,
Z. Dai, M. Olguín, and R. Colditz

Natural Resources Canada   Ressources naturelles Canada

Integrated Modeling
and Assessment of North American

Forest Carbon Dynamics:

Tools for monitoring, reporting and projecting forest greenhouse gas emissions and removals

Globally, forests are the largest land-based carbon sink, and over the past two decades have removed more than one-quarter of the emissions worldwide from the burning of fossil fuels (Le Quéré et al. 2015; Pan et al. 2011a). The projected future role of forests in the carbon cycle, and the potential impact of climate change mitigation by the forest sector remain highly uncertain (Friedlingstein et al. 2006; IPCC 2014a; Wieder et al. 2015). Therefore, we need a better understanding of the main drivers of forest carbon dynamics and their changes, which include human and natural disturbances, land use and land-use change, as well as climate and environmental changes (Birdsey et al. 2013).

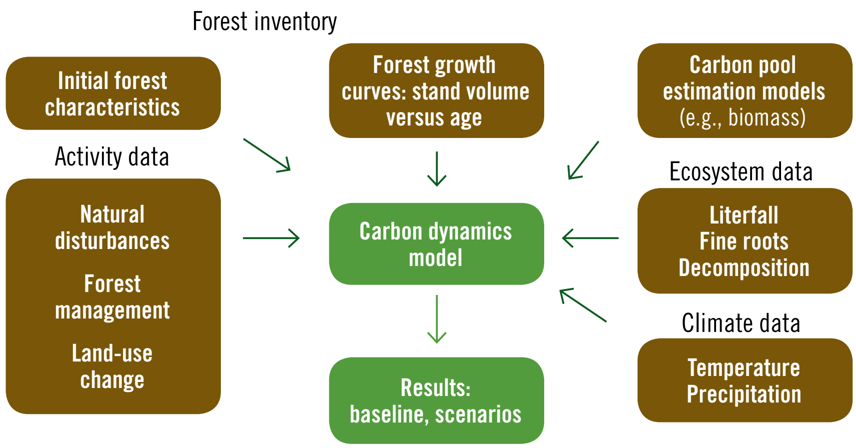
As countries attempt to meet their commitments to greenhouse gas (GHG) emission reduction targets, governments seek to understand better how forests and the forest sector can contribute to climate change mitigation. This understanding is improved, first, by quantifying current drivers of emissions and removals and, second, by identifying and quantifying which changes in human activities reduce emissions or increase forest sinks, relative to a baseline or a reference period (Lemprière et al. 2013).

This project was initiated by the three national forest services of North America, with support from the Commission for Environmental Cooperation (CEC) and other sponsors. The trilateral research cooperation involved experts from multiple agencies and institutions in the three countries. This research contributes to the development of science-based decision support models that quantify the impacts of alternative forest and land management options on the carbon balance of North American forests.

This document highlights some of the key findings of the technical report. The background information, methods, data and tools used in that study, and more detailed results and discussions are presented in a comprehensive report (Kurz et al. 2016, available in English only at: www.cec.org)

The fundamental principles of forest carbon dynamics apply to all forest ecosystem types but the responsible drivers and their impacts on GHG sources and sinks across diverse geographical regions and over time can differ greatly. Science-based models can inform policy by quantifying the past and future impacts of human activities on GHG emissions and removals and by assessing the effectiveness of climate change mitigation strategies designed to reduce GHG sources or increase sinks.

Figure 1 Carbon dynamics model: Integrating data from multiple sources, using input requirements of CBM-CFS3 as example



The primary focus of this project has been on improving forest-sector GHG assessments, through the use of analytical tools that integrate data from forest inventories, ground-plot measurements and intensive site studies, soil carbon measurements, and remote sensing of land-cover and its changes over time (Figure 1). We examined both empirical and process models and developed methods to use new remote sensing products, such as annual time-series analysis of land-cover change at 30-meter resolution, as spatially explicit input to models that estimate annual GHG emissions and removals. We demonstrate the use of such models in the analysis of past and projected future scenarios of GHG emissions. Finally, we provide examples of how these models can support the analysis of mitigation policies aimed at reducing GHG emissions or increasing GHG removals through changes in forest management, and reducing deforestation and forest degradation.

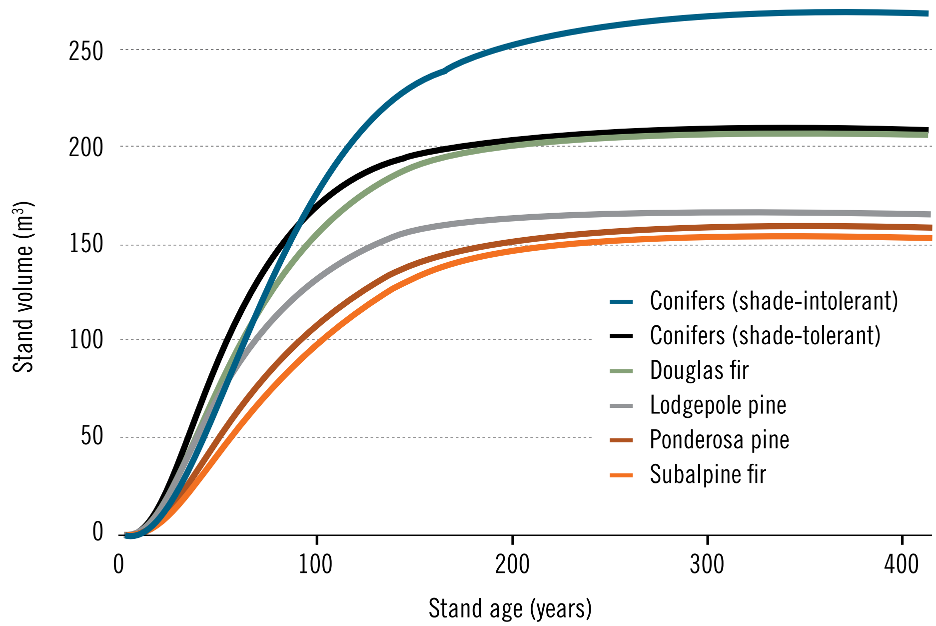
The approaches to estimating national GHG emissions and removals vary among the three countries of North America, because of differences in the available data, tools and other national circumstances. While all three countries follow methods defined by the Intergovernmental Panel on Climate Change (IPCC), this project seeks to harmonize the different scientific approaches. We demonstrate the use of IPCC Tier 3 methods that use empirical or process-based models to integrate data from a variety of sources, and apply these models to three selected regions: the Yucatan Peninsula (YP) in Mexico, the Nez Perce–Clearwater National Forest (NP) in Idaho, US, and the Prince George region (PG) of British Columbia, Canada (Figure 2). For the estimation of GHG emissions and removals, both modeling approaches clearly demonstrate the importance of "activity data," i.e., the information on area annually affected by natural and human disturbances, including harvesting and land-use change and in particular, deforestation, which is defined as the conversion of forest to non-forest land uses.

Figure 2 Selected regions for this study: The Yucatan Peninsula in Mexico, the Nez Perce–Clearwater National Forest in Idaho, US, and the Prince George region of British Columbia, Canada

Note: Yellow area corresponds to the entire Yucatan Peninsula, and green square represents the study area corresponding to the Landsat scene path/row 20/46.

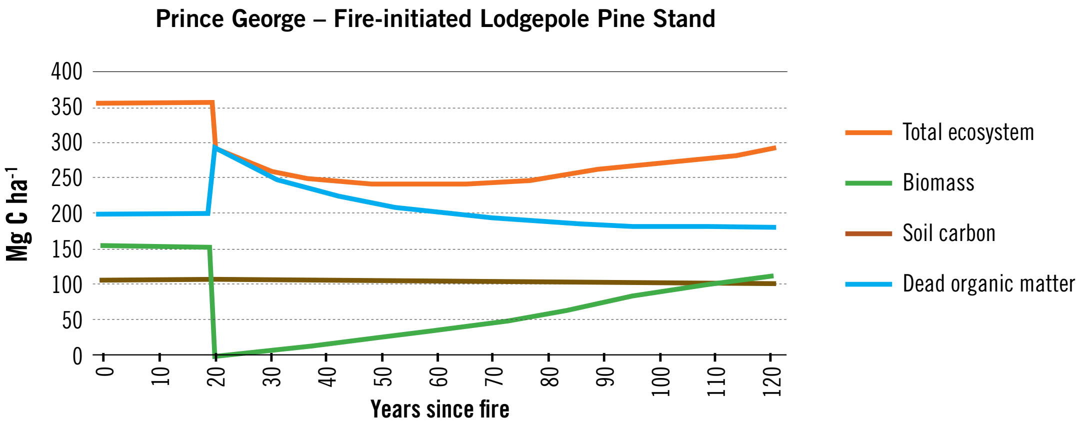
In this study, we predominantly used two forest carbon dynamics models to integrate data from many different sources for the estimation of GHG balances: the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) and the Forest DeNitrification-DeComposition model (DNDC). The CBM-CFS3 relies heavily on empirical measurements obtained from forest inventories (to describe the initial distribution of forest types and their ages) and growth and yield (to quantify growth rates of different forest types) (Figure 3). The CBM-CFS3 uses process-based modeling for the quantification of carbon dynamics in dead organic matter (litter and deadwood) and soil carbon pools (Kurz et al. 2009). The CBM-CFS3 can operate with spatially explicit (map-based) or spatially referenced (table-based) activity data. It is compliant with IPCC guidelines, reports on the five required carbon pools, and reports results that include the transitions among the land-use categories defined by the United Nations Framework Convention on Climate Change (UNFCCC). The model operates in annual time steps, and runs relatively fast, which enables the efficient analysis of multiple projected future scenarios and the exploration of mitigation options. Such scenarios can evaluate the impacts of changes in growth and decomposition rates, disturbance rates, forest management, and land-use change.

Figure 3 Growth curves used in CBM-CFS3 simulation of the Nez Perce–Clearwater National Forest



Note: CBM-CFS3 = Carbon Budget Model of the Canadian Forest Sector (Version 3).

Figure 4 Example of carbon dynamics for different carbon pools after wildfire.

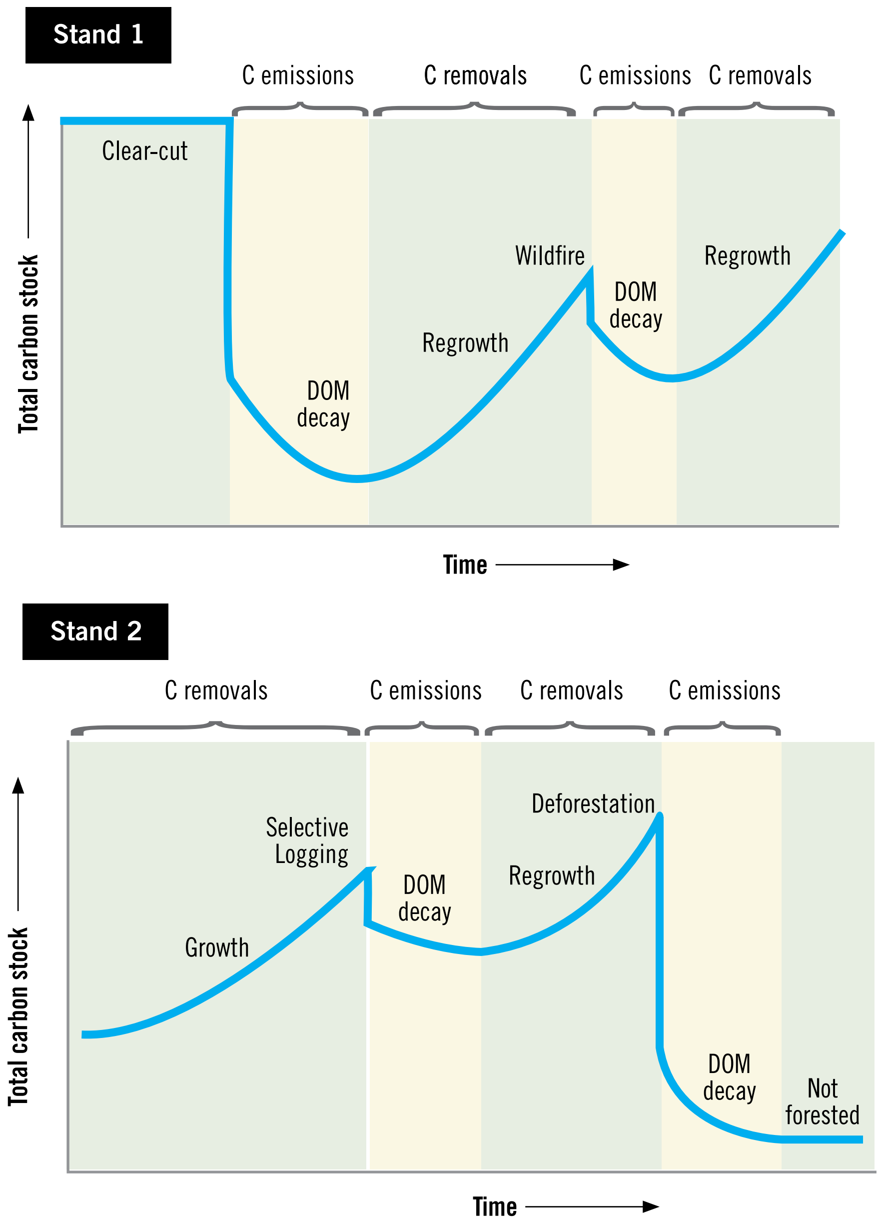


Note: MgC ha^{-1} = megagrams of carbon per hectare

Process models such as DNDC simulate forest growth, as well as the dynamics of dead organic matter and soil carbon, by using information on soil, plant, climate and environmental conditions (Li et al. 2000; Stange et al. 2000). DNDC requires a very large amount of input data about the ecosystem, the tree species, and soil information for five vertical layers, as well as daily climate information. It operates in daily time steps and therefore individual runs can take many days to weeks, depending on the size of the landscape and the time period of the analysis. While it is not practical to use such a model at high spatial resolution for large geographic regions, we demonstrate here that the primary strength of process-based models, once calibrated and validated, is their ability to generate estimates of biomass carbon stocks that are in close agreement with observed values and that can then be used to simulate how different kinds of disturbances have affected or may affect forest carbon stocks. Another use of process models driven by climate and environmental variables (such as atmospheric CO_2 concentration) is their ability to simulate ecosystem responses to future climate changes, which are illustrated in more detail in the technical report from this project (Kurz et al. 2016).

Analyses of GHG emissions in forest ecosystems require detailed information on the initial conditions of the landscape, including the extent, type and age (or time since the last stand-replacing disturbance) of forest ecosystems. Equally important are empirical estimates of how forests grow after disturbances, including detailed accounting of the changes in different carbon pools (Figure 4). Tracking the different carbon pools and transfers among them is a critical element for accurately estimating past and future forest carbon budgets. These values are highly variable among different geographic regions, forest types, and type and intensity of various disturbances (Figure 5). A particular challenge in the tropical forests of the YP is that the forests are uneven aged and are often degraded as a result of recent non-stand-replacing disturbances, which are harder to detect and quantify than stand-replacing disturbances. Generating maps of the initial distribution of forest ages was a challenge in this study because it was difficult to distinguish from forest inventory information whether a plot with low biomass was a young forest or a degraded older stand. Further work will be required to improve the information on the initial forest conditions in these complex forest types, including the initial distribution of biomass and the associated growth rates.

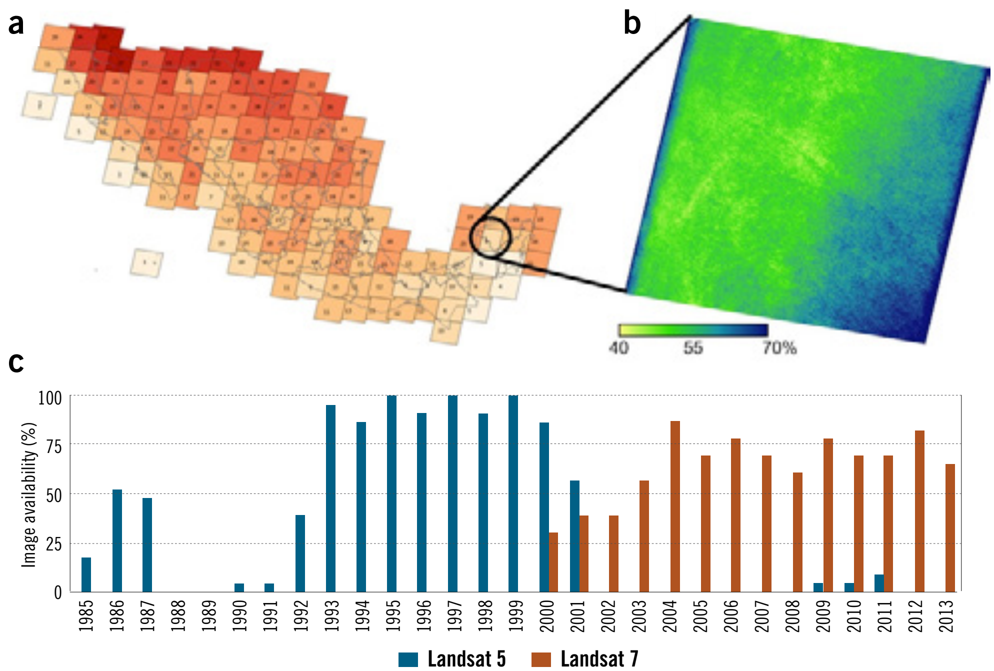
Figure 5 Simplified examples of two forest stands that experience different carbon dynamics due to different patterns of disturbance, growth, and dead organic matter (DOM)decomposition



Note: The resulting differences in GHG emissions and removals over time, due to the different patterns of disturbance, growth, and dead organic matter (DOM) decomposition, can be considerable. C = carbon.

Natural and human disturbances in forests are the key drivers of annual GHG emissions and removals in most forest ecosystems. Therefore, activity data that quantify the rate of natural and human disturbances are important information for the estimation of forest GHG budgets. Remote sensing products are increasingly becoming available that describe land cover at 250-meter, 30-meter or higher resolution, in annual time steps (Figure 6). Methods are being developed to calculate annual land-cover changes through these products (e.g., for Saskatchewan, Canada, see Hermosilla et al. 2015), from which activity data can be derived. Here we developed methods and a tool (Recliner) to use such remote sensing products of annual land-cover change as input to carbon budget models, and tested these in the three selected landscapes in Canada, Mexico, and the US.

Figure 6 Availability of images over Mexico in 2000, distribution of invalid data, and availablility of images from 1985 to 2013

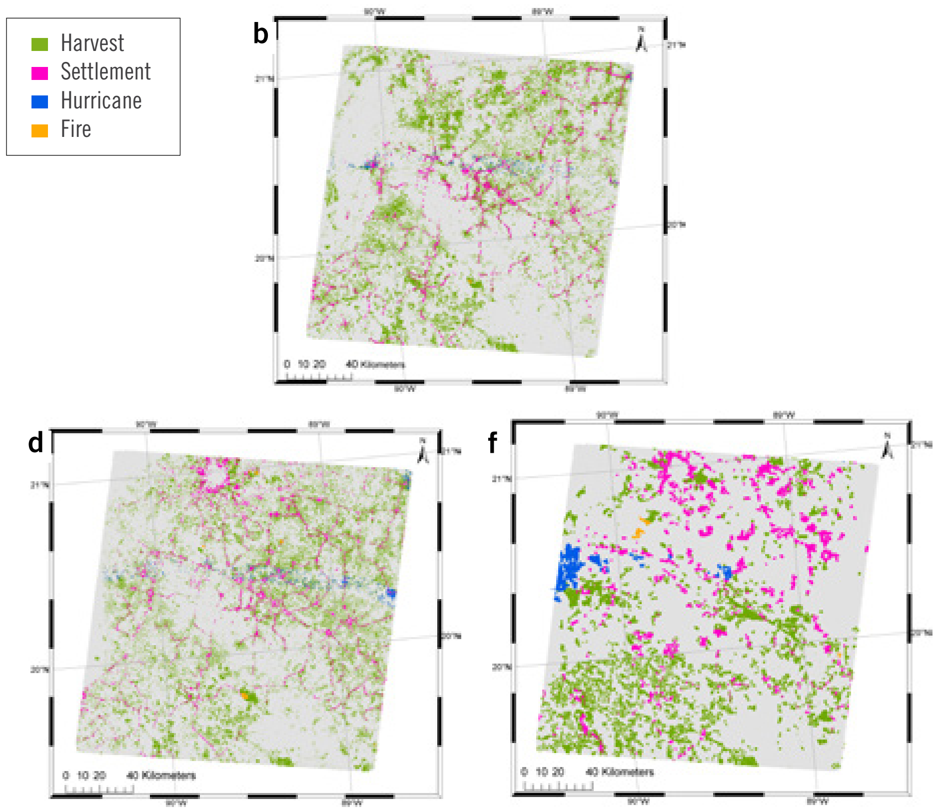


Note: a) Availability of Landsat TM/ETM+ image data over Mexico, with less than 10% cloud cover, for the year 2000.
b) Spatial distribution of invalid data according to FMASK, from available images in path-row 020-046 (black circle), in percent.
c) Availability of Landsat 5 TM and ETM+ images for path row 020-046 from 1985 to 2013.

We also used the CBM-CFS3 with input data for a single Landsat scene in the YP to evaluate the impacts on estimates of GHG emissions and removals of four different remote sensing and map-derived products of annual land-cover change, each with and without attribution of the changes to specific disturbance types (Figure 7). From the eight spatially explicit simulation runs with the CBM-CFS3, we concluded that uncertainties in GHG estimates can be reduced by:

(1) increasing the spatial resolution of remote sensing products from 250 to 30 meters, because at the higher resolution we can detect more small-patch disturbances common in the YP;
(2) increasing the temporal resolution of land-cover products to one year, because we can detect more disturbances that are followed by rapid regrowth; and
(3) attributing the land-cover change to the disturbance type, because this improves the estimation of the disturbance impact on GHG emissions, including, in the case of fire, non–carbon dioxide (CO_2) GHG emissions, such as methane (CH_4) and nitrous dioxide (N_2O), which have much higher global-warming potentials than CO_2.

Figure 7 Land-cover change maps derived from different remote sensing products

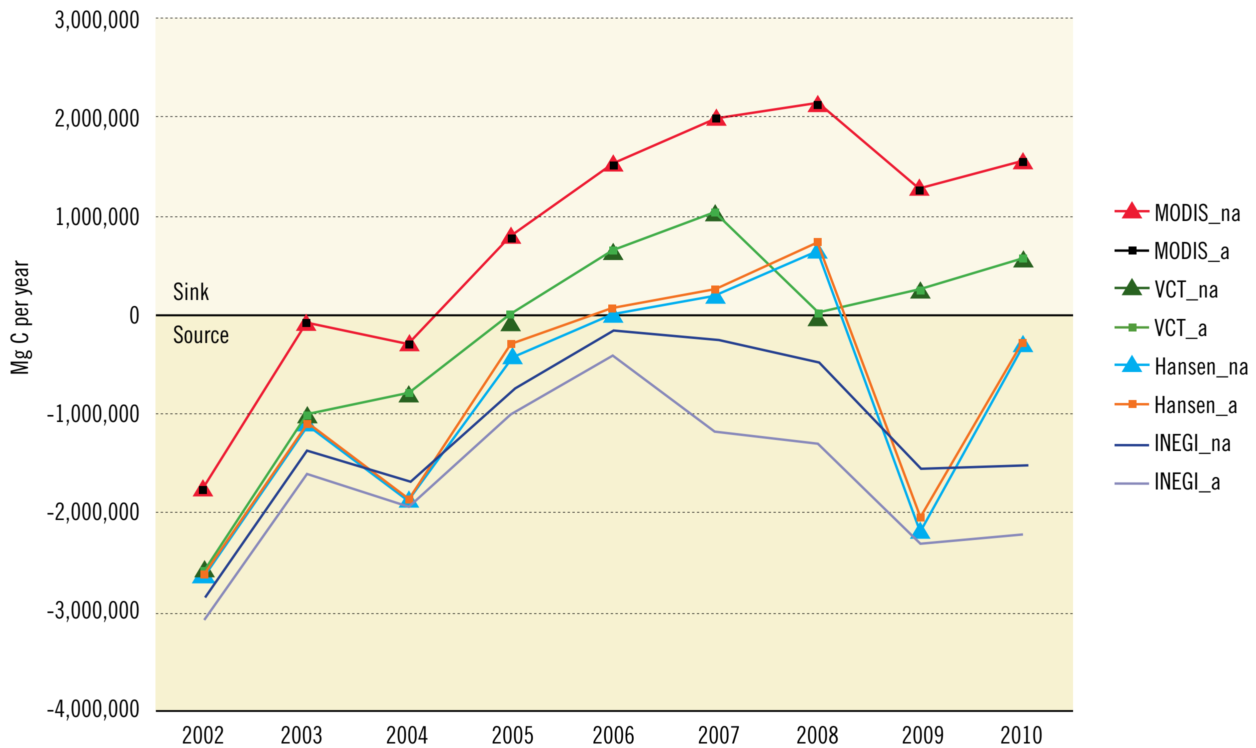


Note: These maps show attributed disturbances:. Vegetation Change Tracker algorithm (VCT) map: (b); Hansen map: (d); and *Instituto Nacional de Estadística y Geografía* (INEGI) map: (f).

Source: Mascorro et al. 2016

The large range of GHG emission estimates from the eight land-cover change products highlights that efforts to improve the accuracy of such products, including the identification of disturbance types, can yield substantial reductions in uncertainty of GHG estimates at the regional or national scale (Figure 8).

Figure 8 Annual carbon fluxes in the Yucatan Peninsula, 2002–2010, estimated with different sources of activity data



Note: MgC = megagrams of carbon; a = attributed; na = non-attributed; MODIS = Moderate Resolution Imaging Spectroradiometer (NASA, United States); VCT = Vegetation Change Tracker algorithm; and INEGI = *Instituto Nacional de Estadística y Geografía*

Source: Mascorro 2014.

The study also explored the choice of timing of the remote sensing scenes (dry season vs. peak growing season) and the choice of change-detection algorithms, on the accuracy of land-cover change products. We tested a change detection algorithm (Vegetation Change Tracker—VCT) (Huang et al. 2010) that is well established and successful in temperate forest ecosystems. Unfortunately, due to cloud cover and lack of suitable imagery for some years, it failed to detect some significant disturbances—particularly during the year 2009 of the simulation period, whereas the Hansen et al. algorithm (Hansen et al. 2013), which makes use of all available cloud-free pixels, was able to detect these disturbances. Results also showed that time series of land-cover changes derived from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) detected significantly fewer disturbances than the three other methods tested, all of which used higher-resolution Landsat imagery. Improved methods to remotely detect disturbances in persistently cloudy regions is a high-priority research issue for Mexico.

We examined the impacts on GHG estimates and trade-offs between the choice of spatially explicit and spatially referenced activity data. Spatially explicit approaches (IPCC Reporting Method 2, IPCC 2003, 2006) identify the location of every polygon (or pixel) in a landscape. In contrast, spatially referenced approaches (IPPC Reporting Method 1, ibid.) identify the geographic boundaries of land areas, such as management units, to which all data are referenced. Thus it can be known that a spatial unit contains X hectares (ha) of a particular forest type, but the exact location(s) of the forest type within the spatial unit is unknown. Spatially referenced input data, such as rates of firewood collection or other activities that are not readily mapped, require rule-based information in order to allocate these activities to the appropriate polygon or pixel.

Process-based models such as DNDC currently cannot use spatially referenced data, and the CBM-CFS3 is limited to using either spatially referenced or spatially explicit data sources—it cannot combine the two types of input data in one simulation. Spatially referenced approaches greatly reduce the volume of input data, and are more conducive for analyses of future scenarios as they do not require spatially explicit forecasts of the location of future disturbances or human activities such as deforestation.

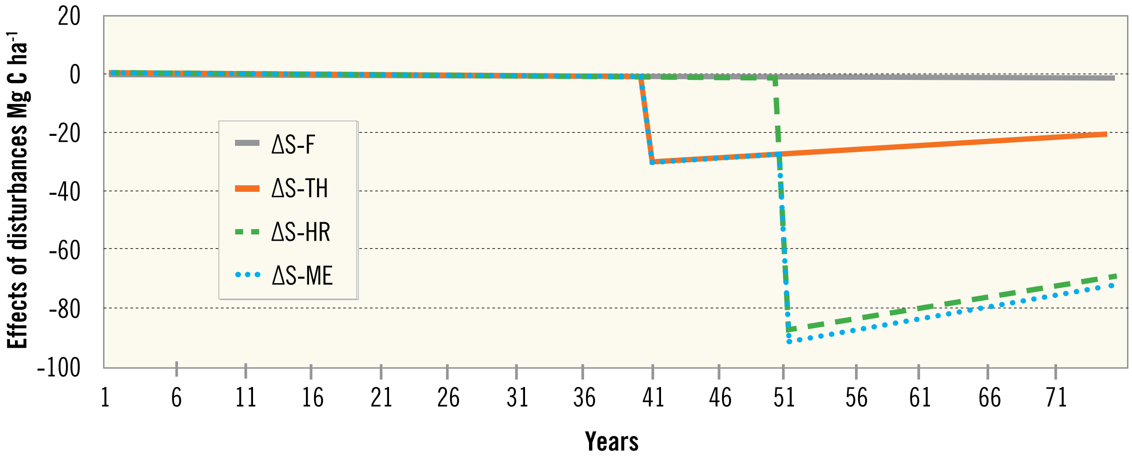
Natural Resources Canada, Canadian Forest Service

We evaluated the differences of GHG estimates derived from spatially referenced and spatially explicit simulations. We compared cumulative GHG emission estimates, obtained from a single spatially explicit simulation, with several sets of 400 spatially referenced simulations, for the NP forest in Idaho, US. The uncertainties in GHG estimates obtained from spatially referenced simulations decreased when there were increasing constraints on the eligibility of forest stands for selection, by each disturbance type. However, with increasingly stringent rules, the number of stands that were repeatedly disturbed increased. These repeat disturbances in the spatially referenced simulations introduced a bias in estimates compared to the spatially explicit simulations because emissions resulting from second and subsequent disturbances in the same stands are lower. Adding a rule to prevent repeat disturbances in the spatially referenced simulations reduced the bias, but changed the sign of the bias because in reality, a few repeat disturbances were observed in the spatially explicit simulations. Thus, rule sets that are used to implement spatially referenced data in simulations of GHG estimates need to consider both the eligibility of stands and the amount of repeat disturbances in the same stands. The study demonstrated that, with the appropriate rule sets, spatially referenced activity data can be used in the CBM-CFS to quantify past GHG emission and removal estimates and to simulate scenarios of future forest management and land-use change scenarios.

We used the process model DNDC to estimate the impact of different kinds of disturbances on carbon stocks of different pools. After calibrating and validating DNDC using independent data from field observations, we simulated the effects of fire, hurricane, harvest, and combinations of these disturbances (Figure 9). At each site, these disturbances showed significant losses of stored carbon immediately following the event, after which stocks began to recover quickly. In the YP, the simulated category 4 (severe) hurricane caused a significant loss of about 86% of the live biomass, 70% of which was assumed to be salvaged and the remainder added to woody debris and soil carbon pools. Biomass added to dead organic matter pools decomposed quickly in the tropical climate of the YP. Disturbances in temperate and boreal forests also have profound effects that last for decades. For the NP, harvests during 1991–2011 removed about 763.5 Gg C from the aboveground biomass; however, other disturbances caused a larger loss of live trees than harvest in the same period—about 4131 Gg C of live, aboveground biomass were lost to fires and insects, and most of the live biomass was transferred to deadwood pools. These disturbances also left a large amount of dead roots in the soils of the forest, which produced a subsequent increase in soil CO_2 flux due to decomposition (heterotrophic respiration). Fires caused significant loss of litter carbon, over 10 Mg C ha^{-1} at the locations where canopy fires occurred.

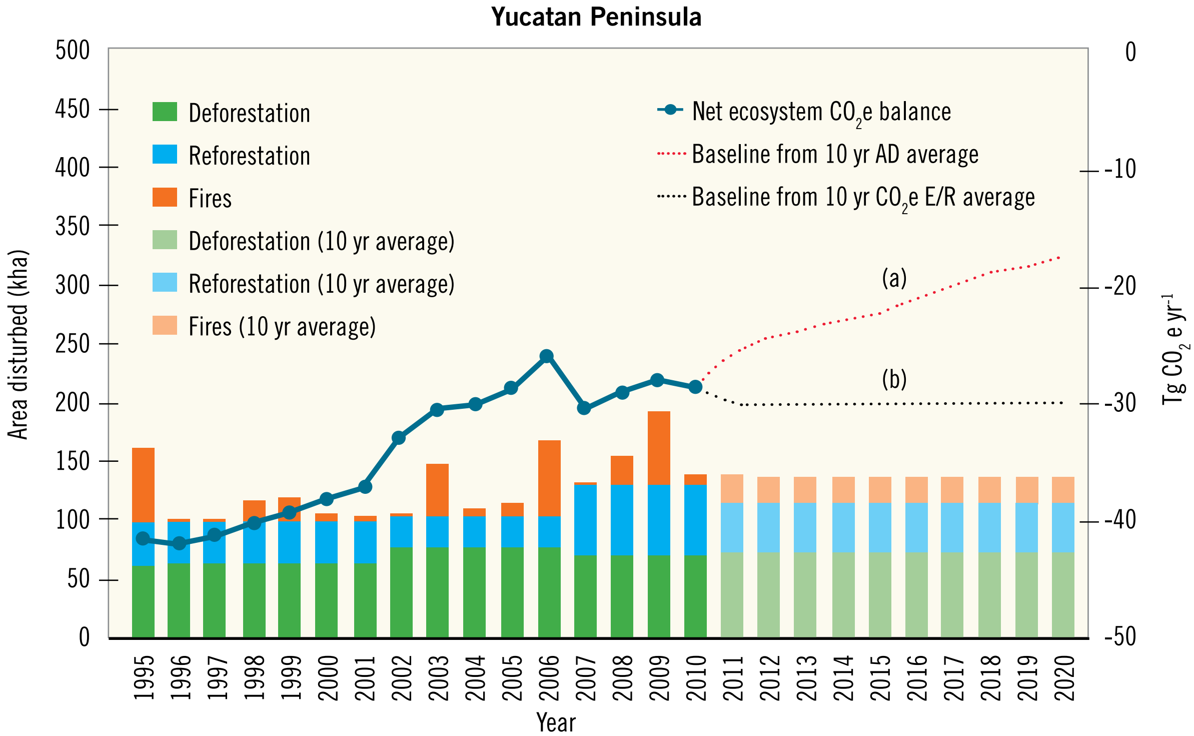
We also used DNDC to simulate the expected effects of selected climate changes and increases in atmospheric CO_2 concentrations, which may affect future forest productivity and significantly affect projected changes in carbon stocks. In the YP we found significant relationships between biomass stocks and both temperature and precipitation. Based on climate variability in the last 33 years (1981–2013), DNDC projected that carbon storage in moist forests could increase with an increase in temperature in the YP. However, biomass carbon storage in dry forest could decrease with an increase in temperature. Biomass carbon could increase by a large amount with an increase in precipitation in moist forests, and by a much smaller amount in dry forests. In the NP forest, DNDC suggested that biomass increases with increasing temperature, and decreases with increasing precipitation, although these relationships were inconsistent for different forest types.

Figure 9 Impacts of a low-intensity ground fire, thinning, hurricane, and multiple disturbances plus warming, on biomass carbon stocks in the semi-dry forest in the Yucatan Peninsula relative to the base scenario



Note: Mg C ha^{-1} = megagrams carbon per hectare; Δ = difference in carbon stock between base scenario and scenario; S-F = fire scenario; S-TH = thinning scenario; S-HR = hurricane scenario; S-ME = scenario of multiple disturbances (effects) plus warming. Note that the ground fire in year 30 of the S-F scenario had only a negligible effect on ecosystem carbon stocks.

Figure 10 Annualized area of the Yucatan Peninsula affected, by forest land-use change and by annual fire events, 1995–2010, and estimated net CO_2e emissions



Note: CO_2e = carbon dioxide–equivalent; kha = thousand hectares; Tg = teragrams. Negative flux denotes removal from the atmosphere, i.e., a sink. Historic information: (a) 10-year activity data (AD) average, and (b) 10-year average of greenhouse gas (GHG) emissions versus removals (E/R).

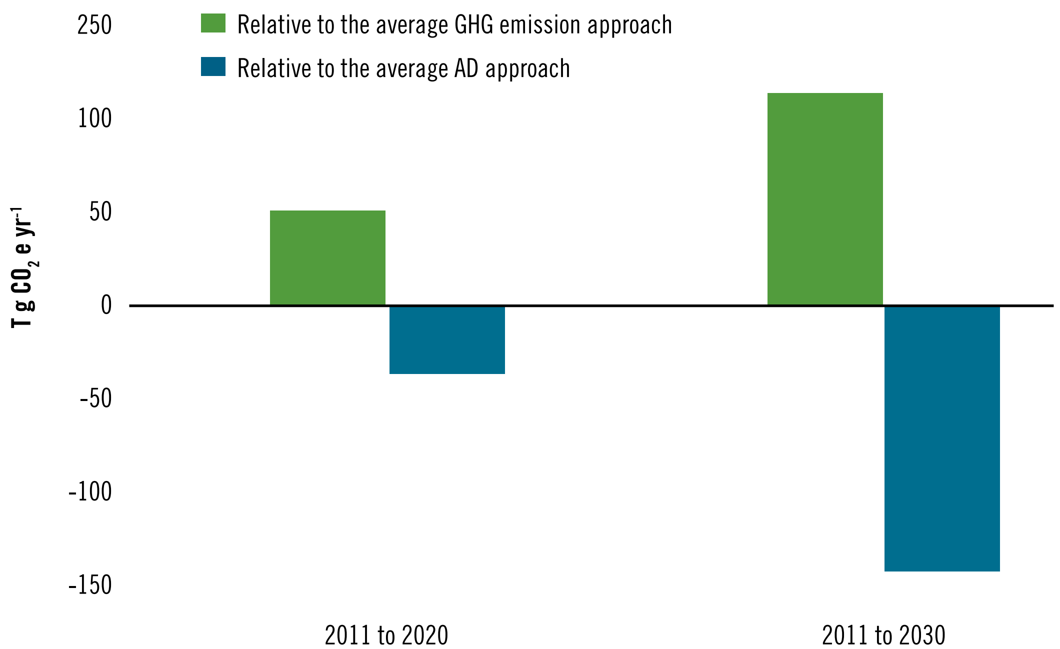
Source: Adapted from Olguín et al. 2015.

Using the CBM-CFS3 in a spatially referenced approach, we conducted analyses of the historic and projected future carbon balance for the entire Yucatan Peninsula, stratified into six spatial units. We used the spatial framework that was developed for national-scale analyses in Mexico (94 spatial units) and simulated six spatial units in the YP which result from the intersection of the boundaries of three states and two ecoregions (Level 1, CEC 1997). We developed estimates of annual activity data from land-use change matrices that were derived by comparing land-cover maps for the periods 1993–2002, 2002–2007 and 2007–2011. We estimated the contribution of disturbances (fires) and land-use change to the GHG balance of the entire YP and the results showed a small annual carbon sink that diminished over time as the total forest area decreased due to net deforestation, the growth rate of the remaining forests decreased with age, and the emissions per hectare deforested increased with increasing forest age (Figure 10). We also documented the contribution of the three main land-use categories to the overall GHG balance of the peninsula. We estimated the average GHG fluxes from 2001 to 2010 to be: Forest Land remaining Forest Land (a big sink; -52 Tg CO_2e yr^{-1}), Forest Land converted to Other Land (a medium source; 27 Tg CO_2e yr^{-1}), and Other Land converted to Forest Land (a small sink; -8 Tg CO_2e yr^{-1}). However, it is likely that the overall GHG balance of the peninsula will approach zero as additional more-complex and finer-scale disturbances (i.e., degradation) are included in the analysis (Olguín et al. 2015).

Future mitigation efforts, including the reduction of emissions from REDD+ (Reducing Emissions from Deforestation and Forest Degradation [and Sustainable Forest Management]) activities, are evaluated against a reference level or baseline. We evaluated two possible methods to define such a baseline: the average emissions over the past decade, or the emissions resulting from average activities over the past decade. We demonstrated that the results differ greatly. In the first approach, the annual sink is assumed to remain the same, while in reality (as represented by the second approach) the sink decreases as the cumulative impacts of deforestation reduce the forest area and thus reduce the capacity of the overall area to absorb atmospheric CO_2.

We also demonstrated the use of the CBM-CFS3 for the estimation of changes in emission resulting from changes in future deforestation rates in the YP. The annual gross deforestation rate is estimated to be about 0.6% yr^{-1} from 2001 to 2010 and we simulated a second scenario in which that rate was reduced by 2.5% yr^{-1}. We estimated that, relative to the REDD+ baseline defined by average activity data, net GHG emissions from deforestation can be reduced by 16% by 2020 if the gross deforestation rate is reduced by 25% in 2020, or these emissions can be reduced by 41% in 2030 if deforestation can be cut by half in 2030 (Figure 11). It is important to note that selecting the REDD+ baseline defined by past average emissions would result in an accounted increase in emissions (relative to the baseline) even when the deforestation rates are reduced.

Figure 11 Example of cumulative reduction in GHG emissions by decreasing annual deforestation rates by 2.5% (of the original rate) per year relative to the two baseline scenarios: from 2011 to 2020 and from 2011 to 2030



Note: GHG = greenhouse gas; AD = activity data; Tg CO_2e yr^{-1} = teragrams carbon dioxide–equivalent per year. Relative to a baseline derived using the average GHG emission approach, accounted emissions would increase despite the reduction of deforestation rates.

US Forest Service

We compared selected results from the different modeling approaches with each other and with available data sets, to improve understanding of the ecosystem responses to perturbations and to highlight some uncertainties about how forests will respond in the future, as a result of anthropogenic or natural factors. In practice, empirical models are well suited to representing carbon stock changes of the different carbon pools due to impacts from management activities, fires, insects, and land-use change; to quantifying the uncertainty of directly measured carbon pools; and to validating the independent estimates from process models. Process models are more useful for simulating forest ecosystem response to changes in climate or the concentration of atmospheric CO_2, and may be used to make estimates or projections outside the spatial and temporal boundaries of the data used for parameterization. It is important to validate models with independent data sets before attempting to use them outside the range of parameterization data.

Comparing results of the two models revealed that a high level of analytical skills may be required to use empirical and process models, since both classes of model usually require significant efforts for acquiring and managing the input data—which may not be readily available, representative of the region or forest type of interest, or properly prepared for the model. As a general rule, empirical models are easier to understand whereas process models usually involve detailed representation of mechanisms and their responses to environmental drivers, which should be well understood by the modeler. Model comparisons are exceedingly difficult to perform. Different models have different data requirements, may or may not be spatially explicit, may include representation of different environmental drivers, and may use different definitions of variables. Estimates of key variables, such as net primary production (NPP), net ecosystem production (NEP) and net biome production (NBP), are significantly different among modeling approaches, and the causes of these differences are hard to interpret. Sorting out these differences is labor-intensive and was beyond the scope of this project.

We concluded that Tier 3 models are powerful and flexible tools for the integration of data from multiple sources. They can generate the data required for regional and national estimates of GHG emissions and removals in the forest sector: the CBM-CFS3 has been used since 2006 to generate the input data for Canada's national GHG inventory report (Stinson et al. 2011; Environment Canada 2015) and it has been used to estimate reference emission levels for Mexico's submission to the Emission Reductions Program Idea Note, of the Forest Carbon Partnership Facility (FCPF 2013). We also demonstrated some of the abilities of process models to enhance the analysis of, validate results of, and estimate ecosystem responses to climate change.

US Forest Service

The results of this study contribute to the desired outcome of improved design and assessment of climate change mitigation activities aimed at sustainable forest management and REDD+ activities in the forest and land-cover change sector in North America. This study revealed some issues and opportunities in data availability and modeling applications that could improve results, and these lessons learned will help guide additional work to improve forest greenhouse gas assessment at different scales. Future CEC-funded work will focus on the use of these tools for the analysis of climate change mitigation options in the forest sector in representative landscapes of North America. Analyses of mitigation options will require that additional analytical capabilities and supporting data are developed, because such analyses require an assessment of changes in forest carbon stocks, changes in harvested wood product carbon stocks, and the changes in emissions in other sectors resulting from the substitution of emissions-intensive products such as concrete, steel and plastics with harvested wood products (Lemprière et al. 2013), as demonstrated for national-scale analyses in Canada (Smyth et al. 2014). Work will also continue on the development and testing of approaches to improving remote sensing products of land-cover change and the integration of such products with models of GHG emissions and removals.

Acknowledgements

The success of this project is the result of the cooperation of many experts in key institutions in Canada, Mexico and the United States. We thank the Commission for Environmental Cooperation (CEC) for project funding and for its assistance in administration, coordination and organization of the work: Karen Richardson, Itzia Sandoval, and Sarah Heiberg provided great support.

We thank the three North American Forest Services (*Comisión Nacional Forestal* (Conafor), Canadian Forest Service, and US Forest Service) for in-kind support of the project and we thank remote sensing and other governmental agencies, including *Comisión Nacional para el Conocimiento y Uso de la Biodiversidad* (Conabio), Canada Centre for Mapping and Earth Observation, United States Geological Survey and the US National Aeronautics and Space Administration). Many other programs and institutions contributed to this work. From Mexico we acknowledge the collaboration and support from Conafor's project Reinforcing REDD+ and South-South Cooperation, and the *Colegio de Postgraduados*. From the United States, we greatly appreciate the substantial contribution of funds from the Agency for International Development, the US Forest Service International Program Office, and the SilvaCarbon program, all of which supported participation by scientists and technicians from agencies and institutions in the US and Mexico.

We also acknowledge the contributions of the following individuals:

Graham Stinson, Sally Tinis, Dennis Paradine and Don Leckie (Canadian Forest Service) developed the land-cover change datasets that supported the modeling of the Prince George region in Canada. Alexa Dugan (US Forest Service) provided datasets, information about US forests, and process model results for the US forest used in the case study. Craig Wayson (US Forest Service) provided support in the development of activity data and estimating the impacts of activities on forest carbon. Shannon Franks and Jeff Masek (NASA) contributed the data on forest disturbances for Mexico. Gregorio Ángeles-Pérez (*Colegio de Postgraduados*) helped to estimate the impacts of different activities on forest carbon.

Natural Resources Canada   Ressources naturelles Canada

References

Birdsey, R., G. Ángeles Pérez, W.A. Kurz, A. Lister, M. Olguin, Y. Pan, C. Wayson, B. Wilson, and K. Johnson. 2013. Approaches to monitoring changes in carbon stocks for REDD+. *Carbon Management* 4(5): 519–537. doi: 10.4155/cmt.13.49

Environment Canada. 2015. National Inventory Report 1990-2013. Greenhouse gas sources and sinks in Canada. *The Canadian Government's Submission to the UN Framework Convention on Climate Change*, 199.

FCPF. 2013. Emission Reductions Program Idea Note (ER-PIN). Forest Carbon Partnership Facility (FCPF) Carbon Fund.

Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W. von Bloh, V. Brovkin, P. Cadule, et al. 2006. Climate–carbon cycle feedback analysis: Results from the C 4 MIP model intercomparison. *Journal of Climate* 19(14): 3337–53. doi:10.1175/JCLI3800.1.

Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342(6160): 850–53. New York, N.Y.) doi:10.1126/science.1244693.

Hermosilla T., M.A. Wulder, J.C. White, N.C. Coops, G.W. Hobart. 2015 An integrated Landsat time series protocol for change detection and generation of annual gap-free surface reflectance composites. *Remote Sensing of Environment* 158: 220–234. http://dx.doi.org/10.1016/j.rse.2014.11.005.

Huang, C., S.N. Goward, J.G. Masek, N. Thomas, Z. Zhu, and J.E. Vogelmann. 2010. An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sensing of Environment* 114(1): 183–98. Elsevier Inc.. doi:10.1016/j.rse.2009.08.017.

IPCC. 2014a. 2013 *Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol*. Edited by T.G. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler. Switzerland: Intergovernmental Panel on Climate Change (IPCC).

Kurz, W.A., C.C. Dymond, T.M. White, G. Stinson, C.H. Shaw, G.J. Rampley, C. Smyth, et al. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* 220(4): 480–504. doi:10.1016/j.ecolmodel.2008.10.018.

Kurz, W.A., R.A. Birdsey, V.S. Mascorro, D. Greenberg, Z. Dai, M. Olguín, and R. Colditz.2016. Integrated modeling and assessment of North American forest carbon dynamics: Tools for monitoring, reporting and projecting forest greenhouse gas emissions and removals. Montreal: Commission for Environmental Cooperation, Montreal.

Le Quéré, C., R. Moriarty, R.M. Andrew, G.P. Peters, P. Ciais, P. Friedlingstein, S.D. Jones, et al. 2015. Global Carbon Budget 2014. *Earth System Science Data* 7(1): 47–85. Copernicus GmbH. doi:10.5194/essd-7-47-2015.

Lemprière, T.C., W.A. Kurz, E.H. Hogg, C. Schmoll, G.J. Rampley, D. Yemshanov, D.W. Mckenney, et al. 2013. Canadian boreal forests and climate change mitigation 1. *Environmental Reviews* 21(4): 293–321. doi:10.1139/er-2013-0039.

Li, C., J. Aber, F. Stange, K. Butterbach-Bahl, and H. Papen. 2000. A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development. *Journal of Geophysical Research: Atmospheres* 105(D4): 4369–84. doi:10.1029/1999JD900949.

Mascorro, V.S. 2014. *Assessing Forest Disturbances for Carbon Modelling: Building the Bridge between Activity Data and Carbon Budget Modelling*, M.Sc. Thesis, Faculty of Forestry, University of British Columbia, Vancouver, Canada. 106 pp. doi: 10.14288/1.0165575

Mascorro, V.S., N.C. Coops, W.A. Kurz, and M. Olguin. 2015. Choice of satellite imagery and attribution of changes to disturbance type strongly affects forest carbon balance estimates. *Carbon Balance and Management* 10:30 doi: 10.1186/s13021-015-0041-6.

Mascorro, V.S., N.C. Coops, W.A. Kurz, and M. Olguín. 2014. Attributing changes in land cover using independent disturbance datasets: A case study of the Yucatan Peninsula, Mexico. *Regional Environmental Change*. Canadian Forest Service Publications. doi:10.1007/s10113-014-0739-0.

Olguín, M., C. Wayson, W. Kurz., M. Fellows, V. Maldonado, D. López, G. Ángeles, O. Carrillo, and V.S. Mascorro. 2015. Adaptation of the CBM-CFS3 modeling framework to Mexico: Towards a Tier 3 reporting in strategic landscapes for REDD+. Mexico City, Mexico: Mexico-Norway Project of the National Forestry Commission of Mexico.

Pan, Y, R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, et al. 2011. A large and persistent carbon sink in the world's forests. *Science* 333(6045): 988–93. New York, N.Y. doi:10.1126/science.1201609.

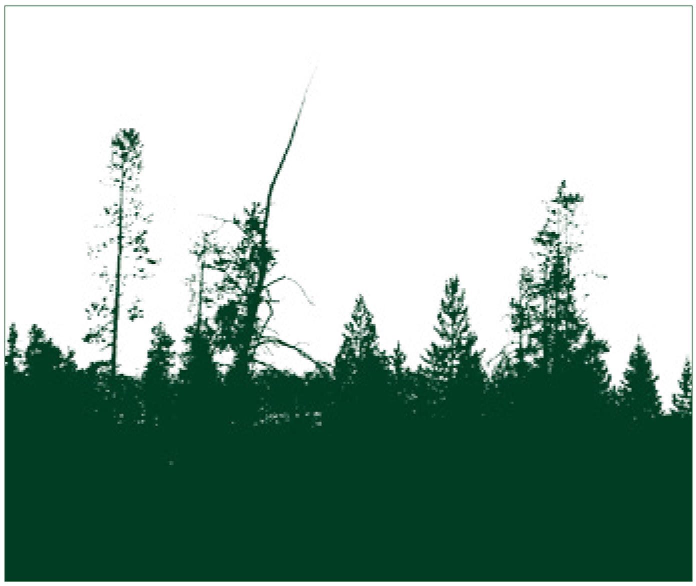
Smyth, C.E., G. Stinson, E. Neilson, T.C. Lemprière, M. Hafer, G.J. Rampley, and W.A. Kurz. 2014. Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences* 11(13): 3515–29. Copernicus GmbH. doi:10.5194/bg-11-3515-2014.

Stange, F., K. Butterbach-Bahl, H. Papen, S. Zechmeister-Boltenstern, C.S. Li, and J. Aber. 2000. A process-oriented model of N_2O and NO emissions from forest soils: 2. Sensitivity analysis and validation. *Journal of Geophysical Research: Atmospheres* 105(D4): 4385–98. doi:10.1029/1999JD900948.

Stinson, G., W. A. Kurz, C. E. Smyth, E. T. Neilson, C. C. Dymond, J. M. Metsaranta, C. Boisvenue, et al. 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology* 17(6): 2227–44. doi:10.1111/j.1365-2486.2010.02369.x.

Wieder, W.R., C.C. Cleveland, W.K. Smith, and K. Todd-Brown. 2015. Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience* April: 1–5. doi:10.1038/ngeo2413. doi:10.1029/2011JG001930.

Zhu, Z., and C.E. Woodcock. 2012. Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment* 118: 83–94. doi:10.1016/j.rse.2011.10.028.



Commission for Environmental Cooperation
393, rue St-Jacques Ouest, bureau 200
Montreal (Quebec)
H2Y 1N9 Canada
t 514.350.4300 f 514.350.4314
info@cec.org / www.cec.org

Natural Resources Canada
Ressources naturelles Canada