Modeling dynamic vegetation for decadal to century climate change studies

Nancy Y. Kiang[1], Andrew D. Friend[2], Paul Moorcroft[3], Wenge Ni-Meister[4], Igor Aleinov[1]

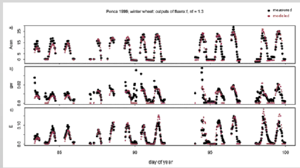
[1]Center for Climate Systems Research, Columbia University Earth Institute, NASA Goddard Institute for Space Studies, NY, USA
[2]Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France
[3]Depatment of Organismal and Evolutionary Biology, Harvard University, Cambridge, MA, USA
[4]Department of Geography, Hunter College, City University of New York, NY, USA

OVERVIEW

A dynamic global vegetation model (DGVM) is being developed specifically to provide full coupling between the terrestrial biosphere and climate in atmospheric general circulation models (GCMs). This DGVM is designed to be a stand-alone model that can be embedded in GCMs to improve their ability to make climate change predictions at decadal and century time scales, in a way that is both biologically realistic and computationally efficient.

The model treats both the carbon and nitrogen cycles through self-consistent biophysics, biogeochemistry, and ecological dynamics in a prognostic, process-based manner. Self-consistency is necessitated by the role of canopy radiative transfer, which determines: 1) the rate of photosynthesis (biophysical link), 2) the partitioning of photosynthetic and non-photosynthetic nitrogen in plant tissue during growth (biogeochemical link), 3) the spatial heterogeneity of light due to disturbed canopy gaps (biogeographical/ecological link), and 4) the albedo of the land surface as determined by 1-3 (atmosphere link). Each model component as well as their full combination provides a tool both for understanding past climate and for policymakers to estimate potential interactions between greenhouse gases, climate, and terrestrial ecosystems under global change.

The biophysical model has been implemented in the NASA Goddard Institute for Space Studies (GISS) GCM, significantly improving the prediction of regional surface temperatures. Other model components have been designed and are undergoing testing and development.



Canopy conductance/photosynthesis model fit to eddy flux data for various plant functional types. Shown here: winter wheat.

BIOPHYSICS (Friend & Kiang, submitted)

Canopy conductance is responsive to CO_2 and vapor pressure. A conductance parameter and a photosynthesis parameter are derived from eddy flux data.

$$gw_{canopy} = \alpha\beta_D\left[(1-0.0075h)\right]\left[A_{\max}\left(light, T, N_p, n_{f,pft}, LAI\right)\right]\left[\left(\frac{C_i+0.004}{5C_i}\right)\right]\left[2.8^{-80dqs}\right]$$

PHOTOSYNTHESIS (Kull & Kruijt, 1998)

Ratio of chlorophyll to total N follows radiation decline with canopy depth.

$$A_L = \left(1-\frac{\Gamma_*}{C_i}\right)\left[m_{sat}\left(n_f, C_i\right)N_{sat} + q\left(\frac{C_i}{C_i+2\Gamma_*}\right)(1-r_l)PAR\left(e^{-k_a n_3 (LAI_L) N_{sat}} - e^{-k_a n_3 N_{p,L}}\right)\right]$$

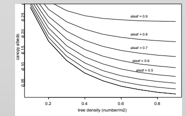
$gw_{canopy}[m_{H_2O}\, s^{-1}]$ = canopy conductance
α[dimensionless] = 1.1, eddy flux - fitted conductance parameter
β_D[fraction] = soil moisture stress
$A_{\max}[\mu mol_{CO_2}\ m^{-2}{}_{ground}\ s^{-1}]$ = CO_2 – saturated photosynthetic rate
$A_L[\mu mol_{CO_2}\ m^{-2}{}_{ground}\ s^{-1}]$ = CO_2 assimilation by photsynthesis for layer L
$T_{canopy}[Kelvin]$ = canopy temperature
$N[gN\ m^{-2}{}_{ground}]$ = total leaf nitrogen content
$n_{f,pft}$[dimensionless] = pft - dependent eddy flux – fitted parameter for adjusting capacities of electron transport and Rubisco catalsysis per unit leaf nitrogen
$C_i[mol_{CO_2} m^{-3}]$ = leaf internal CO_2 concentration
$dq_s[kg_{H_2O} kg^{-1}_{H_2O}]$ = surface – to – leaf interior water vapor mixing ratio deficit
$\Gamma_*[mol_{CO_2} m^{-3}]$ = photorespiratory compensation point
$m_{sat}[\mu mol_{CO_2}(mmol\,N)^{-1} s^{-1}]$ = rate of radiation - saturated carboxylation per unit N
$N_{sat}[gN\ m^{-2}_{ground}]$ = cumulative leaf N along radiation path at which chloroplasts are limited by radiation absorption.
$N_{p,L}[gN\ m^{-2}_{foliage}]$ = total foliage N in layer L
q [electrons/molecule CO_2] = intrinsic quantum efficiency
r_l [fraction] = leaf reflectivity
k_a [dimensionless] = 0.0055 = PAR extinction on chlorophyll
n_3 [ratio] = ratio of chlorophyll to total N

PROGNOSTIC ALBEDO

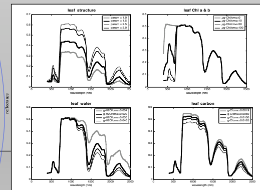
(Ni, et.al., 1999; Jacquemoud, et.al., 1990)

Canopy albedo in different wavelength bands is derived from the GORT model of Ni, et.al. (1999), which calculates bidirectional reflectance over discontinuous canopies. The model uses canopy height, h, clumping of leaves within tree crowns, LAI/vol, as provided by the growth mode, and tree density, D, as provided by the demography modell. Sunlit and shaded fractions of foliage are distinguished.

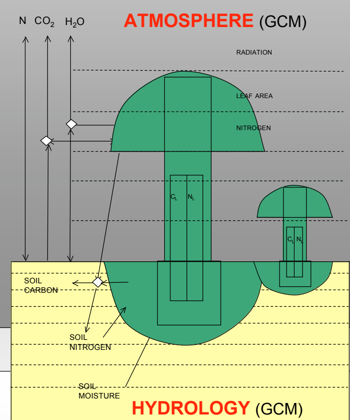
Leaf reflectance spectra are calculated by the PROSPECT model of Jacquemoud, et.al., (1990). The growth and photosynthesis models together provide leaf chlorophyll (n_3,N_{pL}) and carbon content. Leaf structure depends on plant functional type. Leaf water status is derived from soil moisture status from the growth model.



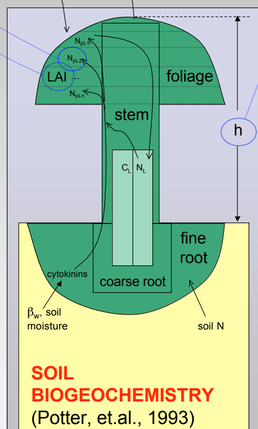
Canopy albedo predicted by GORT (Ni-Meister, et.al., 1999) for different tree densities and leaf albedoes. Other parameters: solar zenith angle, tree crown dimensions, leaf orientation, soil albedo. Code courtesy of W. Ni-Meister.



Reflectance spectra of leaves as calculated by the PROSPECT model (Jacquemoud, et.al., 1990). Clockwise from upper left, sensitivity to: leaf structure, chlorophyll a and b content, carbon content, and water content. PROSPECT code courtesy of Stephane Jacquemoud.



$\sum_L A_L$ E_{plant}



GROWTH/ALLOCATION

(Friend, in prep.)

Allocation of labile C and N to above- vs. below-ground structure (foliage, stems, coarse roots, fine roots) depends on plant N status. Foliage and fine root growth are constrained by supporting stem and coarse roots. Foliage N is continuously degraded to and replenished from the labile N pool, and is distributed in foliage layers relative to transpiration transport of fine root-generated hormonal signals, determining photosynthetic N from both radiation distribution and soil moisture acquisition.

Plant specifications:
Volume occupied
C_{labile} : whole plant pool
$C_{structural}$: stem, foliage; coarse root, fine root
N_{labile} : whole plant pool
$N_{structural}$:
stem, fine root, coarse root
foliage - photosynthetic N vertical distribution via relative transpiration & cytokinins
hormones - produced in fine roots, transported via transpiration to canopy layers:

SOIL BIOGEOCHEMISTRY

(Potter, et.al., 1993)

$$cytokinin_{xylem} = \beta_w M_{fine\,root} P_{cyt} / E_{plant}$$

$$N_{in,L} = V_{\max Nin}\frac{cyt_{Nin}E_L}{cyt_{Nin}E_L + K_E}$$

$cytokinin_{xylem}[kg_{cyt}\ kg_{H2O}^{-1}]$ = concentration of hormonal signal in transpiration stream
β_w [fraction] = soil moisture status
$M_{fineroot}$[kg] = mass of fine roots
$P_{cyt}[kg_{cyt}\ kg_{root}^{-1}\ s^{-1}]$ = rate of hormone production
$E_{plant}[kg_{H2O}\ s^{-1}]$ = whole plant transpiration rate

ECOLOGICAL DYNAMICS

(Moorcroft, et.al., 2001)

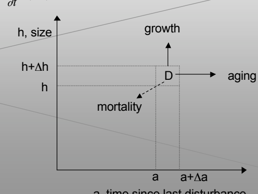
Vertical and horizontal heterogeneity in light distribution are primary environmental gradients for plant competition. Mortality and disturbances open up sub-grid patches (horizontal) with different plant canopy heights (vertical) due to different stages of regeneration. The statistical behavior of individual plant competition for light and patch dynamics is captured in a computationally efficient manner by Moorcroft. et.al. (2001) by representing plant and patch demography via size (height) and age (since last disturbance) density distributions.

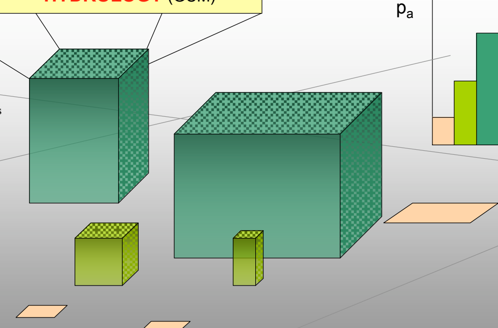
change in plant density

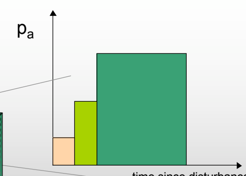
$$\frac{\partial}{\partial t}D(h, pft, a, t) = \text{growth into/out of size class} + \text{aging into/out of patch age class} + \text{mortality out of size - and - age class}$$

change in patch age structure

$$\frac{\partial}{\partial t}p(a,t) = -\text{aging} - \text{disturbance}$$







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