

May 2004

The Community Land Model's Dynamic Global Vegetation Model (CLM-DGVM): Technical Description and User's Guide

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NCAR/TN-459+IA

NCAR TECHNICAL NOTE

May 04

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Preface

A Dynamic Global Vegetation Model (DGVM) has been coupled to the Community Land Model (CLM3.0). We refer to this coupled model as CLM-DGVM. The present document serves as a combined technical description and user's guide for this model. The technical description is designed to be used in conjunction with the source code to explain the processes included in the DGVM. The user's guide provides information on running CLM-DGVM. This document is considered an addendum to the standard CLM technical description (Oleson *et al.* 2004), user's guide (Vertenstein *et al.* 2004), developer's guide (Hoffman *et al.* 2004), and other available CLM and Community Climate System Model (CCSM) documentation. The CLM-DGVM work summarized here was supported in part by the NASA Land Cover Land Use Change program through grant W-19,735.

Samuel Levis

Boulder, 26 May 2004

Acknowledgements

The authors thank Stephen Sitch at the Potsdam Institute for Climate Impact Research for providing LPJ-DGVM version 1; Chris Kucharik and Jon Foley at the University of Wisconsin-Madison for sharing IBIS version 2; and Peter Thornton for reviewing a draft of this document.

Part I: Technical Description

1. Introduction

1.1 Dynamic Global Vegetation Models

The CLM-DGVM belongs to a group of models that simulate the distribution and structure of natural vegetation dynamically, using mostly mechanistic parameterizations of large-scale vegetation processes (Foley *et al.* 1996; Brovkin *et al.* 1997; Friend *et al.* 1997; Cox *et al.* 1998; Potter and Klooster 1999; Woodward *et al.* 2000; Sitch *et al.* 2003). This group of models (DGVMs) was designed to fit in the framework of existing land models, such as the CLM, to facilitate the coupling to global climate models (GCMs). Such coupling enables the simulation of two-way biogeophysical and biogeochemical feedbacks between climate and vegetation. The coupling design allows for internal consistency in the representation of simulated processes and ensures conservation of energy and mass in the modeled system. We refer to this as “synchronous” climate-vegetation coupling (Foley *et al.* 1998), in contrast to the widely used iterative coupling introduced to vegetation modeling by Henderson-Sellers (1993).

Before DGVMs emerged, scientists used equilibrium biogeography models, terrestrial biogeochemistry models, and forest gap models. Equilibrium biogeography models could simulate equilibrium vegetation given a certain climate (e.g. Prentice *et al.* 1992). Terrestrial biogeochemistry models focused on the simulation of biogeochemical cycles through plant ecosystems (e.g. Parton *et al.* 1987). Forest gap models could simulate ecological succession at the species level (e.g. Solomon *et al.* 1980). Each of these types of model offered extraordinary insight into a variety of scientific questions. However, important shortcomings became apparent with these model families with respect to

their coupling to GCMs. Equilibrium biogeography models do not represent transient responses of vegetation to climate change because the ecological time scales of vegetation dynamics are neglected. Hence, such models are used in iterative climate-vegetation coupling. Terrestrial biogeochemistry models are not designed to simulate changing plant biogeography with climate change. Forest gap models simulate tens of thousands of individual trees and require excessive computer power when applied to the global scale.

DGVMs reconcile these shortcomings by integrating aspects of all these model families in an internally consistent framework. DGVMs include: 1) simple biogeography rules to delineate the presence of vegetation types according to climate (e.g. Table 1); 2) carbon and, sometimes, nitrogen cycle modules to track the biogeochemistry, while simulating plant growth and decay; and 3) vegetation dynamics modules which use a top-down approach, e.g. using the concept of an average individual, to increase the computational efficiency compared to forest gap models. To generalize plant function to the global scale, DGVMs represent vegetation as plant functional types (pfts) instead of species (used in forest gap models).

1.2 History of the CLM-DGVM

The Lund-Potsdam-Jena model or LPJ (Sitch *et al.* 2003) was selected for coupling to the CLM among existing DGVMs for three primary reasons: 1) LPJ's sub-grid representation of plant cover resembles that of CLM, where a grid cell consists of distinct areas for each pft, rather than potentially overlapping areas; 2) LPJ bridges the concept of allometry at the *plant* individual level with the concept of the *average* individual at the grid cell level, unlike other models where either the individual is not represented at all or

the individual is still the central concept as in forest gap models; 3) LPJ's code and model applications are documented and indicate a well tested and robust dynamic vegetation model (Cramer *et al.* 2001; McGuire *et al.* 2001; Smith *et al.* 2001; Sitch *et al.* 2003).

Prior to the first release of CLM (CLM2.0, May 2002), we coupled LPJ to NCAR's Land Surface Model (LSM) (Bonan *et al.* 2003). Later the coupling was repeated identically using CLM2.0, and three studies were completed with CLM-DGVM coupled to the CCSM. The first documents the terrestrial biogenic volatile organic compound (VOC) emission module in CLM and estimates the potential contribution of dynamic vegetation to the interannual variability of such emissions (Levis *et al.* 2003). The second strengthens the argument for interactively simulated rather than prescribed plant phenology by comparing simulated and observed springtime temperature trends (Levis and Bonan 2004). The third explores climate-vegetation interactions in North Africa during the mid-Holocene (about 6000 years before present) (Levis *et al.* 2004).

CLM-DGVM is publicly available as part of CLM3.0. Although the host model (LSM, CLM2.0, CLM3.0) has changed over time, the DGVM has not changed relative to the version used in the studies listed in the preceding paragraph. The present document explains the processes simulated by this DGVM drawing mainly from Bonan *et al.* (2003), Sitch *et al.* (2003), and directly from the CLM-DGVM code.

1.3 Overview of the model

We coupled LPJ to the CLM following the IBIS approach (Foley *et al.* 1996; Kucharik *et al.* 2000). This means that the end product consists of one integrated, yet modular, program that does not duplicate processes. For example, LPJ and CLM both include

parameterizations for photosynthesis, evapotranspiration, and snow accumulation. We retained CLM's parameterizations (characterized by greater complexity than LPJ's) and specifically introduced LPJ's vegetation dynamics routines to CLM. Plant phenology (the seasonal emergence and senescence of foliage) was introduced to CLM from IBIS instead of LPJ for practical reasons explained in part II section 5.

CLM-DGVM consists of CLM3.0 as described by Oleson *et al.* (2004) plus a set of routines that allow vegetation cover and structure to be simulated instead of prescribed from data. Annual (or slow) processes include the update of vegetation biogeography and structure. The plant-atmosphere exchange of carbon (in the form of CO₂) occurs at a sub-hourly time step. Plant phenology is calculated daily (Figure 1).

Vegetation is represented by the carbon stored in leaves, roots, stems (sapwood), and heartwood. Given these carbon pools, the model can derive every pft's leaf area index, canopy height, and fractional cover relative to the portion of the grid cell allocated to natural vegetation. (In standard CLM simulations, these variables come from input datasets.) The leaf area index participates in the calculation of photosynthesis. Generally, photosynthesis minus autotrophic respiration (defined as net primary production) minus mortality determines a pft's success at the grid cell level. Carbon from live plants eventually ends up in above and below ground litter and turns to soil carbon, which decomposes at various rates to close the terrestrial carbon cycle. At this time, CLM-DGVM has been tested only with a prescribed atmospheric CO₂ concentration. CLM-DGVM is not supported for fully coupled carbon simulations where atmospheric CO₂ is predicted.

In CLM-DGVM the maximum number of pfts in a grid cell's naturally vegetated landunit has changed from 4 (standard CLM) to 10 to allow all pfts to coexist when cli-

mate permits. CLM-DGVM keeps track of all 10 pfts, even when a pft's area is zero, in order to allow for the annual introduction and removal of pfts. This differs from the standard CLM, where pfts are maintained only when their area is greater than zero. Filters may be used at run time to eliminate redundant calculations for pfts with zero area. CLM-DGVM's list of pfts is shorter than CLM's by not including crop and shrub pfts and by merging boreal deciduous pfts into one pft (Table 1).

Figure 1. CLM-DGVM wire diagram. Adapted from Figure 1 of Bonan *et al.* (2003).

Note the coupling between fast processes such as energy exchange, photosynthesis, and respiration and slower processes such as tissue turnover, mortality, establishment, and disturbance. Gross primary production, GPP, is equal to the assimilation of carbon through photosynthesis, denoted A throughout the text.

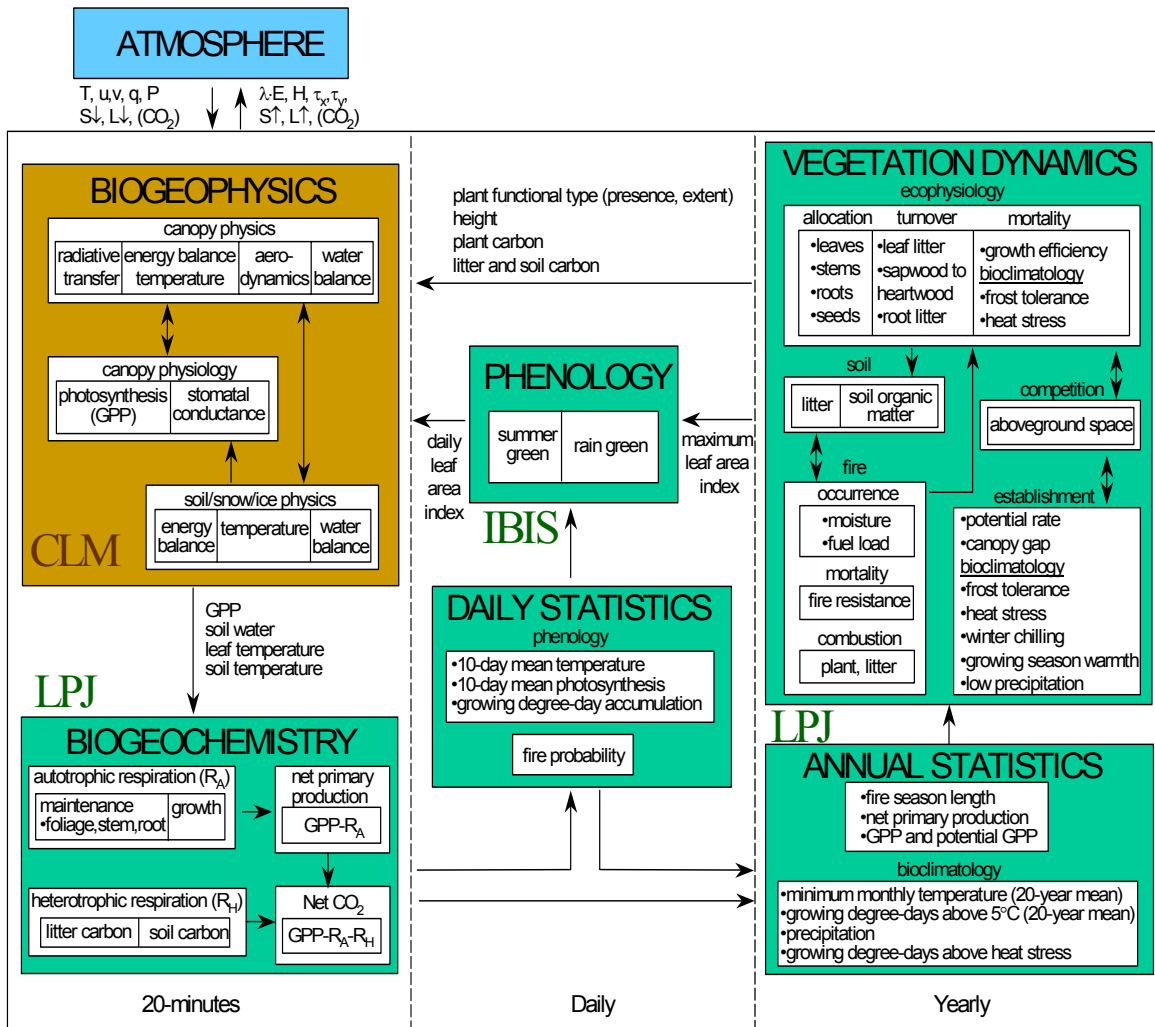


Table 1. Rules that delineate plant functional type biogeography according to climate. Adapted from Table 1 of Bonan *et al.* (2003). $T_{c,min}$, coldest minimum monthly air temperature (20-year running mean) for survival of previously established pfts; $T_{c,max}$, warmest minimum monthly air temperature (20-year running mean) for establishment of new pfts; GDD_{min} , minimum annual growing degree-days above 5°C (20-year running mean) for establishment of new pfts. Annual precipitation must exceed 100 mm yr⁻¹ for establishment of new pfts. Pfts must be able to survive in order to establish.

Plant Functional Type (pft)	Survival		Establishment
	$T_{c,min}$ (°C)	$T_{c,max}$ (°C)	GDD_{min}
Trees			
Tropical broadleaf evergreen tree (BET)	15.5	No limit	0
Tropical broadleaf deciduous tree (BDT)	15.5	No limit	0
Temperate needleleaf evergreen tree (NET)	-2.0	22.0	900
Temperate broadleaf evergreen tree (BET)	3.0	18.8	1200
Temperate broadleaf deciduous tree (BDT)	-17.0	15.5	1200
Boreal needleleaf evergreen tree (NET)	-32.5	-2.0	600
Boreal deciduous	No limit	-2.0	350
Grasses			
C ₄	15.5	No limit	0
C ₃	-17.0	15.5	0
C ₃ arctic	No limit	-17.0	0

2. The Processes

2.1 Net Primary Production: Linking Processes Across Time Scales

Simulated vegetation processes span a wide range of temporal scales in CLM-DGVM. We start our detailed description with fast processes calculated at a sub-hourly time step and explain how these link to processes at longer time scales.

Net primary production is defined as plant photosynthesis, A (see section 8, Oleson *et al.* (2004)) minus autotrophic respiration, R_a , where R_a is given by:

$$R_a = R_g + R_m \quad (\text{Eq. 1})$$

where R_g is growth respiration and R_m is the sum of maintenance respiration for leaves, R_{leaf} , sapwood, R_{sapwood} , and roots, R_{root} :

$$R_g = 0.25 (A - R_m) \quad (\text{Eq. 2})$$

$$R_m = R_{\text{leaf}} + R_{\text{sapwood}} + R_{\text{root}} \quad (\text{Eq. 3})$$

$$R_{\text{leaf}} = r \cdot k \frac{C_{\text{leaf}}}{\text{cn}_{\text{leaf}}} \phi \cdot g(T) \cdot \frac{2 \times 10^6 P}{28.5 \cdot \text{FPC}} \quad (\text{Eq. 4})$$

$$R_{\text{root}} = r \cdot k \frac{C_{\text{root}}}{\text{cn}_{\text{root}}} \phi \cdot g(T) \cdot \frac{2 \times 10^6 P}{28.5 \cdot \text{FPC}} \quad (\text{Eq. 5})$$

$$R_{\text{sapwood}} = r \cdot k \frac{C_{\text{sapwood}}}{\text{cn}_{\text{sapwood}}} \cdot g(T) \cdot \frac{2 \times 10^6 P}{28.5 \cdot \text{FPC}} \quad (\text{Eq. 6})$$

where A and the respiration terms have units of $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ pft area s}^{-1}$; r is a pft-dependent coefficient in grams of carbon per gram of nitrogen (g C g N^{-1}) (Table 2); k is a rate of $6.34 \times 10^{-7} \text{ s}^{-1}$; annually updated C_{leaf} , C_{sapwood} , and C_{root} represent pools of carbon in g C per average pft individual; annually updated P is the population density or number of individuals per area in the naturally vegetated landunit; constants cn_{leaf} , $\text{cn}_{\text{sapwood}}$, and cn_{root} are mass ratios equal to 29, 330, and 29 g C g N^{-1} respectively; ϕ is the

daily leaf phenology or the fraction of leaves present on a pft on a given day (section 2.11); 2×10^6 (μg biomass per g C) converts g C to μg of biomass; 28.5 (μg biomass per μmol CO_2) is a CO_2 to biomass conversion factor; FPC is the fraction of the naturally vegetated landunit occupied by a particular pft; and $g(T)$ is a temperature function:

$$g(T) = e^{308.56 \left(\frac{1}{56.02} - \frac{1}{T-227.13} \right)} \quad (\text{Eq. 7})$$

where vegetation temperature is used for leaf and sapwood respiration (Eqs. 4 and 6). The weighted average of CLM's soil temperature in the top 25 cm of soil is used for root respiration (Eq. 5). Temperature units are degrees K, unless noted otherwise.

Net primary production or dry biomass increment, Δm (μg biomass m^{-2} pft area s^{-1}), summed annually gives annual net primary production, NPP (g C m^{-2} pft area):

$$\Delta m = 28.5 (A - R_a) \quad (\text{Eq. 8})$$

$$\text{NPP} = \sum_{\text{beginning}}^{\text{endofyear}} \Delta m \cdot \Delta t \cdot 0.5 \times 10^{-6} \quad (\text{Eq. 9})$$

where 28.5 (μg biomass per μmol CO_2) is a CO_2 to biomass conversion factor, Δt is CLM's time step in seconds, and 0.5×10^{-6} g C per μg biomass converts from μg biomass to g C. The summation includes all the time steps in a year.

NPP is the main input required by the slow dynamic vegetation processes, which occur in the following order: reproduction, turnover, mortality due to negative NPP, allocation, competition for light, background and stress mortality, mortality due to fire, establishment. These processes will be described in subsequent sections in the same order.

The slow processes update the following pft variables: annual maximum leaf area index (LAI_{max}), tree canopy height (H), and fraction of the naturally vegetated landunit occupied by the pft (FPC). Phenology determines a daily value for the leaf area index,

LAI_{daily} (where $LAI_{\text{daily}} \leq LAI_{\text{max}}$ and units are m^2 leaf area m^{-2} ground area). These variables take part in the model's sub-hourly biogeophysical calculations, including photosynthesis (Oleson *et al.* 2004).

Other plant related variables needed in the model's fast biogeophysical calculations are set using equations from IBIS (Kucharik *et al.* 2000). Stem area index is defined as 25% of LAI_{max} for trees and 5% of LAI_{daily} for grasses. To prevent numerical problems associated with very small leaf and stem areas, leaf and/or stem area index is set to 0.05 when found to be between 0 and 0.05. Canopy height for grasses (in meters) is given by:

$$H = 0.25 LAI_{\text{daily}} \quad H > 0.25 \text{ m} \quad (\text{Eq. 10})$$

Canopy bottom height for trees is 1 m below H but never more than 3 m from the ground, while for grasses it is 0.20 m below H and no more than 0.05 m from the ground.

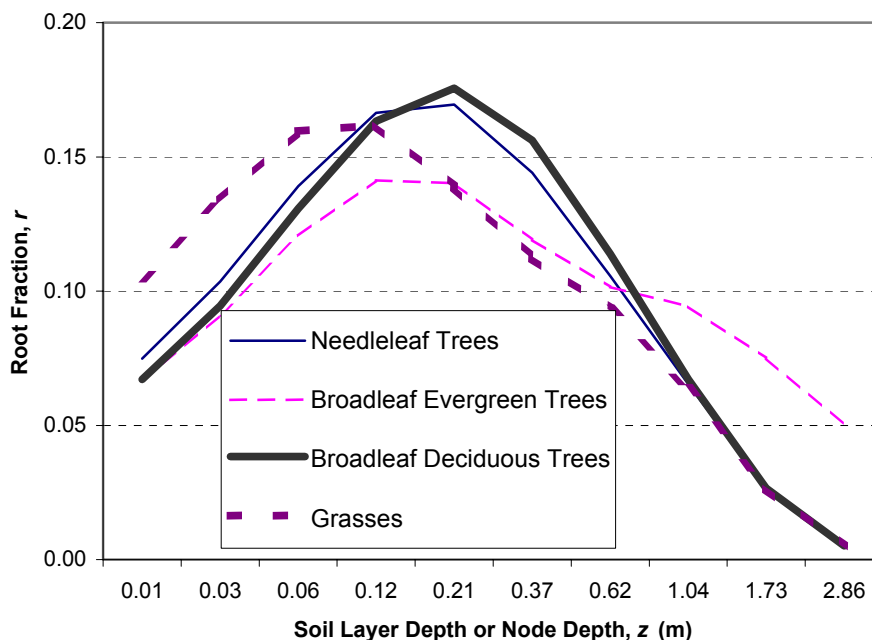
Table 2. Plant functional type-dependent parameters. Adapted from Table 2 of Bonan *et al.* (2003). Phenology denotes evergreen (E), raingreen (R), or summergreen (S) leaf phenology. The plant functional types are defined in Table 1.

Plant Functional Type (pft)	Phenology	Unstressed	Live Leaf	Tissue Longevity (yr)			Maximum	Respiration	Fire
		Leaf-to-Root Ratio	Longevity (yr)	f_{leaf}^{-1}	f_{sapwood}^{-1}	f_{root}^{-1}	Mortality (% yr ⁻¹)	Coefficient (g C g N ⁻¹)	Resistance
		l_{rmax}	a_{leaf}				k_{mort1}	r	r_{fire}
Trees									
Tropical BET	E	1.00	2.0	2	20	2	1	0.50	0.12
Tropical BDT	R	1.00	0.5	1	20	1	1	0.50	0.50
Temperate NET	E	1.00	2.0	2	20	2	1	1.20	0.12
Temperate BET	E	1.00	1.0	1	20	1	1	1.20	0.50
Temperate BDT	S	1.00	0.5	1	20	1	1	1.20	0.12
Boreal NET	E	1.00	2.0	2	20	2	1	0.60	0.12
Boreal deciduous	S	1.00	0.5	1	20	1	3	0.60	0.12
Grasses									
C ₄	-	0.75	1.0	1	1	2	1	1.20	-
C ₃	-	0.75	1.0	1	1	2	1	0.60	-
C ₃ arctic	-	0.75	1.0	1	1	2	1	0.60	-

2.2 Competition for Water

In CLM's photosynthesis calculation, pfts located in the same grid cell compete for soil water. In particular, CLM-DGVM places all pfts in one column of the naturally vegetated landunit. Although pfts share the same soil water, their rooting profiles determine access to that water, and this influences their productivity. Grasses have more roots near the surface than other pfts, which allow them to access rainwater first, giving them an advantage in relatively dry climates. Broadleaf evergreen trees have more roots than other pfts in deeper soils, which allow them to access the long-term storage of soil moisture, limiting them to relatively wet climates (Figure 2).

Figure 2. Root fraction profiles. The plant functional types in this figure correspond to the ones listed in Table 1 grouped according to rooting profiles (Oleson *et al.* 2004).



2.3 Reproduction

The cost of reproduction, ΔC_{reprod} , is assumed to be a constant fraction of annual net primary production, NPP. This fraction is set to 0.1 for all pfts (Sitch *et al.* 2003). Reproductive structures enter above ground litter, $C_{L,\text{ag}}$, directly. NPP is reduced by the same amount:

$$C_{L,\text{ag}} = C_{L,\text{ag}} + \Delta C_{\text{reprod}} \quad (\text{Eq. 11})$$

$$\text{NPP} = \text{NPP} - \Delta C_{\text{reprod}} \quad (\text{Eq. 12})$$

2.4 Turnover

The amount of living carbon that enters the above and below ground litter pools and the amount of sapwood that turns to heartwood annually are calculated given pft-specific longevity values for various types of plant tissue (Table 2). Each year's so-called biomass turnover, ΔC_{turn} (g C yr^{-1}), is calculated as the following sum:

$$\Delta C_{\text{turn}} = C_{\text{leaf}} f_{\text{leaf}} + C_{\text{sapwood}} f_{\text{sapwood}} + C_{\text{root}} f_{\text{root}} \quad (\text{Eq. 13})$$

where C_{leaf} , C_{sapwood} , and C_{root} are leaf, sapwood, and root carbon (g C per average individual), while f_{leaf} , f_{sapwood} , and f_{root} are leaf, sapwood, and root turnover times (yr^{-1}) or the inverse of the pft-dependent tissue longevities (Table 2). C_{leaf} , C_{sapwood} , and C_{root} are reduced by each carbon pool's turnover amount, ΔC_{leaf} , $\Delta C_{\text{sapwood}}$, or ΔC_{root} :

$$\Delta C_{\text{leaf}} = C_{\text{leaf}} f_{\text{leaf}} \quad (\text{Eq. 14})$$

$$\Delta C_{\text{sapwood}} = C_{\text{sapwood}} f_{\text{sapwood}} \quad (\text{Eq. 15})$$

$$\Delta C_{\text{root}} = C_{\text{root}} f_{\text{root}} \quad (\text{Eq. 16})$$

Sapwood, C_{sapwood} , turns over to heartwood, $C_{\text{heartwood}}$, while leaves and roots turn over to above and below ground litter, $C_{L,\text{ag}}$ and $C_{L,\text{bg}}$:

$$\Delta C_{\text{heartwood}} = C_{\text{sapwood}} f_{\text{sapwood}} \quad (\text{Eq. 17})$$

$$\Delta C_{\text{L,ag}} = C_{\text{leaf}} f_{\text{leaf}} P \quad (\text{Eq. 18})$$

$$\Delta C_{\text{L,bg}} = C_{\text{root}} f_{\text{root}} P \quad (\text{Eq. 19})$$

where P is the population density (number of individuals m^{-2} naturally vegetated landunit area). Note the difference in units between carbon in litter (g C per m^2 of naturally vegetated landunit area) and carbon in plant tissue (g C per average individual).

2.5 Mortality Due to Negative Net Primary Production

When a pft ends the year with negative net primary production, NPP, the pft is removed from the grid cell and its carbon is converted to litter. Above and below ground litter, $C_{\text{L,ag}}$ and $C_{\text{L,bg}}$, increase by $\Delta C_{\text{L,ag}}$ and $\Delta C_{\text{L,bg}}$ respectively:

$$\Delta C_{\text{L,ag}} = (C_{\text{leaf}} + C_{\text{sapwood}} + C_{\text{heartwood}}) P \quad (\text{Eq. 20})$$

$$\Delta C_{\text{L,bg}} = C_{\text{root}} P \quad (\text{Eq. 21})$$

Refer to section 2.4 for a description of these variables.

2.6 Allocation

The year's NPP allocated to tree leaves, sapwood, and roots (C_{leaf} , C_{sapwood} , C_{root}) is determined assuming three basic allometric relationships (Sitch *et al.* 2003):

1) Leaf area, LA (m^2 of leaves per individual), is proportional to the sapwood cross sectional area, SA (m^2 of sapwood cross sectional area per individual), according to the “pipe model” (Shinozaki *et al.* 1964a,b; Waring *et al.* 1982):

$$\text{LA} = k_{\text{la:sa}} \cdot \text{SA} \quad (\text{Eq. 22})$$

The proportionality coefficient, $k_{\text{la:sa}}$, equals 8000 m^2 of leaf area per m^2 of sapwood area.

2) Leaf mass, C_{leaf} (g C per individual), is proportional to root mass, C_{root} (g C per individual), with greater allocation to roots as water stress increases:

$$C_{\text{leaf}} = l_{\text{rmax}} \omega C_{\text{root}} \quad (\text{Eq. 23})$$

where l_{rmax} is the ratio of leaf to root mass assuming unlimited soil water (Table 2) and ω (fraction ranging from 0 to 1) is the ratio of actual annual gross primary production to the potential annual production assuming unlimited soil water. Annual gross primary production is defined as the annual sum of photosynthesis, A . Potential gross primary production assuming unlimited soil water is calculated by removing the effect of β_t on photosynthesis (section 8, Oleson *et al.* (2004)). (In LPJ version 1, ω is the ratio of soil water supply to potential demand.)

3) Height, H (m), and crown area, CA (m^2), are allometric functions of stem diameter, D (m):

$$H = k_{\text{allom2}} D^{k_{\text{allom3}}} \quad (\text{Eq. 24})$$

$$CA = k_{\text{allom1}} D^{k_{\text{rp}}} \quad CA \leq 15 \text{ m}^2 \quad (\text{Eq. 25})$$

where $k_{\text{allom1}} = 100$, $k_{\text{allom2}} = 40$, $k_{\text{allom3}} = 0.5$, and $k_{\text{rp}} = 1.6$.

Starting with these three assumptions, a complete mathematical derivation of the year's biomass increments for leaves, ΔC_{leaf} , roots, ΔC_{root} , and sapwood, $\Delta C_{\text{sapwood}}$, can be found inside CLM-DGVM in the comments section of subroutine Allocation. Negative allocation to a particular carbon pool is permitted. In this case, the killed leaf, root, or sapwood carbon becomes above ground litter, $C_{\text{L,ag}}$, below ground litter, $C_{\text{L,bg}}$, and heartwood, $C_{\text{heartwood}}$, respectively.

Allocation for herbaceous plants is simpler. Leaves and roots share each year's NPP according to the leaf-to-root ratio, l_{rmax} (Table 2). In CLM-DGVM the effect of wa-

ter stress on herbaceous leaf-to-root ratio was removed to improve the global distribution of grasses in offline simulations.

For each pft, the average individual's leaf area index, LAI_{ind} , and fractional projective cover, FPC_{ind} , are updated given the new C_{leaf} , where the subscript "ind" refers to the average individual pft. Also, each pft's fractional projective cover relative to the naturally vegetated landunit area, FPC , is updated:

$$LAI_{ind} = \frac{C_{leaf} \cdot SLA}{CA} \quad CA > 0 \quad (\text{Eq. 26})$$

$$LAI_{ind} = 0 \quad CA \leq 0$$

$$FPC_{ind} = 1 - e^{-0.5 \cdot LAI_{ind}} \quad (\text{Eq. 27})$$

$$FPC = CA \cdot P \cdot FPC_{ind} \quad (\text{Eq. 28})$$

where CA is the average individual's crown area in m^2 . CA for grasses is set to 1 because they are assumed to always consist of only one individual per naturally vegetated landunit. Specific leaf area, SLA ($m^2 \text{ leaf } g^{-1} C$), is given according to Reich *et al.* (1997):

$$SLA = 2 \times 10^{-4} \cdot \frac{e^{6.15}}{(12a_{leaf})^{0.46}} \quad (\text{Eq. 29})$$

where a_{leaf} is the pft-specific longevity of live leaves (Table 2), as opposed to the longevity of leaf tissue, which is used in turnover calculations (section 2.4).

2.7 Competition for Light

Due to taller stature, trees capture incoming solar radiation before it reaches the grasses below. As a result, trees outcompete grasses when other resources (e.g. water) are not limiting. Mortality due to shading, otherwise named aboveground competition or competition for light, is treated in CLM-DGVM as competition for available space.

First, the fractional projective cover calculated in section 2.6 summed over all tree pfts, FPC_{woody} , is limited to 95% of the naturally vegetated landunit. Excess tree cover, FPC_{excess} , is removed from each tree pft in proportion to the pft's FPC increment, ΔFPC_{pft} :

$$FPC_{\text{excess}} = (FPC_{\text{woody}} - 0.95) \frac{\Delta FPC_{\text{pft}}}{\Delta FPC_{\text{woody}}} \quad (\text{Eq. 30})$$

where

$$\Delta FPC_{\text{pft}} = FPC_y - FPC_{y-1} \quad (\text{Eq. 31})$$

where y is the current year, $y-1$ is the previous year, and $\Delta FPC_{\text{woody}}$ is the FPC increment summed for tree pfts. If $\Delta FPC_{\text{woody}}$ equals 0 and FPC_{woody} is greater than 0.95, then FPC_{excess} is divided equally among existing tree pfts.

The amounts of leaf, sapwood, heartwood, and root carbon (C_{leaf} , C_{sapwood} , $C_{\text{heartwood}}$, C_{root}) corresponding to FPC_{excess} are transferred to above and below ground litter, $C_{L,\text{ag}}$ and $C_{L,\text{bg}}$. The population density, P , of trees is adjusted accordingly, representing a self-thinning process due to finite space in a grid cell:

$$P_{\text{excess}} = \frac{P \cdot FPC_{\text{excess}}}{FPC} \quad (\text{Eq. 32})$$

$$P = P - P_{\text{excess}} \quad (\text{Eq. 33})$$

$$C_{L,\text{ag}} = C_{L,\text{ag}} + P_{\text{excess}} (C_{\text{leaf}} + C_{\text{sapwood}} + C_{\text{heartwood}}) \quad (\text{Eq. 34})$$

$$C_{L,\text{bg}} = C_{L,\text{bg}} + P_{\text{excess}} C_{\text{root}} \quad (\text{Eq. 35})$$

Tree and grass cover combined, FPC_{woody} plus FPC_{herb} , cannot exceed 100% of the naturally vegetated landunit. Excess grass cover, FPC_{excess} , is given by:

$$FPC_{\text{excess}} = \frac{(FPC_{\text{woody}} + FPC_{\text{herb}} - 1) FPC}{FPC_{\text{herb}}} \quad (\text{Eq. 36})$$

Leaf and root carbon, above and below ground litter (C_{leaf} , C_{root} , $C_{\text{L,ag}}$, and $C_{\text{L,bg}}$) are all updated by calculating the change in leaf and root carbon, ΔC_{leaf} and ΔC_{root} , with the removal of $\text{FPC}_{\text{excess}}$:

$$\Delta C_{\text{leaf}} = C_{\text{leaf}} - \frac{-2 \log[1 - (\text{FPC} - \text{FPC}_{\text{excess}})]}{\text{SLA}} \quad (\text{Eq. 37})$$

$$\Delta C_{\text{root}} = C_{\text{root}} - \frac{C_{\text{root}} \cdot \Delta C_{\text{leaf}}}{C_{\text{leaf}}} \quad (\text{Eq. 38})$$

$$C_{\text{leaf}} = C_{\text{leaf}} - \Delta C_{\text{leaf}} \quad \text{and} \quad C_{\text{root}} = C_{\text{root}} - \Delta C_{\text{root}} \quad (\text{Eq. 39})$$

$$C_{\text{L,ag}} = C_{\text{L,ag}} + \Delta C_{\text{leaf}} \quad \text{and} \quad C_{\text{L,bg}} = C_{\text{L,bg}} + \Delta C_{\text{root}} \quad (\text{Eq. 40})$$

FPC is now updated for tree and grass pfts given the new C_{leaf} (as shown in Eq. 28).

2.8 Background Mortality and Mortality Due to Stress

For each tree pft, a fraction of individuals is removed and converted to litter every year due to background mortality, $\text{mort}_{\text{greff}}$, and mortality due to heat stress, $\text{mort}_{\text{heat}}$:

$$\text{mort}_{\text{greff}} = \frac{k_{\text{mort1}}}{1 + k_{\text{mort2}} \cdot \text{greff}} \quad (\text{Eq. 41})$$

$$\text{mort}_{\text{heat}} = \frac{\text{GDD}_{23^\circ\text{C}}}{300} \quad 0 \leq \text{mort}_{\text{heat}} \leq 1 \quad (\text{Eq. 42})$$

$$\text{mort} = \text{mort}_{\text{greff}} + \text{mort}_{\text{heat}} \quad 0 \leq \text{mort} \leq 1 \quad (\text{Eq. 43})$$

$$P = P - P \cdot \text{mort} \quad (\text{Eq. 44})$$

where k_{mort1} is the pft-dependent maximum mortality rate (% yr^{-1}) (Table 2), k_{mort2} is the coefficient of growth efficiency equal to 0.3, and greff ($\text{g C m}^{-2} \text{ leaf yr}^{-1}$) is the growth efficiency itself, given by:

$$\text{greff} = \frac{\frac{\text{NPP}}{P} - \Delta C_{\text{turn}}}{C_{\text{leaf}} \cdot \text{SLA}} \quad \frac{\text{NPP}}{P} - \Delta C_{\text{turn}} \geq 0 \quad (\text{Eq. 45})$$

where $\frac{\text{NPP}}{P} - \Delta C_{\text{turn}}$ is the annual biomass increment per individual not including turnover, ΔC_{turn} (section 2.4). $\text{GDD}_{23^\circ\text{C}}$ is the annual growing degree days above 23°C smoothed by using $T_{10\text{d}}$ (K), the 10-day running mean of surface air temperature, T_{2m} :

$$\text{GDD}_{23^\circ\text{C}} = \sum_{\text{beginning}}^{\text{endofyear}} \Delta T \quad \Delta T = [T_{10\text{d}} - (T_f + 23)] \cdot \frac{\Delta t}{86400} \geq 0 \quad (\text{Eq. 46})$$

where T_f equals 273.16 K, Δt is the CLM-DGVM time step in seconds, and 86400 is the number of seconds per day. $\text{GDD}_{23^\circ\text{C}}$ may exceed zero for boreal pfts only.

2.9 Mortality Due to Fire

Thonicke *et al.* (2001) describe this fire algorithm in detail. Fire affects every grid cell annually. However, the effect of fire depends on the length of the fire season, which is accumulated sub-hourly over the course of a year.

The length of the fire season, N (days), reset to zero every January 1st, equals the annual sum of sub-hourly fire probability, $p(W)$, calculated at time steps when surface air temperature, T_{2m} , exceeds T_f (273.16 K), and above ground litter, $C_{L,\text{ag}}$, exceeds zero:

$$p(W) = e^{-\pi \left(\frac{W}{2m_e}\right)^2} \cdot \frac{\Delta t}{86400} \quad T_{2m} > T_f \text{ and } C_{L,\text{ag}} > 0 \quad (\text{Eq. 47})$$

$$N = \sum_{\text{beginning}}^{\text{endofyear}} p(W) \quad (\text{Eq. 48})$$

where m_e , a moisture extinction coefficient, equals 0.15 and W is the top 0.5 m soil water as a fraction of the water holding capacity. W is calculated as the ratio of volumetric soil

water, $\theta_{liq} + \theta_{ice}$, to volumetric soil water at saturation, θ_{sat} (to 0.5 m soil depth). Volumetric soil water is defined in section 7 of Oleson *et al.* (2004). Δt and 86400 were defined in Eq. 46.

Once per year, fire affects a fraction, $A(s)$, of the area occupied by each pft, where s is the length of the fire season as a fraction of a year:

$$s = \frac{N}{365} \quad (\text{Eq. 49})$$

$$A(s) = s \cdot e^{\left[\frac{s-1}{-0.13(s-1)^3 + 0.6(s-1)^2 + 0.8(s-1) + 0.45} \right]} \geq 0.001 \quad (\text{Eq. 50})$$

$$A(s) = 0.001 \quad \text{when} \quad C_{L,ag} \leq 200 \text{ g C m}^{-2} \cdot \text{FPC}$$

where the expression containing above ground litter, $C_{L,ag}$, represents a fuel limitation on the propagation of fire. Fuel becomes limiting when $C_{L,ag}$ is less than 200 g C m^{-2} of naturally vegetated landunit area. This value multiplied by FPC becomes g C m^{-2} of pft area. The coefficients in the formula for $A(s)$ have changed in later versions of LPJ, leading to increased $A(s)$ for $s > 0.5$ yr and decreased $A(s)$ for $s < 0.5$ yr.

Fire affects trees by removing a number of individuals, P_{disturb} :

$$P_{\text{disturb}} = (1 - r_{\text{fire}}) A(s) P \quad (\text{Eq. 51})$$

where r_{fire} is a pft dependent resistance to fire (Table 2). Fire does not kill grasses because they are assumed to be annuals ($P_{\text{disturb}} = 0$).

The carbon flux to the atmosphere due to biomass burning is Φ_{fire} (g C m^{-2}):

$$\Phi_{\text{fire}} = P_{\text{disturb}} (C_{\text{leaf}} + C_{\text{sapwood}} + C_{\text{heartwood}} + C_{\text{root}}) + A(s) C_{L,ag} \quad (\text{Eq. 52})$$

2.10 Establishment and Survival

Pft survival in a grid cell requires the 20-year running mean of the minimum monthly temperature, T_c , to exceed pft-dependent $T_{c,\min}$ (Table 1). Existing pfts cease to exist if they cannot survive or if they drop in density, P , below 10^{-10} individuals m^{-2} of naturally vegetated landunit area. Killed biomass becomes litter ($C_{L,\text{ag}}$ and $C_{L,\text{bg}}$) and FPC becomes zero. Existing pfts that can survive in the current climate continue to exist without change. Pfts not present in the grid cell continue to not exist unless they can establish.

Establishment is stricter than survival, requiring additionally that T_c be less than pft dependent $T_{c,\max}$ (Table 1), $\text{GDD}_{5^\circ\text{C}}$ be greater than pft dependent GDD_{\min} (Table 1), and $\text{GDD}_{23^\circ\text{C}}$ be equal to 0. $\text{GDD}_{5^\circ\text{C}}$ is the 20-year running mean of the annual growing degree days above 5°C , which on an annual basis is calculated as $\text{GDD}_{23^\circ\text{C}}$ (Eq. 46) but using T_{2m} instead of T_{10d} . Establishment also requires the 365-day running mean of precipitation be greater than 100 mm yr^{-1} .

When tree pfts establish, a grid-level establishment rate of new individuals, ΔP , is determined:

$$\Delta P = \Delta P_{\max} \frac{1 - e^{-5(1 - \text{FPC}_{\text{woody}})}}{n_{\text{est,woody}}} (1 - \text{FPC}_{\text{woody}}) \quad (\text{Eq. 53})$$

where $\Delta P_{\max} = 0.24$ individuals $\text{m}^{-2} \text{ yr}^{-1}$, $\text{FPC}_{\text{woody}}$ is the fractional projective cover of trees in the naturally vegetated landunit, and $n_{\text{est,woody}}$ is the number of tree pfts establishing in the naturally vegetated landunit in the current year. If $n_{\text{est,woody}} = 0$ then $\Delta P = 0$. Multiplication by $(1 - \text{FPC}_{\text{woody}})$ results in the establishment rate at the landunit level. Now population and carbon can be incremented:

$$P_{\text{new}} = P + \Delta P \quad (\text{Eq. 54})$$

$$C_{\text{tissue}} = \frac{C_{\text{tissue}}P + C_{\text{tissue,sapl}} \cdot \Delta P}{P_{\text{new}}} \quad (\text{Eq. 55})$$

where tissue stands for leaf, sapwood, heartwood, or root. Newly established individuals are referred to as saplings. Sapling carbon pools, $C_{\text{tissue,sapl}}$, are defined using the allometric properties described in section 2.6 with the added assumptions that leaf area index is $1.5 \text{ m}^2 \text{ m}^{-2}$ and heartwood diameter is 20% of the sapwood diameter:

$$C_{\text{leaf,sapl}} = \frac{1.5 \cdot k_{\text{allom1}} \cdot 1.2^{k_{\text{rp}}} \left(\frac{4 \cdot \text{SLA}}{\pi \cdot k_{\text{la:sa}}} \right)^{0.5k_{\text{rp}}}}{\text{SLA}^{\frac{2}{2-k_{\text{rp}}}}} \quad (\text{Eq. 56})$$

$$C_{\text{sapwood,sapl}} = \frac{\rho_{\text{wood}} \cdot H_{\text{sapl}} \cdot C_{\text{leaf,sapl}} \cdot \text{SLA}}{k_{\text{la:sa}}} \quad (\text{Eq. 57})$$

$$C_{\text{heartwood,sapl}} = 0.2 \cdot C_{\text{sapwood,sapl}} \quad (\text{Eq. 58})$$

$$C_{\text{root,sapl}} = \frac{C_{\text{leaf,sapl}}}{l_{\text{rmax}}} \quad (\text{Eq. 59})$$

H_{sapl} is calculated as H (Eq. 24) and ρ_{wood} , the density of wood, equals $2 \times 10^5 \text{ g C m}^{-3}$. The complete mathematical proof for these equations is in the comments of subroutine EcosystemDynDGVMMini.

Given the new amounts of carbon per carbon pool calculated in Eq. 55, a height, H , diameter, D , and crown area, CA , must be calculated for the new average individual to satisfy the same allometric relationships one last time. C_{sapwood} and $C_{\text{heartwood}}$ may be adjusted again to satisfy these relationships. Given the new C_{leaf} , LAI_{ind} and FPC are updated and subsequently adjusted to make sure that tree cover, $\text{FPC}_{\text{woody}}$, does not exceed 95% of the naturally vegetated landunit.

Grasses can establish in areas that still remain unvegetated. If the number of new grass pfts, $n_{\text{est,herb}}$, is greater than zero, then the increase in grass cover, ΔFPC , for each grass pft becomes:

$$0 \leq \Delta\text{FPC} = \frac{1 - \text{FPC}_{\text{total}}}{n_{\text{est,herb}}} \leq \Delta\text{FPC}_{\text{max}} \quad (\text{Eq. 60})$$

where

$$\Delta\text{FPC}_{\text{max}} = \frac{\frac{-2 \cdot \text{CA} \cdot \log(1 - \Delta\text{FPC} - \text{FPC})}{\text{SLA}} - C_{\text{leaf}}}{C_{\text{leaf,sapl}}} \quad (\text{Eq. 61})$$

where $(1 - \Delta\text{FPC} - \text{FPC}) \geq 10^{-6}$. Given ΔFPC for each grass pft, the change in leaf and root carbon, ΔC_{leaf} and ΔC_{root} , are calculated:

$$\Delta C_{\text{leaf}} = \Delta\text{FPC} \cdot C_{\text{leaf,sapl}} \quad (\text{Eq. 62})$$

$$\Delta C_{\text{root}} = \Delta\text{FPC} \cdot C_{\text{root,sapl}} \quad (\text{Eq. 63})$$

to be added to C_{leaf} and C_{root} respectively. Sapling leaf carbon, $C_{\text{leaf,sapl}}$, is calculated as:

$$C_{\text{leaf,sapl}} = \frac{\text{LAI}_{\text{sapl}}}{\text{SLA}} \quad (\text{Eq. 64})$$

where LAI_{sapl} for grasses is not 1.5 as for trees but $0.001 \text{ m}^2 \text{ m}^{-2}$. Sapling root carbon, $C_{\text{root,sapl}}$, is calculated as above (Eq. 59).

Finally, LAI_{ind} is updated and the sum of FPC for all pfts is adjusted so as not to exceed 100% in each naturally vegetated landunit. The adjustment process ensures the conservation of carbon and is similar to the process discussed in section 2.7.

2.11 Phenology

Daily leaf area index, LAI_{daily} , is a fraction of the annual maximum leaf area index, LAI_{max} :

$$LAI_{\text{daily}} = \phi LAI_{\text{max}} \quad (\text{Eq. 65})$$

where LAI_{max} equals LAI_{ind} (section 2.6). The variable ϕ represents plant phenology, which is constrained to be between zero and one and determined from temperature and soil moisture. Tree phenology may be evergreen ($\phi = 1$ always), summergreen, or rain-green. Grass pfts have no predetermined phenology (Table 2).

Summergreen trees drop their leaves at a rate of $1/15 \text{ day}^{-1}$:

$$\phi = \phi - \frac{1}{15} \geq 0 \quad \text{when } T_{10\text{d}} < \max(T_f, T_c + 5) \quad (\text{Eq. 66})$$

where $T_{10\text{d}}$ is the 10-day running mean of surface air temperature (K), T_f equals 273.16 K, and T_c is the 20-year running mean of the minimum monthly temperature (K).

Leaves emerge on summergreen trees over a period equal to 50 degree-days starting when the accumulated growing degree-days above 0°C , $GDD_{0^\circ\text{C}}$, exceed 100:

$$\phi = (GDD_{0^\circ\text{C}} - 100) / 50 \quad T_{10\text{d}} \geq \max(T_f, T_c + 5) \quad (\text{Eq. 67})$$

$GDD_{0^\circ\text{C}}$ is calculated as $GDD_{23^\circ\text{C}}$ (Eq. 46), but $GDD_{0^\circ\text{C}}$ resets to 0 when $T_{10\text{d}} < T_f$.

Raingreen trees drop their leaves at a rate of $1/15 \text{ day}^{-1}$:

$$\phi = \phi - \frac{1}{15} \geq 0.1 \quad \text{when } A_{10\text{d}} - R_{\text{leaf}} < 0 \quad (\text{Eq. 68})$$

where $A_{10\text{d}}$ is the 10-day running mean of photosynthesis and R_{leaf} is leaf maintenance respiration (Eq. 4). $A_{10\text{d}} - R_{\text{leaf}} < 0$ suggests drought conditions in a water-limited climate.

While $A_{10\text{d}} - R_{\text{leaf}} < 0$, ϕ retains a minimum value of 0.1 to permit non-zero A and R_{leaf} .

Leaf emergence occurs at the same rate as senescence:

$$\phi = \phi + \frac{1}{15} \leq 1 \quad \text{when } A_{10d} - R_{\text{leaf}} \geq 0 \quad (\text{Eq. 69})$$

While testing this code, raingreen trees dominated much of the tropical rainforest by behaving like evergreen trees. For this reason we introduced the concept of enforced drought phenology as used in LPJ's phenology algorithm. When raingreen trees keep their leaves for more than 6 months, they are required to drop their leaves and must remain without leaves for six months.

Grasses respond to a blend of the summergreen and raingreen phenologies. Either way, the leaves drop at a rate of $1/5 \text{ day}^{-1}$:

$$\phi = \phi - \frac{1}{5} \geq 0 \quad \text{when } T_{10d} < T_f \quad (\text{Eq. 70})$$

$$\phi = \phi - \frac{1}{5} \geq 0.1 \quad \text{when } A_{10d} - R_{\text{leaf}} < 0 \quad (\text{Eq. 71})$$

When the senescence criteria are not true, leaves emerge at the same rate of $1/5 \text{ day}^{-1}$:

$$\phi = \phi + \frac{1}{5} < 1 \quad (\text{Eq. 72})$$

2.12 Soil Organic Matter

Litter ($C_{L,\text{ag}}$ and $C_{L,\text{bg}}$) becomes soil organic matter, which decomposes in response to heterotrophic (microbial) respiration, R_h . Although LPJ has been shown to simulate soil carbon and R_h satisfactorily (Sitch *et al.* 2003), we have not performed a similar evaluation for CLM-DGVM. Therefore, the relevant algorithm in CLM-DGVM is considered a placeholder and will not be documented or supported as part of the CLM3.0 release. For this reason CLM-DGVM has also not been tested and is not supported for fully coupled carbon simulations where atmospheric CO_2 is predicted.

Part II: User's Guide

1. Introduction

The present document will lead the user through the new option in CLM3.0 of simulating vegetation interactively. The default option of prescribing vegetation from an input file remains available as discussed in the CLM technical description (Oleson *et al.* 2004) and user's guide (Vertenstein *et al.* 2004). All CLM3.0 documentation remains valid when using the CLM-DGVM. Please consider the present document an addendum to such other documentation.

2. Three Simple Steps

2.1 Obtaining the Code

There are no special instructions for obtaining the CLM-DGVM code. CLM3.0 includes the DGVM. Also there are no special input datasets associated with the CLM-DGVM. Please follow the downloading instructions in CLM's user's guide (Vertenstein *et al.* 2004).

2.2 Running the CLM-DGVM

To enable dynamic vegetation, the user will need to “define DGVM” in the job-script provided with the code. This is identical to the change needed to enable river routing using the river transport model (“define RTM”), as detailed in CLM's user's guide (Vertenstein *et al.* 2004).

The model time step can be as long as 30 minutes in offline mode. The model time step can be 30 minutes in CAM mode at T31 horizontal resolution and 20 minutes in CAM mode at T42 horizontal resolution. The model time step must be 20 minutes when running in CCSM mode at T31 or T42 horizontal resolution. In CAM mode and CCSM mode, the land model and the atmosphere model must use the same time step.

Once the above issues are taken care of, the model can run with dynamic vegetation in any configuration allowed by the standard CLM. The model may be applied globally, regionally, or locally; the model can have river transport defined; the model may start as an initial, restart, or branch run. (NB: Bit-for-bit restarts are not supported with DGVM enabled on the Cray X1 when processor configuration is changed mid-run.)

2.3 CLM-DGVM Output

CLM-DGVM produces a dynamic vegetation history file in addition to the usual CLM output. The file name follows the naming convention caseid.clm2.hv.yyyy-01-01-00000.nc, where yyyy-01-01-00000 refers to midnight on January 1st of model year yyyy. (See the CLM user's guide for the model's general file naming convention.) This history file contains grid information, as well as the following annually updated variables:

BURN: fraction of naturally vegetated landunit burned (variable $A(s)$: part I section 2.9).

CFLUXFIRE: carbon flux to the atmosphere due to fire (g C m^{-2} of naturally vegetated landunit area) (variable Φ_{fire} : part I section 2.9).

NPP: net primary production (g C m^{-2} of plant functional type area; note different area unit) (variable NPP: part I section 2.1)

Rh: heterotrophic respiration (g C m^{-2} of naturally vegetated landunit area) (variable R_h : part I section 2.12).

PFT: plant functional type (pft: concept first mentioned in part I section 1.1).

FPCGRID: pft fractional cover relative to the naturally vegetated landunit area (FPC: first defined in part I section 2.1).

LCIND: grams of leaf carbon per individual (C_{leaf} : part I section 2.1).

RCIND: grams of root carbon per individual (C_{root} : part I section 2.1).

SCIND: grams of sapwood carbon per individual (C_{sapwood} : part I section 2.1).

HCIND: grams of heartwood carbon per individual ($C_{\text{heartwood}}$: part I section 2.1).

NIND: number of individuals per m^2 naturally vegetated landunit area (P : part I section 2.1).

3. Initialization and Spin Up

An initial CLM-DGVM simulation may start with or without an initial file. If without, the model will use initial conditions hardwired in the code (arbitrary initialization), as described in the CLM user's guide. In this case, vegetation starts as bare ground, which means that naturally vegetated landunits have no vegetation at all. Since the model updates vegetation cover once per year, vegetation will appear on January 1st of year 2. Over the course of a few years, herbaceous pfts (grasses) will begin to dominate globally except in arid regions. Woody pfts (trees) take a long time to develop forests (from a minimum of 50 years in the tropics to more than 100 years in boreal regions). The succession of some forest ecosystems from deciduous to evergreen forest (e.g. in the boreal zone) may take more than 150 years. The accumulation of carbon in some of the slower pools may take several hundred years to reach equilibrium. The slowest carbon pool in standing vegetation is heartwood. CLM-DGVM also tracks soil carbon, but this part of the model has not been evaluated and is not discussed further.

At run time the CLM-DGVM outputs history, initial, and restart files. History files are discussed in part II section 2.3. Initial files and restart files contain variables pertaining to the dynamic vegetation. Such files may be used to begin a simulation with spun up data. A restart file contains enough information to allow a simulation to continue seamlessly from any stopping point, as though the model run had never stopped. An initial file may be used when a restart file is not available. In this case, the simulation must begin on January 1st and the vegetation will go through an adjustment period of about a decade, due to the absence of certain restart variables from initial files. (NB: Bit-for-bit

restarts are not supported with DGVM enabled on the Cray X1 when processor configuration is changed mid-run.)

4. Examples

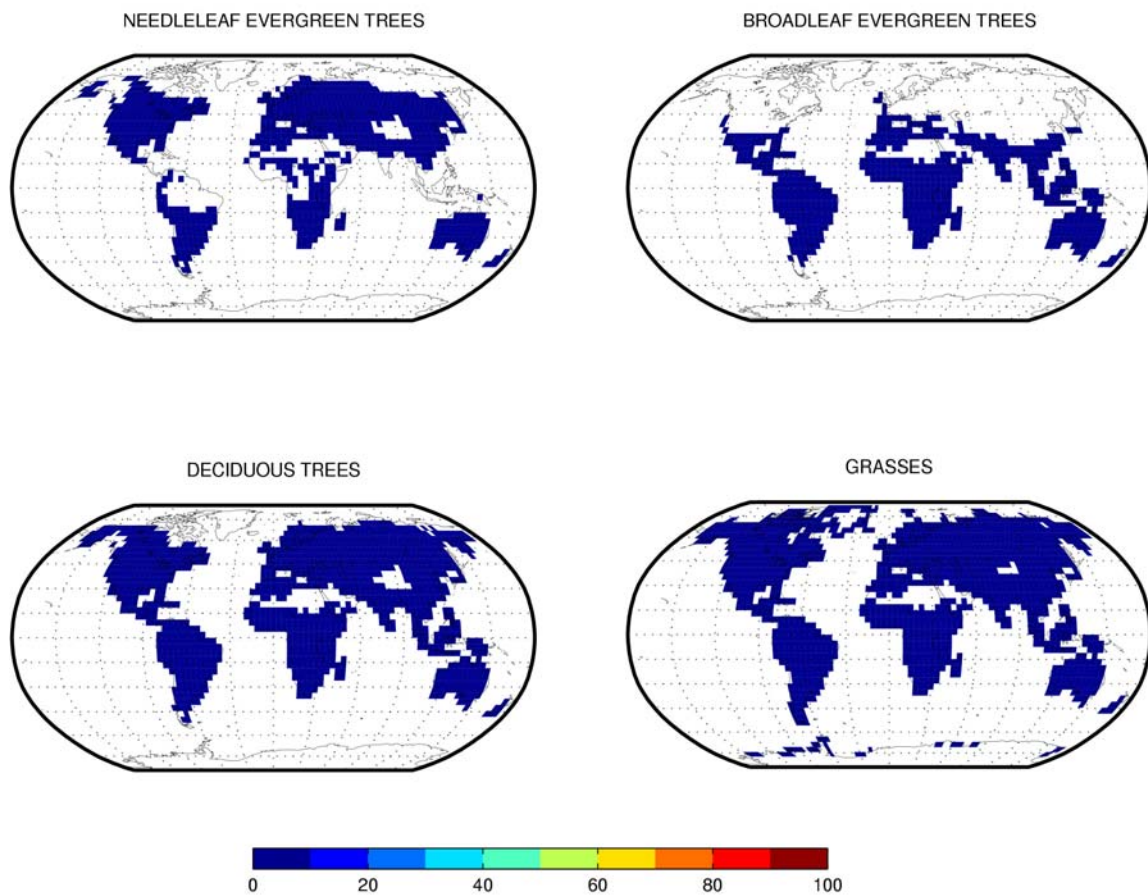
The following examples demonstrate the use of CLM-DGVM. In particular, examples 1 and 2 explain how the user may spin up the model from initially bare ground with prescribed atmospheric data. Example 3 uses spun-up vegetation from Example 2 to initialize a coupled simulation of CLM with a global climate model. Example 4 describes three methods of prescribing the vegetation in CLM-DGVM to perform sensitivity simulations. The user should not expect results identical to Figures 3 through 9 when repeating these examples due to differences in computing environments (platforms, compilers, etc.).

4.1 Example 1: One-Year Initial Simulation

Only the line “define DGVM” must be added to the jobscript of a standard CLM simulation to submit a CLM-DGVM simulation. All else may be the same. In this example, `finidat = ''` in the namelist. This means that arbitrary initial conditions will be used as explained in part II section 3 and all pfts will start from bare ground.

The slowest processes in this model are updated annually. While primary and auxiliary history files appear at a frequency defined by the user (see CLM user’s guide), the first history file containing vegetation output appears at the completion of one year. Seed amounts of vegetation begin to establish globally at that time allowing for a rough evaluation of the global pft distribution (Figure 3).

Figure 3. Global distribution of plant functional types at the end of year 1 in a CLM-DGVM simulation driven with National Center for Environmental Prediction (NCEP) data as described by Bonan *et al.* (2003). The simulation was initialized using arbitrary initialization (explained in part II section 3). The variable shown is FPC given as a percentage of the naturally vegetated landunit.



4.2 Example 2: Restart Simulation and 400-Year Spin-Up

To continue the simulation in Example 1 as a restart, the user should change `nsrest = 0` to `nsrest = 1` in the namelist. The model automatically knows which restart file to access by checking an ascii file deposited in the user's home directory when the previous simulation ended. The model can restart on any model time step, not just on January 1st. (NB: Bit-for-bit restarts are not supported with DGVM enabled on the Cray X1 when processor configuration is changed mid-run.) A history file containing vegetation output will be produced at the end of every model year. Vegetation activity will continue to appear imperceptible at first. Grass pfts will be the first to show perceptible activity after a few years (Figure 4).

After running the model for a few hundred years, the global vegetation distribution and structure stops evolving much except in response to grid cell level interannual variability (Figures 5 and 6). Only a few carbon pools continue to approach equilibrium over several more centuries, e.g. heartwood (Figure 7) and soil carbon (not shown).

Compared to a similar simulation performed using the DGVM coupled to the NCAR LSM (Bonan *et al.* 2003), which overestimated global tree cover at the expense of grass cover, the CLM-DGVM underestimates global tree cover (Figure 8). Biases in the simulation of global vegetation using the CLM-DGVM have served to point out weaknesses in the model's biogeophysical parameterizations.

Figure 4. Percent cover of plant functional types by the end of year 10 in the simulation shown in Figure 3. Variable shown is $FPC \cdot 100$ as in Figure 3.

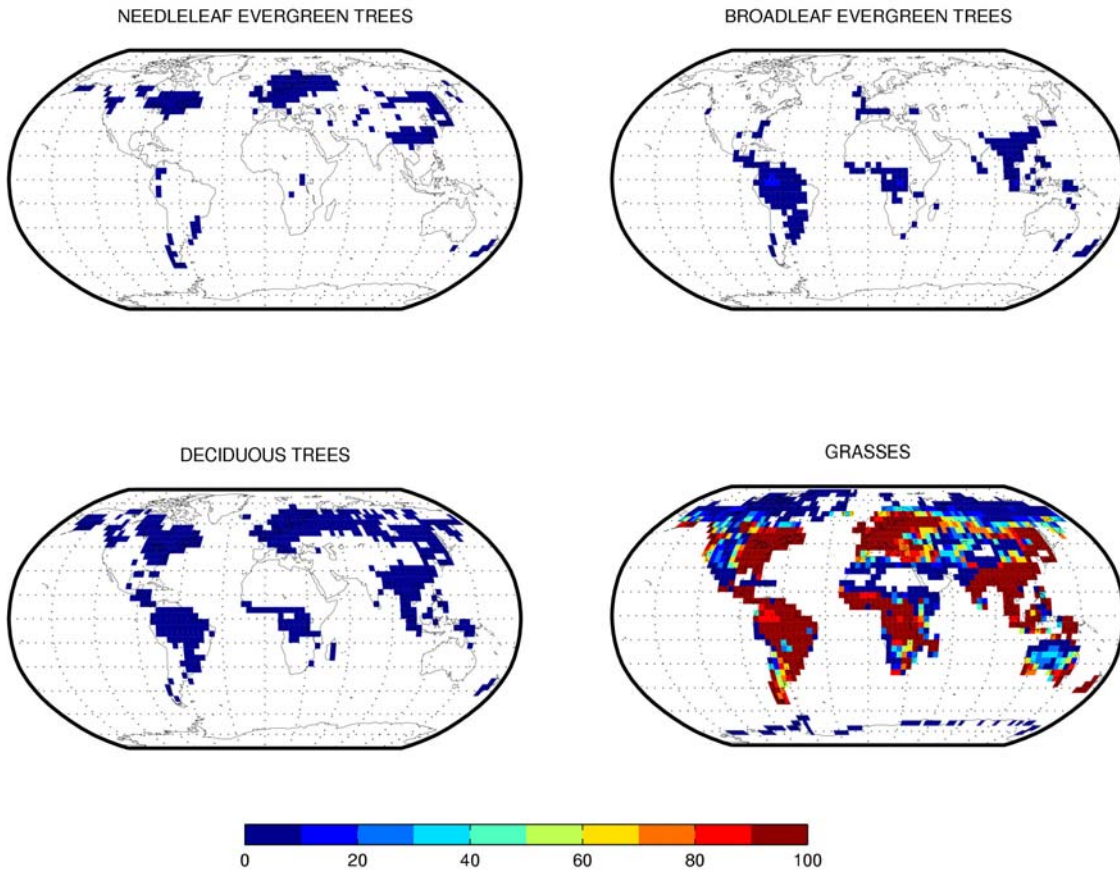


Figure 5. Global carbon flux trends in the simulation shown in Figures 3 and 4, continued to year 400. Carbon fluxes shown include net primary production, NPP (Eq. 9), heterotrophic respiration, R_h (part I section 2.12), net ecosystem production, $NEP = NPP - R_h$, and net biome production, $NBP = NEP - \Phi_{\text{fire}}$. NEP and NBP are calculated only for diagnostic purposes in CLM-DGVM. This model has not been tested and is not supported for fully coupled carbon simulations where atmospheric CO_2 is predicted.

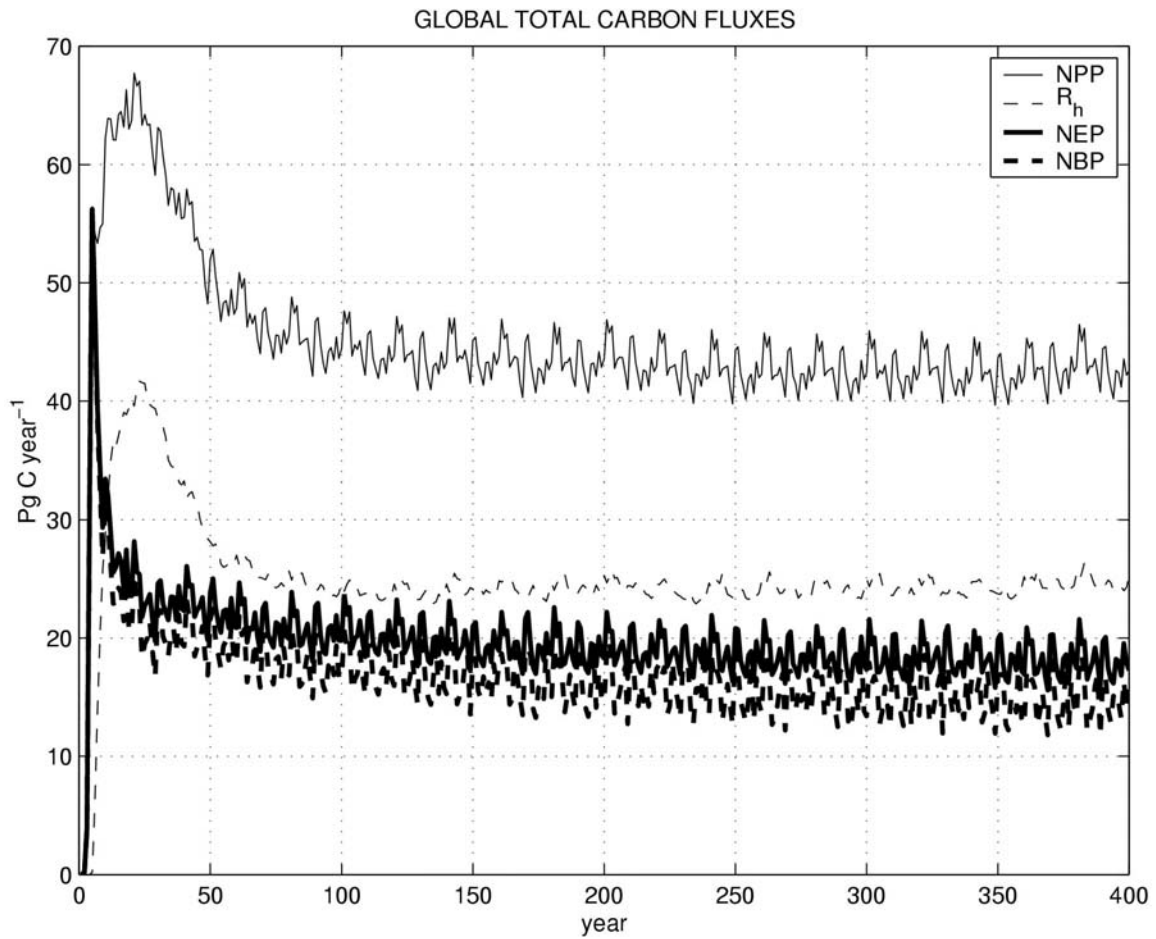


Figure 6. Global average trends in vegetation cover (variable is $FPC \cdot 100$) in the simulation shown in Figures 3 to 5. Averages include glaciated land areas, such as Antarctica and Greenland.

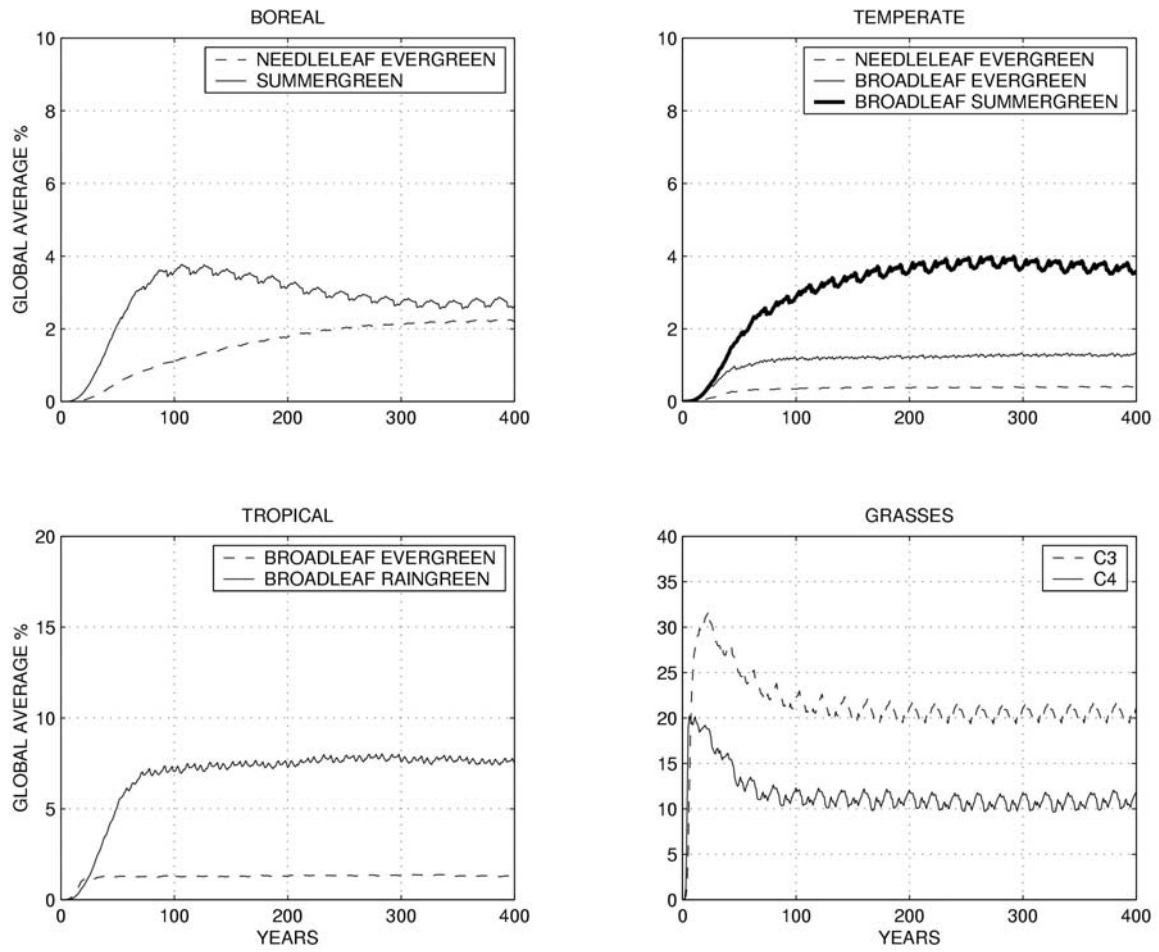


Figure 7. Global trends of the leaf, root, sapwood, and heartwood carbon pools (C_{leaf} , C_{root} , C_{sapwood} , $C_{\text{heartwood}}$) in the simulation shown in Figures 3 to 6. After 400 years C_{sapwood} and $C_{\text{heartwood}}$ are less than in Bonan *et al.* (2003) because CLM's NPP is lower (Figure 5). Please note that CLM-DGVM has not been tested and is not supported for fully coupled carbon simulations where atmospheric CO_2 is predicted.

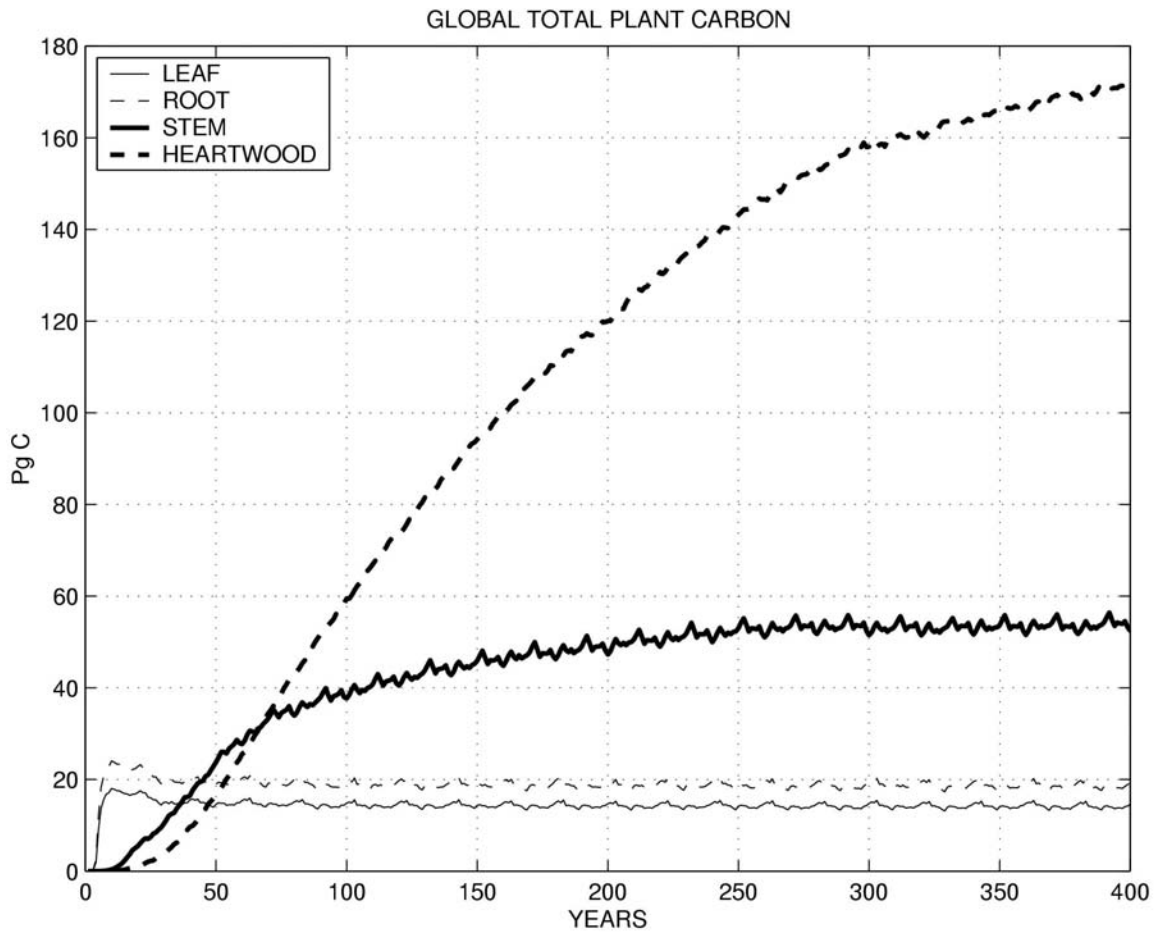
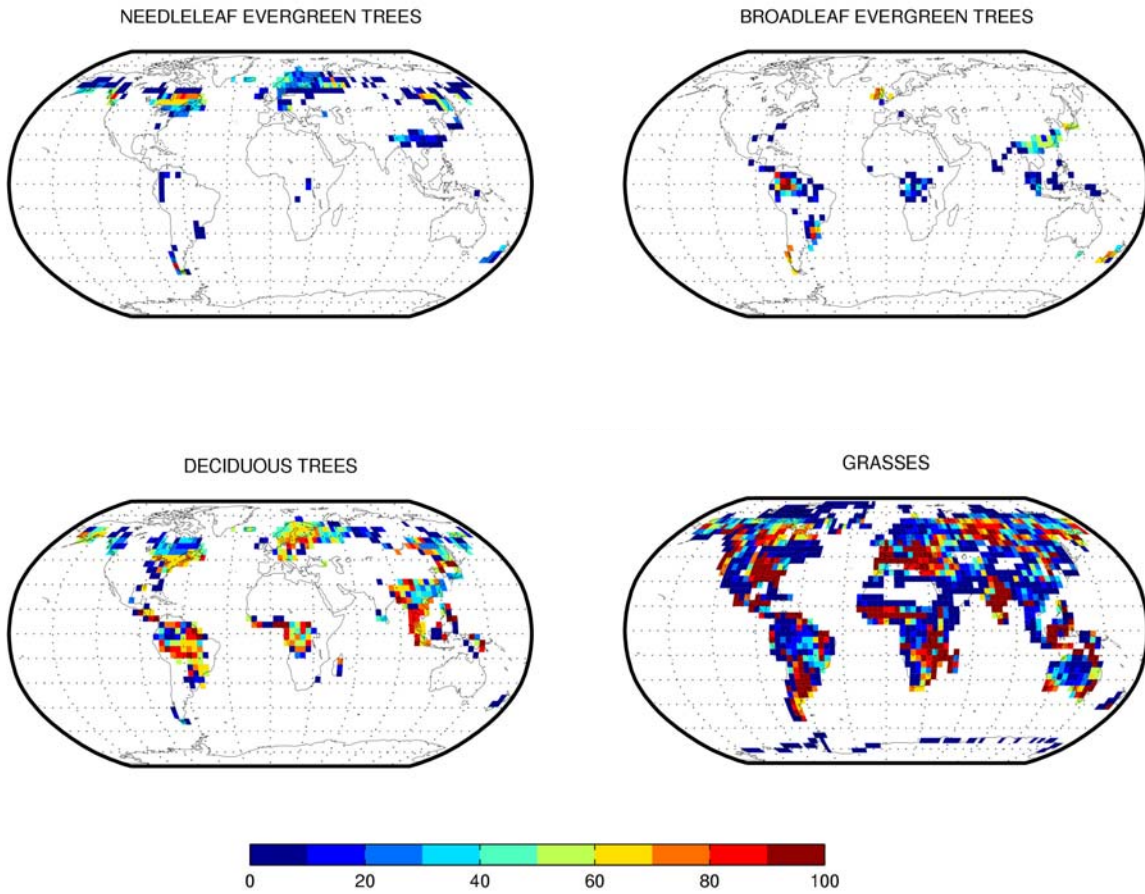


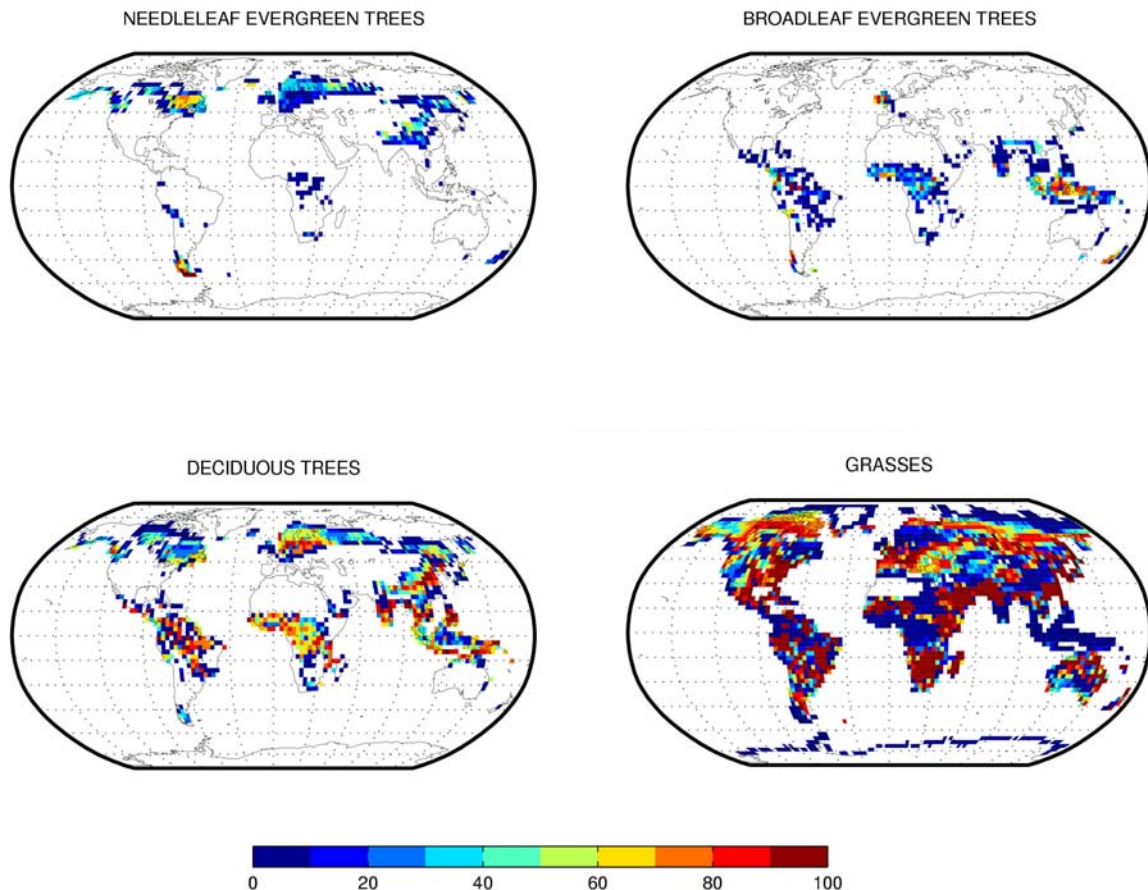
Figure 8. Percent cover of plant functional types by the end of year 400 in the simulation shown in Figures 3 to 7. Variable shown is $FPC \cdot 100$ as in Figures 3, 4, and 6.



4.3 Example 3: Running CLM-DGVM Coupled to CAM or to the CCSM

The CLM user's guide explains how to run CLM coupled to the Community Atmosphere Model (CAM) or to the Community Climate System Model (CCSM). Initializing a coupled simulation with an initial or restart file from an offline simulation saves computer resources. Figure 9 shows output from a CAM/CLM simulation initialized from year 400 of our offline simulation (Figure 8). Flaws in the coupled model's simulated vegetation serve to diagnose biases in CAM's and CCSM's simulations.

Figure 9. Percent cover ($FPC \cdot 100$) of plant functional types by the end of year 188 in a CAM/CLM simulation initialized from the simulation shown in Figures 3 to 8.



4.4 Example 4: Running with Prescribed Vegetation

Prescribing the vegetation using datasets can help isolate the effects of interactive vegetation in a CLM-DGVM simulation. We recommend three methods in order of increasing complexity:

1. Prescribed vegetation from satellite data: Set “undef DGVM” in the jobscript to run the standard CLM with prescribed present-day vegetation from satellite data. Leaf area index for every pft follows a fixed annual cycle of twelve mid-month values interpolated to daily, unique in every grid cell. The vegetation cover and structure prescribed using this method may differ considerably from the cover and structure simulated in a DGVM simulation.
2. Vegetation from prior CLM-DGVM simulation (interactive phenology): Restart from a simulation with DGVM defined but comment out the annual call to subroutine `lpj` (and related calls to `lpjreset1`, `lpjreset2`, `histDGVM`). The vegetation keeps the characteristics found in the restart file, but daily phenology remains interactive because DGVM is defined. If the climate changes during the simulation, daily leaf area index may differ considerably from that simulated in the prior, fully interactive simulation.
3. Vegetation from prior CLM-DGVM simulation (fixed phenology): Use one year or average more years of vegetation output from a CLM-DGVM simulation to make a new surface dataset. Set “undef DGVM” in the jobscript to run the standard CLM with prescribed vegetation taken from your CLM-DGVM simulation in this case. This method ranks higher than the previous methods in terms of complexity due to potential difficulties involved in making a new surface dataset. Please read the documentation on surface data in the other CLM3.0 manuals.

5. List of Subroutines

The CLM-DGVM consists of CLM3.0 as described by Oleson *et al.* (2004) plus a set of routines that allow vegetation cover and structure to be simulated instead of prescribed from data. Most of these routines are called from subroutine `lpj`, which is called from subroutine `driver` once per year. Annual (or slow) processes called from subroutine `lpj` include the update of vegetation biogeography and structure (Figure 1). On the other hand, subroutine `EcosystemDynDGVM` calls the daily or sub-hourly routines (fast processes). In particular, the exchange of carbon between plants and the atmosphere (in the form of CO_2) occurs at a sub-hourly time step. Plant phenology is calculated daily.

Following is a list of subroutines related to the DGVM portion of CLM:

DGVMrespiration: Sub-hourly. Calculates autotrophic respiration for each existing pft. The corresponding equations were adapted from the equations in subroutine npp in LPJ version 1.

Lpj: Annual. Calls the so-called slow processes in the order listed here. The model returns from subroutine lpj with updates to the following pft variables: maximum leaf area index, canopy height, and fraction of the naturally vegetated landunit occupied by the pft. These variables are used in the model's sub-hourly biogeophysical calculations.

Reproduction: Annual. Adapted from subroutine reproduction in LPJ version 1. Calculates the cost of reproduction for existing pfts and updates above ground litter and annual net primary production.

Turnover: Annual. Adapted from the subroutine by the same name in LPJ version 1. Given pft-specific longevity values for various types of plant tissue (Table 2), calculates the amount of living carbon that enters the above and below ground litter pools and the amount of sapwood that turns to heartwood.

Kill: Annual. Adapted from the subroutine by the same name in LPJ version 1. When a pft ends the year with negative net primary production, the pft is removed and its carbon converted to litter.

Allocation: Annual. Adapted from the subroutine by the same name in LPJ version 1. Determines the fractions of the year's biomass increment that become leaf, sapwood, and root carbon.

Light: Annual. Adapted from the subroutine by the same name in LPJ version 1. Deals with aboveground competition, otherwise described as mortality due to shading.

Mortality: Annual. Adapted from the subroutine by the same name in LPJ version 1. A fraction of trees is removed and converted to litter every year due to background mortality and mortality due to heat stress.

Fire: Annual. Adapted from subroutine fire in LPJ version 1. A fraction of trees and above ground litter is removed and converted to atmospheric CO₂.

Establishment: Last of the annual processes. Adapted from subroutines bioclim and establishment in LPJ version 1. This subroutine provides a seed amount of vegetation for new pfts in the presence of suitable climate conditions.

Phenology: Daily. Called from subroutine EcosystemDynDGVM to determine daily leaf area index as a fraction of the annual maximum value. Adapted from subroutine pheno in IBIS version 2 (Kucharik *et al.* 2000). Unlike LPJ's equivalent algorithm, the IBIS algorithm requires no prior knowledge of the meteorological conditions of the upcoming year. Since CLM doesn't have access to such information when coupled to a GCM, the algorithm found in IBIS was used.

FireSeason: Sub-hourly. Called from subroutine EcosystemDynDGVM to determine the length of the year's fire season. Adapted from subroutine fire in LPJ version 1.

LitterSOM: Sub-hourly. Called from subroutine EcosystemDynDGVM to convert litter to soil organic matter. Adapted from the corresponding subroutine in LPJ version 1.

EcosystemDynDGVM: Calls Phenology to determine daily leaf area index, which takes part in the photosynthesis calculation (Oleson *et al.* 2004). EcosystemDynDGVM also sets stem area index, height of the bottom of the canopy for trees, and top and bottom canopy heights for grasses, all needed in the model's biogeophysical calculations.

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