The influence of competition between plant functional types in the Canadian Terrestrial Ecosystem Model (CTEM) v. 2.0

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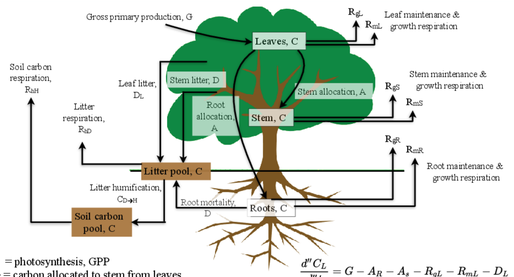
Simulating Competition

Earth system models (ESMs) commonly use prescribed vegetation cover that is unable to respond to evolving climate, [CO_2] or disturbance regimes with changes in vegetation distribution. In reality, plants continually adjust to their environment as well as competitive pressures from neighbouring vegetation. Simulating competition in ESMs is difficult due in part to large grid cells and inherently small scale processes.

To address this challenge, we **incorporated competition between plant functional types (PFTs) in the Canadian Terrestrial Ecosystem Model (CTEM). Our competition representation uses modified Lotka-Volterra (LV) predator-prey equations** [Arora & Boer, 2006]. As other vegetation models use unmodified LV relations (such as TRIFFID [Cox, 2001]), the impact of our modification is investigated here along with an evaluation of CTEM's competition scheme.



- G = photosynthesis, GPP
- A_S = carbon allocated to stem from leaves
- A_R = carbon allocated to roots from leaves
- R_{gL} = Growth respiration for leaves, and similarly for stem (S) and roots (R).
- R_{mL} = Maintenance respiration for leaves and similarly for stem (S) and roots (R)
- D_L = leaf litter and similarly for stem (S) and roots (R)
- R_{hD} = Heterotrophic respiration from the litter or debris pool
- R_{hH} = Heterotrophic respiration from the soil carbon (humus) pool
- $C_{D\to H}$ = carbon transferred from the litter to the soil carbon pool

$$\frac{d''C_L}{d''t} = G - A_R - A_s - R_{gL} - R_{mL} - D_L$$

$$\frac{d''C_S}{d''t} = A_s - R_{gS} - R_{mS} - D_S$$

$$\frac{d''C_R}{d''t} = A_R - R_{gR} - R_{mR} - D_R$$

$$\frac{d''C_D}{d''t} = D_L + D_S + D_R - R_{hD} - C_{D\to H}$$

$$\frac{d''C_H}{d''t} = C_{D\to H} - R_{hH}$$

Figure 1: Schematic representation of the CTEM's carbon pools and fluxes

The Lotka-Volterra Equation

$$\frac{df_a}{dt} = \sum_{i=1}^{N+1} (c_{a\to i}\epsilon_{a\to i} f_a^{\beta} f_i - f_a c_{i\to a}\epsilon_{i\to a} f_i^{\beta}) - m_{tot,a} f_a$$

Changes in the fractional cover of PFT *a* (df_a/dt) depends on competition and colonization interactions as well as mortality. The first term represents invasion by PFT *a* into the area of other PFTs or bareground, the second term is the encroachment by other PFTs into the area of PFT *a* while the last term represents loss of area due to mortality. **Unmodified LV equations use a β value of 1, i.e. PFTs can only interact in overlapping fractions. We use a β value of 0 which allows interaction over the entire area of each PFT.**

Simulations

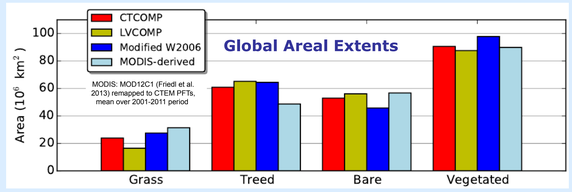
CTEM (v.2.0) is coupled to CLASS (Canadian Land Surface Scheme v.3.6 [Verseghy 2012]) and **forced offline** with CRU-NCEP climate. Each **preindustrial simulation** is run to equilibrium by cycling over 1901 – 1940 climate with a [CO_2] of 286 ppm (year 1861) at 3.75°x~3.75° resolution. The **CTCOMP simulation is the CTEM competition scheme with modified LV equations, LVCOMP has unmodified LV equations, and W2006 are the observation based fractions from Wang et al. 2006**. CTEM simulates 7 natural and 2 crop PFTs (crops have prescribed areal extent in all simulations). Bioclimatic limits restrict the regions that PFTs can attempt colonization.

Bioclimatic parameters used in the competition parameterization of CTEM v. 2.0. T_{min}^{cold} and T_{max}^{cold} are the minimum and maximum coldest month temperatures, respectively. T_{max}^{warm} is the maximum warmest month temperature and $GDD5_{mt}$ is the minimum growing degree days above 5 °C (GDD5). $arid_{min}$ is the minimum aridity index and $dryseason_{min}$ and $dryseason_{max}$ are the minimum and maximum length of the dry season, respectively.

Plant functional type	Short name	T_{min}^{cold} (°C)	T_{max}^{cold} (°C)	T_{max}^{warm} (°C)	$GDD5_{mt}$ (°C)	$arid_{min}$ (unitless)	$dryseason_{min}$ (months)	$dryseason_{max}$ (months)
Needleleaf evergreen	NDL-EVG	–	≤18.0	–	≥375.0	–	–	9.0
Needleleaf deciduous	NDL-DCD	–	≤-28.0	≤25.0	≥600.0	–	–	–
Broadleaf evergreen	BDL-EVG	≥2.5	–	–	≥1200.0	–	–	–
Broadleaf cold deciduous[a]	BDL-DCD-COLD	≥-35.0	≤ 16.0	–	≥300.0	–	–	–
Broadleaf drought/dry deciduous[a]	BDL-DCD-DRY	≥4.0	–	–	–	≥0.9	≥5.5	–
C_3 crop	C3-CROP	–	–	–	–	–	–	–
C_4 crop	C4-CROP	–	–	–	–	–	–	–
C_3 grass	C3-GRASS	–	–	–	–	–	–	–
C_4 grass	C4-GRASS	–	–	–	–	–	–	–

[a] Both broadleaf cold deciduous and broadleaf drought/dry deciduous trees are not allowed to coexist in a grid cell.

Grass, Tree, Bare, & Vegetated



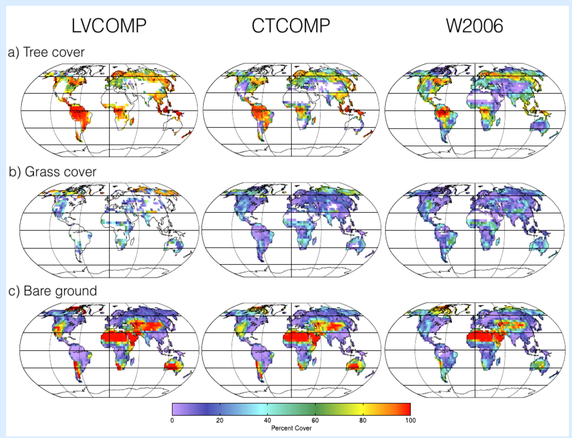
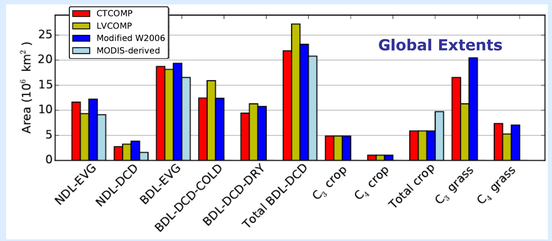


Figure 2: LVCOMP - unmodified LV relations, CTCOMP - modified LV equations, and W2006 is the Wang et al. 2006 observation-based dataset. **CTCOMP reasonably captures broad-scale patterns. LVCOMP does not allow appropriate co-existence between grasses and trees.**

PFT Level



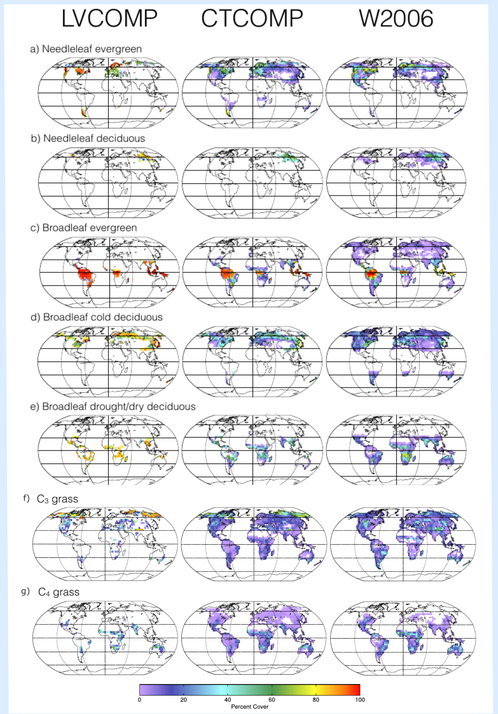


Figure 3: Simulated fractional coverage of CTEM's 7 non-crop PFTs. CTCOMP overestimates C_3 grasses at high latitudes due to only a single C_3 grass PFT globally. CTEM also has no shrubs which are extensive in both hot and cold semi-arid to arid regions and would displace grasses. The limitation of the small number of PFTs in CTEM is evident, e.g. needleleaf evergreens are in the southwest US and the Yukon territory but physiological adaptations for these very different environments are ignored by using only one needleleaf evergreen PFT. Climate niches are also not resolved, e.g. western Mexico where the Sierra Occidental mountains creates climatic niches on the windward side allowing forests.

Impact of modifying the LV equations

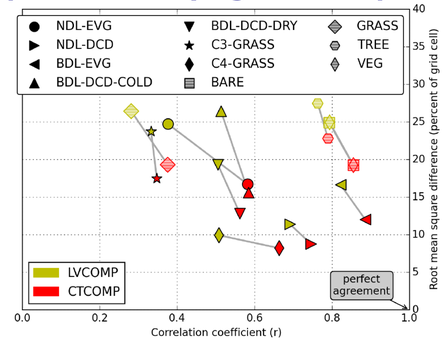


Figure 4: Scatter plot of the CTEM simulated vegetation cover root mean square difference and correlation coefficient as compared to the observation based Wang et al. (2006) dataset. **All CTCOMP aggregated and individual PFTs show closer agreements with W2006 than the LVCOMP simulations.**

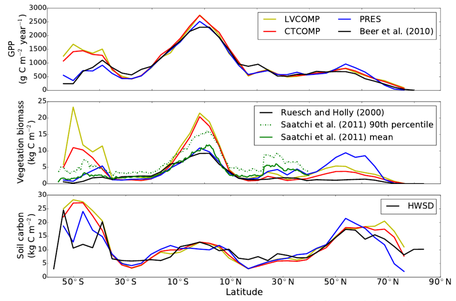


Figure 5: Zonal means agree reasonably with observation-based estimates of GPP, vegetation biomass, and soil carbon for both CTCOMP, LVCOMP and a simulation using prescribed cover from W2006 (PRES).

Conclusions

- **Simulated areal extents of CTEM's 7 natural PFTs using modified Lotka-Volterra equations compare reasonably well to observations**
- **Differences remain due to:**
  - **Limited number of PFTs used to represent the diversity of natural vegetation**
  - **Coarse grid cell resolution**
  - **Unresolved climate niches**
- **The use of unmodified LV equations (LVCOMP simulations) results in unrealistic plant distributions**

CLASS-CTEM Description

CLASS operates on a half-hourly timestep taking in the atmospheric forcing data and solving for the energy and water balances of the soil, snow, and vegetation canopy. CTEM operates on a daily timestep (excluding the photosynthesis, respiration, and canopy conductance calculations which operate on the CLASS time step) to simulate vegetation dynamics including establishment, growth, mortality, competition, turnover, and allocation. The CLASS surface scheme includes three soil layers of thickness 0.10, 0.25, and up to 3.75 m. Soil temperature, liquid and frozen water contents are simulated for each layer of the total 4.10 m of soil column. The surface flux calculations are performed on grid cell regions of (as required): i) bare soil, ii) vegetation, iii) bare soil with snow cover, and iv) vegetation over snow. CLASS does not presently have an operational peatland module. The CTEM disturbance (fire) module was used in all simulations presented here.

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