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Validating CO_2 Fluxes and $\delta^{13}CO_2$ in Land Surface Model For Coupling With GEOS-Chem

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Overview

Human activities and land use changes, such as deforestation and cropland cultivation, have substantially altered land surface. At present, 12% of land area is used for growing crops and 30% is dominated by forests. Crop phenology is distinct from natural vegetation. Cropland establishment is fast, and the biomass/crop residue are rapidly removed/cultivated during harvest. For forest ecosystems, soil respiration is the second largest carbon flow after gross ecosystem photosynthesis. Previously we have demonstrated that the carbon source/sink status of agricultural lands depends partly on management practices and phenology, and is associated with considerable uncertainty. Designing an realistic modeling mechanism for plant growth helps to improve accuracy of simulated terrestrial biosphere CO_2 emission.

Because of the large and variable isotope discrimination during carbon exchange between biosphere and atmosphere, carbon isotopic ratios of atmospheric CO_2 are sensitive to land use/land cover in terrestrial ecosystems. These land surface changes influence the carbon source for soil organic carbon decomposition and the physiological state at the photosynthetic level. The quantity and carbon isotopic ratio of CO_2 fluxes are regulated by the rates of soil respiration and carbon assimilation, as well as carbon isotopic discrimination during photosynthesis. Modeling an accurate diurnal/seasonal variation in carbon isotopic ratios of atmosphere depends on the reliable simulation of plant growth and kinetic isotope effects of the terrestrial biosphere.

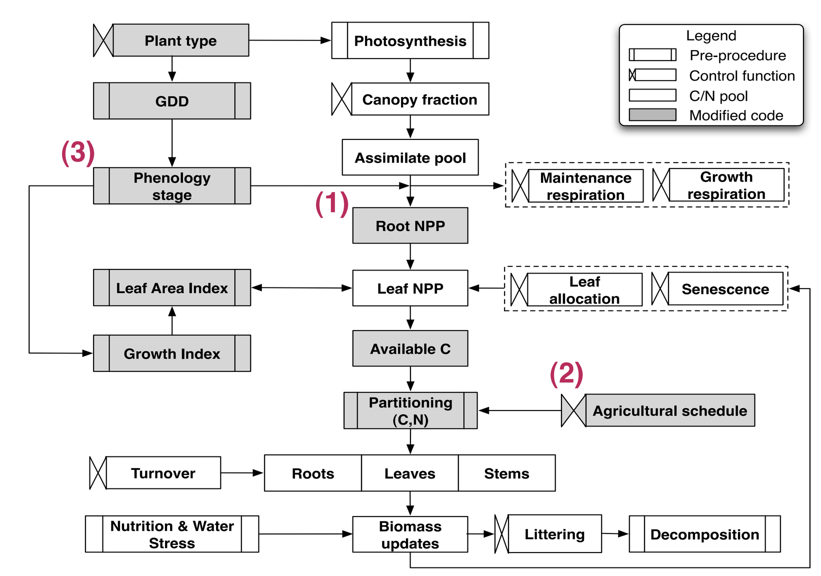
Research Objectives

(1) The Improvement of a land surface model, Carbon- and Nitrogen-coupled Canadian Land Surface Scheme (CN-CLASS) to better estimate CO_2 fluxes, including carbon assimilation, plant component respiration, soil respiration and biomass accumulation in agricultural and forest ecosystems. This work is validated with field measurements and another ecological model, the daily version of CENTURY model (DayCENT).

(2) The development of an isotope-enabled CN-CLASS to predict the isotopic composition of CO_2 fluxes — including fractionation during photosynthetic carbon assimilation, various soil organic carbon pools, and water in the terrestrial hydrologic cycle. Results of CO_2 fluxes and isotopic fractionation will be validated with isotopic measurements and coupled with the GEOS-Chem model.

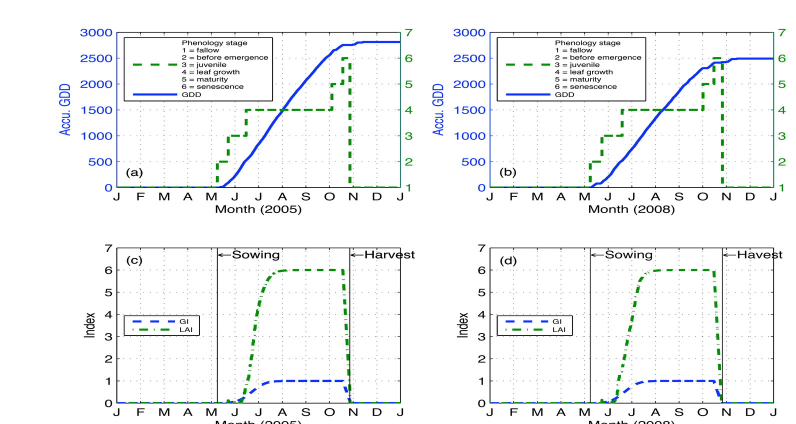
Crop-Specific Phenology Module

Three major modifications for crops are (1) root NPP function for crop scheme; (2) agricultural schedule regulating the partitioning and growing season; (3) crop-specific phenology stages linking assimilation with leaf growth. The right panel shows the GDD dynamics regulating crop phenology stages. The agricultural schedule constrains the duration of carbon fixation and further controls LAI and respiration.



Leaf Growth Index (GI) is governed by canopy light extinction rate (k_{rad}), leaf growth rate (k_{grow}), GDD for canopy development (D_{ae}; D_{ln}) and LAI threshold (LAI_{max}). GI approaches to 1 for a full canopy; it reshapes potential LAI based on above factors.

$$GI = \frac{1}{k_{rad}} \ln \left[\frac{1+\exp\{k_{grow}(D_{ae}-D_{ln})\}}{1+\exp\{k_{grow}(D_{ae}-D_{ln})-k_{rad}\,LAI_{max}\}} \right]$$



(1) Plant Growth & Carbon Allocation

The photosynthate is allocated to the three main vegetation components: leaves, stem and roots. The initial value for each allometry pool was set to zero or to a very small value where needed to avoid model instability. The allocation is governed by the available non-structural carbon reservoir, partitioning coefficients and respiration. The non-structural reservoir was regulated by the photosynthetic mechanism to assimilate carbon. The non-structural carbon reservoir is increased by allocations from the residues from net photosynthesis and leaf structure. Leaf structure is described as a function of LAI, and LAI is computed as a function of SLA and net leaf biomass and senescence.

$$
\begin{aligned}
C_{leaf} &= \frac{LAI_{net}}{SLA} - K_{leaf}\, f_{leaf}\, C_{pool} \\
C_{stem} &= X_{stem,stage}\,\frac{C_{post}}{1+f_{resp}} \\
C_{root} &= X_{root,stage}\,\frac{C_{pool,post}}{1+f_{resp}}
\end{aligned}
$$

SLA : Leaf area index

K/X : rate of C for plant

$$C_{post} = (1-f_{pool})\,C_{pool} - (C_{root}+R_{root}+C_{leaf}+R_{leaf})$$

$$C_{pool} = f_{pool}\,A_{net} - k_{leaf}\,(1-f_{pool})\exp\{-LAI\}\,C_{pool} - R_m$$

$$f_{pool} = [1-\exp\{-(C_{leaf}+C_{froot})\}]\ \exp\left\{-\frac{C_{pool}}{0.1}\right\}$$

$$LAI = (C_{leaf} + K_{leaf}\, f_{leaf}\, C_{pool} - C_{sens})\ SLA$$

(2) CO_2 in Canopy & Photosynthesis

The major respiration components are autotrophic respiration and heterotrophic respiration. Ra is composed of growth respiration and maintenance respiration.

Soil respiration is the sum of root autotrophic respiration and heterotrophic respiration resulting from soil organic carbon decomposition. The carbon sources for decomposition are plant litter and the three soil organic carbon pools. The decomposition is governed by the dynamics of carbon pools, soil climatic factors, soil physical conditions and associated N:C ratios using the concept of first order kinetics.

$$C_{ca} = R_a + R_h$$

$$A_n = f(w_j, w_c, w_e) - R_d$$

$$C_{lbl} = C_{pbl} * A_n * r_{lbl}$$

$$C_i = C_{lbl} - C_{pbl} * A_n * r_s$$

$$C_{cc} = C_i - A_n * r_{cc}$$

R_a : Autotrophic respiration

R_h : Heterotrophic respiration

R_d : Dark respiration

w_j : light limited A_n

w_c : rubisco limited A_n

w_e : export limited A_n

CT : Canopy temperature

ST : Soil temperature

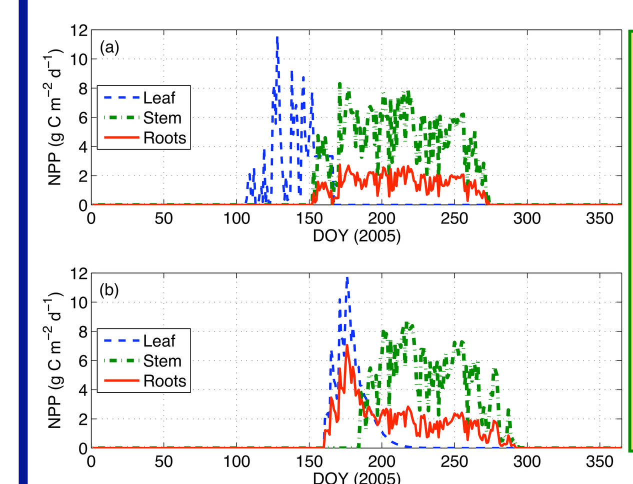
SWC : Soil water content

$$R_{soil} = R_{a,root} + R_h = f(C_{pool}, R_{base}, Q_{10}, CT, ST, SWC)$$

Preliminary Results

An accurate $\delta^{13}CO_2$ simulation requires a reliable calculation of carbon allocation, canopy CO_2 exchange, and soil CO_2 emissions. The model is validated intensively using nine-year and one-year field measurements for agricultural and forest ecosystems, respectively. The validation demonstrates that the CN-CLASS model performs reasonably well for water/energy balance, biomass production and plant component CO_2 emissions. In addition, the modeling structure of crop phenology is improved to describe a better carbon allocation and carbon exchange in a crop field. The respiration algorithms are also modified to simulate better soil respiration and respiration partitioning in deciduous forests.

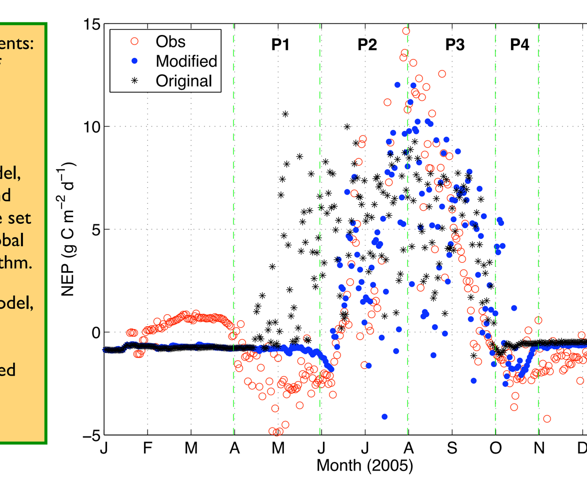
(1) Agricultural Management Site — Elora Research Station (ERS)



Two major improvements: a practical duration of carbon fixation, and a more realistic carbon allocation for crops.

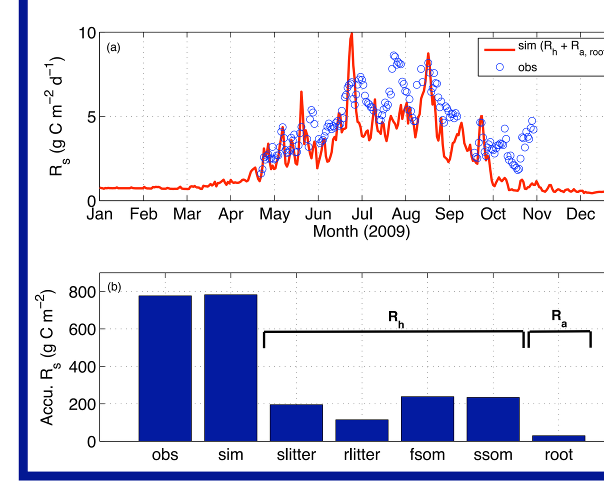
(a) In the original model, the growth pattern and growing duration have set values fixed by the global growing season algorithm.

(b) In the modified model, carbon is allocated to roots and leaves simultaneously, followed by stems.



Crop phenology scheme significantly improves the NEP simulation. The modified model follows the general pattern of carbon sink/source, while the original model starts growth too early. The depleted NEP in P1 is caused by a single-year agricultural simulation; the crop residue in the previous year needs to be taken into account for the soil organic carbon decomposition.

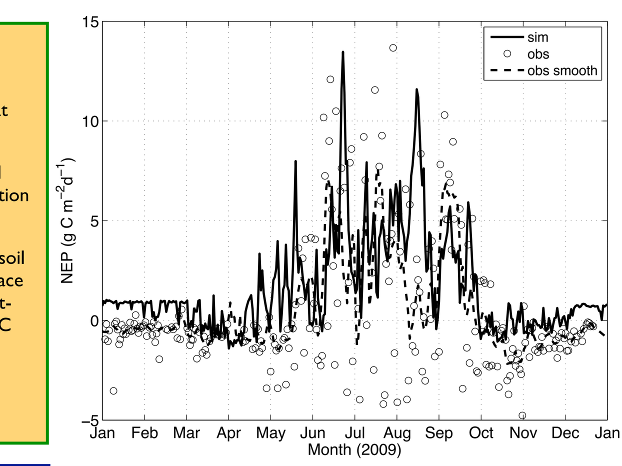
(2) Deciduous Mixedwood Forests Site — Borden Forest Research Station (BFRS)



The dynamics of soil respiration and its emission source partitioning in 2009 at the BFRS.

(a) The simulated and observed soil respiration at daily time-step.

(b) The accumulated soil respiration from surface litter, root litter, short-lived SOC, stable SOC and root respiration, respectively.



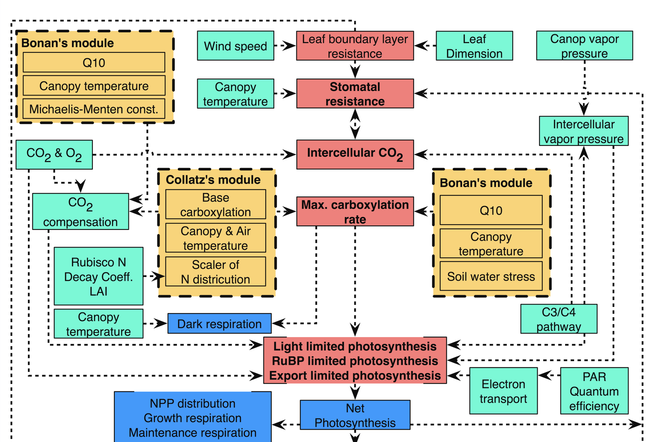
The comparison of simulated NEP and eddy-covariance carbon flux in 2009 at the BFRS. The dash line indicates the smoothed measurements.

Our NEP simulation shows a reasonable annual pattern, similar to eight-year carbon flux measurements at the BFRS, indicating 5 and –1 g C m^{-2} d^{-1} of NEP approximately for the growing and non-growing season, respectively.

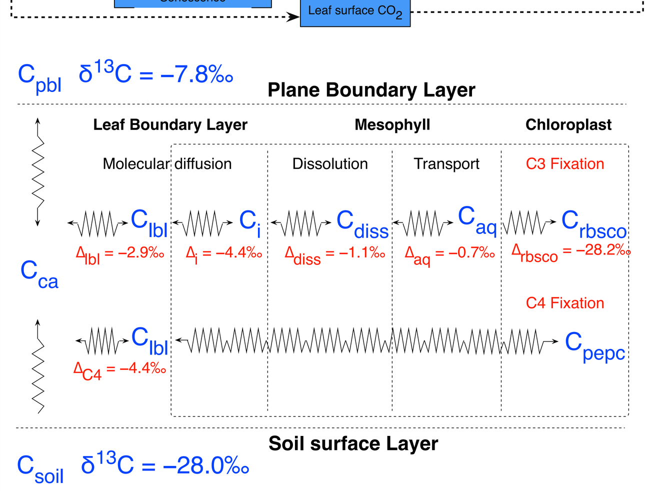
Method

Modeling Structure in CN-CLASS

The CLASS model was initially developed by Verseghy et al. (1991; 1993) at Environment Canada. CLASS is maintained to model terrestrial processes in the Canadian Centre for Climate Modeling and Analysis (CCCma) GCM. The version with carbon and nitrogen cycles (CN-CLASS) of Arain et al., (2002, 2006; Yuan et al., 2008) was initially validated by using CO_2 flux data from a temperate forest in British Columbia, Canada. The model has been used for examining the carbon balance in coniferous forest ecosystems. Few studies have been done by using the CN-CLASS model in crop related simulation, although Kothavala et al. (2005) have applied C-CLASS (CLASS with a carbon cycle) for common crops. In this study, the isotope discrimination module (Suits et al., 2005) is also adopted into CN-CLASS for examining ecological responses to climate change in agriculture and temperate deciduous forests.



The CN-CLASS model contains two main C3/C4 photosynthetic modules. The information about the CO_2 compensation point, Rubisco N decay rate, LAI and canopy temperature are required by these two modules. Each module provides a maximum carboxylation rate for calculating the dark respiration and net carbon assimilation. This non-structural reservoir is further limited by light absorption efficiency, RuBP and enzyme kinetics. Plant growth, growth respiration, maintenance respiration and leaf surface CO_2 concentration are generated within the carbon subroutine. The intercellular CO_2 is determined by stomatal resistance.



Carbon isotope discrimination in C3 photosynthetic pathway can be described as a systemic multiple process (Suits et al., 2005). CO_2 concentration and carbon isotope ratios within the canopy are assimilated by plants. The assimilated $\delta^{13}CO_2$ is determined by the canopy $\delta^{13}CO_2$ gradients associated with each step and by the kinetic isotope effects during the enzymatic carbon fixation process. Therefore, exchanged $\delta^{13}CO_2$ is the steady state $\delta^{13}C$ of plant carbon that is regulated by the differences in assimilated $\delta^{13}CO_2$ (enriched $\delta^{13}C$) and respirated $\delta^{13}CO_2$ (depleted $\delta^{13}C$). The carbon exchange tends to restore canopy $\delta^{13}CO_2$ to the plane boundary background level due to the natural response of photosynthesis. These variables are simulated every 30 minutes.

Carbon Isotope Module

(1) Carbon Isotopic CO_2 Fluxes in the Canopy

CO_2 in the canopy is a balanced concentration resulting from C3/C4 photosynthetic pathways, soil respiration, and turbulent exchange between the canopy and plane boundary layer. The carbon isotope calculation requires calculation of kinetic isotope effect, CO_2 concentration, carbon isotopic ratio and CO_2 concentration during the process of carbon exchange.

The isotopic ratio is determined by the depleted/enriched isotopic CO_2 condition in the canopy resulting from the effect of the PBL turbulent mixing ($\delta^{13}C_{pbl}$; $\delta^{13}C_{ca}$), photosynthetic assimilation ($\delta^{13}C_n$) and soil respiration ($\delta^{13}C_{soil}$).

$$\frac{d}{dt}(C_{ca}\overset{\text{model}}{\delta^{13}C_{ca}}) = \frac{d}{dt}(R_{soil}\overset{-28.0‰}{\delta^{13}C_{soil}}) - \frac{d}{dt}(A_n\overset{\text{model}}{\delta^{13}C_n}) + \frac{d}{dt}\left(\frac{C_{pbl}\overset{-7.8‰}{\delta^{13}C_{pbl}} - C_{ca}\overset{\text{model}}{\delta^{13}C_{ca}}}{r_a}\right)$$

Concentrations of CO_2 in the canopy (C_{ca}), at the soil surface (R_{soil}), net carbon assimilation (A_n), in the plane boundary layer (C_{pbl}), and resistance to turbulent exchange in the PBL (r_a) are determined by CN-CLASS in every 30 minutes.

C_{ca} : Canopy CO_2

R_{soil} : Soil CO_2

A_n : Net assimilated CO_2

C_{pbl} : PBL CO_2

$\delta^{13}C_{ca}$: C isotopic ratio of canopy CO_2

$\delta^{13}C_{soil}$: C isotopic ratio of soil CO_2

$\delta^{13}C_n$: C isotopic ratio of assimilated CO_2

$\delta^{13}C_{pbl}$: C isotopic ratio of PBL CO_2

(2) Kinetic Isotope Effect

The isotope discrimination in molecular diffusion CO_2 from the plane boundary layer to the chloroplast are based on Craig (1952), Farquhar (1984), Mook (1974) and O'leary (1984).

$$\Delta_{C3} = \overset{-2.9‰}{\Delta_{lbl}}\frac{C_{ca}}{C_{ca}} + (\overset{-4.4‰}{\Delta_i} - \overset{-2.9‰}{\Delta_{lbl}})\frac{C_{lbl}}{C_{ca}} + (\overset{-1.1‰}{\Delta_{diss}} + \overset{-0.7‰}{\Delta_{aq}} - \overset{-4.4‰}{\Delta_i})\frac{C_i}{C_{ca}} + (\overset{-28.2‰}{\Delta_{rbsco}} - \overset{-1.1‰}{\Delta_{diss}} - \overset{-0.7‰}{\Delta_{aq}})\frac{C_{cc}}{C_{ca}}$$

Concentrations of CO_2 in the canopy (C_{ca}), at the leaf surface (C_{lbl}), within the stomatal cavity (C_i), and chloroplast (C_{cc}) are determined by CN-CLASS in every 30 minutes.

$$\Delta_{C4} = -4.4^0/_{00}$$

Δ_{C3} : C isotopic discrimination of C3 plant

Δ_{lbl} : C isotopic discrimination of leaf surface

Δ_i : C isotopic discrimination of stomata

Δ_{diss} : C isotopic discrimination of dissolution

Δ_{aq} : C isotopic discrimination of transport

Δ_{rbsco} : C isotopic discrimination of rubisco

C_{lbl} : Leaf surface CO_2

C_i : Stomatal cavity CO_2

C_{cc} : Chloroplast CO_2

Δ_{C4} : C isotopic discrimination of C4 plant

(3) ^{13}C- and ^{12}C-CO_2 Fluxes in C3/C4 Plants

$$\delta^{13}C_x = \left(\frac{(\frac{^{13}C}{^{12}C})_{reservoir}}{(\frac{^{13}C}{^{12}C})_{std}} - 1\right) * 1000 \Rightarrow \left(\frac{^{13}C}{^{12}C}\right)_{reservoir} = \frac{\delta^{13}C_x(\frac{^{13}C}{^{12}C})_{std}}{1000} + \left(\frac{^{13}C}{^{12}C}\right)_{std} \Rightarrow \left(\frac{^{13}C}{^{12}C}\right)_{std} = \frac{(\frac{^{13}C}{^{12}C})_{reservoir}}{\frac{\delta^{13}C_x}{1000}+1}$$

$$\left(\frac{^{13}C}{^{12}C}\right)_{reservoir,C3} = \frac{\delta^{13}C_{ca}}{\frac{\Delta_{C3}}{1000}+1}$$

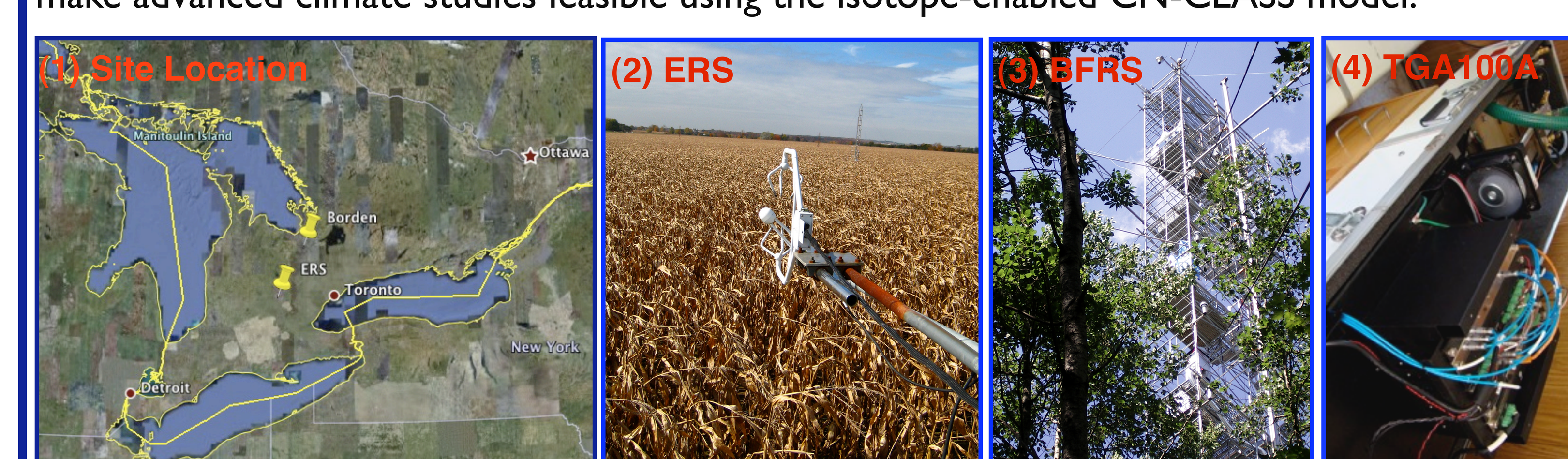
$$^{12}C = \frac{C_x}{1+(\frac{^{13}C}{^{12}C})_{reservoir}} \Rightarrow {}^{12}C_{C3} = \frac{An_{C3}}{1+(\frac{^{13}C}{^{12}C})_{reservoir,C3}}$$

$$^{13}C = \frac{(\frac{^{13}C}{^{12}C})_{reservoir}C_x}{1+(\frac{^{13}C}{^{12}C})_{reservoir}} \Rightarrow {}^{13}C_{C3} = \frac{(\frac{^{13}C}{^{12}C})_{reservoir,C3}An_{C3}}{1+(\frac{^{13}C}{^{12}C})_{reservoir,C3}}$$

The ^{13}C- and ^{12}C-CO_2 reservoirs with specific isotopic ratios and discriminations mitigate the uncertainty of mass-balance calculation due to the implications of fixed ratios for the conc. gradients.

Future Work & Model Validation

CO_2 fluxes and $\delta^{13}CO_2$ field measurements are obtained using eddy covariance techniques at the University of Guelph Elora Research Station (ERS) and Environment Canada Borden Forest Research Station (BFRS). The two sites provide the model forcing data at half-hourly time-step. Instrumentation (TGA100A, Campbell Sci.) for measurement of $^{13}CO_2/^{12}CO_2$ concentrations was installed at ERS and BFRS since 2005 and 2009, respectively. These isotope measurements make advanced climate studies feasible using the isotope-enabled CN-CLASS model.



(1) Agricultural site ERS is located 100 km W of Toronto, at an elevation of 376 m. The size of four plots was 150m x 100m x 4 (plot 1 & 4 for NT; 2 & 3 for CT). The field has been rotated with corn, soybean and winter wheat since 2000. Deciduous forest site BFRS is located 200 km NW of Toronto, at 120 m. Canopy height is 22 m, and stand age is 120 years. (2) An open-path infrared gas analyzer (LI-7500; Li-Cor, Lincoln, NE, USA) and a 3-D sonic anemometer(CSAT3; Campbell Scientific; Logan, UT, USA) at ERS, (3) 40 m height of flux tower at BFRS. (4) Tunable diode laser absorption spectroscopy (TDLAS).

References

[1] Arain M. A., Yuan F., Black T. et al. (2006). "Soil-plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada." Agricultural and Forest Meteorology 140: 171-192.

[2] Parton W. J., Stewart J. B., et al. (1988). "Dynamics of C, N, P and S in grassland soils - A model." Biogeochemistry 5(1): 109-131.

[3] Suits N. S., Denning A. S., Berry J. A., Still C. J., Kaduk J., Miller J. B., Baker I. T., et al. (2005). "Simulation of carbon isotope discrimination of the terrestrial biosphere." Global Biogeochemical Cycles, 2005, 19 (1), GB1017.

[4] Verseghy D. L., McFarlane N. A., et al. (1993). "CLASS - A canadian land-surface scheme for GCM. 2. Vegetation model and coupled runs." International Journal of Climatology 13(4): 347-370.

Acknowledgements & Contact information

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