Final Project Report

Climate Change Modelling and Monitoring Research Program

**Assessing Climate Change Impact on Carbon Cycles in the Ontario’s Far North Ecosystems**

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1. Introduction

The 2013 Inter-governmental Panel for Climate Change (IPCC) 5th Assessment Report (AR5) (Stocker et al. 2013) asserts that warming of the climate is unequivocal and the degree of warming is strongly correlated with the accumulated anthropogenic greenhouse gas emission since 1850. Under several representative concentration pathways (RCP), general circulation models (GCM) used by the AR5 project that the global temperature will rise in a range from 2 to 6 °C by the end of this century, and higher latitudes are expected to warm much more than the global average. Annual mean temperatures across the Canadian boreal zone could be 4–5 °C warmer than today’s by 2100 (Price et al., 2013). In Ontario, the average air temperature could rise by as much as 3 to 8 °C over the next century. Ontario’s Far North (OFN) is expected to experience the largest warming rate in Ontario.

Global warming has already made dramatic impacts on terrestrial ecosystems, and these impacts will likely accelerate in the near future. At high latitudes, air warming will induce permafrost thawing and unlock the large amount of previously frozen peat for oxidation. The rapid warming at high latitudes projected in the near future, therefore, could have dramatic consequences in the greenhouse gas balance in OFN and has the potential to greatly alter the Ontario greenhouse gas budgets over the Far North. OFN, consisting of the world’s third largest area of wetland, one of the largest remaining tracts of unmanaged natural boreal forest and the most southerly area of tundra (The Far North Science Advisory Panel, 2010) is sensitive to climate change. The OFN contains the largest single extant block of unmanaged pristine forests that are in part situated on the northern edge of the Boreal Shield extending into the Hudson’s Plain ecozone, yet very little is known about its C stock and balance or how it may respond to climate change. It is therefore highly desirable to estimate the current status of OFN ecosystems in terms its carbon (C) cycling and to project its changes in the future under the changing climate.

The provincial Far North Act, 2010 described the assessments of ecological processes and functions, including the storage and sequestration of C to be included in Far North Land Use Strategy. Thus far, previous OFN studies included plot-level assessment of historic and present peatland C cycle, depth, and age; inventory based non-forested permafrost peatland C storage and sequestration at Hudson Bay Lowland (HBL); the impact of projected climate change on Clay Belt forested peatland edaphic paludification in northeastern Ontario; and past, present and future C balance of forested OFN (e.g., Preston et al., 2012; Lafleur et al., 2013; McLaughlin and Webster, 2013; Gonsamo et al., 2015). However, Federal, Provincial, and Territorial Governments of Canada, 2010, reported that there is both knowledge and data gap which hinders the existing findings to be incorporated into the Far North Land Use Strategy. The previous studies show clear scientific evidence that the OFN ecosystems will be subjected to a magnitude and rate of climate change that exceeds historic levels. However, without the consideration of past, present and future C cycle of the entire OFN, including the treed wetlands and forests, the previous results cannot be used to develop landscape planning strategies which may aid in the preservation of northern ecosystems, and develop climate change mitigation and adaptation strategies for reduction of greenhouse gas emission.

The primary goal of this project is to assess the current status of the carbon budgets in recent years and C source and sink distributions over the OFN forested ecosystems including treed wetland and tundra. To achieve this goal, we developed three phase work packages: (1) calibrate an existing ecosystem model against carbon flux measurements in the last two years at two towers located in HBL, i.e. the Kinoje Lake site (51.62 N, 81.77 W) and the Attawapiskat
River site (52.71 N, 83.95 W) funded by the Province and apply the model to all OFN treed ecosystems based on remote sensing data in recent years; (2) further validate this model for simulating the lateral water redistribution over the landscape around these two towers, and combine high-resolution (30 m) remote sensing data in recent years with historical climate data for long-term C cycle modeling since 1900, and (3) develop an upscaling methodology with the additional consideration of the spatial variability in hydrological regimes for long-term C cycle modeling for OFN at 250 m resolution, and project the C cycle to year 2100 under future climate scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5). This report presents the results of phase (1) work package including annual C source and sink maps using validated ecosystem process model at the two flux tower sites over the period from 2010 to 2013 for Ontario’s Far North treed ecosystems including treed wetlands and tundra.

2. Materials and Methods

2.1 Data

All spatial datasets in this project are in raster format at 250 m spatial resolution covering 2010-2013. The land cover data for entire far north Ontario was compiled from 99 arcinfo coverage files obtained from Ontario Land Cover - National-Scale (1:250,000) Version - NTS 040G (http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/2f097461-8c46-537a-84a6-7a8e654f4467.html) data prepared for Natural Resources Management Information Branch of Ontario Ministry of Natural Resources by SPECTRANALYSIS Inc., Remote Sensing and GIS Services, Oakville, Ontario. The land cover contains 14 classes including treed wetland, marshes and open wetlands separately from other classes. The land cover data indicates that, 115625 km² (25%) of OFN is consisted of marshes and open wetlands, 124356 km² (27%) treed wetland, and 175797 km² (39%) forest (Figure 1).

![Land Cover map](image)

**Figure 1. Land cover map for Ontario’s Far North.**
Soil texture data were generated from the Soil Landscapes of Canada (SLC) Version 3.2 (http://sis.agr.gc.ca/cansis/nsdb/slc/index.html). The entire area of far north Ontario was found to be only two parental mineral texture classes based on a United States Department of Agriculture (USDA) soil texture triangle namely: loamy sand (class 2) and clay (class 11). A third soil texture class namely, organic, was added to all non-mineral soils predominantly classified as “organic” according to Soil Order Map of Canada. The original vector data were rasterized into 250 m spatial resolution. Soil drainage data were also generated from the Soil Landscapes of Canada (SLC) Version 2.2 (Figure 2).

Leaf area index (LAI) surface data for 2010-2013, every 10 days, at 250 m spatial resolution, was prepared using the Version 2 University of Toronto (UofT) LAI algorithm (Gonsamo et al. 2014) including enhanced spatial resolution (250 m) by considering an improved land cover map, local topography, clumping index, and background reflectance variations. The mean annual LAI for the 4 years is given below in Figure 3.
Figure 3. Leaf area index time series for Ontario’s Far North landmass for 2010-2013 at 250 m spatial resolution. Grey is non-vegetated areas shown in Figure 1 as class water, marshes, open wetlands, and others.
For entire far north Ontario study site, we use the 6-hourly reanalysis data obtained from National Centers for Environmental Prediction (NCEP) and interpolated temporally to produce hourly values. Different interpolation methodologies were used for the different variables. Specific humidity and wind speed were assumed to remain constant within each 6 h NCEP interval. Total precipitation was equally distributed across the 6 h interval. Incoming shortwave radiation was calculated for each hour as a function of the solar zenith angle and the 6 h total incoming shortwave radiation from NCEP. Hourly air temperature was determined from the 6 h data and daily maximum/minimum values also available in the NCEP data. The hourly NCEP data were then interpolated bilinearly to a 250 m grid for far north Ontario BEPS simulations.

The current sizes of various ecosystem C-pools (9 in total) to run the biogeochemical processes that indirectly affect hydro-ecological processes were produced for entire OFN (Figure 4). Ecosystem C-pools were initialized using a long-term model, called Integrated Terrestrial Ecosystem C-budget model (InTEC) (Chen et al., 2002), considering the historical variation in climate, variations in atmospheric CO₂ concentration, disturbance effects and temporal trends in N-deposition from 1900 to present.

![Figure 4. Nine soil carbon pools (grams/m²) for Ontario’s Far North landmass.](image)

### 2.2 Ground-based land-atmosphere carbon exchange measurements

To calibrate and validate an existing ecosystem model, we use C flux measurements for 2011-2012 at two micrometeorological towers located in the Hudson Bay Lowland (HBL), i.e. the low shrub bog at the north end of Kinoje Lake (Kinoje Lake site: 51.62 N, 81.77 W) and the bog-fen complex in the Attawapiskat River region of the HBL (Attawapiskat River site: 52.71 N, 83.95 W) funded by Ontario Ministry of Environment and Climate Change (MOECC towers
The Kinoje Lake site is dominated by low shrub bogs characterized by *Sphagnum* moss, some sedges, low ericaceous shrubs, scattered *P. mariana*, and isolated stunted *P. mariana* trees on some hummocks. *Sphagnum* accounts for 50–60% of the surface cover, while lichens and sedges account for the remaining cover (20–30% and 10–25%, respectively) (Humphreys et al. 2014). Peat depth ranged from 1.4 to 2.7 m. The Attawapiskat River tower site is situated in a treed/low shrub bog. *Sphagnum* mosses including *S. fuscum*, (Schimp.) H.Klinggr., *S. rubellum* Wils., and *S. magellanicum* Brid. cover about 50% of the surface in well-drained areas, while lichens account for the remaining 50% (the *Cladonia* group of lichens). The under-story is dominated by *Chamaedaphne calyculata* (L.) Moench while lichens are virtually absent in low areas. In hummock areas of the bog, stunted black spruce [*Picea mariana*, (Miller) BSP], and to a lesser extent tamarack [*Larix laricina* (Du Roi) K. Koch] are found (Figure 5). Peat thickness is just over 2 m near the center of the flux footprint area (Humphreys et al. 2014).

**Kinoje Lake site**

- Shrub bog, LAI = 0.35
- Tree density (<1 cm dbh) (stems/ha) = 0
- Small tree density (>50 cm height (stems/ha) = 929
- Total above ground understory biomass (g m⁻²) = 104.2
- Sphagnum covers 50–60%, lichens and sedges the remaining
- Stunted black spruce and ericaceous shrubs
- Peat depth from 1.4 to 2.7 m

**Attawapiskat River site**

- Treed bog, LAI = 0.45
- Tree density (<1 cm dbh) (stems/ha) = 446
- Small tree density (>50 cm height (stems/ha) = 1419
- Total above ground understory biomass (g m⁻²) = 84
- Sphagnum covers 50% while lichens account for the remaining
- Stunted black spruce and tamarack
- Peat depth > 2 m

Figure 5. Summer images (top), map location (middle), and site characteristics (bottom). See details in Humphreys et al. 2014.

The eddy covariance method is used to measure nearly continuous fluxes of CO₂ and energy exchange at both sites using 30 min covariance of vertical velocity and the appropriate
scalar entity is used to compute a flux. All measurements were made at a rate of 10 Hz. At Kinoje Lake site, the eddy covariance instruments were mounted on a stainless steel tripod 3 m above the surface, 75 cm from the tower mast, and oriented to the southeast (Humphreys et al. 2014). The fetch from the tower is restricted to ~200 to 300 m between the south and southeast and to the west by trees along riparian areas but otherwise extends ~500 m. At Attawapiskat River tower site, a 5 m scaffold structure supported a mast on which the eddy covariance instruments were mounted 7.5 m above the surface and 60 cm from the tower mast, oriented to the northwest. Sensors were high enough so that any nearby trees were below these heights and could be considered within the flux footprint. At both sites the daytime 80% cumulative flux footprint contour was typically <300 m upwind of the tower.

Several meteorological and soil variables were measured at each monitoring tower to provide context to the flux measurements. A common eddy covariance procedure was used at both sites to compute fluxes, assess quality, and fill gaps in the data set (Humphreys et al. 2014). We use site level measured meteorological data including, air temperature, radiation, precipitation, wind speed and humidity to run the ecosystem process model used in this study. Net ecosystem exchange (NEE) at both sites is calculated as the sum of CO$_2$ flux and the rate of change in storage below the eddy covariance instrumentation. Net ecosystem productivity (NEP) then calculated as -NEE and gaps less than 1 hour are filled with linear interpolation while longer gaps were filled using an exponential temperature response model (Lloyd and Taylor, 1994). Daytime estimates of gross primary production (GPP) during the non-cold season were estimated by adding measured and modeled ecosystem respiration (ER) to the negative of measured NEE (Humphreys et al. 2014). We use both the measured NEP and GPP to validate the ecosystem process model.

### 2.3 Ecosystem process model description and simulations

We use a process-based two-leaf enzyme kinetic terrestrial ecosystem model called boreal ecosystem productivity simulator (BEPS). BEPS is designed to simulate energy, water, and C fluxes at hourly time steps using spatial data sets of meteorology, remotely sensed land surface parameters (LAI, land cover type, and clumping index), soil parameters, and land cover-dependent parameters for photosynthesis and respiration rates (Ju et al., 2006; Chen et al., 2007). Photosynthesis is calculated by scaling Farquhar's instantaneous leaf biochemical model up to canopy-level with a spatial and temporal scaling scheme (Chen et al., 1999; Liu et al., 2003). The latest BEPS includes a land surface scheme to calculate energy balance, sensible and latent heat fluxes, soil water, and soil temperature status (Ju et al., 2006; Chen et al., 2007). The stomatal conductance is calculated using the Ball-Woodrow-Berry model (Ball et al., 1987). BEPS have been through several validation exercises (Liu et al., 1997; Chen et al., 1999; Liu et al., 1999, 2002; Chen et al., 2007; Chen et al., 2012; Sprintsin et al., 2012; Zhang et al., 2012; Gonsamo et al., 2013). Comparison studies of state-of-the-art ecosystem models show superior performance of BEPS compared to other models mainly attributed to the two-leaf spatial scaling scheme employed in BEPS (Schwalm et al., 2010; Schaefer et al., 2012). A variety of BEPS model with the inclusion of topographic effects to realistically simulate water table depth and soil moisture content movement of soil water via a subsurface saturated flow mechanism was also proved to be capable of simulating C balance of different terrestrial ecosystems including treed peatlands (Sonnentag et al., 2008; Govind et al., 2009).

Several modifications were made on hourly scale BEPS model in order to properly simulate energy and gas exchange in soil-vegetation-atmosphere continuum in treed peatland. Organic
soil layer property and profile were added for entire OFN treed peatland ecosystems. Hydraulic and thermal property of organic soil were also added in the updated model including, saturated hydraulic conductivity, soil porosity, field capacity, wilting point, thermal conductivity, and soil water potential. Firstly, the updated BEPS model was run at the two flux tower sites using measured meteorological variables. And finally, BEPS model was run for entire OFN, for 2010-2013, at 250 m spatial resolution using the updated code, and satellite remote sensing information and NCEP gridded meteorological variable inputs.

3. Results and Discussion

3.1 BEPS calibration and validation at two flux tower sites

The comparison of 30-minute flux tower GPP with hourly BEPS GPP aggregated temporally to daily values shows good agreement (Figure 6) with overall correlation above 0.91 and an RMSE below 0.43 g C m⁻² day⁻¹. The BEPS simulations for year 2011 showed better results although slightly underestimated late summer and autumn GPP. The high correlations show that BEPS simulations reasonably capture diurnal and seasonal GPP variability. For year 2012, BEPS simulations underestimated the June GPP at both flux towers sites (Figure 6) which also affected the simulated NEP in Figure 7. One of the remarkable results of the BEPS simulations is that both spring initiation and autumn cessation of the growing season were very well captured.

![Figure 6. Simulated and measured gross primary productivity (GPP) at the two flux tower sites for 2011-2012. RMSE is root mean square error and R is Pearson correlation coefficient.](image)
The 30-minute NEP from flux tower measurements and hourly BEPS simulations aggregated temporally to daily values show reasonable agreement (Figure 7) but with lower BEPS performance compared to the GPP simulations. The seasonal course of measured NEP is well captured with BEPS simulations although the simulations show diminished daily NEP variability (Figure 7). The poor performance of BEPS GPP simulations for June 2012 further affected the concurrently simulated NEP values. In order to suppress the inference from the expected errors both in the measurements and simulations during the off-seasons, we show the annual sums of GPP and NEP for both sites in Table 1 for growing season period (days 120-300). The comparisons show BEPS slightly underestimated GPP for both sites. However, the underestimation is within the expected error ranges of the eddy covariance measurements technique which could be as big as ±50 g C m⁻² yr⁻¹ in nearly ideal site (Baldocchi, 2003). Other sources of disagreement could also be from the differences between footprints of the simulated values and the dynamic fetch areas of the two towers. Although, we use measured meteorological input data to run the BEPS model at the two flux tower sites, the remote sensing LAI may also contribute to some of the disagreements of the C flux simulations. Overall, BEPS performance was commendable for these two shrub-bog and bog-fen peat complexes. The results however, show a room for model improvement particularly for the difficulties of simulating the June 2012 GPP values which was relatively warmer than the June of 2011.

Figure 7. Simulated and measured net ecosystem productivity (GPP) at the two flux tower sites for 2011-2012. RMSE is root mean square error and R is Pearson correlation coefficient.
Table 1. Growing season (day 120-300) annual sums of gross primary productivity (GPP) and net ecosystem productivity (NEP) measured (Flux) and simulated (BEPS) at the two flux tower sites.

<table>
<thead>
<tr>
<th>Year</th>
<th>GPP (g C m$^{-2}$ year$^{-1}$)</th>
<th>NEP (g C m$^{-2}$ year$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kinoje Lake site</td>
<td>Attawapiskat River site</td>
</tr>
<tr>
<td></td>
<td>Flux</td>
<td>BEPS</td>
</tr>
<tr>
<td>2011</td>
<td>291</td>
<td>265</td>
</tr>
<tr>
<td>2012</td>
<td>290</td>
<td>232</td>
</tr>
<tr>
<td></td>
<td>293</td>
<td>71</td>
</tr>
</tbody>
</table>

3.2 GPP and NEP mapping for entire far north Ontario

Figure 8 presents the OFN maps of total GPP and NEP estimated using BEPS at 250 m spatial resolution for 2010–2013. A reasonable spatial agreement is found among the simulated total photosynthesis indicated by GPP in Figure 8, and LAI and land cover maps (Figure 1 and 3). General speaking, non-peat forests have higher LAI and GPP. Simulated GPP increased through the simulation period from mean annual value of 281 g C m$^{-2}$ y$^{-1}$ in 2010 to 298 g C m$^{-2}$ y$^{-1}$ in 2013. Although GPP showed clear pattern between treed-wetland and forests, the latter having higher values, NEP does not show land cover patterns (Figure 8).

Year 2013 had the highest C sink over treed ecosystem of OFN amounting to 9.6 Tg C y$^{-1}$ (Table 2). Year 2011-2013 were moderate C sinks (Table 2). Year 2010 was a large C source (Table 2) although the mean and total summer temperature and precipitation, respectively were not anomalous compared to other years (Table 2). However, the highest standard deviation (SD) of 2010 NEP shown in Table 2 compared to other years indicate that although the mean climate variables were not anomalies for 2010, the hourly and daily values were perhaps extreme.

Table 2. Annual sums of net ecosystem productivity (NEP) simulated using BEPS for entire Ontario Far North (OFN) treed ecosystems together with summer temperature and precipitation.

<table>
<thead>
<tr>
<th>Year</th>
<th>OFN C budget from BEPS NEP simulations</th>
<th>June, July and August weather</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean C budget (SD) (g C m$^{-2}$ y$^{-1}$)</td>
<td>Total C budget (Tg C y$^{-1}$)</td>
</tr>
<tr>
<td>2010</td>
<td>-103 (211)</td>
<td>-20.9</td>
</tr>
<tr>
<td>2011</td>
<td>34 (57)</td>
<td>7.0</td>
</tr>
<tr>
<td>2012</td>
<td>30 (66)</td>
<td>6.1</td>
</tr>
<tr>
<td>2013</td>
<td>47 (51)</td>
<td>9.6</td>
</tr>
</tbody>
</table>
Figure 8. Simulated gross primary productivity (GPP) and net ecosystem productivity (GPP) for entire Ontario far north treed ecosystem at 250 m spatial resolution for 2010-2013. Grey is non-vegetated areas shown in Figure 1 as class water, marshes, open wetlands, and others.
4. Conclusions
The main objective of this project was to calibrate an existing ecosystem model against C flux measurements at two towers located in HBL, i.e. the Kinoje site (51.62 N, 81.77 W) and the Attawapiskat River site (52.71 N, 83.95 W) and apply the model to all OFN treed ecosystems using remote sensing and gridded meteorology dataset. The calibrated ecosystem process model, BEPS, was eventually used to map the annual C source and sink distributions over the period of 2010–2013 over OFN treed ecosystems including treed wetlands and tundra. At the end of phase one of this project (the current report) and in preparation to the upcoming phases of the project related to the climate change impact assessment on C cycles in the OFN ecosystems, several lessons have been learned. The 250 m spatial resolution mapping of both GPP and NEP at hourly time scale for years 2010–2013 involved enormous amount of computing resource and time. We have successfully modified the hourly scale BEPS model in order to properly simulate the energy and gas exchanges in soil-vegetation-atmosphere continuum in treed wetland including the definition and addition of organic soil layer hydraulic and thermal properties. Furthermore, the BEPS model was successfully calibrated and validated at the two flux tower sites. Both GPP and NEP simulations at the two flux tower sites were reasonable. The GPP and NEP mapping for the entire OFN treed ecosystem also showed reasonable spatial distribution following the land cover, leaf area index and soil C pool and property patterns. Between year 2010 and 2013, the OFN treed ecosystems were small C sink amounting 0.45 Tg C y\(^{-1}\).

Estimating C dynamics based on ecosystem process models derived by remote sensing and meteorology variables inherently contains the potential for significant error. Model predictions can deviate substantially from reality particularly due to the highly unpredictable nature of soil C pool and lateral water flow dynamics in the treed wetlands, and C budget dependence on stand age. To accommodate these limitations, we will further validate the BEPS model for simulating the lateral water redistribution over the landscape around the two towers by combining high-resolution (30 m) remote sensing data in recent years with historical climate data for long-term C cycle modeling since 1900, and develop an upscaling methodology with the additional consideration of the spatial variability in hydrological regimes for long-term C cycle modeling for OFN at 250 m resolution to project the C cycle to year 2100 under future climate scenarios during the upcoming phases of the project. This report is the first of its kind to spatially simulate treed ecosystems C budget including those growing on peatland for such large area as Ontario’s Far North. Ultimately the results presented in this study should be used as a guide to further supplement the predictive modelling scheme in order to achieve greater levels of confidence in future estimations. It is nevertheless a certainty that changing climates will alter the composition of the ecosystems as we know them today and much more study and attention must be paid to the potential consequences of these changes. The OFN ecosystem consisting the highest soil C density in the world is susceptible to future climate change as shown in this study where in a matter of one year, the treed ecosystem changed from a large C source in 2010 to moderate sink during 2011–2013.

5. Publications and dissemination of the project results
References


Stocker, T.F., et al. (2013). IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.


THE GOVERNING COUNCIL OF THE UNIVERSITY OF TORONTO

per: [Signature]

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Principal Investigator:
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