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Review Article

Dynamic Global Vegetation Models (DGVMs) and its Applicability to Climate Simulations- A Review

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Abstract

The terrestrial biosphere interacts with the atmosphere through exchanges of energy, water and momentum. On one hand, climate conditions determine the distributions and types of local vegetation and on the other the terrestrial vegetation tends to greatly influence the: (i) thermal structure of the atmosphere by changing the physical properties at the surface, such as albedo, Bowen ratio and roughness length, and (ii) chemical composition of the atmosphere via biogeochemical processes, such as photosynthesis, respiration, allocation and decomposition. Ultimately, these biophysical and biogeochemical processes of the terrestrial vegetation give substantial feedback to the climate. However, these processes and feedbacks are dependent on time and space (Myoung. *et al.*, 2011). In this regard, understanding the underlying mechanisms of the response of vegetation to climate change and, in turn, the effects of vegetation on the climate (both past and present) at various temporal and spatial scales are crucial for predicting the effects of the future climate change on terrestrial ecosystems and global carbon cycles. Reliable simulations of these interactions are crucial for predicting the potential impacts of future climate change and anthropogenic intervention on terrestrial ecosystems.

Keywords: *Biosphere, climate, vegetation, temporal and spatial ecosystems and carbon cycle*

Introduction

The terrestrial biosphere interacts with the atmosphere through exchanges of energy, water and momentum. On one hand, climate conditions determine the distributions and types of local vegetation and on the other the terrestrial vegetation tends to greatly influence the: (i) thermal structure of the atmosphere by changing the physical properties at the surface, such as albedo, Bowen ratio and roughness length, and (ii) chemical composition of the atmosphere via biogeochemical processes, such as photosynthesis, respiration, allocation and decomposition. Ultimately, these biophysical and biogeochemical processes of the terrestrial vegetation give substantial feedback to the climate. However, these processes and feedbacks are dependent on time and space (Myoung. *et al.*, 2011). In this regard, understanding the underlying mechanisms of the response of vegetation to climate change and, in turn, the effects of vegetation on the climate (both past and present) at various temporal and spatial scales are crucial for predicting the effects of the future climate change on terrestrial ecosystems and global carbon cycles. Reliable simulations of these interactions are crucial for predicting the potential impacts of future climate change and anthropogenic intervention on terrestrial ecosystems.

Terrestrial ecosystems play a significant role in the Earth system in terms of biophysical interactions and biogeochemical exchanges with the atmosphere (Prentice. *et al.*, 2000). Consequently, understanding the interactions and feedback between vegetation and the

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climate, both in the past and present, are necessary for predicting the effects of future climate change on terrestrial ecosystems and global carbon cycles (Denman. *et al.,* 2007). In the early stage of general circulation model (GCM), simple parameterizations of the land surface were employed to describe the influences of the land surface on the atmosphere and to illustrate the biophysical processes. Later, soil-vegetation- atmosphere transfer (SVAT) schemes were introduced to GCMs to estimate the interactions between the land surface, including vegetation and the atmosphere. Where in, the land surface was treated as a predefined boundary rather than as an interactive component, and vegetation itself was not allowed to respond to any changes in the climate (Arora. 2002). Thus, GCMs with SVAT schemes were not very useful for studying the influence of global warming on vegetation and their interactions. Over the last a few decades, much effort has been made to develop vegetation models to address the life cycle (e.g., establishment, growth, death, litterfall and decomposition) and geographical distribution of vegetation in other fields, such as forestry, agriculture and geography, which can be adapted and modified for use in the field of atmospheric science (Arora. 2002). For example, GCMs can be coupled with vegetation models, rather than with SVAT schemes, to describe the complex vegetation-atmosphere interactions. Simple vegetation models describe the vegetation distribution associated with local climatic conditions (e.g., biogeographical models) or estimate the growth and death of plants and carbon and nitrogen cycling under a given condition (e.g., patch and gap models). The latter often incorporates biogeochemical modules for estimating the terrestrial water and carbon fluxes (e.g., biogeochemical models).

Static Vegetation Models

Biogeographical Models

It simulate the potential natural distribution of vegetation under a given climate and place emphasis on determining the spatial distribution and types of vegetation rather than the growth of plants and cycling of the carbon, nitrogen and nutrients within ecosystems. Since the vegetation distribution is the main interest of these models, their spatial scales are relatively large, i.e., regions to global.

In general, biogeographical models are categorized into-

1. Rule-based and
2. Process-based models.

Rule-Based Model (Neilson. *et al.,* 1989)
The rule-based models employ a set of rules for determining the distribution and types of vegetation using several predictors (e.g. often a cumulative function of one or more climate variables like annual mean precipitation, temperature and soil moisture). The rules are, essentially, if-then-else statements and the values of the thresholds are empirically calibrated. The rule-based model of Neilson (Neilson. *et al.,* 1989) is based on the assumption that the global vegetation distribution is primarily determined by the climate, and can be adjusted by variations in disturbance, soil and topography.

Process-Based Models: *Biome*
In this model, terrestrial vegetation is determined by plant functional types (PFTs). PFTs are a classification of individual plant species w.r.t the plant phenology, allocation and competition for resources. In the BIOME model, PFTs are considered as an assigned climate tolerance based on variations in the climate variables (coldness, dryness, heat, chilling and moisture requirements). These climatic constraints, which are considered the fundamental ecological and physiological processes, make the BIOME model different from other bioclimatic models that largely rely on the empirical correlations between vegetation and the climate. While biomes are provided in the latter models, they are determined by the interactions of the PFTs allowed for a given climate in the BIOME model. Therefore, although BIOME is not suitable for simulating the dynamics of vegetation in a transient climate, the responses of potential vegetation patterns with different climates in an equilibrium state

can be investigated using BIOME (Myoung. *et al.*, 2011).

Biogeochemical Models

Biogeochemical models simulate the cycles of carbon, nitrogen, and nutrients in terrestrial ecosystems. Their main goal is to investigate the influences on the fluxes and allocations of carbon and nitrogen due to changes in temperature, soil water, irradiance and atmospheric CO_2 concentration. The spatial scale of the biogeochemical models is more local than that of the biogeographical models. The biogeochemical models lack the ability to make a determination on what kind of vegetation could live in a given location, and simulate changes in the species or community composition, assuming the successional shift in biogeochemical processes.

Eg- BIOME BGC and PnET

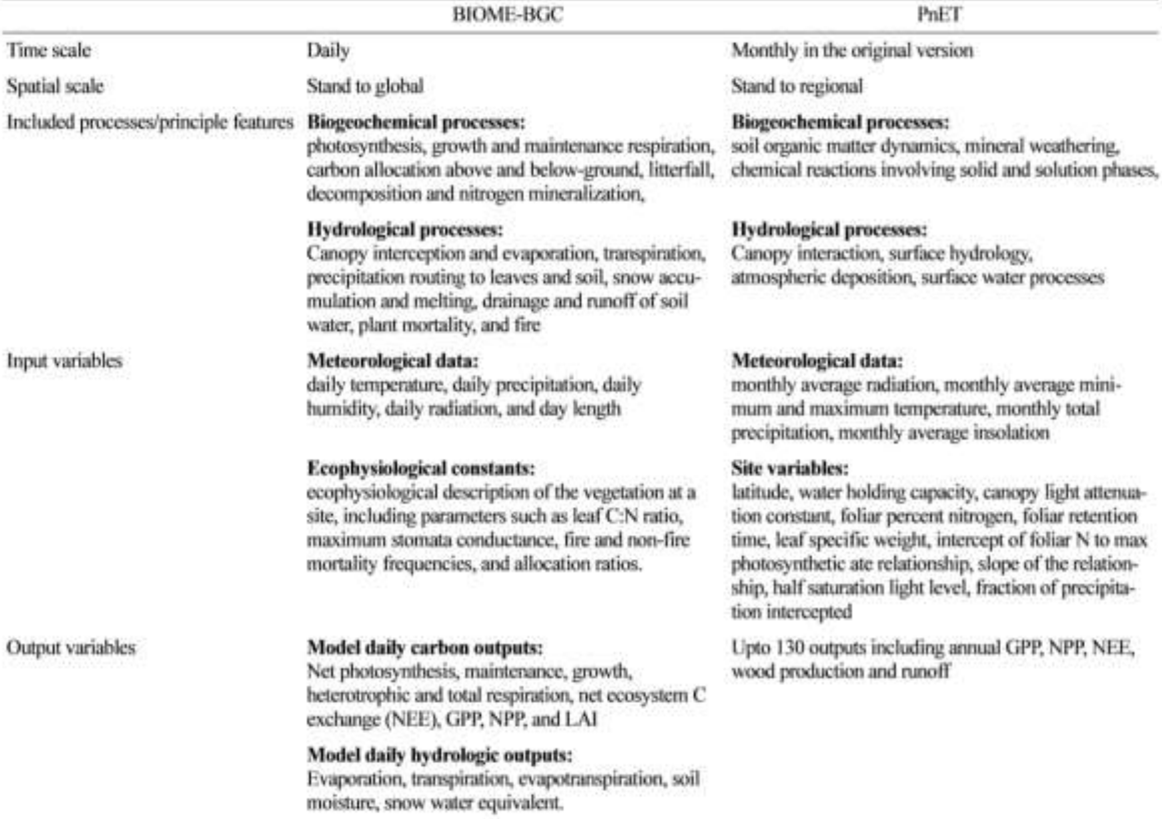
BIOME-BGC

It is an eco-physiological model with a daily time step, which captures the important plant physiological processes (e.g., photosynthesis, respiration, carbon allocation, litterfall and decomposition) and essential characteristics of the terrestrial ecosystem.Several simple rules concerning the land cover and weather conditions are employed to smooth the progress of its application on multiple spatial scales. In BIOME-BGC, dynamic vegetation processes (e.g., establishment, growth, competition, and mortality) are simply incorporated.

PnET-BGC

The group of PnET models is a forest physiology model describing the generalized relationships of vegetation processes, such as photosynthesis, respiration, transpiration, litter production and decomposition, for estimating the interactive cycles of carbon, water and nitrogen in forest ecosystems. While BIOME-BGC is applicable on a global scale, the PnET is more focused on a regional scale (Table 1).

Table 1: Distinguished features of the BIOME-BGC and PnET models



	BIOME-BGC	PnET
Time scale	Daily	Monthly in the original version
Spatial scale	Stand to global	Stand to regional
Included processes/principle features	**Biogeochemical processes:** photosynthesis, growth and maintenance respiration, carbon allocation above and below-ground, litterfall, decomposition and nitrogen mineralization,	**Biogeochemical processes:** soil organic matter dynamics, mineral weathering, chemical reactions involving solid and solution phases,
	Hydrological processes: Canopy interception and evaporation, transpiration, precipitation routing to leaves and soil, snow accumulation and melting, drainage and runoff of soil water, plant mortality, and fire	**Hydrological processes:** Canopy interaction, surface hydrology, atmospheric deposition, surface water processes
Input variables	**Meteorological data:** daily temperature, daily precipitation, daily humidity, daily radiation, and day length	**Meteorological data:** monthly average radiation, monthly average minimum and maximum temperature, monthly total precipitation, monthly average insolation
	Ecophysiological constants: ecophysiological description of the vegetation at a site, including parameters such as leaf C:N ratio, maximum stomata conductance, fire and non-fire mortality frequencies, and allocation ratios.	**Site variables:** latitude, water holding capacity, canopy light attenuation constant, foliar percent nitrogen, foliar retention time, leaf specific weight, intercept of foliar N to max photosynthetic ate relationship, slope of the relationship, half saturation light level, fraction of precipitation intercepted
Output variables	**Model daily carbon outputs:** Net photosynthesis, maintenance, growth, heterotrophic and total respiration, net ecosystem C exchange (NEE), GPP, NPP, and LAI	Upto 130 outputs including annual GPP, NPP, NEE, wood production and runoff
	Model daily hydrologic outputs: Evaporation, transpiration, evapotranspiration, soil moisture, snow water equivalent.	

***BIOME* 4**

BIOME4 is a coupled biogeography and biogeochemistry model which simulates the equilibrium distribution of 28 major potential natural vegetation types (Biomes). It is a globally accepted model to calculate net primary productivity in a large scale. This model successfully reproduces the distribution of potential natural vegetation and associated phenological, hydrological and biogeochemical properties (Kaplan. *et al.,* 2003). It is a coupled biogeography and biogeochemistry model which simulates the equilibrium distribution of 28 major potential natural vegetation types (biomes) from latitude (for the calculation of incoming short-wave and photo-synthetically active solar radiation), atmospheric CO_2 concentration, mean monthly climate (i.e. mean monthly precipitation, temperature, and percent sunshine) and soil physical properties (water holding capacity and percolation rate). Photosynthesis, stomatal behaviour and hydrology are simulated as in BIOME3 and the ecosystem dynamics model LPJ (Sitch. *et al.,* 2003).

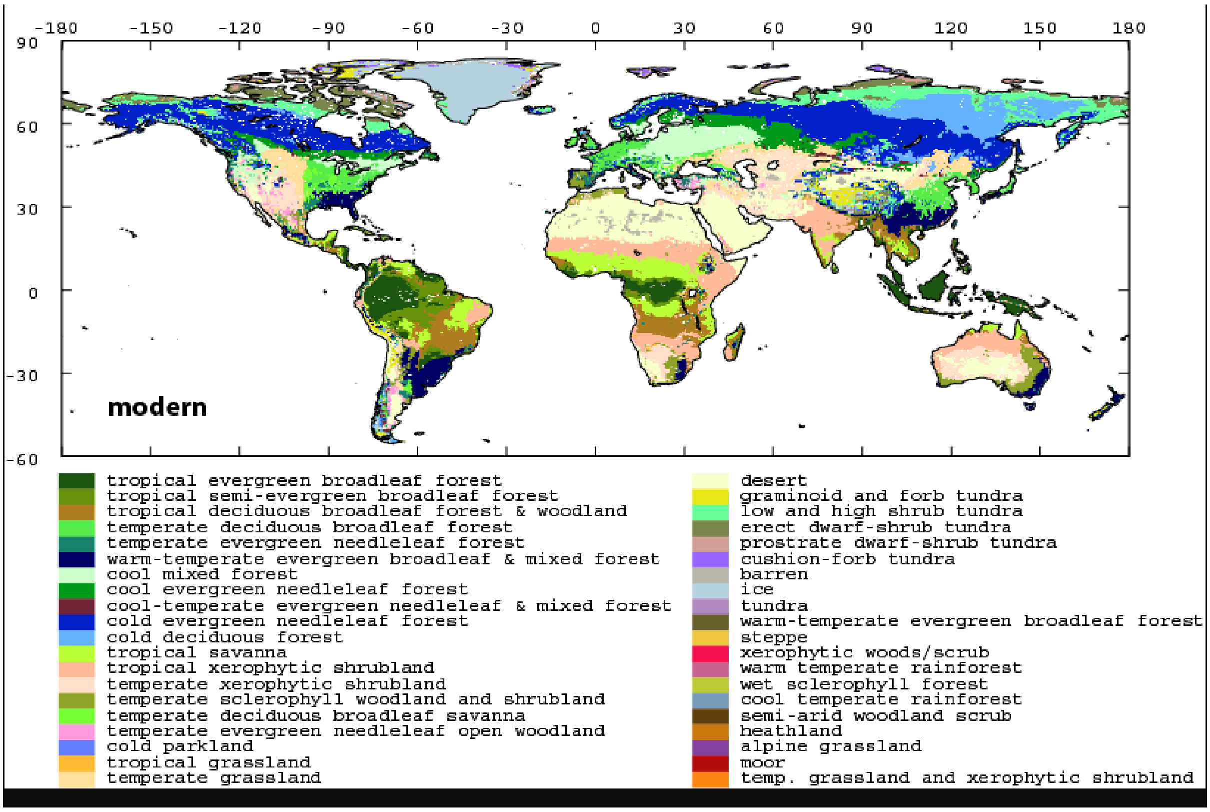


Fig.1 *Biome 4 model (Kaplan. et al., 2003)*

BIOME4 implicitly simulates competition between plant functional types (PFTs) as a function of relative net primary productivity (NPP) and uses an optimisation algorithm to calculate the maximum sustainable leaf area (LAI) of each PFT and its associated NPP. BIOME4 successfully reproduces the distribution of potential natural vegetation and associated phenological, hydrological and biogeochemical properties. In short, in SGVMs, equilibrium conditions are assumed between terrestrial vegetation and the climate and most biogeographical and biogeochemical models are static.

Limitations of the Static Vegetation Models

Bio-geographical models do not include life cycles of plant as well as carbon and nitrogen cycling. In addition, potential natural vegetation is allowed in the bio-geographical models, which do not consider natural disturbances (e.g., wildfires and storms) and anthropogenic land-use changes. The biogeochemical models lack the ability to predict the potential distribution of vegetation under given conditions and locations. Moreover, they focus on annual changes in the biogeochemistry of ecosystems under the assumption that successional shifts in biogeochemical processes and interactions do not occur. In addition, the bio-geographical as static models were initially proposed to calculate steady-state conditions and provide an overall picture of a terrestrial ecosystem in equilibrium with its climate. They are also capable of providing inferential information on the way a biosphere will be transformed from one condition to another.

Development of DGVMs

In a rapidly varying climate, models for predicting the transient changes of vegetation are more suitable for determining future projections of vegetation with respect to global warming. To meet this need, dynamic vegetation models were developed as fully dynamic versions of the spatially explicit global vegetation models through the incorporation of both biogeography and biogeochemistry processes. Complicated vegetation models have been designed to estimate the fluxes and storage of energy, water, and carbon, using algorithms to describe the biophysical and physiological processes in vegetation and soil. While the main purposes of biogeographical models (i.e., structural aspects of plants) are distinct from those of biogeochemical models (i.e., functional aspects of plants), the endeavours to couple the structural and functional aspects of vegetation over the past couple of decades have allowed the development of integrated dynamic global vegetation models (DGVMs) (Myoung. *et al.,* 2011).

Dynamic Global Vegetation Models (DGVMs)

Dynamic vegetation models simulate changes in the ecosystem geography with processes representing the dynamics of the vegetation structure and composition in relation to biogeochemical processes. It tries to simulate the transient responses of vegetation to changing climate conditions, including key ecological processes, such as establishment, growth, competition, mortality and disturbances, as well as the fundamental biophysical and physiological processes of plants (Qulliet. *et al.,* 2010). DGVMs combine biogeochemical, bio-geographical and disturbance models in general.

The key processes represented in the models are:

1. Land surface processes, including energy and water cycles,
2. Physiological processes and carbon cycles, including plant growth and carbon flux, and
3. Dynamic vegetation, including plant establishment, competition and mortality. (Fig.3 Processes in DGVMs).
4. Disturbance often refers to natural wildfires, but could include anthropogenic land-use changes, grazing, storms, insect/pest damage and human-induced wildfires, etc. (Quillet. *et al.,* 2010).

DGVM development integrated four groups of processes viz.

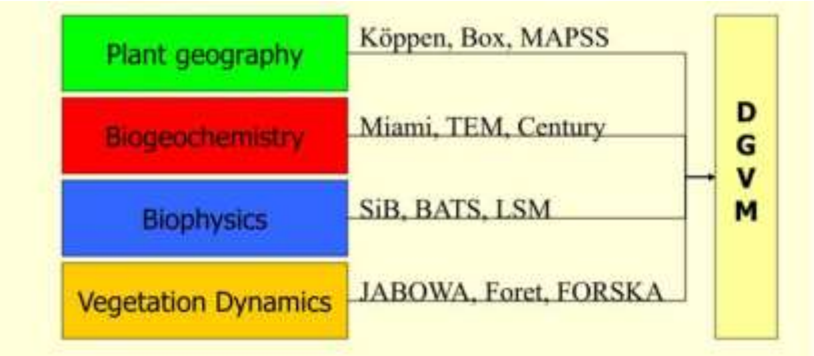


Fig. 2: Processes in DGVMs

In most DGVMs and global vegetation models, the PFT approach rather than individual plant species is employed, i.e., various vegetation species over the globe are grouped together that have similar attributes such as similar leaf form (e.g., needle leaf or broad leaf) and physiological behavior (e.g., deciduous or evergreen). Commonly used PFTs in DGVMs include tropical evergreen broad leaf tree, temperate deciduous needle leaf tree and C3/ C4 grass. Each PFT represents a set of plant species exhibiting different phenology, allocation, mortality and establishment characteristics, which compete for light and water. The typical structure of DGVMs is described in Fig. 3.

In general, meteorological/climatic data (i.e., precipitation, temperature and humidity), soil properties and land-use information are used as inputs. Geophysical and geochemical processes such as photosynthesis, respiration and land-surface processes, such as latent, sensible heat fluxes and evapotranspiration, are calculated on short time scales (hourly or daily). Vegetation dynamics (e.g., establishment, competition, disturbances, and mortality) and carbon cycling, estimated on longer time scales (monthly or yearly).Geographical distributions and structure of vegetation are determined through biogeochemical and dynamic processes of vegetation on annual basis.

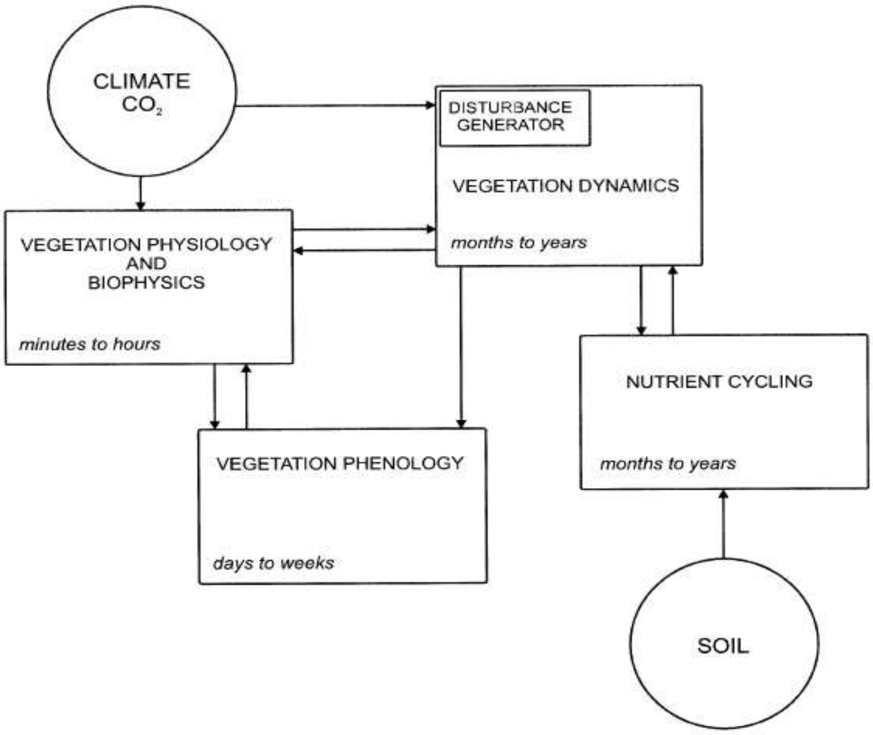


Fig.3: General Structure and processes of a dynamic global vegetation model (DGVM) With time scales of the processes (Cramer. *et al.*, 2001)

These processes include allocation, turnover, mortality, competition, and establishment/ survival. Competitions occur for light and water, and establishment and survival of PFTs are mainly determined by favored bioclimatic limits (e.g., coldest/ warmest minimum monthly air temperature, minimum GDD (growing degree-day) and annual precipitation). In many DGVMs, various outputs are produced, including: Vegetation distribution, Gross primary production (GPP), NPP, LAI, Short and long wave radiations, CO2 concentration etc.

Hybrid-DGVM (Friend. *et al.,* 1997)
The Hybrid model (version 4.1) that has adopted many features from the FOREST-BGC has two unique characteristics as a DGVM.

1. It is an individual based plot model that simulates the growth of individual plants, although it can represent eight PFTs.
2. It includes a full interactive nitrogen cycle. This feature is important in the vegetation models since nitrogen is the most significant limiting factor once light and water are provided sufficiently. Therefore, competition in the model occurs for light, water and nitrogen among individual plants in Hybrid-DGVM.

Tree (grass) in Hybrid-DGVM is composed of foliage, bark/ sapwood/heartwood, and fine root (foliage, support, and fine root) compartments. Stores of nitrogen and carbon in trees and their flows in each compartment are shown in Fig.4. After littering of each compartment, decomposition takes place among the structural, metabolic, and active pools, which causes the release of mineralized nitrogen ('N Min.' in Fig. 4) and CO2. All the flows take place on a daily time scale except the partitioning of nitrogen and carbon from their plant stores. Disturbances such as nutrient stress, fire and land-use changes are not incorporated, and random mortality is included implicitly.

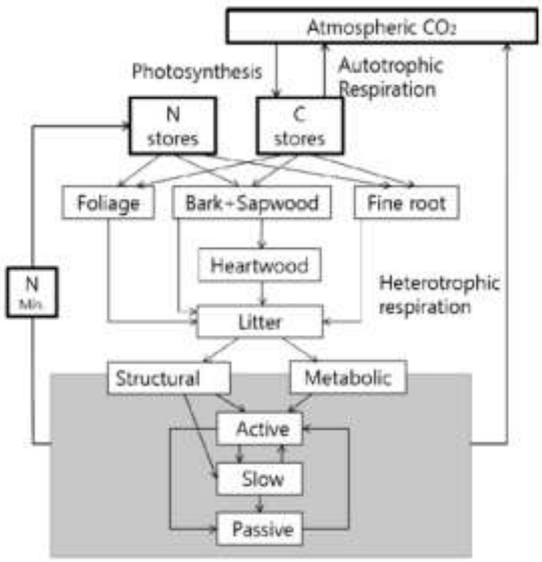


Fig. 4: Flow diagram showing the main flows (arrows) of carbon and nitrogen in trees of Hybrid v 3.0

Boxes with thick (thin) outlines represent state variables of carbon and nitrogen (pools of carbon and nitrogen) and the grey box represents soil organic matter pools. "N Min." indicates nitrogen mineralization.

LPJ-DGVM (Sitch. *et al.,* 2003)
The Lund-Potsdam-Jena Dynamic Global Vegetation Model DGVM = BIOME model + vegetation dynamics. The LPJ-DGVM is a DGVM based on the BIOME model which has nine PFTs that compete for water and light. Fig. 6 shows the flow charts describing the processes in the LPJ model. For each PFT, the GPP is estimated using the coupled water balance and photosynthesis scheme of BIOME3. With respect to C: N ratio, tissue biomass, and environmental conditions, maintenance and growth respiration are calculated daily for each PFT and, then, subtracted from the GPP, and the tissue turnover is calculated.

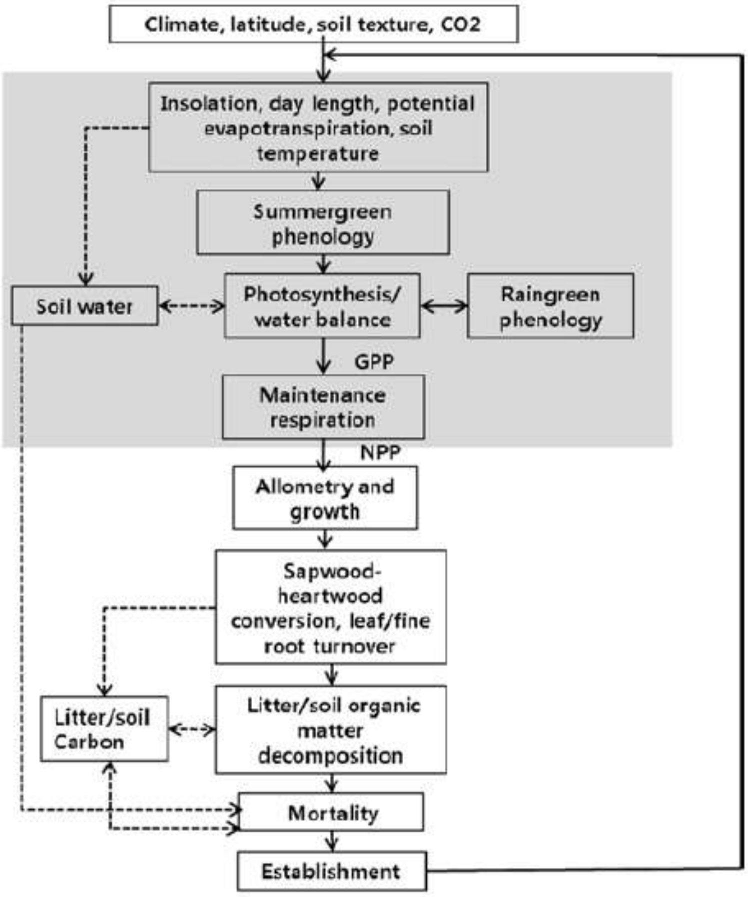


Fig.5: Flowchart describing the multiple processes in the LPJ-DGVM (Myoung. *et al*., 2011).

The solid arrows indicate the directions of information, while dashed arrows represent the information exchange of vegetation with soil state variables and the individual processes. Processes in a shaded box are estimated on a daily or monthly time step, the remainder estimated annually.

Limitations of DGVMs

Heterogeneity of Natural Ecosystem

In many DGVMs, competition occurs between average individuals that are PFTs. However, actual competitions in the real world take place on a local scale and between heterogeneous individuals, since water, light, space and nutrients are locally characterized (Quillet. *et al.,* 2010). This weakness fundamentally originates from the fact that the PFT approach was designed for large spatial and temporal scales, therefore, does not consider the behavior of individual species. Since the PFT approach was originally developed to run on a global scale, the results of a simulation on a regional scale, with a high resolution, may be significantly affected by the PFT parameterization.

Natural and Anthropogenic Disturbances

Fire is considered the most important dynamic disturbance in vegetation modeling. It affects changes not only in the surface energy flux, but in the emissions of carbon and aerosols into atmosphere also. Fire is also associated with competition, mortality and establishment processes of vegetation. For example, the frequency of fires has an impact on the competitive balance between grass and woody plant types. While many DGVMs currently include fire processes, the representations of fire dynamics and the associated impacts are very limited. In addition, DGVMs do not adequately simulate natural disturbances, such as wind storms and insect/pest attacks. Another limitation of DGVMs is that human disturbance (e.g., land-use change) components are poorly represented. The conversion of land-cover into cropland, grazing land, and water withdrawals strongly influences climate change through their effects on the energy fluxes, carbon and nitrogen cycles, as well as the water cycle, which modify the distribution of ecosystems. Human intervention w.r.t terrestrial vegetation and biogeochemical cycles is crucial for understanding the causes of global climate changes and the associated vegetation responses.

Leaf Phenology

Seasonal variations in the LAI leaf phenology are of particular importance because they have a considerable influence on the spatial and inter annual variabilities of the terrestrial water and carbon cycles. Therefore, one of the challenges with DGVMs is the realistic presentation of the seasonal evolution of the LAI. While long-term observational data sets of leaf phonological events are extremely limited, several studies have recently attempted to incorporate satellite observed data sets into DGVMs to reliably present phenological activities.

Applications of Dgvms to Climate Simulations

The coupling of vegetation models with climate models provides the opportunity to explicitly investigate the interactions and feedback between ecological processes and the atmosphere (Quillet. *et al.,* 2010). It is found that regional climates are greatly affected by seasonal variation of vegetation through the modulation of vegetation on land surface water and energy exchange, emphasizing the usefulness of the coupled model as a research tool for investigating the complicated two-way interactions between the atmosphere and biosphere. Regional climate models can be combined with either bio-geographical or biogeochemical models, or dynamic vegetation models, depending on the aim of a study.

Eg: Regional climate model (RAMS) coupled with an ecosystem model (CENTURY).

On the other hand, in RCMs with a finer grid space, the vegetation composition becomes less complicated and the processes of the plants more dynamic. Thus, coupling RCMs with DGVMs can provide a greater amount of integrated information on the influences of local climate on the distributional and physiological processes of vegetation, and vice versa.

Issues to Be Noted

1. Most DGVMs employ a PFT approach, rather than an individual-species approach (based on their biophysical and physiological functions). But, the number of plant types appears to be much less on a regional than global scale and chance for exclusion of dominant plant types. Therefore, either use newly defined PFTs suitable for the ecosystem of the target region or an individual-species approach.
2. High resolution data for land-use categories (e.g., desert, savanna and urban land) are also required with RCM-DGVM coupled models. Balances and cycles of energy and water are greatly influenced by land-use categories as shifts from a forest area to a cropland or urban area completely shifts the local characteristics of the land-atmosphere interactions over that region. So, reliable land-use categories, with higher resolution, will lead to an improved model performance.
3. The parameters used in global models require modifications for applications on a regional scale (Myoung. *et al*., 2011). Because parameterizations within global models are based on the average characteristics over a large-size grid, parametric equations, including constants and relations for estimating specific processes, are scale-dependent. Vegetation processes, and some factors controlling them are likely to be influenced by local climatic and geographical characteristics.

Conclusion

Incorporating realistic vegetation processes in GCMs or regional climate models (RCMs) would be expected to enhance our understanding of the interactions and feedback between the terrestrial biosphere and the atmosphere. Coupling will improve the predictive performance of the climate models. Much effort has been expended to develop static or dynamic vegetation models and their coupling with GCMs in recent decades owing to the growing interests in the impacts of future climate change on the earth ecosystems associated with elevated CO_2 concentrations.

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