Vegetation modelling

Syllabus

Written By

Hans Verbeeck, Felicien Meunier, Marc Peaucelle

Ghent University

2021

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Chapter 1

Introduction

An ecosystem model is an abstract, usually mathematical, representation of an ecological system which is studied to better understand the real system. The scale varies from an individual population to an ecological community or an entire biome.

A dynamic global vegetation model (DGVM) is a computer program that simulates shifts in potential vegetation and its associated biogeochemical and hydrological cycles as a response to shifts in climate (see 1.5). Vegetation models can be used to conduct virtual experiments.

1.1 The central role of vegetation in the Earth system

Plants and vegetation play an essential role in the earth system. In Figure 1.1, we have represented the planetary boundaries and the significant environmental challenges we are facing. For some of them, we are reaching the system's boundary, such as genetic diversity, biogeochemical cycling, and climate change. It is crucial to understand how vegetation reacts to environmental problems (positive or negative feedback), as vegetation plays a central role in many of these boundaries. Environmental challenges we are facing include:

- Stratospheric ozone depletion: The stratospheric ozone layer in the atmosphere filters out ultraviolet (UV) radiation from the sun. If this layer decreases, increasing amounts of UV radiation will reach ground level. Because of the actions taken as a result of the Montreal Protocol, we appear to be on the path that will allow us to stay within this boundary.
- Atmospheric aerosol loading: Through their interaction with water vapour, aerosol play a critically important role in the hydrological cycle affecting cloud formation and global-scale and regional patterns of atmospheric circulation, such as the monsoon systems in tropical regions. They also have a direct effect on climate, by changing how much solar radiation is reflected or absorbed in the atmosphere. Humans change the aerosol loading by emitting atmospheric pollution and through land-use change that increases the release of dust and

smoke into the air. Shifts in climate regimes and monsoon systems have already been seen in highly polluted environments, giving a quantifiable regional measure for an aerosol boundary.

- Ocean acidification: Around a quarter of the CO2 that humanity emits into the atmosphere is ultimately dissolved in the oceans. Here it forms carbonic acid, altering ocean chemistry and decreasing the pH of the surface water. This increased acidity reduces the amount of available carbonate ions, an essential 'building block' used by many marine species for shell and skeleton formation. Beyond a threshold concentration, this rising acidity makes it hard for organisms such as corals and some shellfish and plankton species to grow and survive. Losses of these species would change the structure and dynamics of ocean ecosystems and could potentially lead to drastic reductions in fish stocks. Compared to pre-industrial times, surface ocean acidity has already increased by 30 percent. The ocean acidification boundary has ramifications for the whole planet.

- Biochemical flows: Nitrogen and phosphorus are both essential elements for plant growth, so fertilizer production and application is the main concern. Human activities now convert more atmospheric nitrogen into reactive forms than all of the Earth's terrestrial processes combined. Much of this new reactive nitrogen is emitted to the atmosphere in various forms rather than taken up by crops. When it is rained out, it pollutes waterways and coastal zones or accumulates in the terrestrial biosphere. Similarly, a relatively small proportion of phosphorus fertilizers applied to food production systems is taken up by plants; much of the phosphorus mobilized by humans also ends up in aquatic systems. These can become oxygen-starved as bacteria consume the blooms of algae that grow in response to the high nutrient supply. A significant fraction of the applied nitrogen and phosphorus makes its way to the sea, and can push marine and aquatic systems across ecological thresholds of their own. One regional-scale example of this effect is the decline in the shrimp catch in the Gulf of Mexico's 'dead zone' caused by fertilizer transported in rivers from the US Midwest.

- Freshwater use: Human pressure is now the dominant driving force determining the functioning and distribution of global freshwater systems. The consequences of human modification of water bodies include both global-scale river flow changes and shifts in vapour flows arising from land use change. These shifts in the hydrological system can be abrupt and irreversible. Water is becoming increasingly scarce - by 2050 about half a billion people are likely to be subject to water-stress, increasing the pressure to intervene in water systems.

- Land-system change: Forests, grasslands, wetlands and other vegetation types have primarily been converted to agricultural land. This land-use change is one driving force behind the serious reductions in biodiversity, and it has impacts on water flows and on the biogeochemical cycling of carbon, nitrogen and phosphorus and other important elements. While each incident of land cover change occurs on a local scale, the aggregated impacts can have consequences for Earth system processes on a global scale. Forests play a particularly important role in controlling the linked dynamics of land use and climate, and is the focus of the boundary for land system change.

- Biosphere integrity: The Millennium Ecosystem Assessment of 2005 concluded that changes to ecosystems due to human activities were more rapid in the past 50 years than at any time in human history, increasing the risks of abrupt and irreversible changes. The main drivers of change are the demand for food, water, and natural resources, causing severe biodiversity loss and leading to changes in ecosystem services. The current high rates of ecosystem damage and extinction can be slowed by efforts to protect the integrity of living systems (the biosphere), enhancing habitat, and improving connectivity between ecosystems while maintaining the high agricultural productivity that humanity needs.
- Climate change: Recent evidence suggests that the Earth, now passing 390 ppmv CO2 in the atmosphere, has already transgressed the planetary boundary and is approaching several Earth system thresholds. The weakening or reversal of terrestrial carbon sinks, for example through the on-going destruction of the world's rainforests, is a potential tipping point, where climate-carbon cycle feedbacks accelerate Earth's warming and intensify the climate impacts.
- Novel entities: Emissions of toxic and long-lived substances such as synthetic organic pollutants, heavy metal compounds and radioactive materials represent some of the key human-driven changes to the planetary environment. Even when the uptake and bioaccumulation of chemical pollution is at sub-lethal levels for organisms, the effects of reduced fertility and the potential of permanent genetic damage can have severe effects on ecosystems far removed from the source of the pollution.

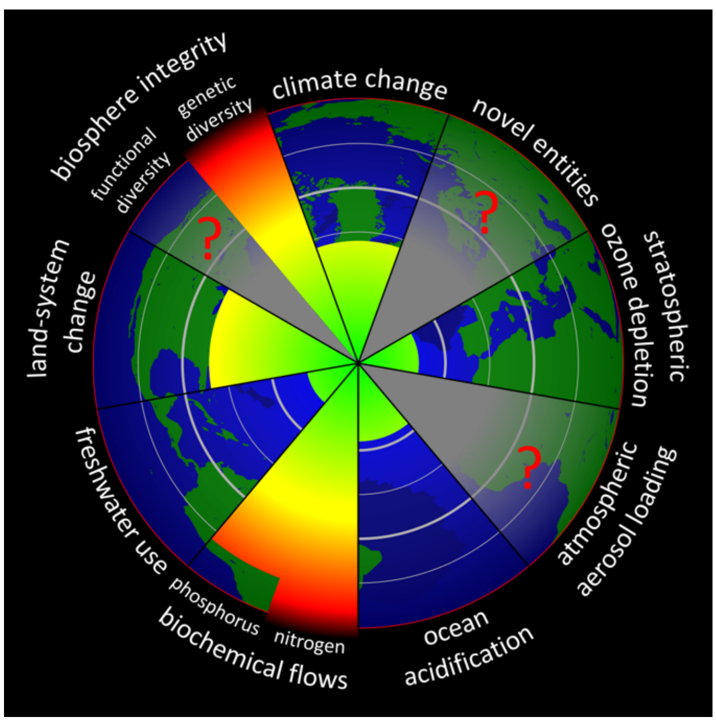


Figure 1.1: The planetary boundaries (www.stockholmresilience.org)

A more specific example of the plant-environment interactions is the global carbon budget. We are currently facing this significant change in biogeochemical cycling due to the rising fossil fuel emission over the last 150 years. Figure 1.2 represents the balance between carbon sources (fossil carbon and land-use changes) and sinks (oceans, land, and atmosphere). The more we emit, the more the Earth system is capturing. Naturally, the emitted CO2 must go somewhere. Approximately half of it is taken up by the ocean and the land (soil + vegetation) sink. As stated earlier, roughly 25% of the emitted CO2 is dissolved in the ocean sink. The land sink is highly variable: land and soils are very heterogeneous and difficult to model. Nevertheless, the land sink has taken up more emissions in the past 60 years than it did before. The atmosphere is responsible for most of the uptake. This takes us to a question, frequently addressed by global vegetation models, about how long these sinks will continue or not capture our increasing carbon emissions. Note that there is an imbalance: there was more CO2 emitted then absorbed. So, where did the surplus go? This is an active area of research.

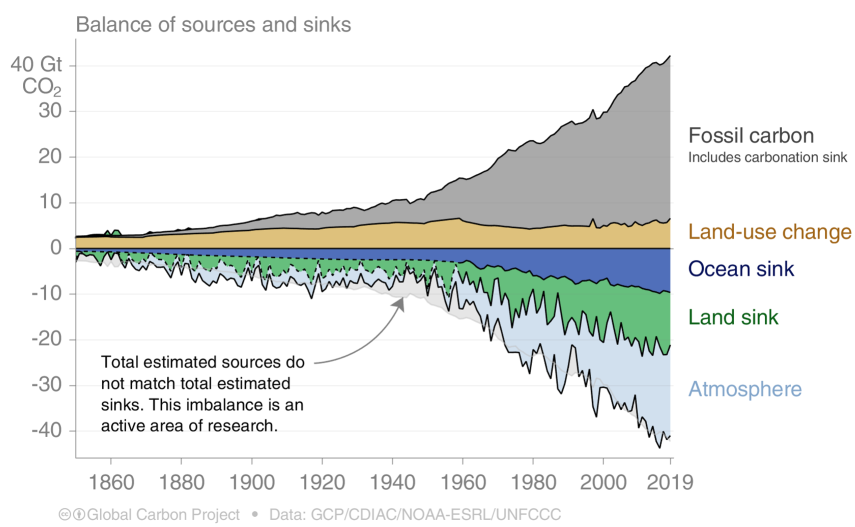


Figure 1.2: The global carbon budget (www.globalcarbonproject.org)

Climate Models predict how the long-term weather variation and average weather will evolve. These models include an atmosphere, land and ocean component (Figure 1.3 top). The original climate models focused on biophysics: energy and water balances, predicting precipitation, radiation and fluxes between the three components. More recently, climate models have evolved into **Earth System Models** (ESM). ESM have a more complex concept because they represents more processes (Figure 1.3 bottom). Why? If you want to predict the end of the century climate, we need to consider greenhouse gases and thus the full carbon cycle. ESM are more complex but also more realistic.

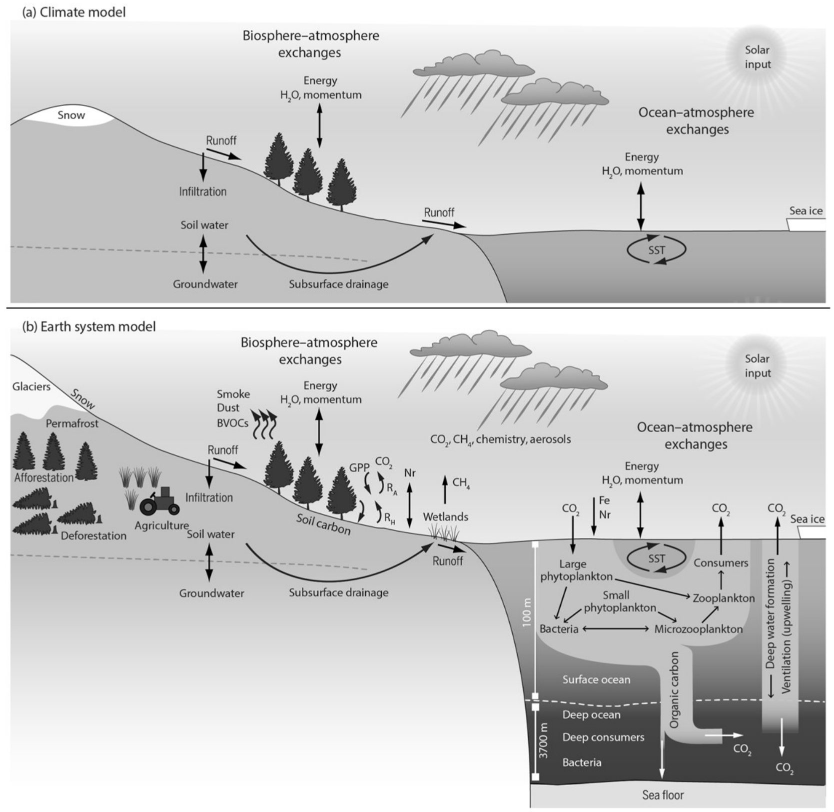


Figure 1.3: Scientific scope of (a) climate models and (b) earth system models. (Bonan 2019)

Vegetation models are often the land component of an earth system model. These 'terrestrial biosphere models'(TBM) or 'land surface models' (LSM)

- simulate **energy fluxes**: radiation, evapotranspiration and sensible heat fluxes between the land and the atmosphere. Depending on the vegetation type, the impacts are different.
- simulate the **hydrology** and the **carbon cycle**.
- simulate slower processes like **vegetation dynamics**: the succession of forest or **land use** and **urbanization**.

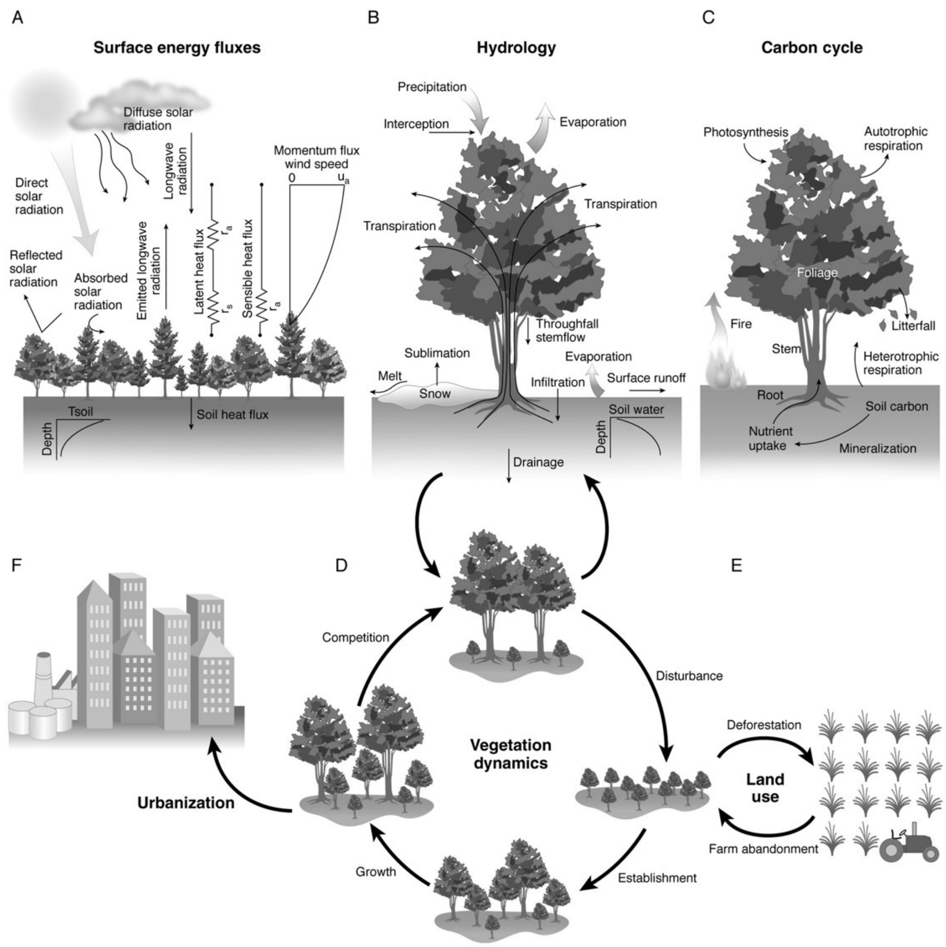


Figure 1.4: Scientific scope of terrestrial biosphere model. (Bonan 2019)

The coupler is a system that links different models. For example the terrestrial biosphere can be seen as the coupler between geochemistry and hydrology. A coupler can be the link between more than two other systems, so that a kind of satellite system is formed. The land model is mostly seen as the coupler. This results in the fact that both fast and slow processes depend on each other. The surface energy flux is an example of a fast process since it varies over the course of one day Vegetation dynamics on the other hand, is a slow process. Succession does not happen overnight.

1.2 Why do we need modelling?

Modelling has proven to be a essential tool:

- For **understanding**: we need good theoretical foundations (understand processes) to generalize knowledge and observations in space and time (upscaling). Studying the inaccuraies in models leads to the formulation of new hypotheses.
- For **prediction**, how vegetation responds to expected changes (temperature or CO2) to develop management strategies and policies.
- For **data integration**: a framework to bring together multiple data sources and to guide future data collection.

1.3 Model types

How can we look at the different model types that exist (Table 1.1)? Models are to be placed in a continuum ranging from empirical to process-based models. **Empirical models** are based on data and correlations, not describing precisely the biophysical processes — **process-based models** describing the biophysical processes and causal relations between the variables (Table 1.2). Most existing vegetation models are hybrid.

Table 1.1: Continuum of terrestrial biosphere/ecosystem models. (Bonan 2019)

Type of model	Description	Example
Biogeochemical	Ecosystem model with emphasis on biogeochemical pools and fluxes	CASA, BIOME-BGC, CENTURY
Forest gap models	Individual trees, population dynamics, demography, community composition	JABOWA, SORTIE
Ecosystem demography	As gap models but cohort based	ED
Dynamic Global Vegetation Models (DGVM)	Biogeochemistry, community composition, global biogeography	LPJ, LPJ-guess, ORCHIDEE, JULES, ED2
Land Surface Models (LSM)	Global models of the land surface, as part of climate models with focus on biophysical coupling with the atmosphere. They now include biogeochemistry, and vegetation dynamics → they became a DGVM	ORCHIDEE, JSBACH, CLM, FATES, ED2, …
Plant canopy	Multilayer models with focus on coupling leaf physiology and canopy physics	CANOAK, FORUG
Canopy- chemistry	Plant canopy models that include chemical transport	CAFE
Ecohydrology	Similar to LSM, but spatially explicit with river routing, lateral flow	RHESSy

Table 1.2: Continuum of process-based versus empirical models. (Adams et al. 2013)

	Process-based	**Empirical**
Relationship type	Causal	Correlative
Relative comprehensiveness	More comprehensive	Less comprehensive
Incorporation of mechanism	Explicit	Implicit
Primary source of error	Unknown parameters and processes	Extrapolation
Model uncertainty	Higher	Lower
Data requirements	Higher	Lower
Spatial scale for calibration	Smaller	Smaller to larger
Spatial scaling of prediction	Smaller to Larger	Best at scale of calibration

The model type depends on: - Purpose: will it be used for management support, policy support, research. - Question: different people will be interested in different questions (foresters, ecologists, policy makers…) - Scale: models that are to be applied for local use can be much more detailed than worldwide models because data gathering is much more straightforward on a small scale. Also the time-scale is of importance: will the model be used for research about the past, the present or the future?

1.4 The history of vegetation models

The history of vegetation models is one that parallels that of the computer. Computers made it possible to calculate much faster and much more, which made them suitable for modelling. The first vegetation models have emerged in the 1960s and 1970s.

One of the first models were the **box models** (1960); these models describe the flow of mass and energy through boxes. These models still exist in current biogeochemical models, where arrows represent the fluxes between the pools. In parallel, **gap models** had emerged. Gap models simulate the dynamics of the development of a gap in a forest and the growth of plants in this gap. Gaps can be created by fallen trees, by dead trees, ... This kind of models are individual-based and focused on population dynamics and the life cycle of species: growth, regeneration and mortality while taking environmental constraints in account. These models are the first models that were ever used for upscaling: from tree level, to plot-level, to landscape level. They were developed by forest scientists using forest inventories to derive growth, regeneration, and mortality in response to environmental variables. In 1973, the first model (MIAMI model by Lieth (1973)) was developed to derive global net primary productivity (NPP), relating NPP in an empirical way to climate variables (temperature) with vegetation productivity. This was the first attempt to make a global upscaling of a vegetation process. In the 1980s surged the first **land surface models**. Land surface models are the models where the other models start to integrate into, and evolved as such into – **Terrestrial biosphere models** (see Figure 1.5), which are now the state-of-the-art land components of ESMs. Vegetation modelling therefore is a very interdisciplinary field because it involves knowledge of different scientific fields, making it difficult to find a common terminology. Global EMS are currently still not good to simulate realistic vegetation dynamics.

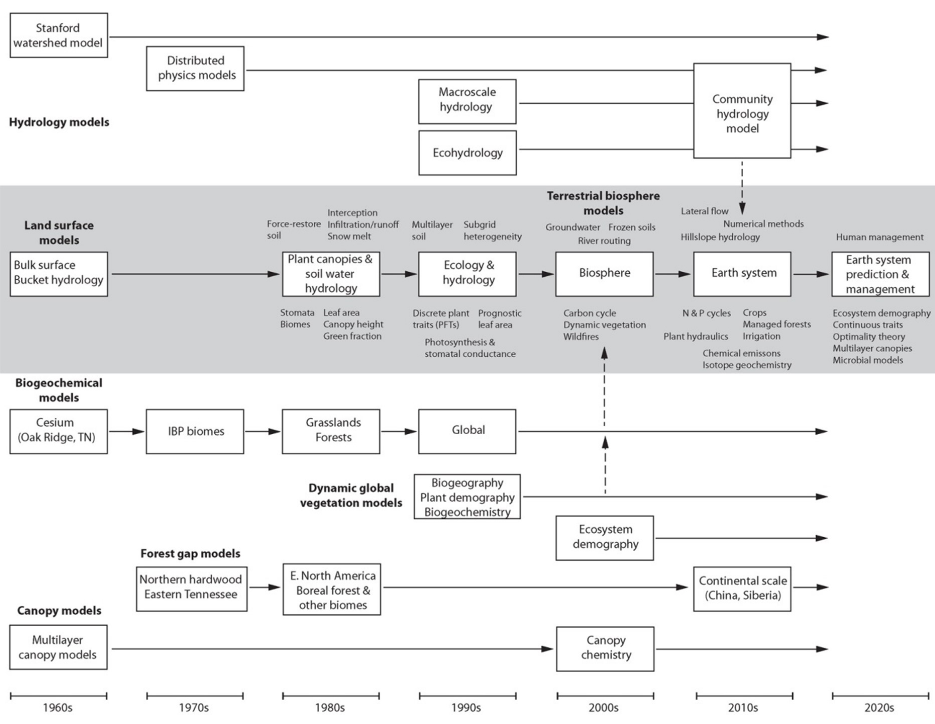


Figure 1.5: Timeline showing the parallel development of model types and the integration of model types into land surface models towards terrestrial biosphere models. (Bonan 2019)

1.5 Components of a model

What is a vegetation model? Two attempts for a definition:

- **Dynamic global vegetation models** (DGVMs) are powerful tools to project past, current and future vegetation patterns and associated biogeochemical cycles (Scheiter et al., 2013).
- A **Dynamic Global Vegetation Model** (DGVM) is a computer program that simulates shifts in potential vegetation and its associated biogeochemical and hydrological cycles as a response to shifts in climate. DGVMs use time series of climate data and, given constraints of latitude, topography, and soil characteristics, simulate monthly or daily dynamics of ecosystem processes. DGVMs are used most often to simulate the effects of future climate change on natural vegetation and its carbon and water cycles (Wikipedia 2021).

Table 1.3: Definition of key model components and examples for a typical TBM

Model component	Definition (syllabus)	Examples for a typical TBM
System boundary	What is in the system and what is out?	Lower atmosphere, deep soil
State variable	Time varying quantity	Carbon pools, soil water content
Model structure	The equations and connectivity	Photosynthesis equations
Parameters	Constants in process equations	Photosynthetic capacity, drought sensitivity parameter, …
Forcing inputs ('forcings')	Quantities needed to evolve the model state	Air temperature, radiation, …. (meteo), atm. CO_2 concentration
Initial conditions	State variables at model start-up	Carbon pools, soil water content
Model outputs	Quantities simulated by the model (state variables, fluxes,…)	Biogeochemical fluxes, dynamics of model states, …

1.5.1 Processes

They are a key component because we are focusing on process-based models in this course. There is a long list of processes (energy, water, turbulent transport, canopy scaling, carbon, nitrogen, trace gasses, demography,…) that the models integrate, especially the more complex ones. These processes will be discussed in detail in the following theory chapters and we will mainly focus on how to translate them into equations.

1.5.2 Equations

These are the mathematical representations of the processes. However, there are important constraints to insert equations into a vegetation model, such as the specific time scale at which a process operates. For example, it makes little sense to resolve the equation for forest composition (succession) on a daily calculation time step. This is a prolonged process with an extremely low variance between consecutive days. The solution for the equation for photosynthesis, on the other hand, varies significantly throughout the day and between consecutive days (cloudy day vs sunny day).

There are three types of equations within vegetation models: - **prognostic equations**: time derivatives of differential equations – they calculate the state's change over time - **conservation equations**: equations describing the conservation of mass and energy -

diagnostic equations: linking multiple variables independent from the time.

Often there is no analytical solution of the equations describing on-linear processes in biological systems; therefore, we must use numerical methods to solve the equations.

1.5.3 Parameters

These are the constants in the model. Some parameters are highly uncertain because we cannot measure them very well at the relevant scale. For example, we can make reliable measurements of the photosynthetic capacity of a single leaf. However, upscaling this parameter so that it is applicable for a forest or multiple PFTs (= plant functional types) induces uncertainty. The more parameters a model uses, the more uncertainties that are to be taken into account.

1.5.4 Time Steps

Vegetation models run at multiple timescales (combining processes that are resolved at multiple timescales). Models present fast processes, which are calculated every hour (e.g. photosynthesis and energy balance), intermediate processes calculated daily (e.g. carbon allocation and growth) and slow processes in order of years (e.g. mortality) (Fig.6).

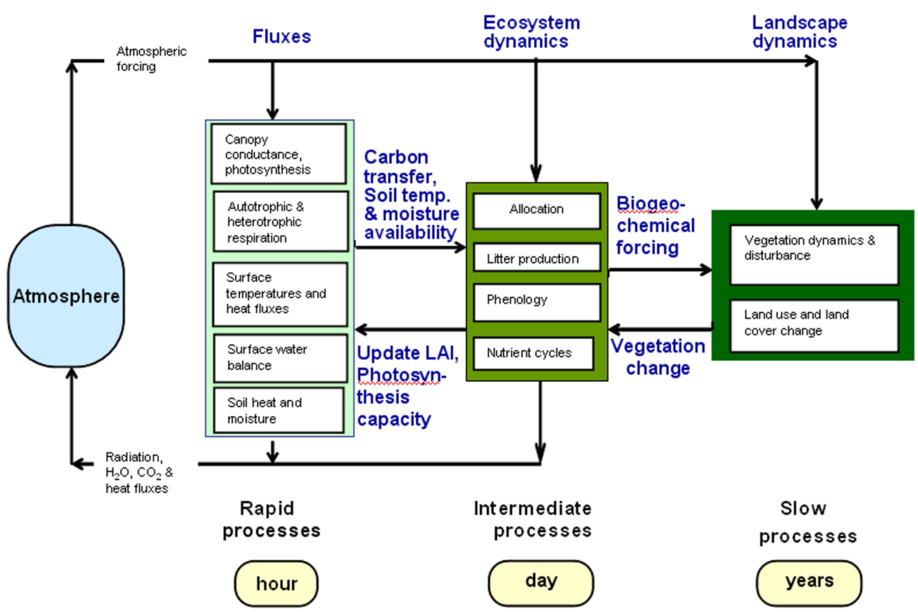


Figure 1.6: Structure of a vegatation model indicating the different time steps at which each process is simulated (Williams et al. 2009)

1.5.5 Spatial structure

The division of space in voxels, layers or grid cells and its resolution determines how many times we repeat our calculations in space. Global vegetation models have a typical spatial grid of 100km or even more and divide the landscape into patches. In each patch, they simulate the vegetation (forest, savannas, grassland...). Models also have a horizontal grid or horizontal layering: some models consider multiple soil layers. The same is true for above ground layers, where some models divide the canopy into multiple layers (Figure 1.7). For example, the Ecosystem Demography Model (ED2.2) divides the forest into multiple grid cells where the same meteorological conditions apply within each grid cell. Then within each cell, this model has different sites with different soils. Each site is divided into multiple patches (forests with a similar disturbance history). For each patch, the model simulates multiple cohorts of trees where size and plant functional types play a role (Figure 1.8).

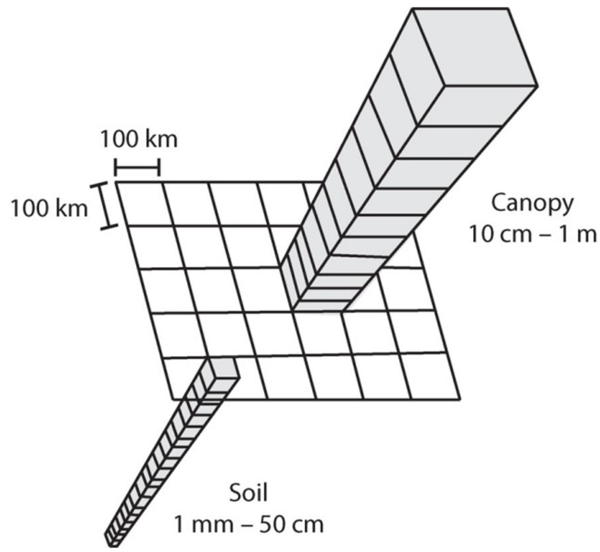


Figure 1.7: Three dimensional grid of a TBM structured in terms of longitude x latitude x level. The number of soil and canopy layers and the geographical resolution is model dependent, (Bonan 2019)

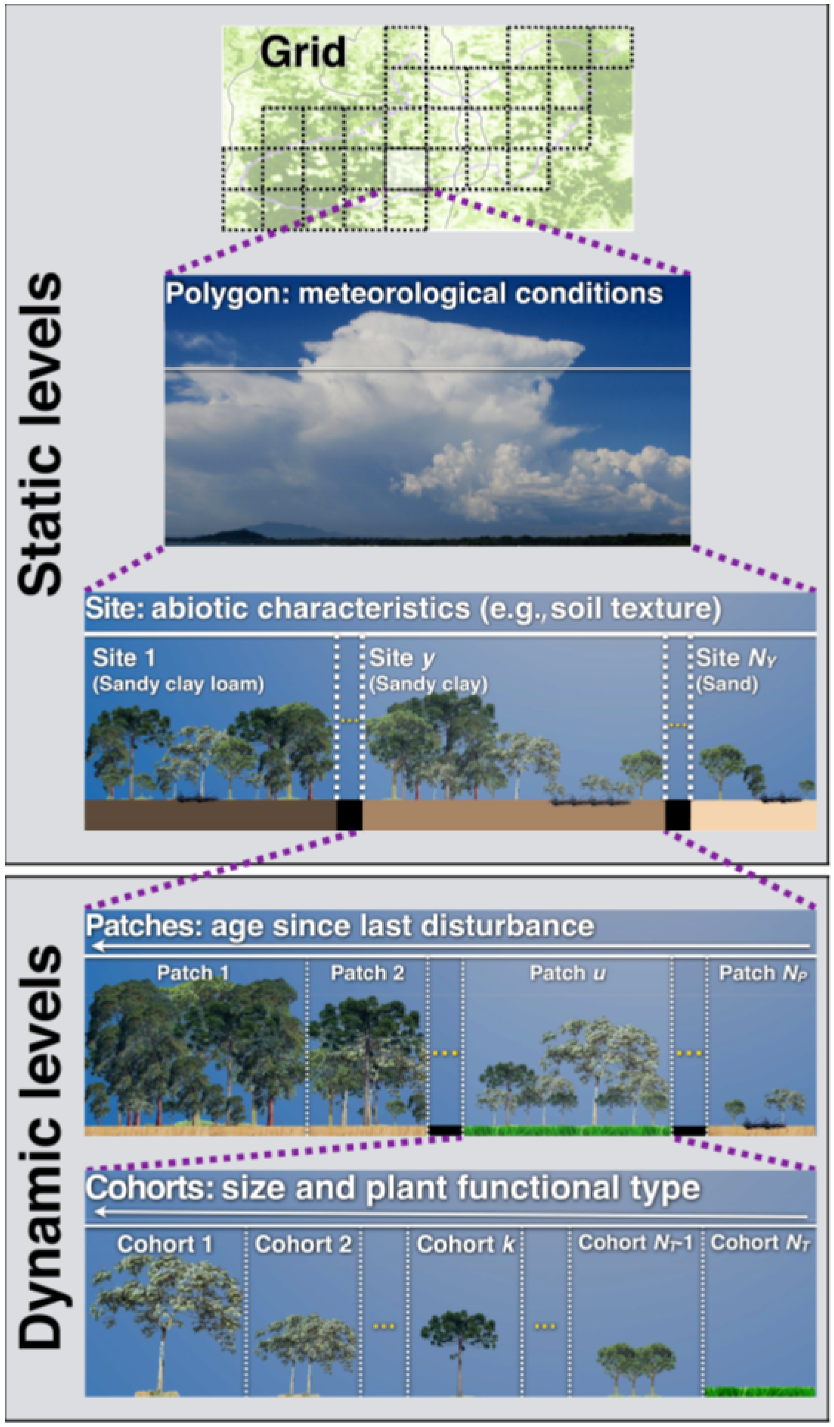


Figure 1.8: Example: the spatial multi-level grid structure of of the ED2 vegetation model (Longo et al. 2019)

1.5.6 Model code, complexity and uncertainty

There is a gap between equations and how the are implemented in the actual model code. Also, a specific process can be implemented into an equation in various ways. Usually, large models also contain a "technical debt", which means over the years, multiple modelers have continued working on models and added code lines, but at some point, the code is so large that none of the developers still knows the entire code, resulting in persistent bugs or overlooked assumptions.

Models are always a simplification of the real world, but they tend to become overly complex.

More complex models (adding more processes) become more realistic, but we also add more sources of uncertainty. Therefore, we should choose our model carefully based on the research question we want to adress.

1.5.7 Data

It is not possible to develop models without data. In general, the more data (multiple data sources), the better.

1.6 Modelling workflow and structure of the course

Vegetation modelling is a multidisciplinary field. This course will mainly focus on the mathematical formulation of processes and translating these equations into a working model.

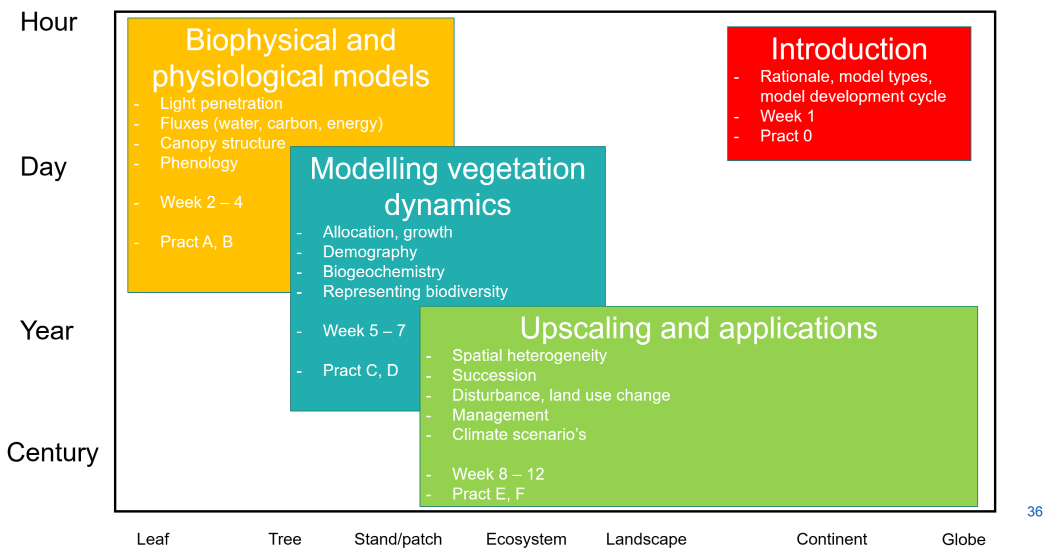


Figure 1.9: Progression through spatial and temporal scales throughout this course

The construction of a model is a continuous process – a model is never finished. As Figure 10 shows us, we start by describing our system in the form of equations, then running the computer program to characterize the model, perform parameter estimation and interpretation, and then apply it to other locations and validate against independent data.

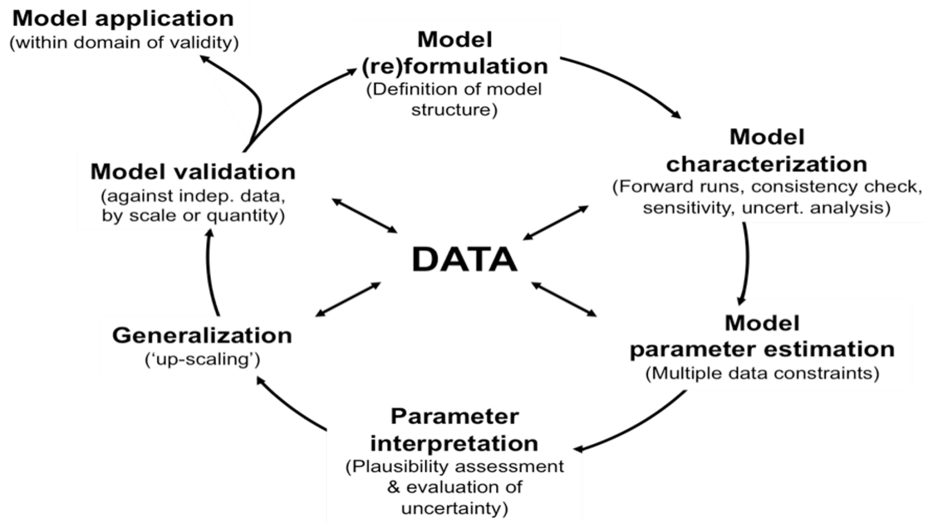


Figure 1.10: Model data fusion in every step of the model development cycle (Williams et al. 2009)

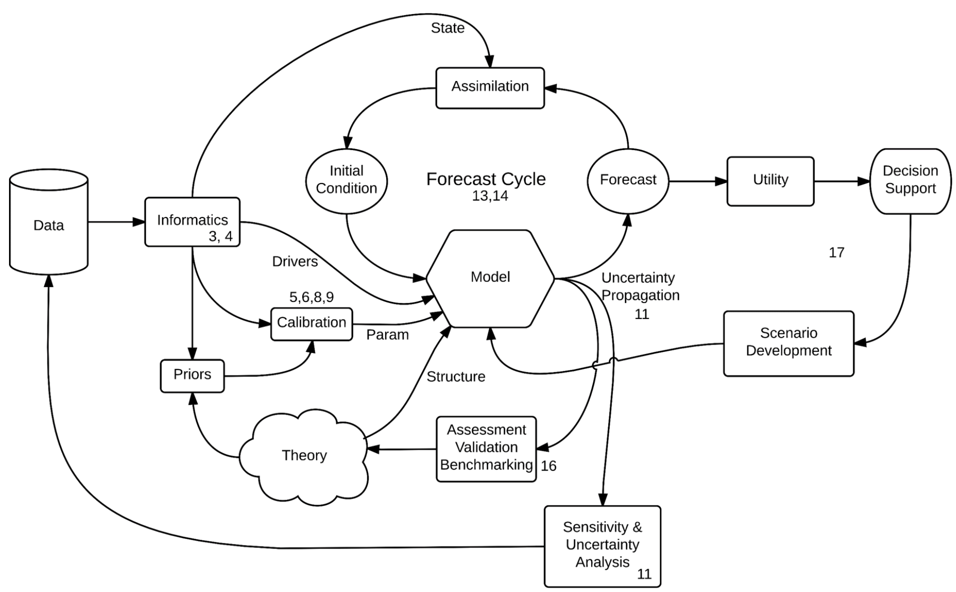


Figure 1.11: Methodological workflow of model data fusion (Dietze: Ecological Forecasting)

Part I

Biophysical and physiological models

Chapter 2

Modelling plant basic processes

For all processes, we provide an overview of existing models and approaches and we will detail only one of them for the practical course. This also apply for the other chapters, the idea of the course is to be more conceptual about how we model vegetation and the different applications and assumptions.

2.1 Photosynthesis models

2.1.1 Refreshing the basic knowledge

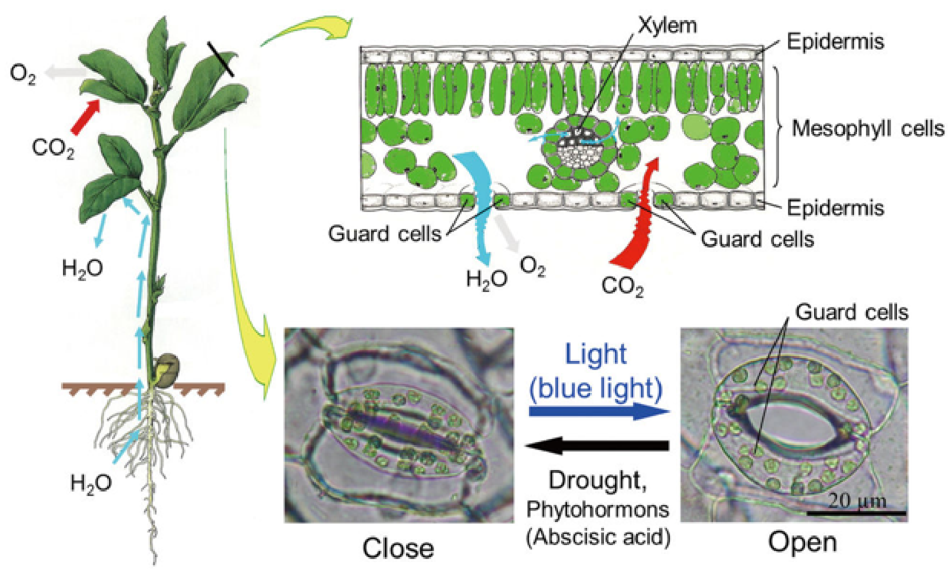


Figure 2.1: Leaf level processes transpiration and photosysnthesis are strongy interlinked and both regulated by stomatal conductance

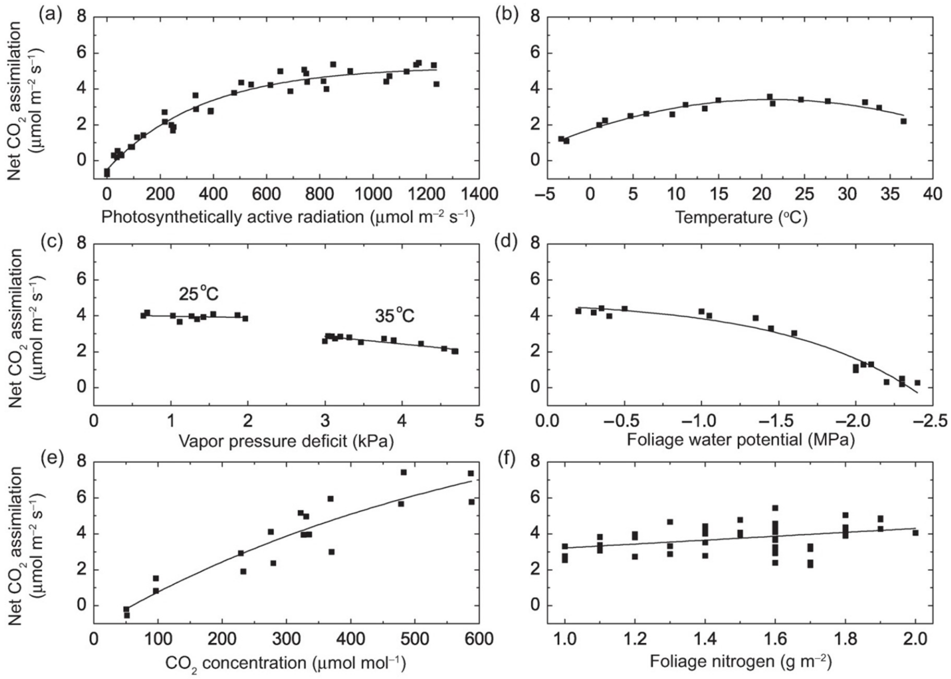


Figure 2.2: Photosynthesis in relation to (a) photosynthetically active radiation,(b) temperature, (c) vapor pressure deficit at 25°C and 35°C,(d) foliage water potential, (e) ambient CO2 concentration, and (f) foliage water potential for jack pine trees (Pinus banksiana). Bonan (2019)

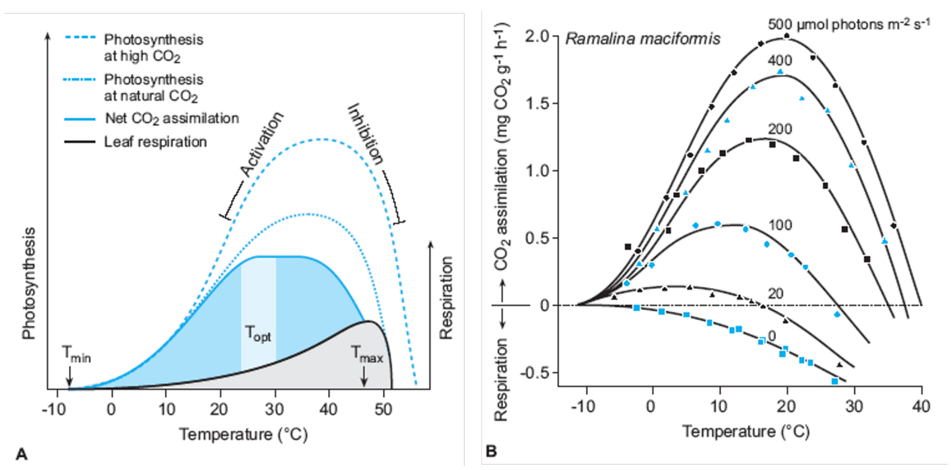


Figure 2.3: Temperature responses of photosynthesis, respiration and net CO2 exchange, interaction with CO2 concentration (A) and light (B) Schulze ()

2.1.2 C3 photosynthesis

2.1.2.1 Light response curve models

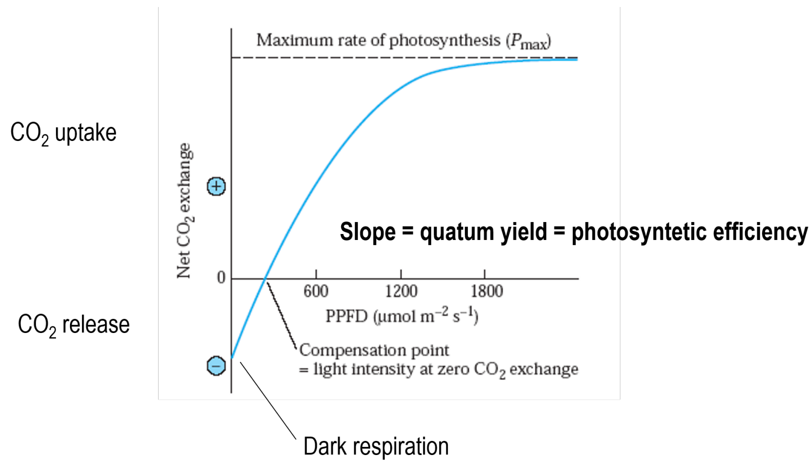


Figure 2.4: Conceptual figure of a leaf-level light reponse curve

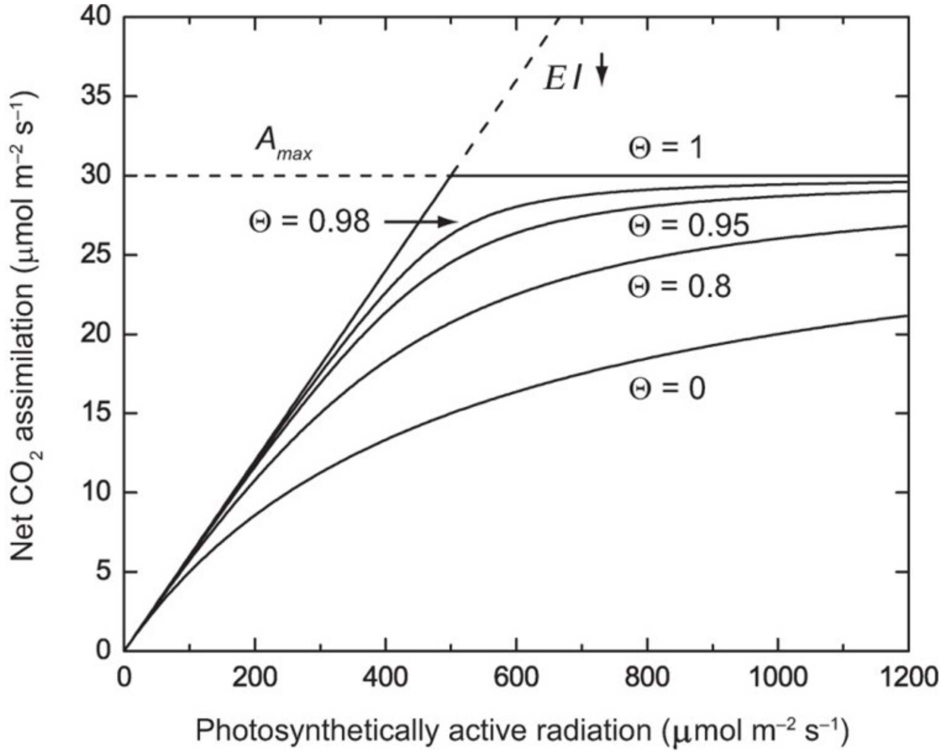


Figure 2.5: Co-limitation illustrated for photosynthetic response to light. The two dashed lines show the rates Amax adn EI The solid lines show the co-limited rate. (Bonan 2019)

2.1.2.2 Light use efficiency models

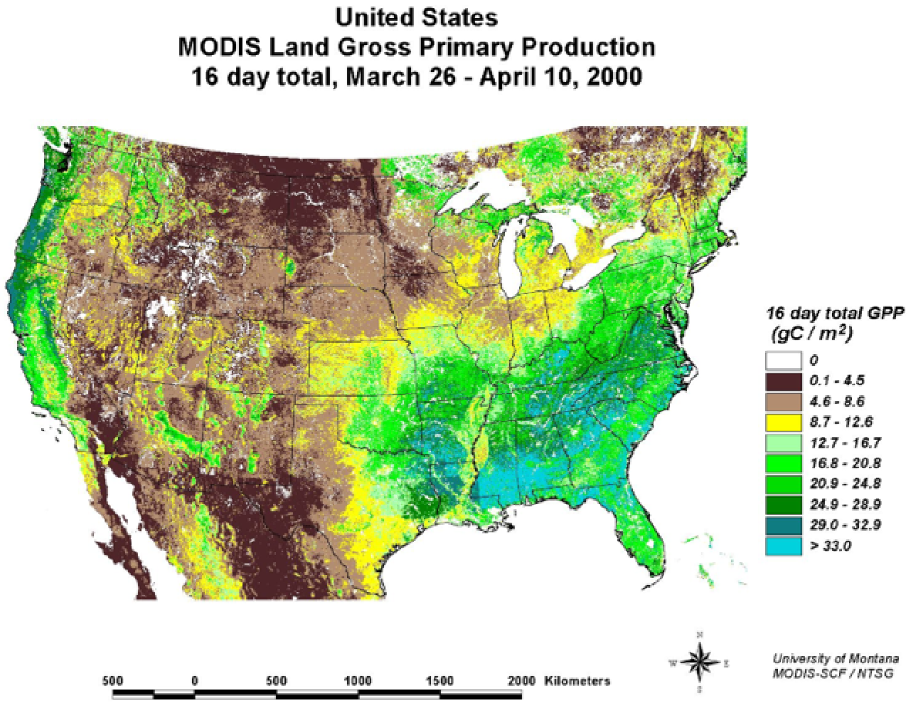


Figure 2.6: MODIS based GPP map of the US, based on a LUE model.

2.1.2.3 The Farquahar model

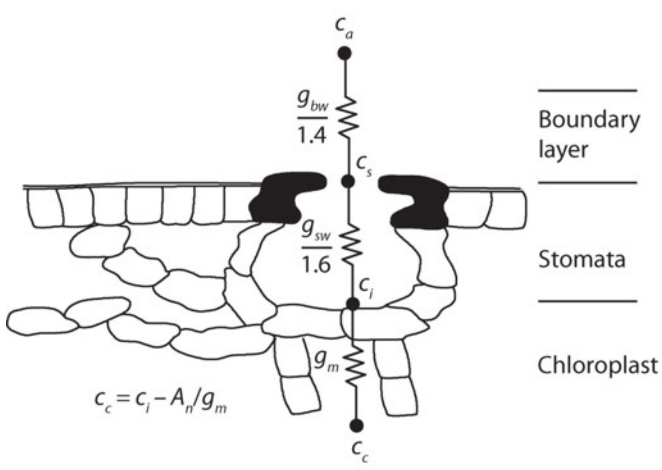


Figure 2.7: Diffusion of CO2 from free air across the leaf boundary layer and through stomata to the intercellular space. Diffusion to the chloroplast is additionally regulated by mesophyl conductance. (Bonan 2019)

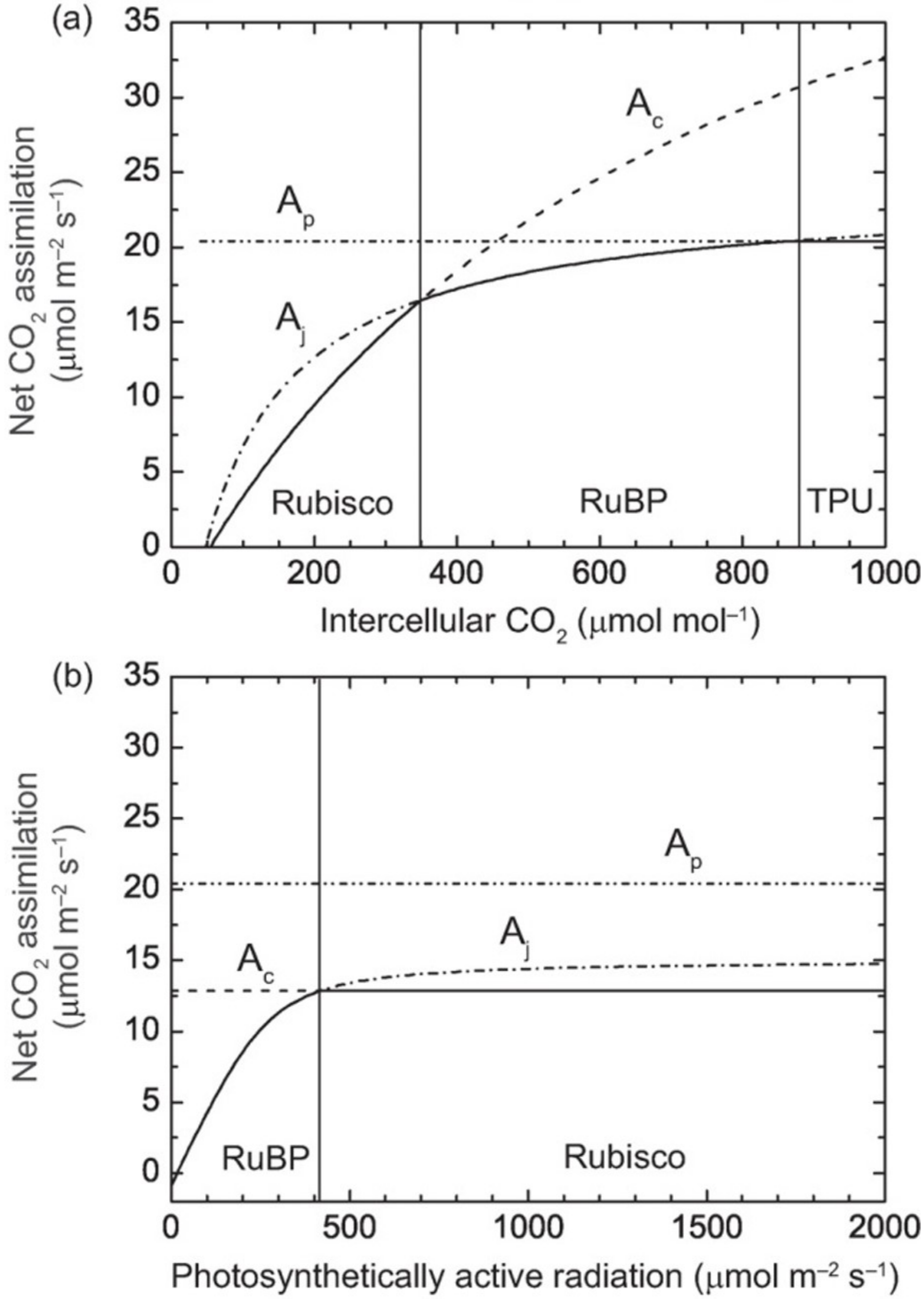


Figure 2.8: Simulated responses of C3 photosynthesis in relation to (a) intercellular CO2 (at I↓ = 2000 mol m–2 s–1) and (b) photosynthetically active radiation (at ci = 266 mol mol–1). (Bonan 2019)

- UCL 4.6.1
- Bonan, Chapter 11.1 The FvCB model Most equations between 11.1 and 11.31 Figure 11.2 a and b Table 11.1 for parameters values + a few simulations to illustrate Table 11.4

2.1.3 Parameter and temperature dependencies

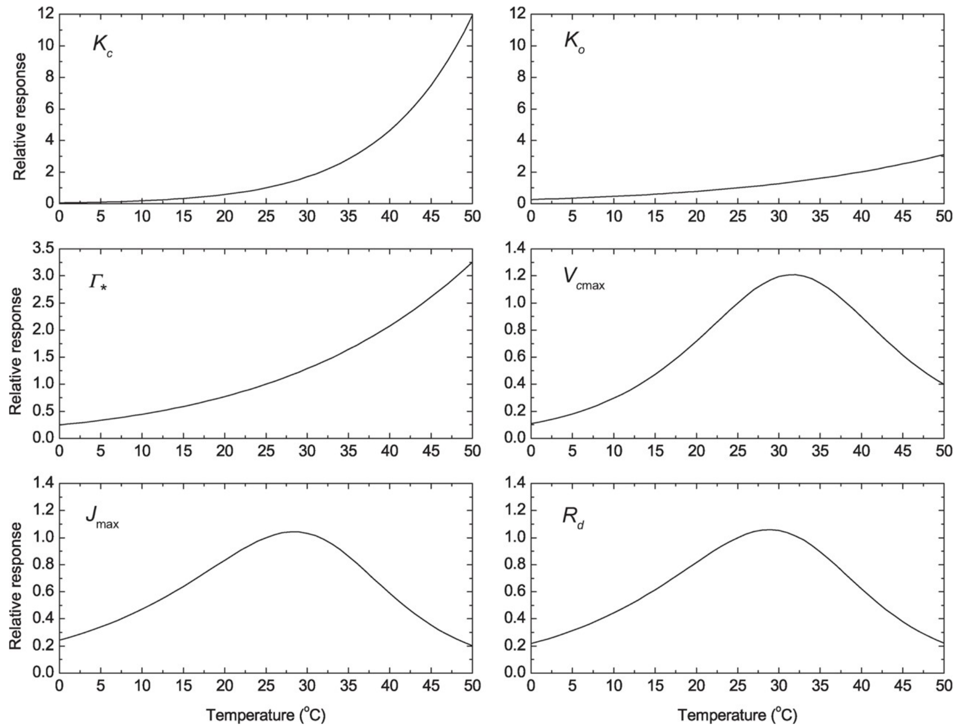


Figure 2.9: Relative temperature responses of the parameters of the Farquhar model (Bonan 2019)

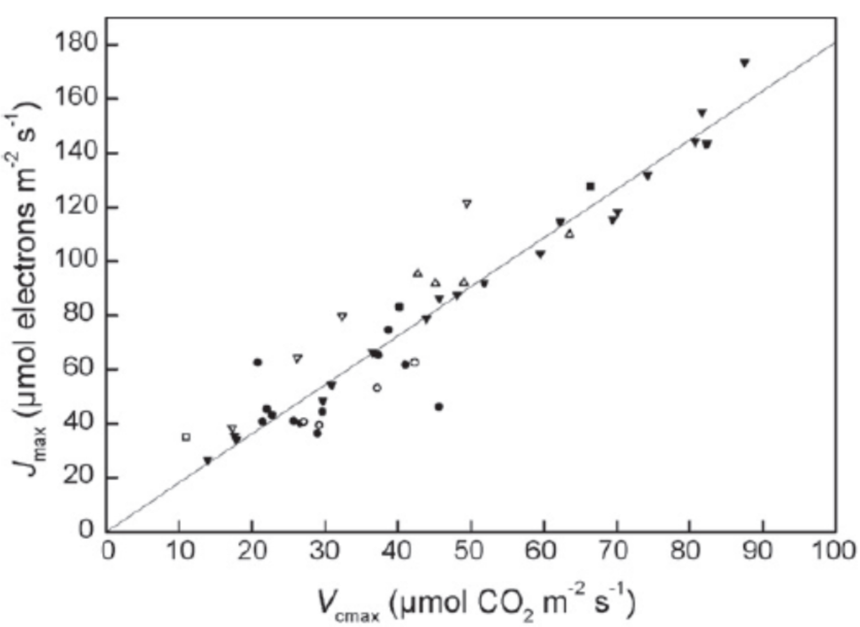


Figure 2.10: Linear relation between observed Vcmax and Jmax values for Beech (Verbeeck et al. 2008)

Definition	Equation
Rubisco-limited assimilation	$A_c = \frac{V_{cmax}(c_i - \Gamma_*)}{c_i + K_c(1 + o_i/K_o)}$
Light-limited assimilation	$A_j = \frac{J}{4}\left(\frac{c_i - \Gamma_*}{c_i + 2\Gamma_*}\right)$
Gross photosynthesis	$A = min(A_c, A_j)$ (no colomitation) $\Theta_A A^2 - (A_c + A_j)A + A_c A_j$ (colimitation)
Net photosynthesis	$A_n = min(A_c, A_j) - R_d$
Electron transport rate	$\Theta_j J^2 - (I_{PSII} + J_{max})J + I_{PSII} J_{max}$
PSII light utilization	$I_{PSII} = \frac{1}{2}\Phi_{PSII}\alpha_l I^{\downarrow}$
Maximum carboxylation rate	$V_{cmax} = V_{cmax25} \cdot f(T_l) \cdot f_H(T_l)$
Maximum electron transport rate	$J_{max} = J_{max25} \cdot f(T_l) \cdot f_H(T_l)$ $J_{max25} = 1.67 \cdot V_{cmax25}$
Leaf respiration	$R_d = R_{d25} \cdot f(T_l) \cdot f_H(T_l)$ $R_{d25} = 0.015 \cdot V_{cmax25}$
Michalis-Menten constant, CO_2	$K_c = K_{c25} \cdot f(T_l)$
Michalis-Menten constant, O_2	$K_o = K_{o25} \cdot f(T_l)$
CO_2 compensation point	$\Gamma_* = \Gamma_* \cdot f(T_l)$
Arrhenius function	$f(T_l) = exp\left[\frac{\Delta H_a}{298.15 \cdot R}\left(1 - \frac{298.15}{T_l}\right)\right]$
Hight temperature inhibition	$f_H(T_l) = \frac{1 + exp\left(\frac{298.15 \cdot \Delta S - \Delta H_d}{298.15 \cdot R}\right)}{1 + exp\left(\frac{T_l \cdot \Delta S - \Delta H_d}{T_l \cdot R}\right)}$

Figure 2.11: Equations of the full Farquhar model

- Bonan, Chapter 11.2 Equations 11.34-11.37 Table 11.2 Figure 11.3 for illustration

Summary with Table 11.5 and Figure 11.4

2.1.4 C4 photosynthesis

- Bonan, Chapter 11.7 PEP carboxylase Equations 11.69-11.74 Find an illustration

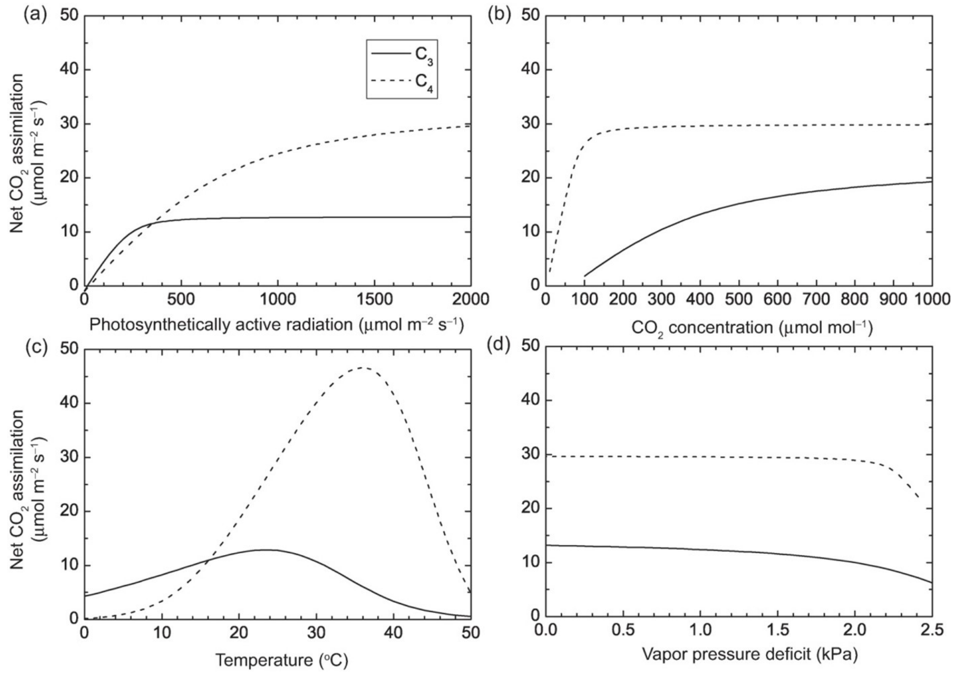


Figure 2.12: Comparison of C3 and C4 photosynthesis in response to (a) photosynthetically active radiation, (b) ambient CO2 concentration, (c) leaf temperature, and (d) vapor pressure deficit. In this figure, stomatal conductance is calculated using the Ball–Berry model and ci is obtained from the diffusion equation

2.2 Stomatal models

2.2.1 Refreshing the basic knowledge

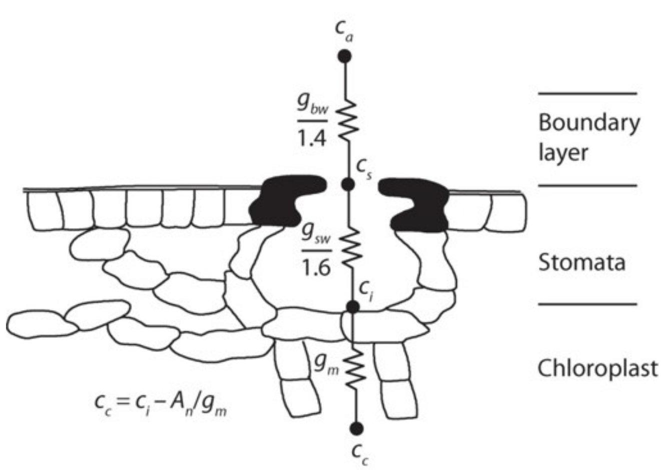


Figure 2.13: Diffusion of CO2 from free air across the leaf boundary layer and through stomata to the intercellular space. Diffusion to the chloroplast is additionally regulated by mesophyl conductance. (Bonan 2019)

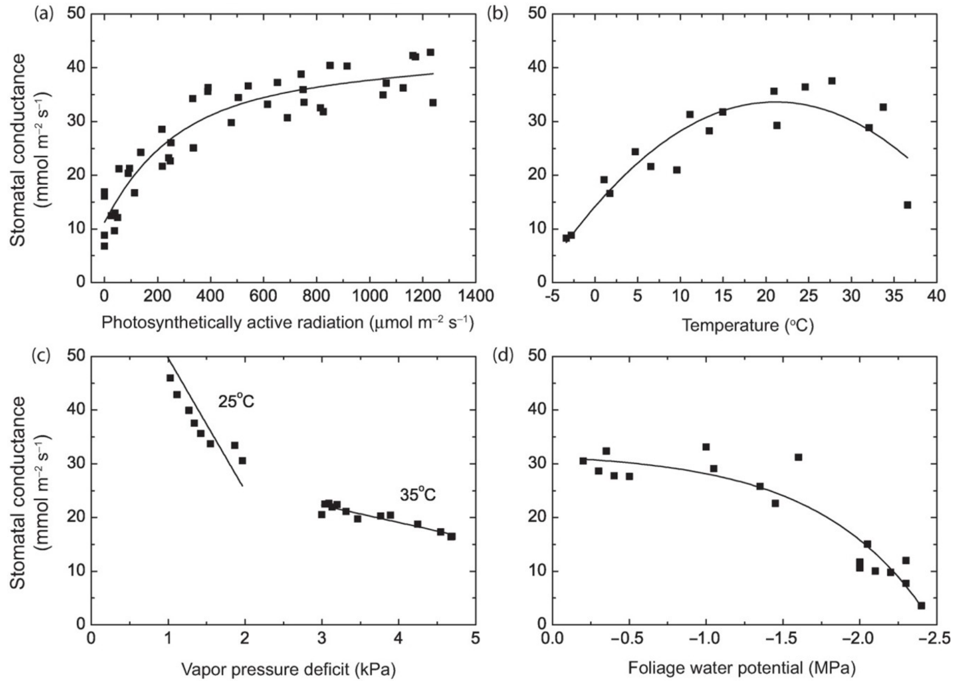


Figure 2.14: Observed responses of stomatal conductance for Pinus banksiana. (Bonan 2019)

2.2.2 Empirical multiplicative models

- Bonan, Chapter 12.2

2.2.3 Semiempirical photosynthesis-based models

- Bonan, Chapter 12.3

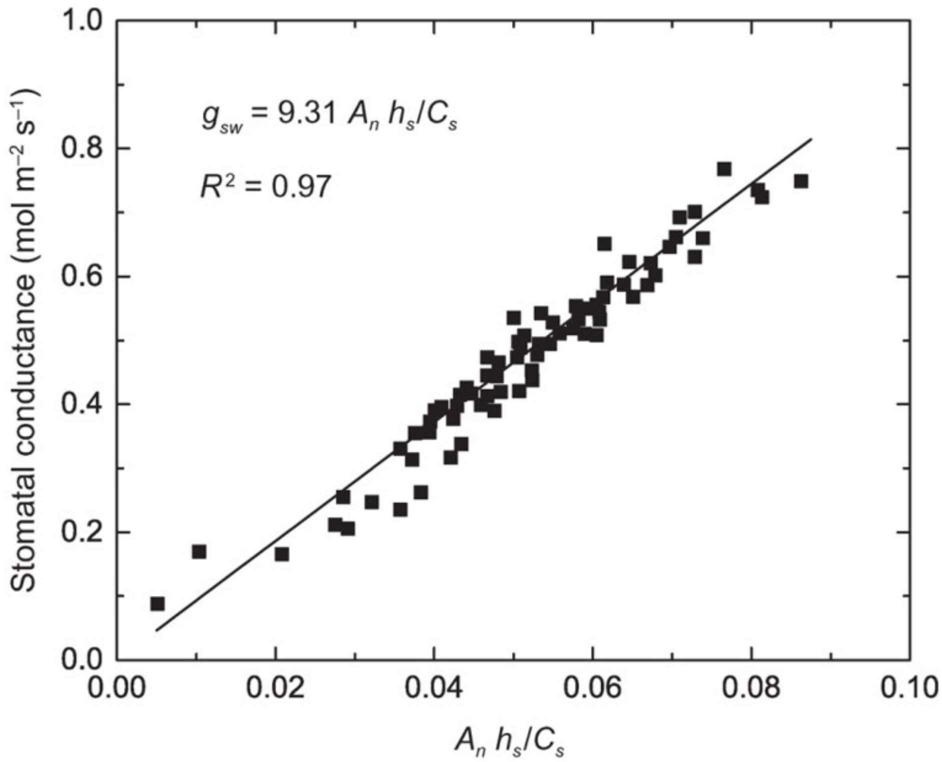


Figure 2.15: Relationship between stomatal conductance and Anhs/cs for soybean.(Bonan 2019)

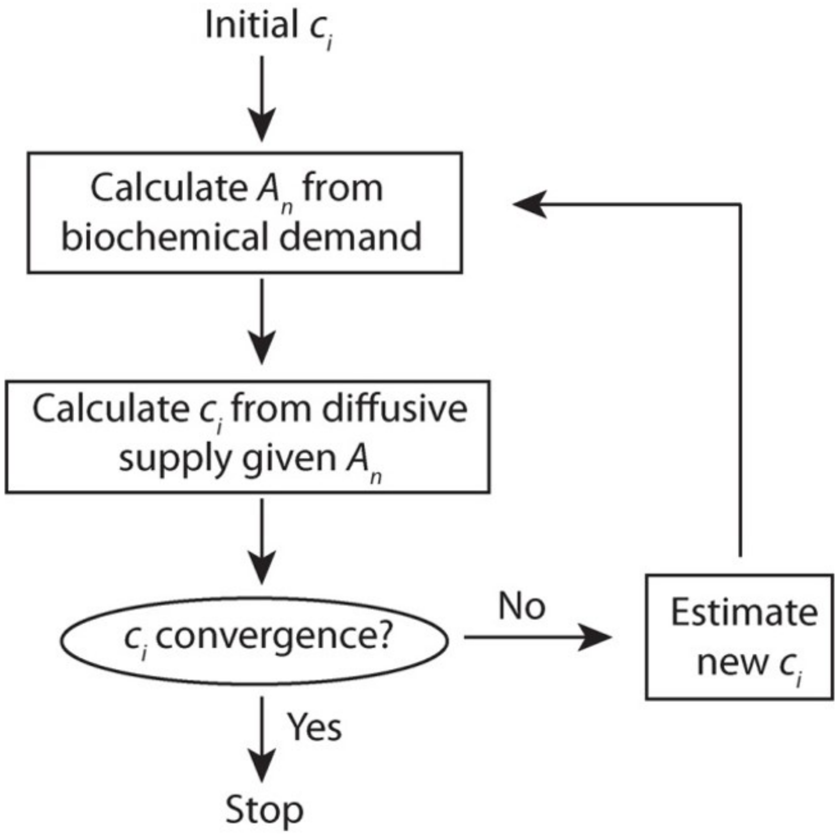


Figure 2.16: Flow diagram of the iterative procedure to numerically calculate ci.(Bonan 2019)

2.2.4 WUE models and optimality theory

- Bonan, Chapter 12.4 + add optimality approach from Prentice et al.

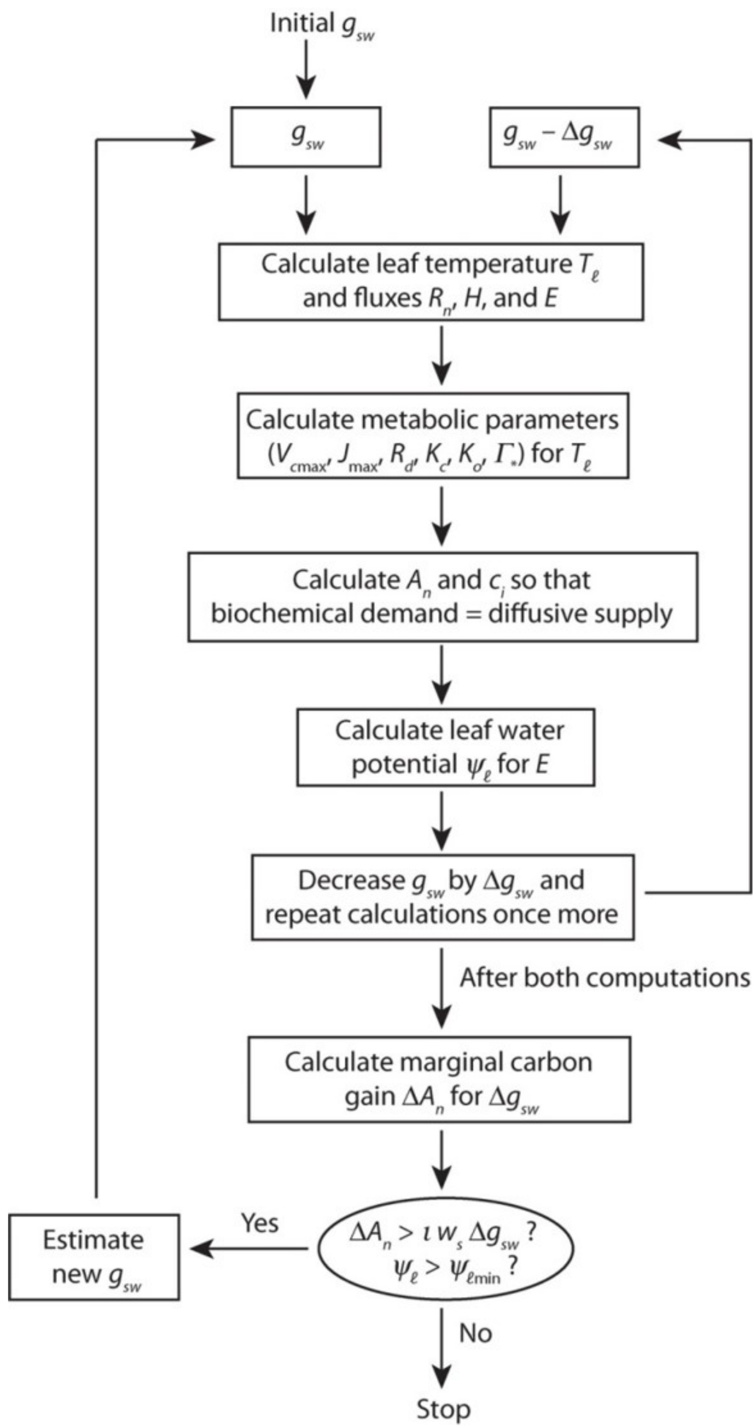


Figure 2.17: Flow diagram of leaf flux calculations to numerically solve for stomatal conductance that optimizes water-use efficiency.(Bonan 2019)

2.2.5 Soil drought stress

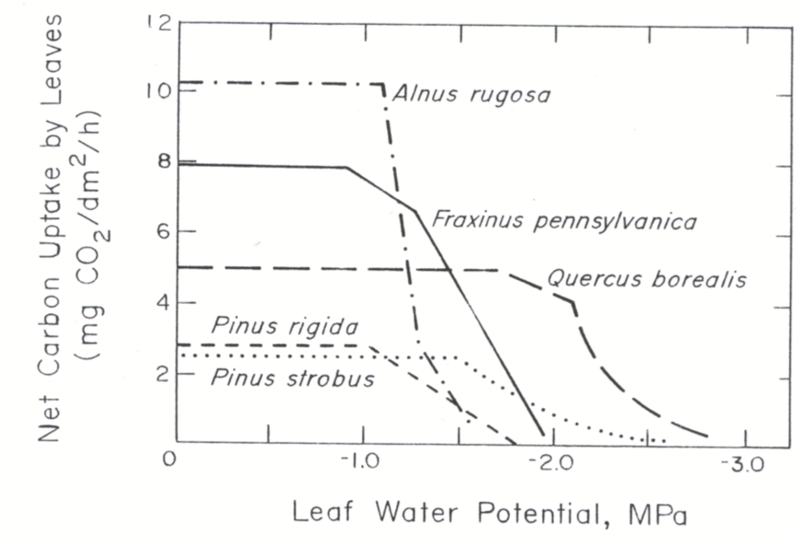


Figure 2.18: Leaf carbon uptake in response to leaf water potential for multiple tree species.

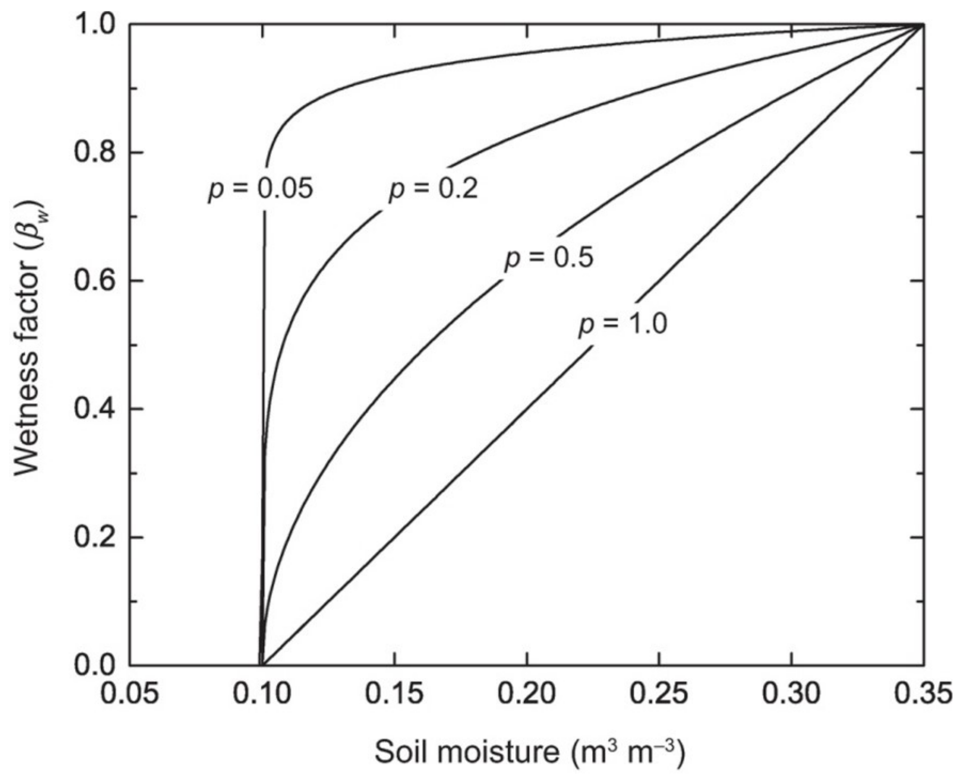


Figure 2.19: Soil moisture wetness factor in relation to volumetric water content. (Bonan 2019)

2.2.6 Hydraulic models

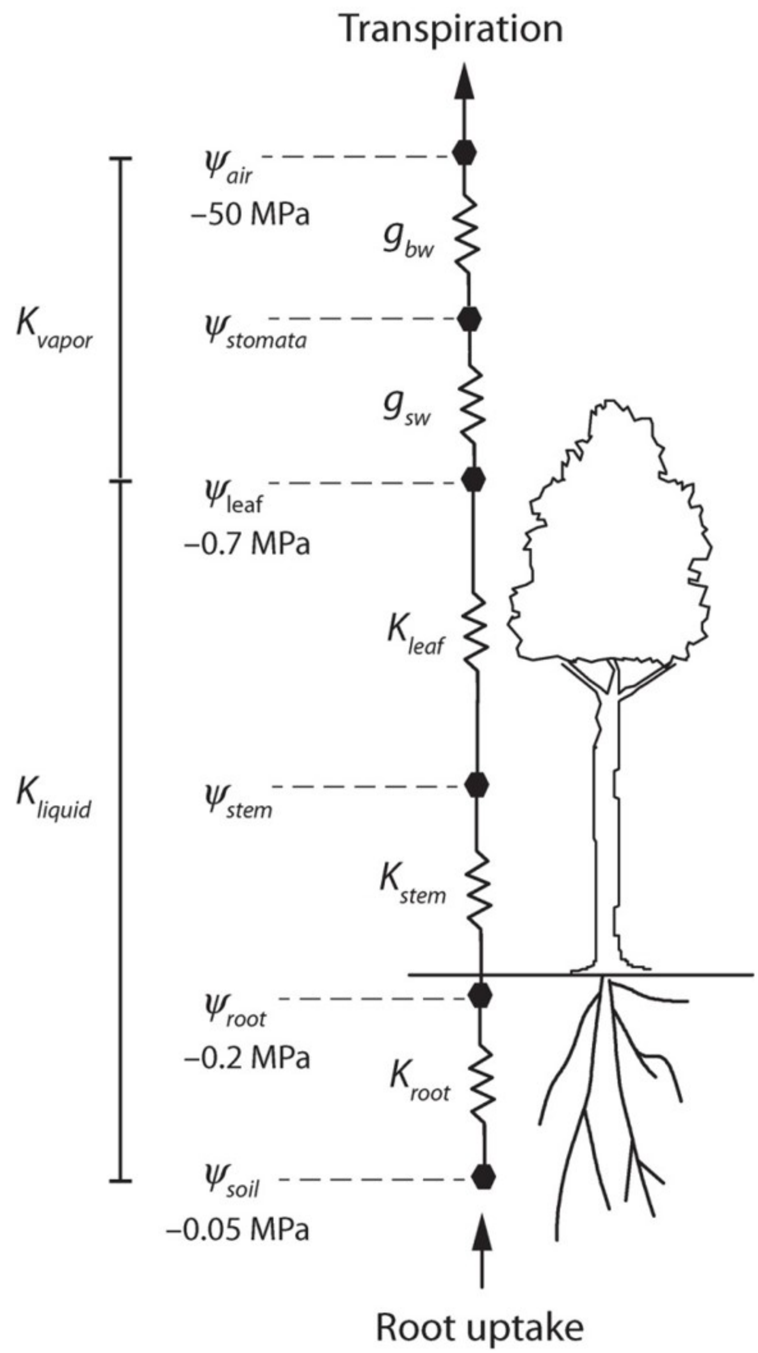


Figure 2.20: Flow of water and representative water potentials along the soil–plant–atmosphere continuum. Also shown are conductances along the hydraulic pathway.(Bonan 2019)

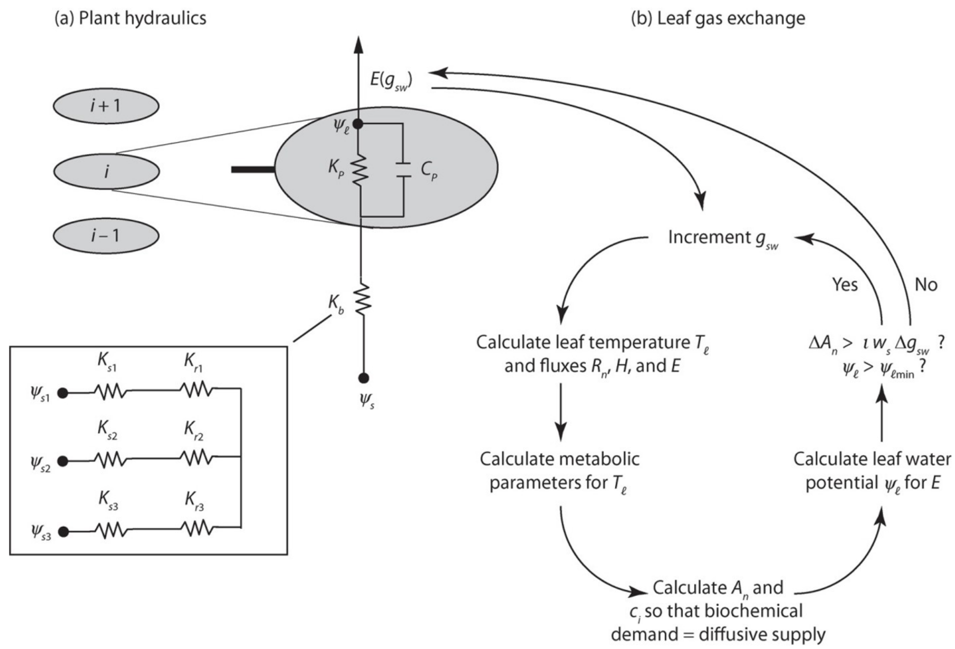


Figure 2.21: Depiction of (a) plant hydraulics and (b) leaf gas exchange in the Soil–Plant–Atmosphere (SPA) model. SPA is a multilayer canopy model.(Bonan 2019)

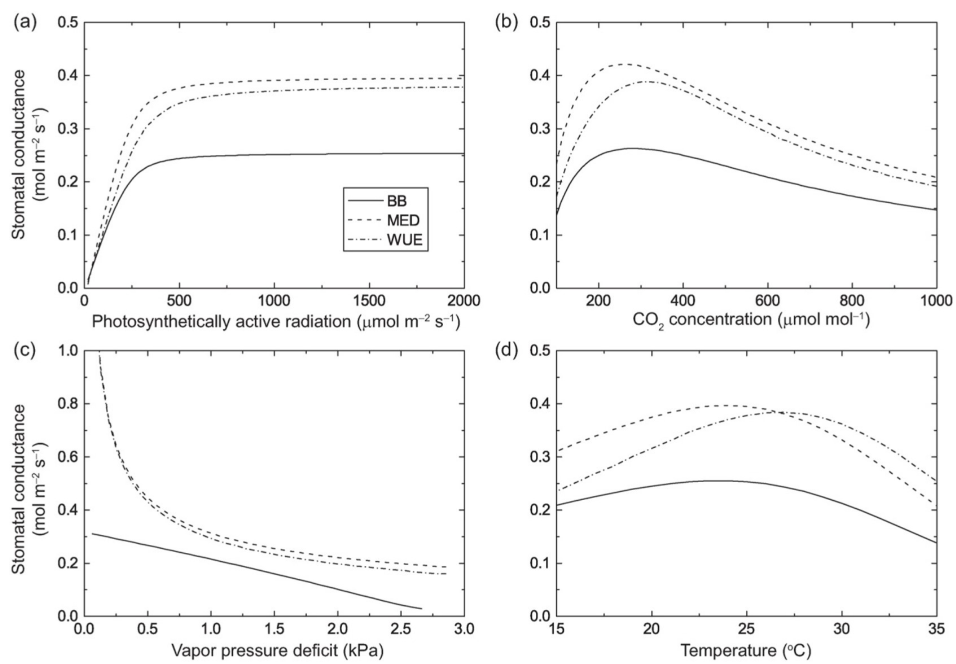


Figure 2.22: Simulated stomatal responses for various modelling approaches. (Bonan 2019)

Figure 13.1 The soil-plant-atmosphere model Leaf water potential Plant water uptake Resistance analogy Multinode models

2.3 Upscaling from leaf to canopy

- Quickly introduce the problem of scaling in ecology (review paper of Jerome Chave) and refer to chapter 10 on upscalling
- Canopy integration: LAI layers, etc… Nice transition to chap 3 with the interception of light by the canopy

Leaf microclimate and boundary layer processes in relation to leaf dimension for sun and shade conditions.

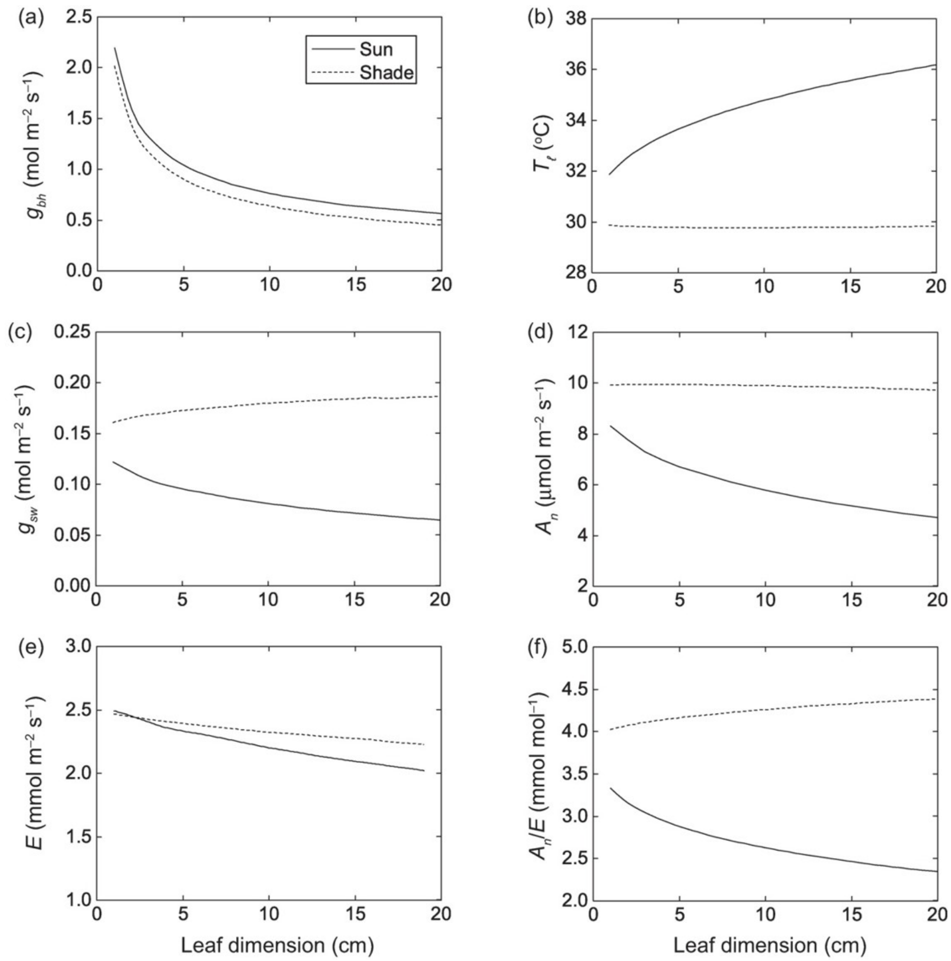


Figure 2.23: Leaf microclimate and boundary layer processes in relation to leaf dimension for sun and shade conditions.(Bonan 2019)

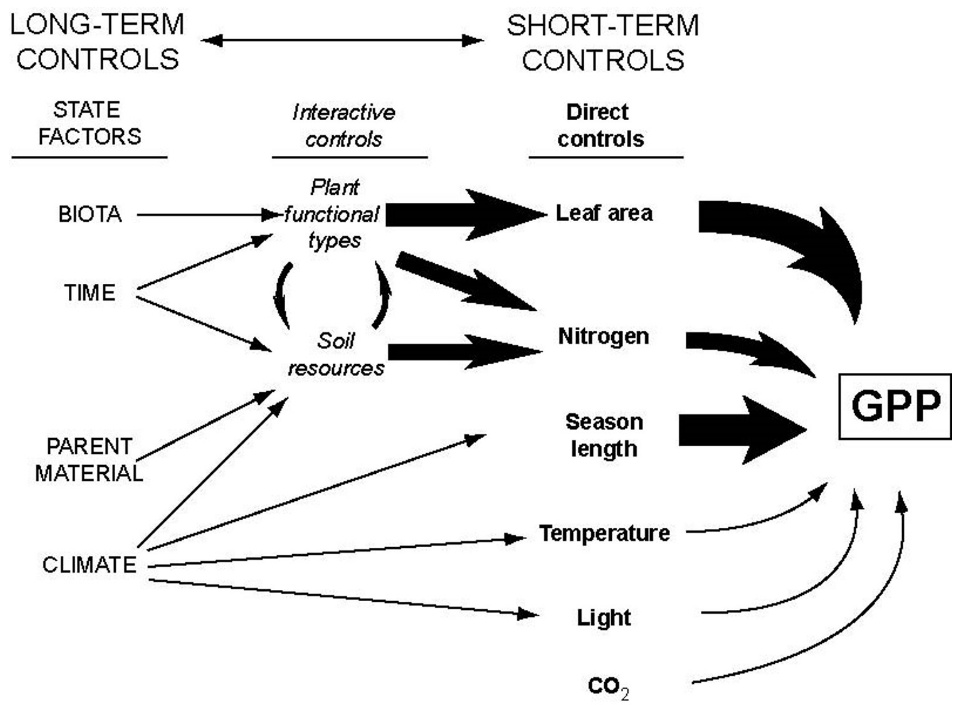


Figure 2.24: Controlling facors on ecosystem GPP. (Chapin)

2.4 Case studies

2.4.1 Case study 2.1 Ozone impact on global GPP

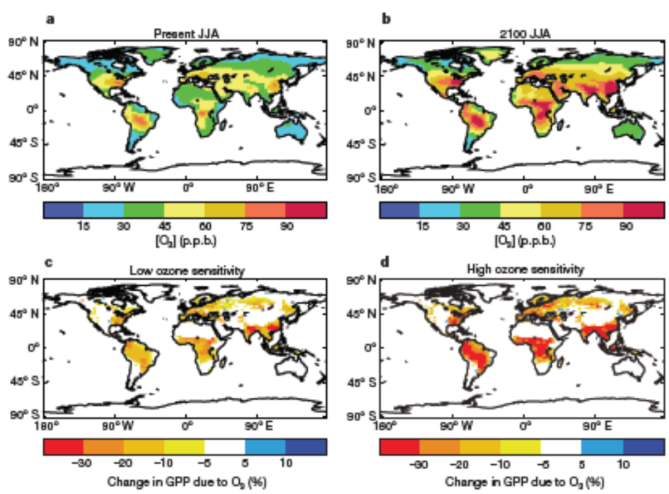


Figure 2.25: Simulated global GPP reduction in response to current and future atmospheric ozone concentrations

2.4.2 Case study 2.2 Drought impact on rainforest GPP

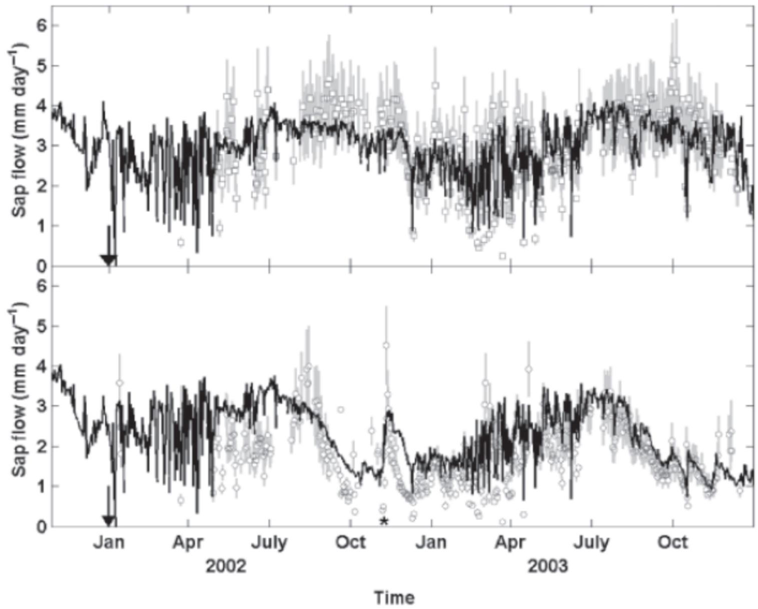


Figure 2.26: Simulated (SPA model) and observed sapflow for a drought experiment in the Amazon; Fisher et al. 2007

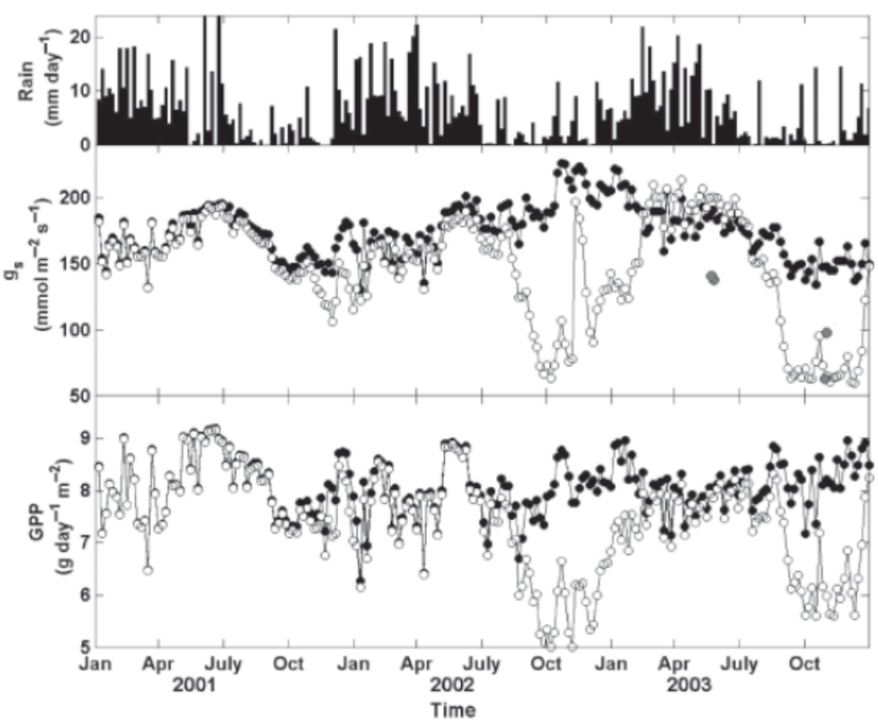


Figure 2.27: Simulated (SPA model) gs and GPP for a drought experiment in the Amazon. Fisher et al. 2007

Chapter 3

Modelling radiation, vegetation canopies, and energy balance

3.1 Introduction

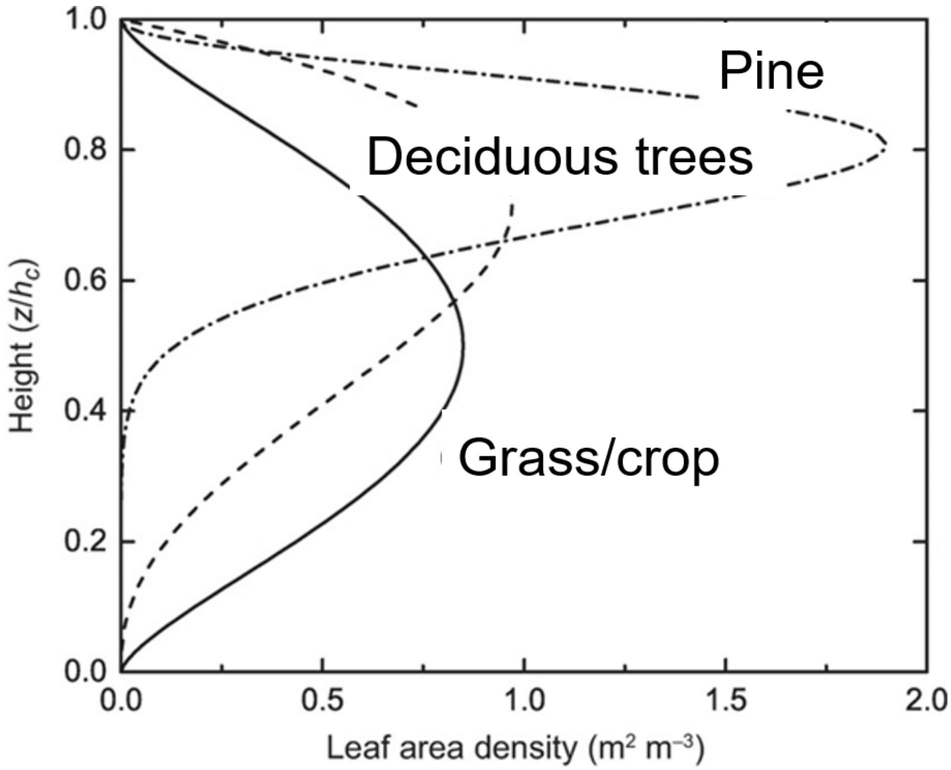


Figure 3.1: Generalized profiles of leaf area density in plant canopies. (Bonan)

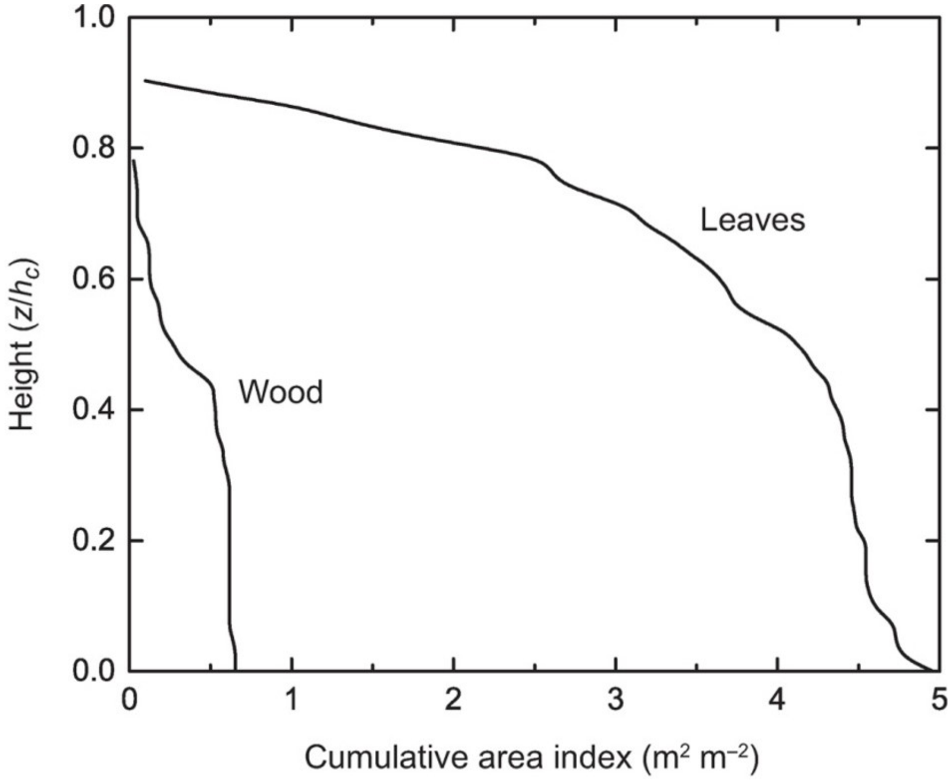


Figure 3.2: Cumulative LAI and WAI in a deciduous oak-hickory forest. (Bonan)

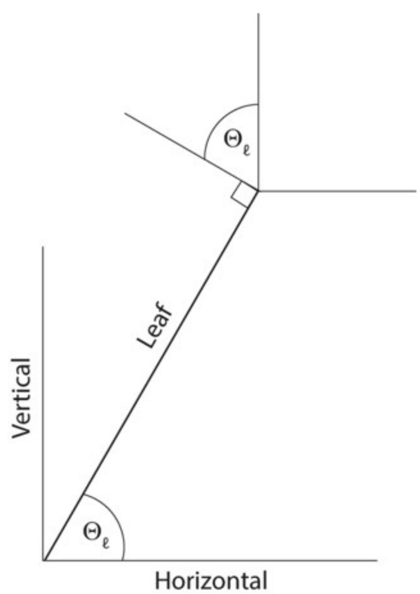


Figure 3.3: Illustration of a leaf (thick line) oriented at an angle Θ to horizontal. (Bonan)

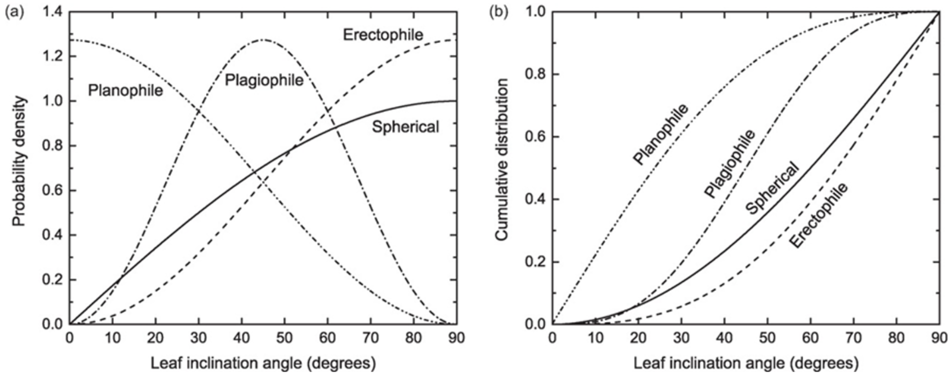


Figure 3.4: Planophile, erectophile, plagiophile, and spherical leaf angle distributions showing (a) the probability density function f(Θ) and (b) the cumulative distribution F(Θ). (Bonan)

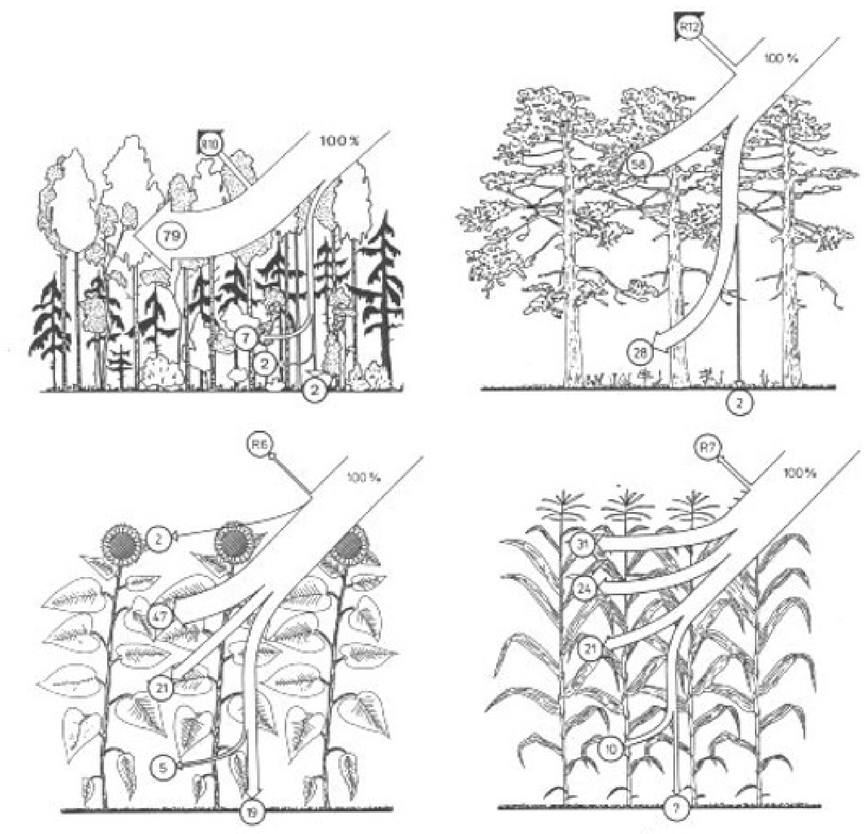


Figure 3.5: Illustration of leaf angle distributions and canopy architecture in general influences radiation attenuation in vegetation canopies.

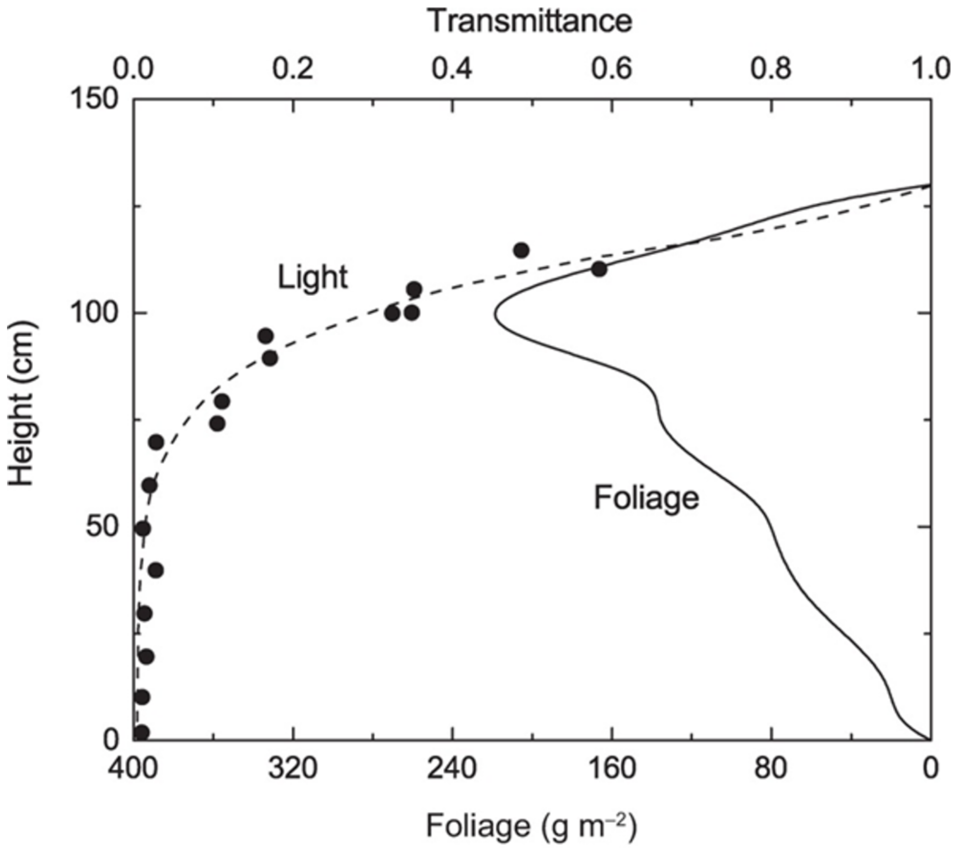


Figure 3.6: Profile of light and foliage in a stand of herbaceous plants approximately 130 cm tall. The horizontal axis shows transmittance as a fraction of incident radiation (top axis) and foliage mass (bottom axis) at various heights in the canopy. (Bonan)

3.2 Radiative transfer modelling

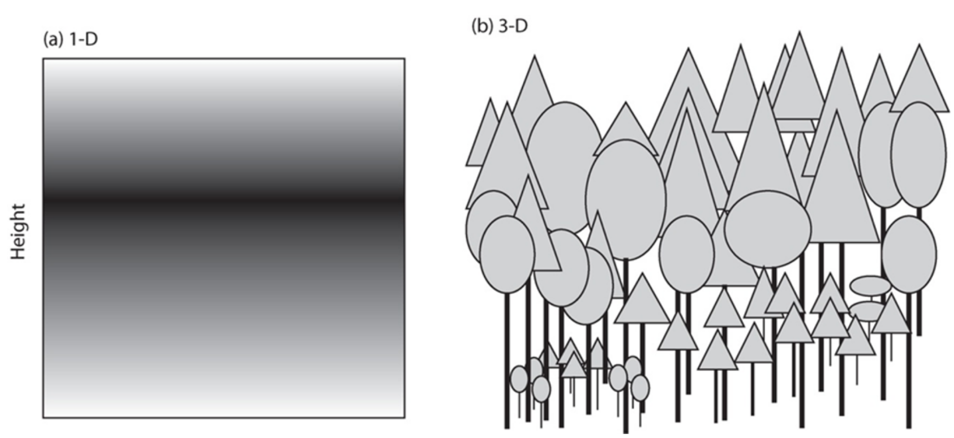


Figure 3.7: Representation of a canopy as (a) one-dimensional with a vertical profile of leaf area (shown by grayscale gradation in which darker shading denotes more leaves) that is horizontally homogenous and (b) threedimensional with vertical and spatial structure determined by crown geometry and spacing. (Bonan)

3.2.1 Leaf optical properties

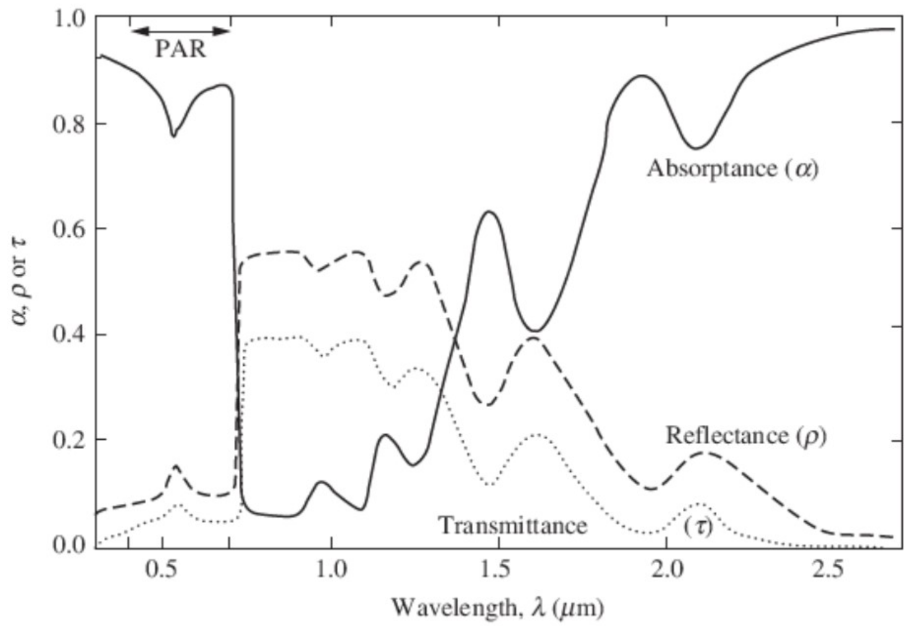


Figure 3.8: Spectrum of absorptance, reflectance and transmittance of a typical plant leaf (Jones, 2014)

	ρ_S (%)	α_S (%)
Single leaves		
Crop species	29–33	40–60
Deciduous broad leaves (low sun)	26–32	34–44
Deciduous broad leaves (high sun)	20–26	48–56
Artemisia sp. (white pubescent, high sun)	39	55
Verbascum sp. (white pubescent, high sun)	36	52
Conifers	12	88
Typical mean values for total shortwave (ρ_S, α_S)	~30	~50
Typical mean values for PAR (ρ_{PAR}, α_{PAR})	~9	~85
Vegetation		
Grass	24	
Crops	15–26	
Forests	12–18	
Typical mean values for total shortwave (ρ_S)	~20	
Typical mean values for PAR (ρ_{PAR})	~5	
Other surfaces		
Snow	75–95	
Wet soil	9 ± 4	
Dry soil	19 ± 6	
Water	5–>20	

Figure 3.9: Table showing typical reflectance and absorptance values for leaves and vegetation canopies of different Plant Functional Types (PFT).(Jones, 2014)

3.2.2 Light transmission without scattering

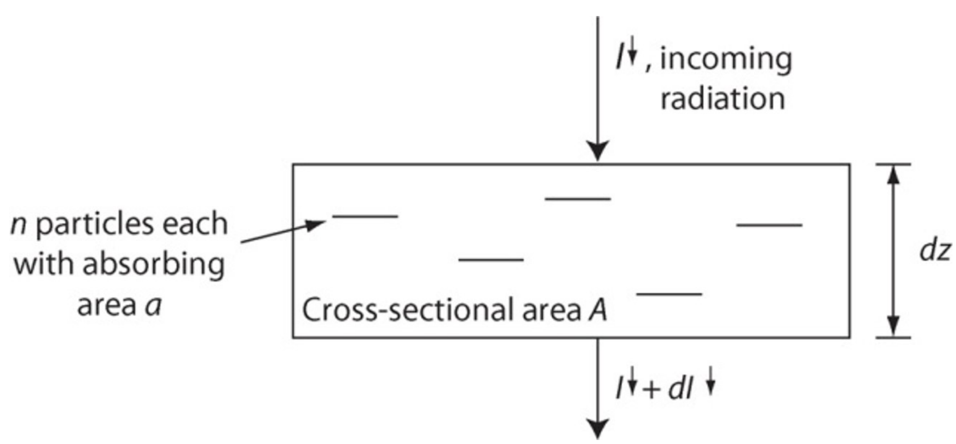


Figure 3.10: Transmission of solar radiation through a homogeneous medium in the absence of scattering. In this example, n non-overlapping opaque particles each with cross-sectional area a oriented perpendicular to the path of light are placed in a medium with cross-sectional area A and thickness dz. The radiation absorbed in the medium is dI.(Bonan)

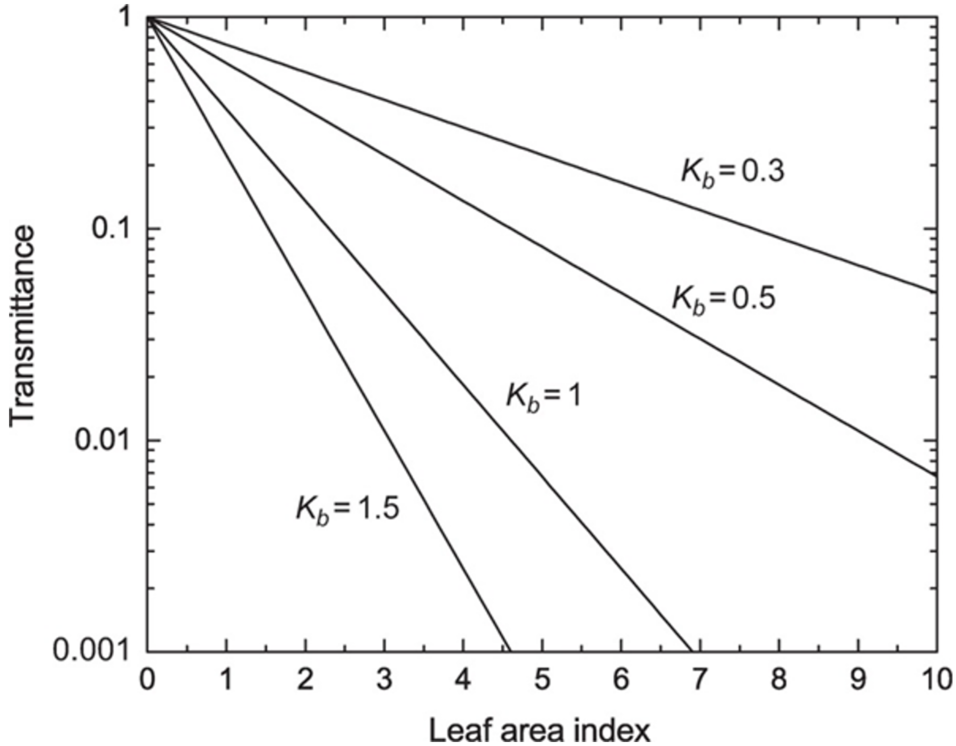


Figure 3.11: Transmission of direct beam radiation b in relation to leaf area index for typical values of the extinction coefficient Kb. (Bonan)

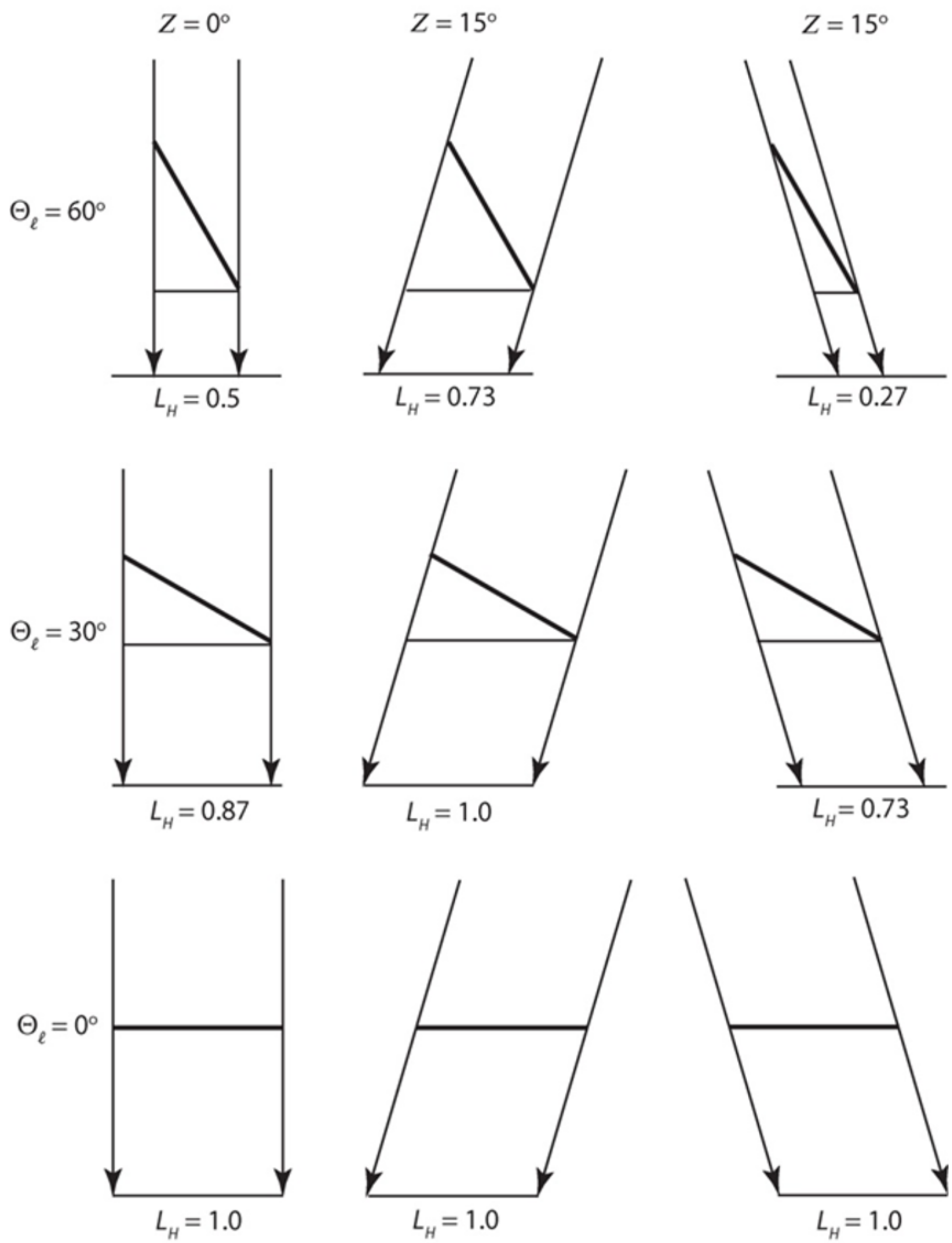


Figure 3.12: Extinction coefficient in relation to solar zenith angle Z and leaf inclination angle Θ . In each panel, a unit leaf area (L = 1), shown with a thick line, is projected onto a horizontal surface LH so that Kb = LH. The leaf inclination angle is 0° (bottom panels), 30° (middle panels), and 60° (top panels). In the left and middle columns, the leaf is oriented towards the Sun (A − A = 0°) and the solar zenith angle is 0° (left column) and 15° (middle column). In the right column, Z = 15°, but the leaf is oriented away from the Sun (A − A = 180°). In each panel, the arrows indicate the solar beam (Bonan)

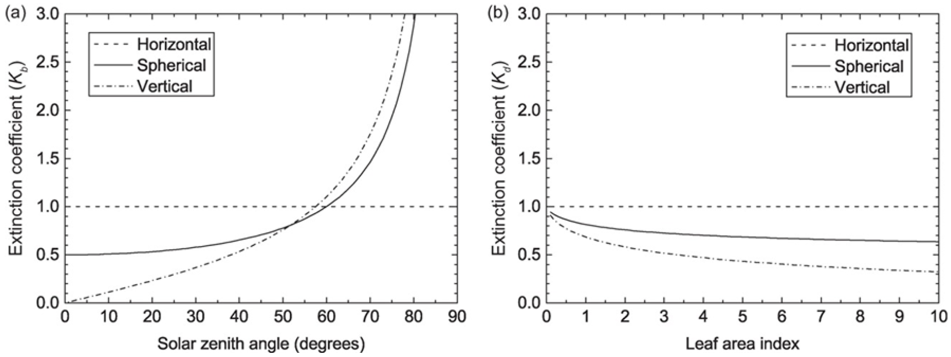


Figure 3.13: Extinction coefficients for horizontal, spherical, and vertical leaf angle distributions. (a) Direct beam radiation Kb in relation to solar zenith angle. (b) Diffuse radiation Kd in relation to leaf area index(Bonan)

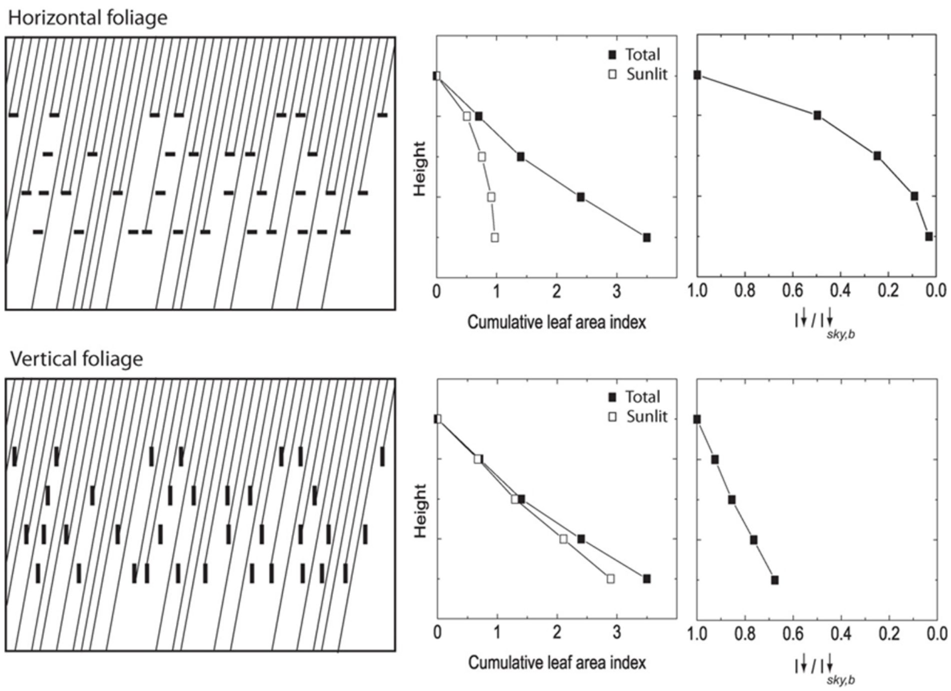


Figure 3.14: Radiative transfer and sunlit leaf area index for a canopy of horizontal leaves (top panels) with Kb = 1 and vertical leaves (bottom panels) with Kb = 0.112. The left-hand panels show a canopy consisting of four layers of leaves. Each thick black line represents a leaf area index of 0.1 m2 m–2. The thin lines depict interception or transmission of beam radiation with a zenith angle of 10°. The middle panels show cumulative leaf area index and sunlit leaf area index with depth in the canopy. The right-hand panels show direct beam transmittance with depth in the canopy. (Bonan)

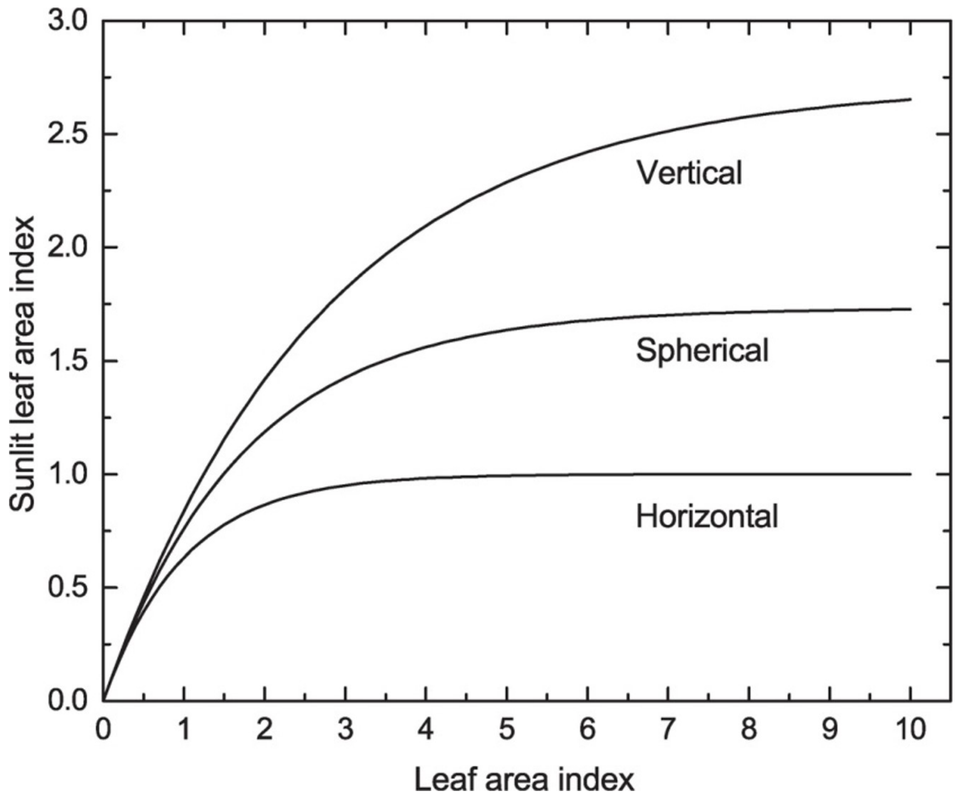


Figure 3.15: Sunlit leaf area index in relation to total leaf area index for horizontal, spherical, and vertical foliage orientations with solar zenith angle Z = 30°. Kb = 1, 0.577, and 0.368 for horizontal, spherical, and vertical foliage. (Bonan)

Figure 3.16: Images illustrating leaf/canopy clumping a various scales: leaf, crown, stand.

3.2.3 Diffuse transmittance

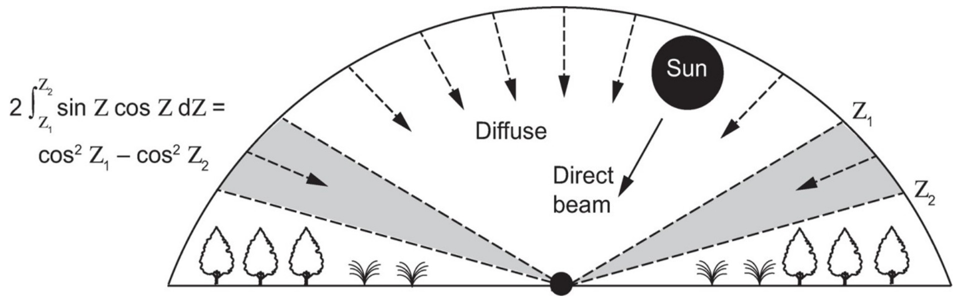


Figure 3.17: Illustration of direct beam and diffuse radiation. The sky forms a bowl, or inverted hemisphere, over a horizontal surface. Shown is a cross section of the sky hemisphere. Direct beam (solid line) originates from the direction of the Sun with zenith angle Z. Diffuse radiation (dashed lines) can be treated as independent beams of radiation each with an angle Z. The shaded region is the relative contribution between sky angles Z1 and Z2 to total sky irradiance.(Bonan)

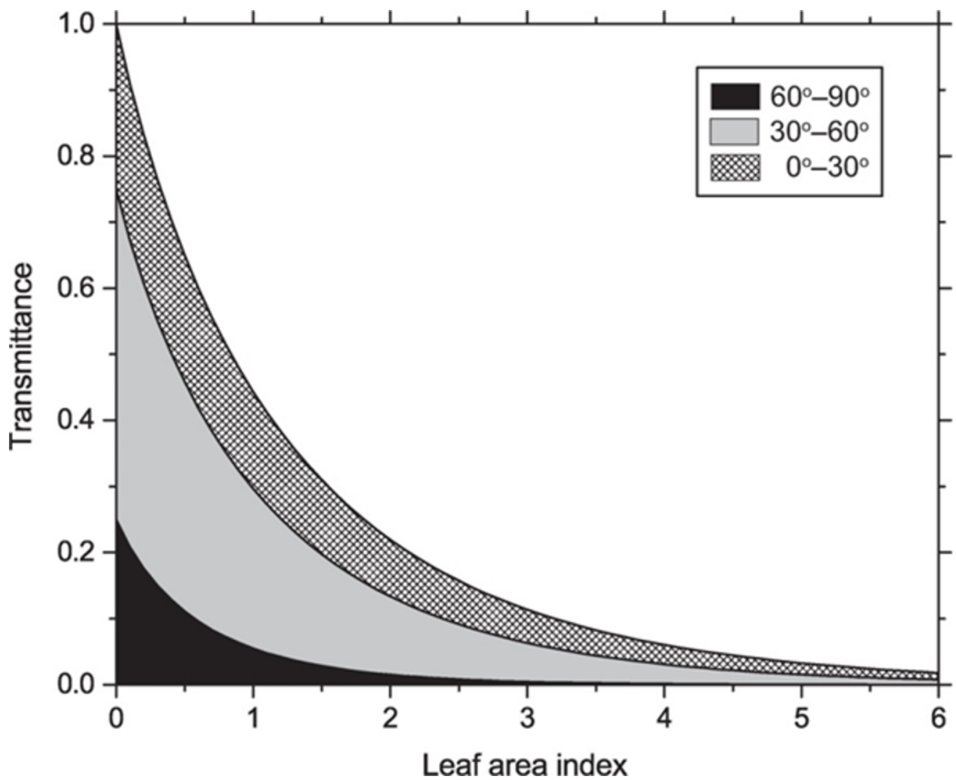


Figure 3.18: Transmittance of diffuse radiation d in relation to leaf area index for a spherical leaf distribution. Show are the transmittances for sky zones of 0°–30°, 30°–60°, and 60°–90° and also the total transmittance. Fill patterns show the contribution of each sky zone to total transmittance.(Bonan)

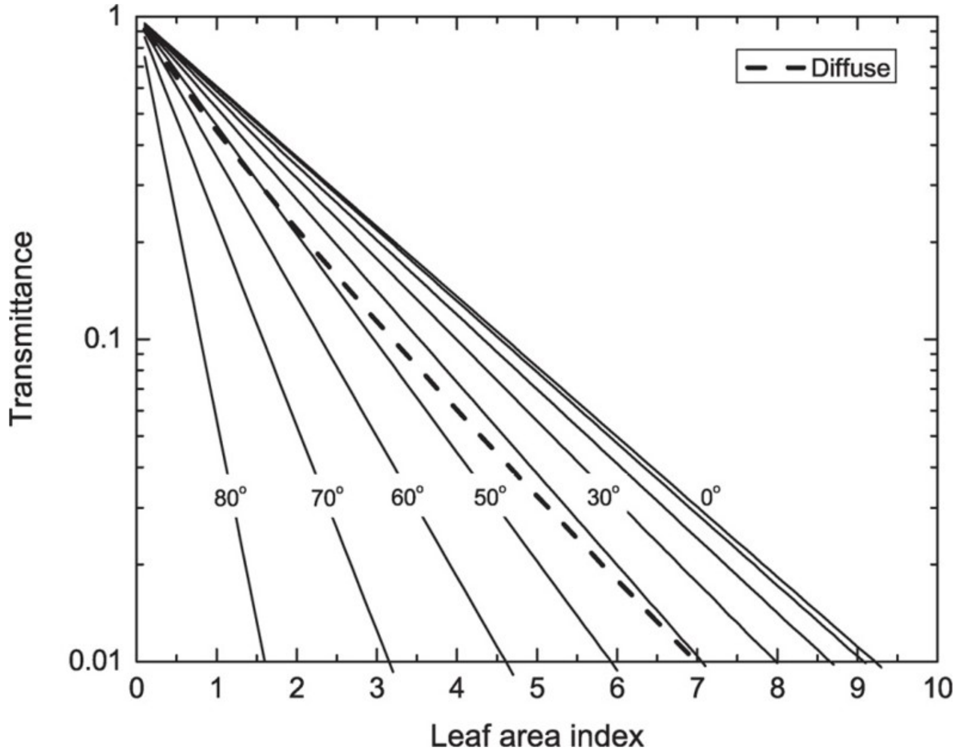


Figure 3.19: Transmission of solar radiation through a canopy with spherical leaf distribution in relation to leaf area index. The solid lines show direct beam transmittance b for solar zenith angles of 0°–80° (in 10° increments).The dashed line shows the diffuse transmittance d. (Bonan)

3.2.4 The Norman Model(1979)

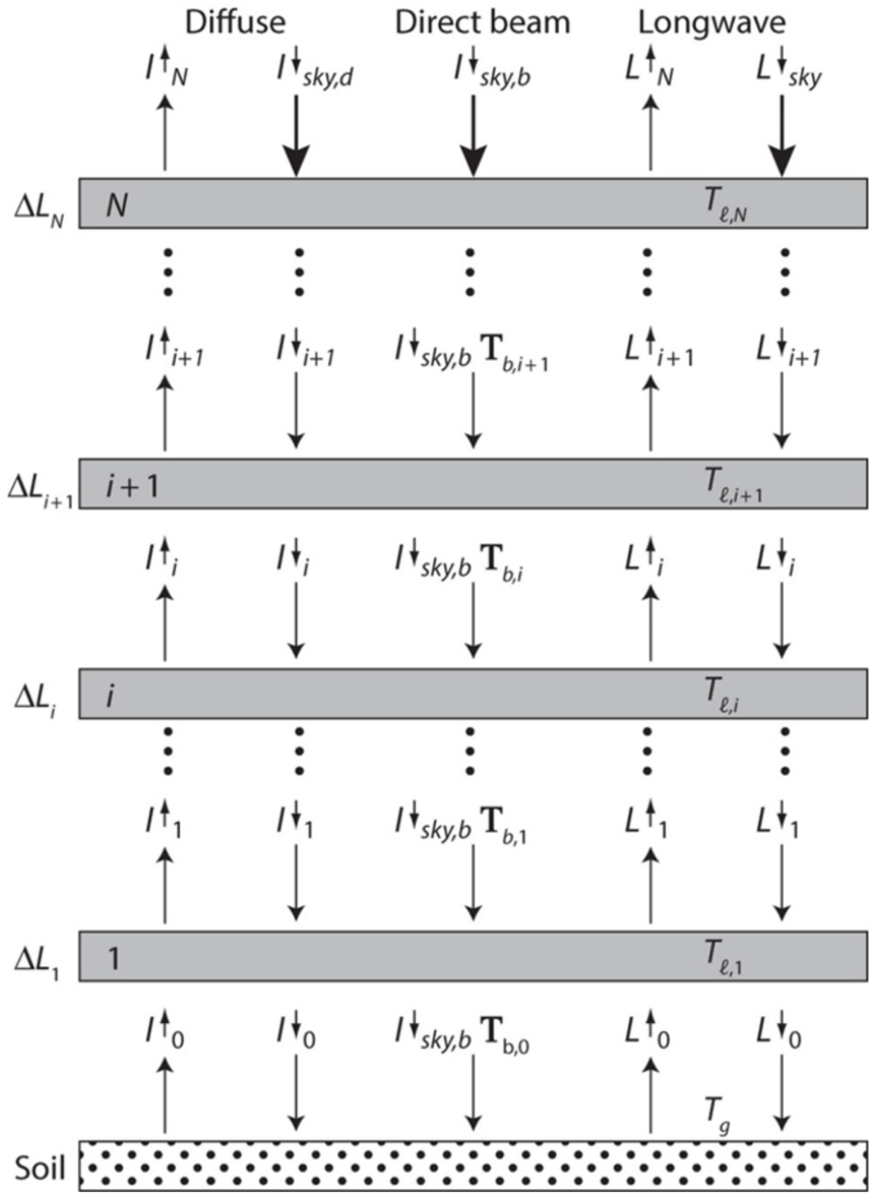


Figure 3.20: Radiative fluxes in a canopy of N leaf layers. The vertical profile is oriented with i = 1 the leaf layer at the bottom of the canopy, leaf layer i + 1 above layer i, and i = N the leaf layer at the top of the canopy. Each layer has a leaf area index ΔL. is the downward diffuse shortwave flux onto layer i, is the upward diffuse shortwave flux above layer i, and is the unscattered direct beam flux onto layer i. and are the corresponding downward and upward fluxes of longwave radiation. These depend on leaf T and ground Tg temperatures. Thick arrows denote boundary conditions of diffuse solar radiation , direct beam solar radiation, and atmospheric longwave radiation at the top of the canopy.(Bonan)

3.2.5 The Goudriaan and van Laar Model (1994)

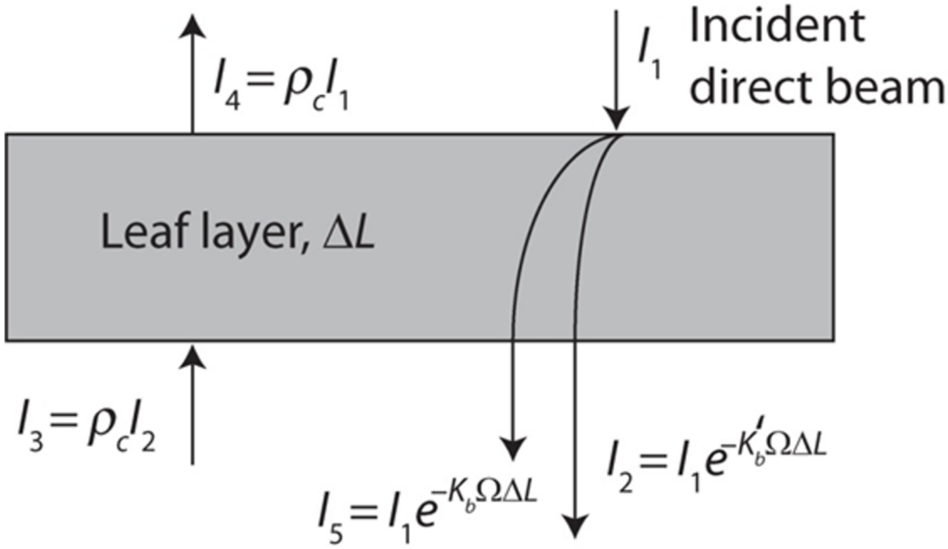


Figure 3.21: Derivation of absorbed direct beam solar radiation for a leaf layer with leaf area index ΔL (Goudriaan 1982). c is the reflectance of the leaf layer.(Bonan)

3.2.6 The Two-Stream approximation

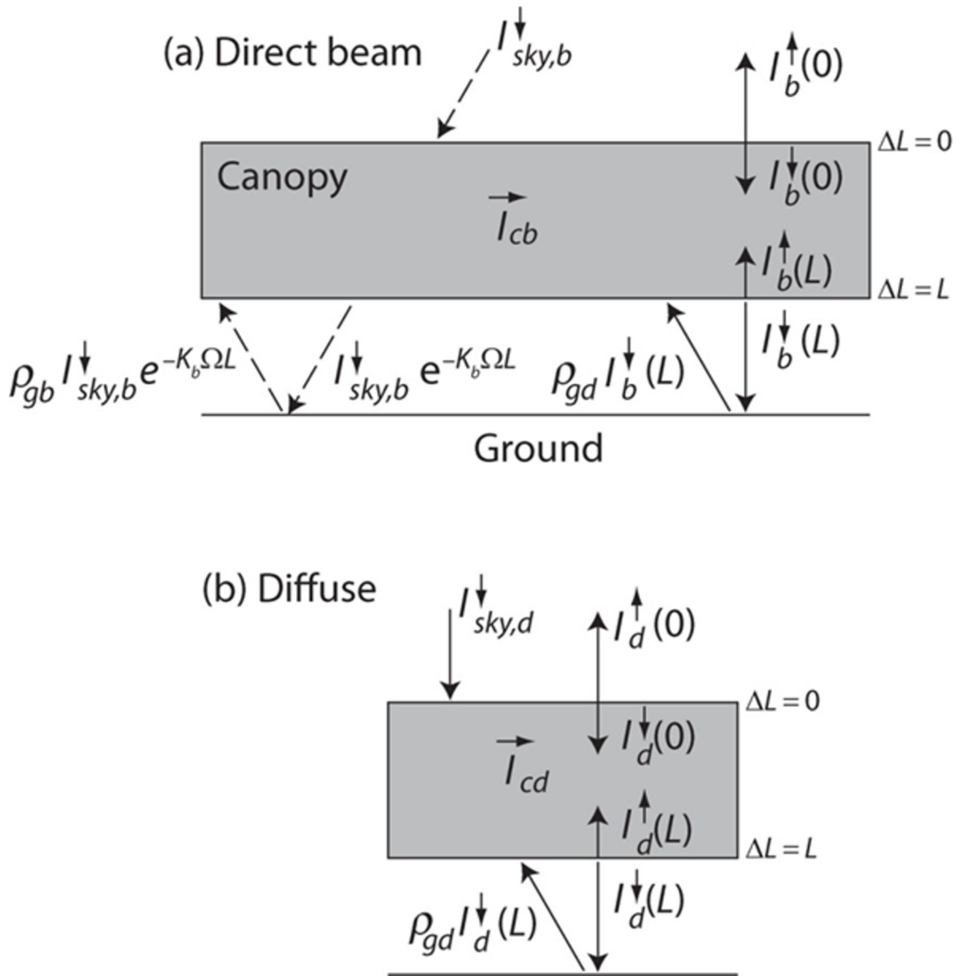


Figure 3.22: Fluxes for (a) direct beam and (b) diffuse radiation in the twostream approximation for a canopy with leaf area index L.(Bonan)

3.2.7 Longwave radiation

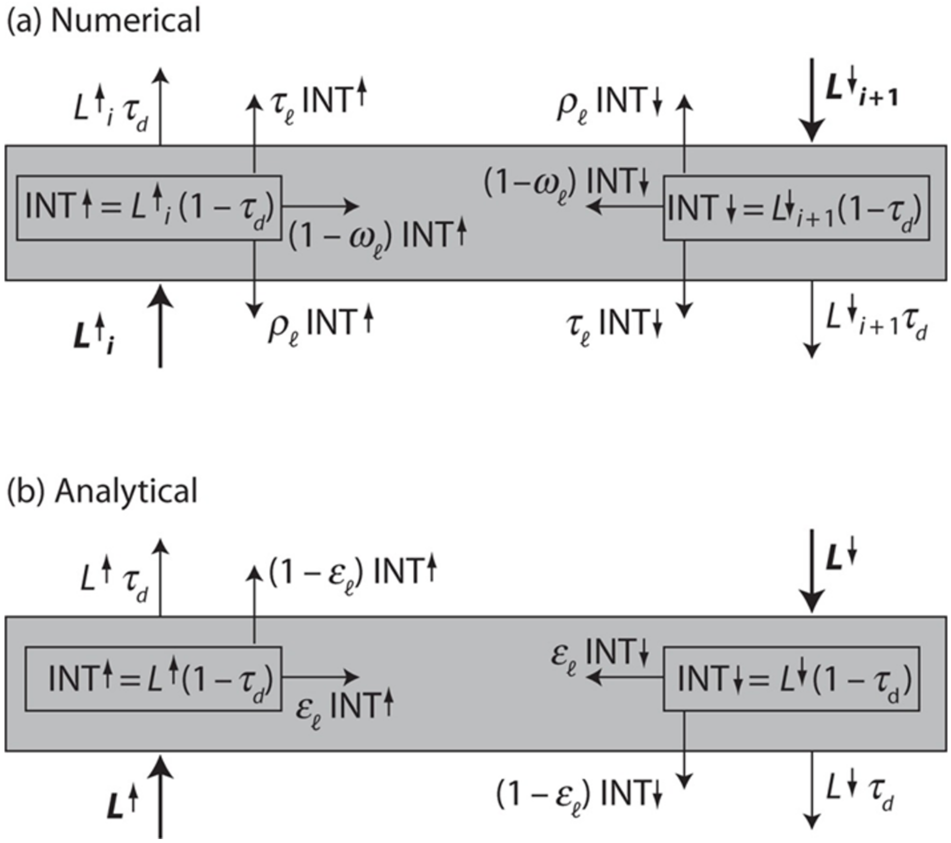


Figure 3.23: Longwave radiation fluxes represented for a single leaf layer.(a) Norman's (1979) numerical model. Shown is the radiative balance for leaf layer i + 1 located above leaf layer i. (b) A simplified model to allow only forward scattering (= 0 and = = 1 −) and to permit an analytical solution integrated over a canopy. In both panels, emitted radiation is excluded. Thick lines denote fluxes incident onto the layer. (Bonan)

3.3 Representing canopy structure in models

3.3.1 Big-leaf models

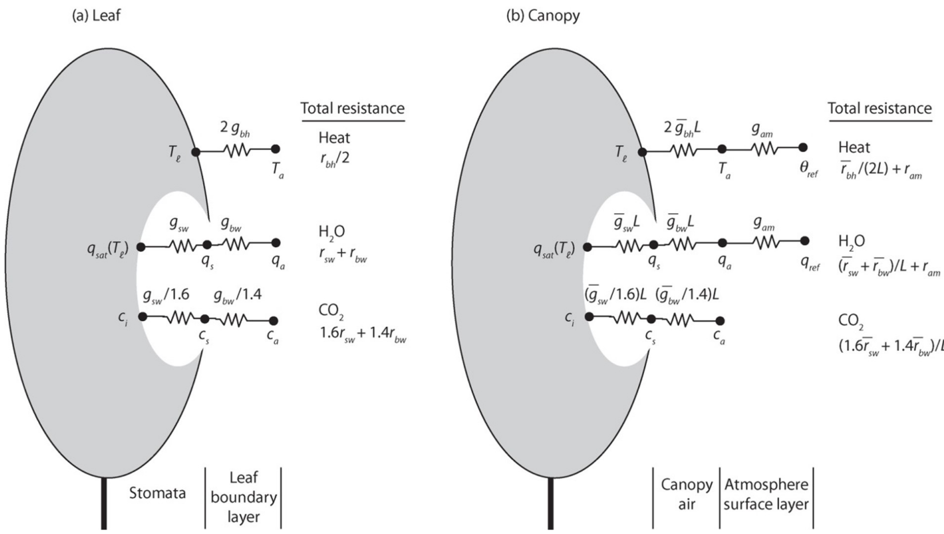


Figure 3.24: Scaling of leaf fluxes to the canopy using a big-leaf model. (a) Shown are leaf sensible heat, transpiration, and CO2 fluxes in relation to various conductances. Fluxes are exchanged between the leaf and air around the leaf. Also shown is the total resistance. (b) Shown are big-leaf canopy fluxes in which leaf fluxes are scaled by the average conductance and leaf area index and are further modified by turbulent transport in the atmospheric surface layer. Surface layer processes are commonly omitted for CO2 exchange. Only a single big leaf is shown, but separate sunlit and shaded big leaves can be similarly depicted. (Bonan)

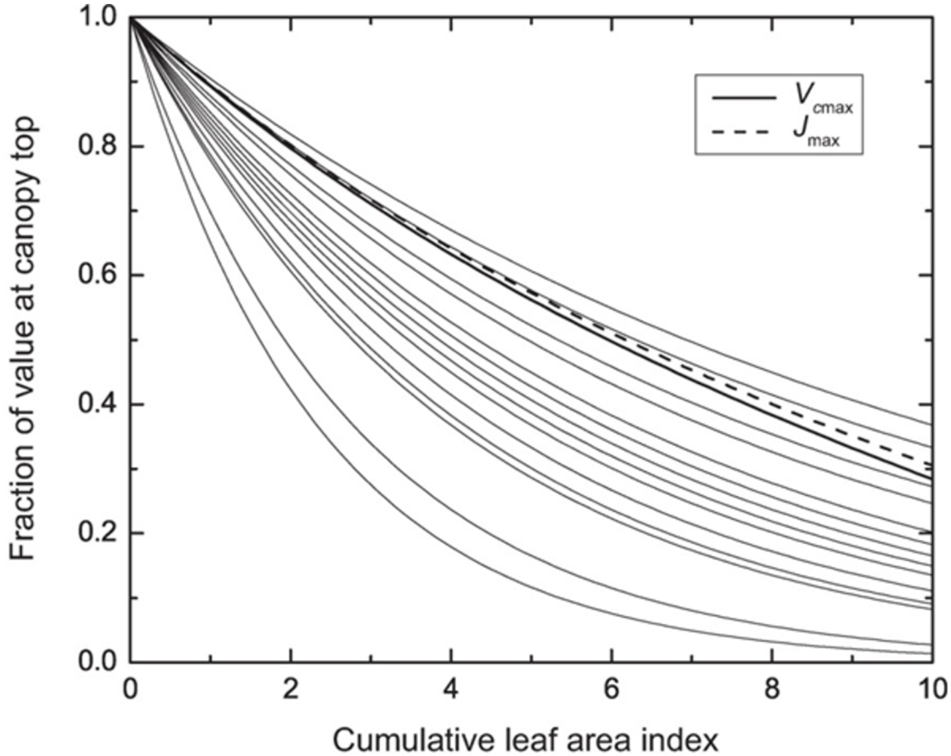


Figure 3.25: Canopy profiles of relative photosynthetic capacity in relation to cumulative leaf area index. Thin lines show exponential profiles using values of Kn for 16 temperate broadleaf forests and two tropical forests ranging from 0.10 to 0.43 (Lloyd et al. 2010). The two thick lines show observed profiles of Vcmax and Jmax from Niinemets and Tenhunen (1997) obtained for sugar maple (Acer saccharum). (Bonan)

3.3.2 Multilayer models

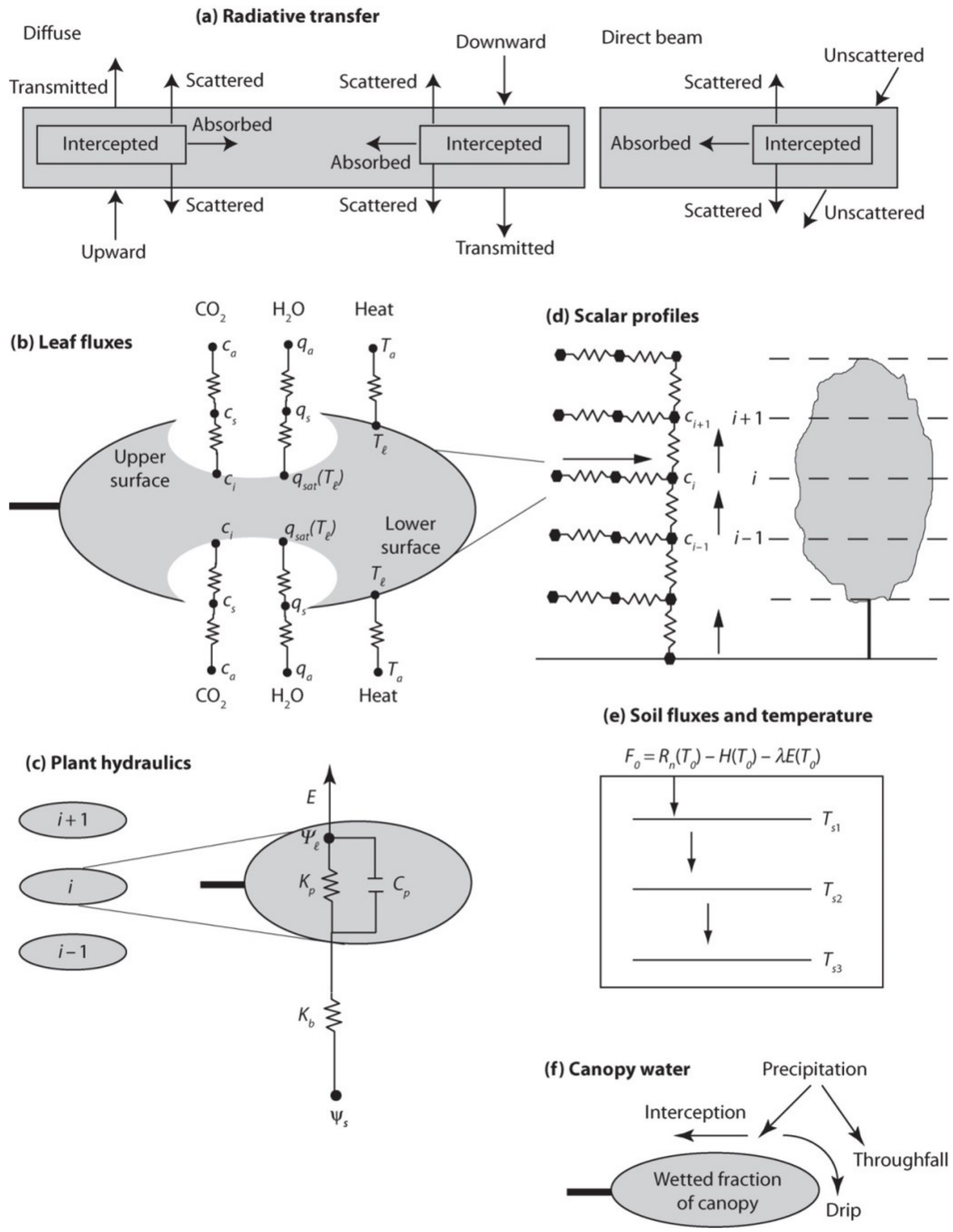


Figure 3.26: Overview of the main processes in a multilayer canopy model.The canopy is represented by N leaf layers with layer i + 1 above layer i. (a) Diffuse and direct beam solar radiation is transmitted or intercepted. The intercepted portion is absorbed or scattered in the forward and backward direction. Longwave radiation is similar to diffuse radiation. (b) Leaf sensible heat, transpiration, and CO2 fluxes depend on absorbed radiation and leaf boundary layer and stomatal conductances. Sensible heat is exchanged from both sides of the leaf. Water vapor and CO2 can be exchanged from one or both sides of the leaf depending on stomata. Leaf temperature is the temperature that balances the energy budget. (c) Stomatal conductance depends on leaf water potential. Plant water uptake for a canopy layer is in relation to belowground soil and root conductance and aboveground stem conductance acting in series and also a capacitance term. See Figure 13.4a for more details. (d) Scalar profiles are calculated from a conductance network. Leaf fluxes provide the source or sink of heat, water vapor, and CO2, along with soil fluxes. (e) Sensible heat, latent heat, and heat storage in soil depend on the ground temperature that balances the soil energy budget. (f) The wetted fraction of the canopy layer depends on the portion of precipitation that is intercepted. (Bonan)

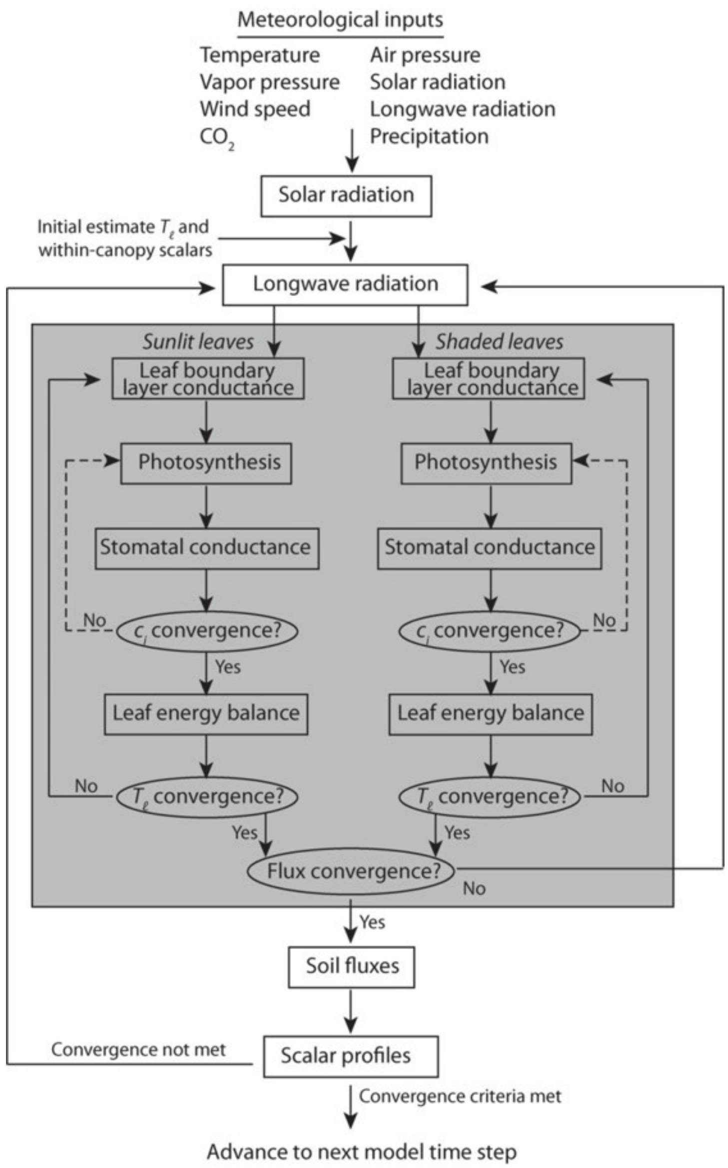


Figure 3.27: Flow diagram of processes in a multilayer canopy model. The shaded area denotes leaf processes resolved at each layer in the canopy. This is a generalized diagram of the required calculations for a dry leaf. Specific models differ in how the equation set is solved and the iterative calculations. Evaporation of intercepted water requires additional complexity.(Bonan)

3.3.3 3D ray tracing models

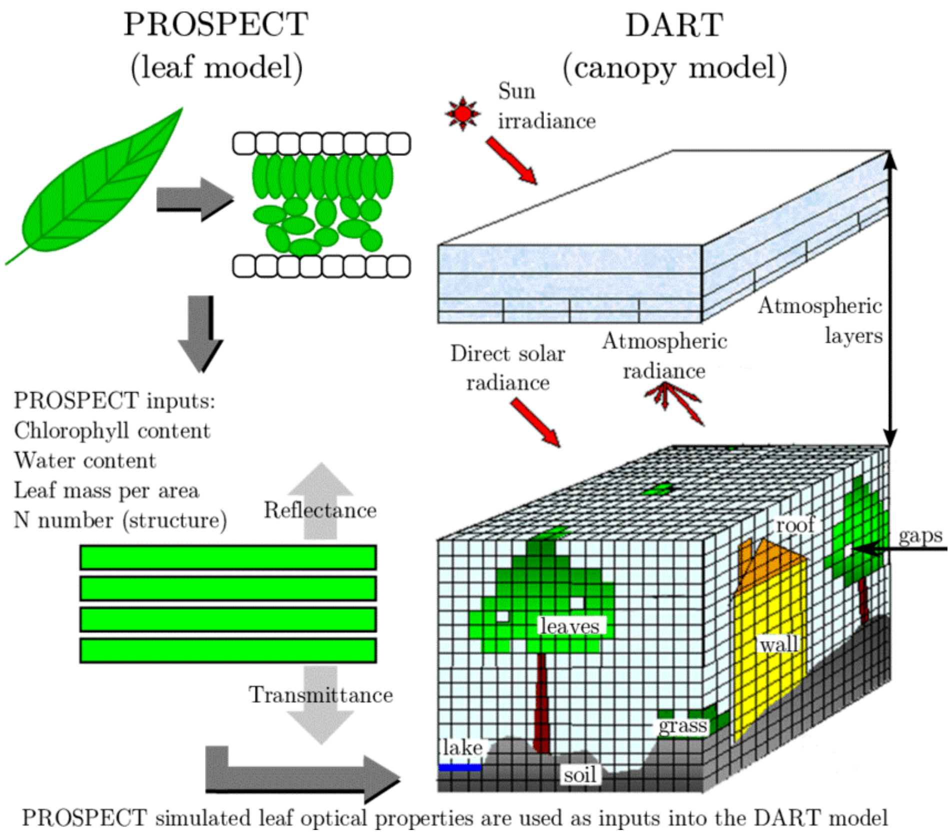


Figure 3.28: Example of the PROSPECT leaf optical model and the DART 3D ray tracing model.

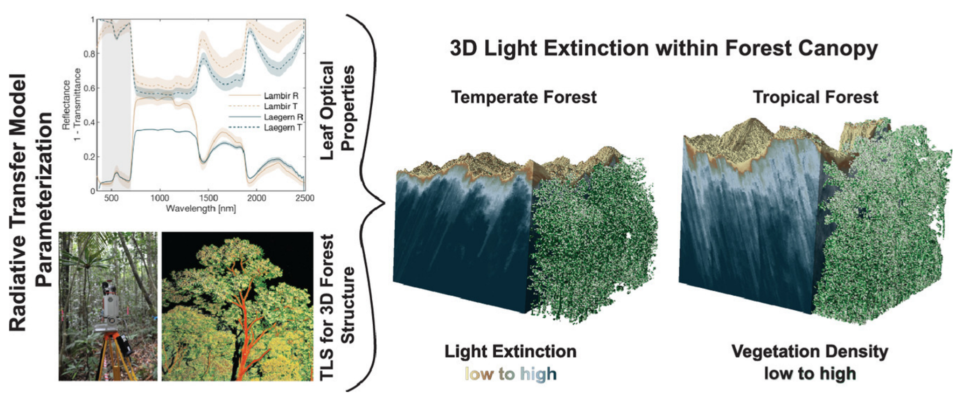


Figure 3.29: Example of a study that uses terrestrial laser scanning (TLS) to construct a full 3D model of a forest as input for a 3D ray tracing model (Kükenbrink et al. 2020)

3.4 Ecosystem energy balance

3.4.1 Basic principles

3.4.2 Surface radiation balance

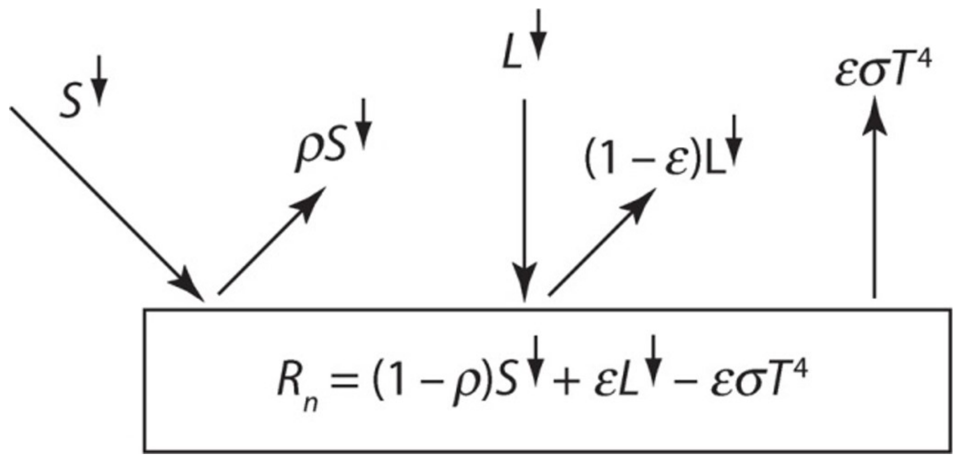


Figure 3.30: Radiative balance of an opaque gray body receiving downwelling solar S↓ and longwave L↓ radiation.(Bonan)

3.4.3 Bulk surface energy balance

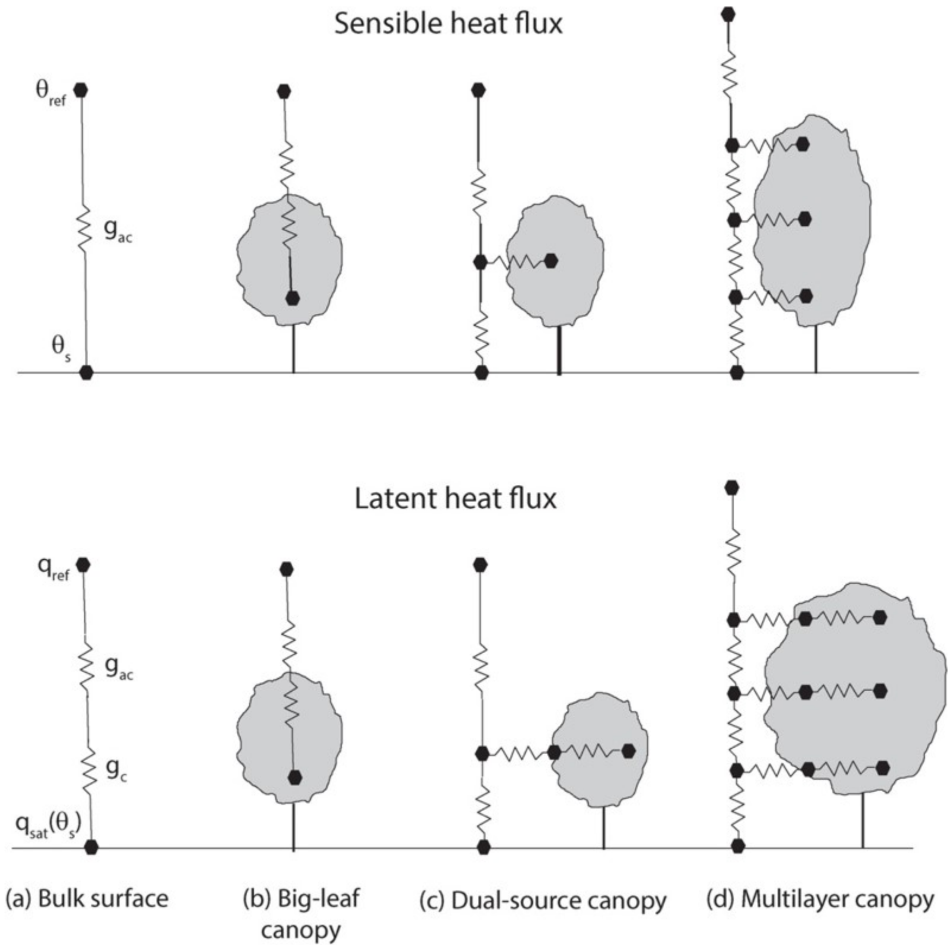


Figure 3.31: Conductance networks for sensible heat flux (top) and latent heat flux (bottom) for various depictions of the land surface. This chapter describes the bulk surface and big-leaf canopies. (Bonan)

3.4.4 Leaf energy balance

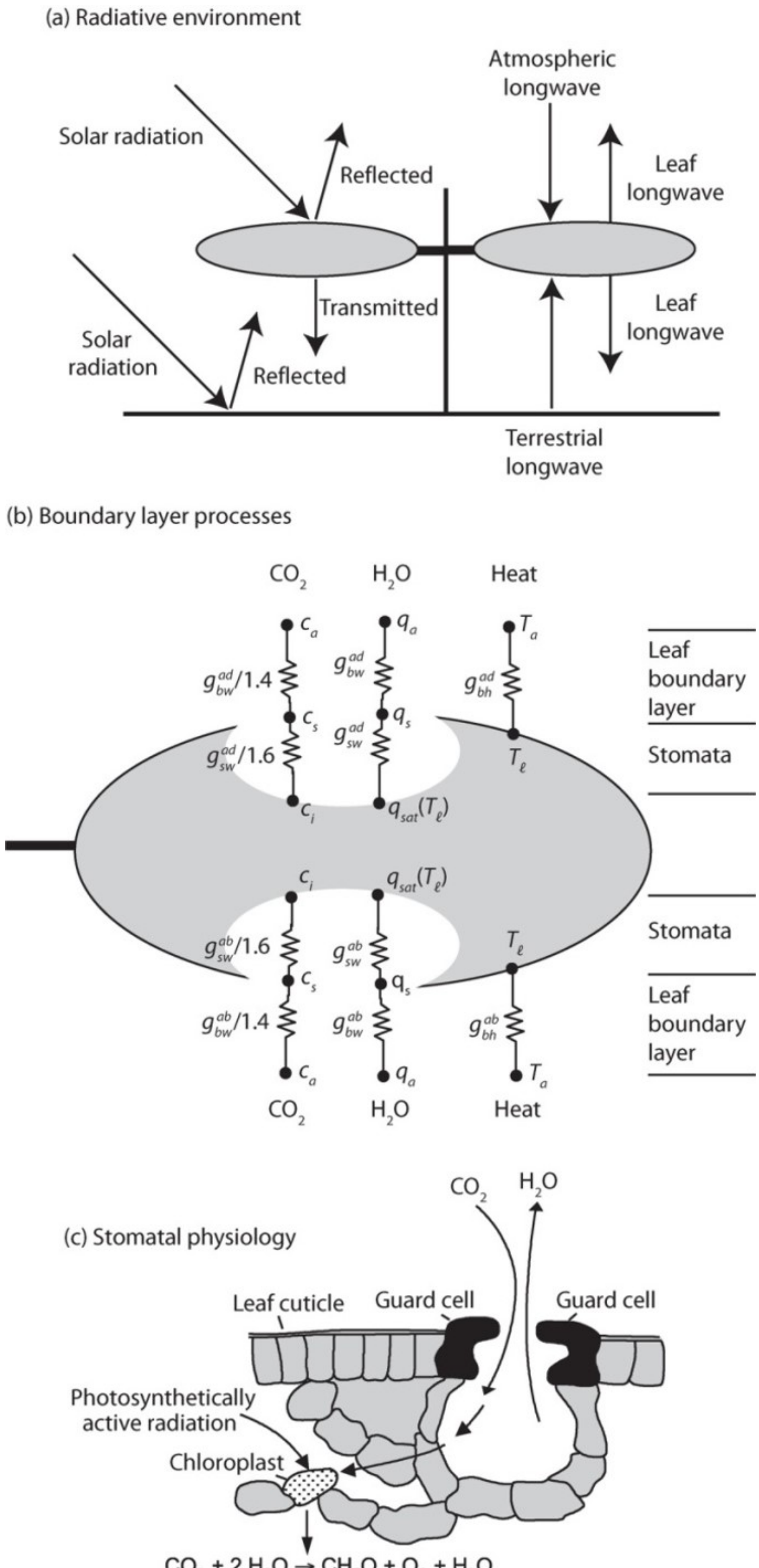


Figure 3.32: Biophysics and biochemistry of leaves. (a) The radiative environment consists of solar radiation (left) and longwave radiation (right). (b) Leaf fluxes include

3.5 Case studies

3.5.1 Case study 3.1

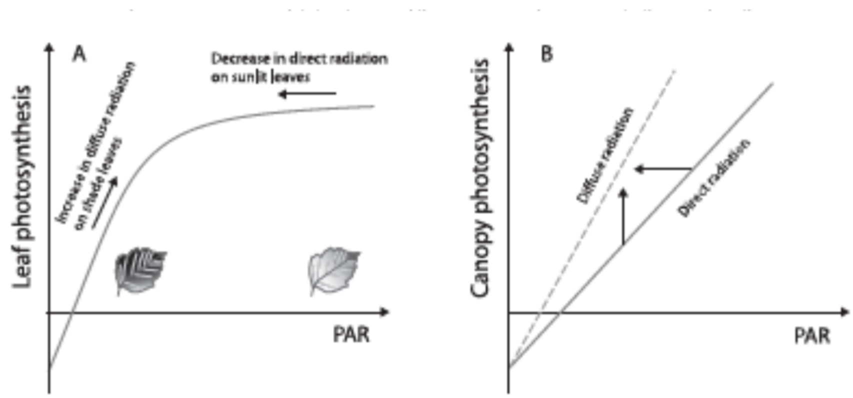


Figure 3.33: Principle of the effect of increased diffuse raditaion on leaf/canopy photosynthesis. (Knohl et al. 2008)

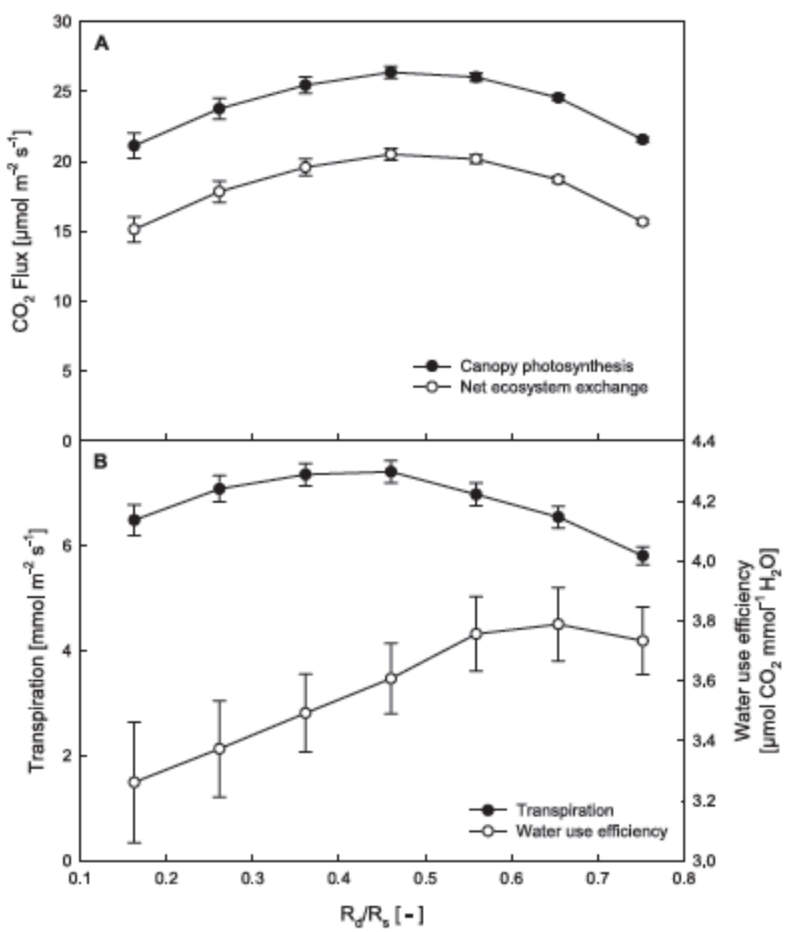


Figure 3.34: Resulting impact of changing diffuse fraction on carbon and water fluxes and WUE (Knohl et al. 2008)

3.5.2 Case study 3.2

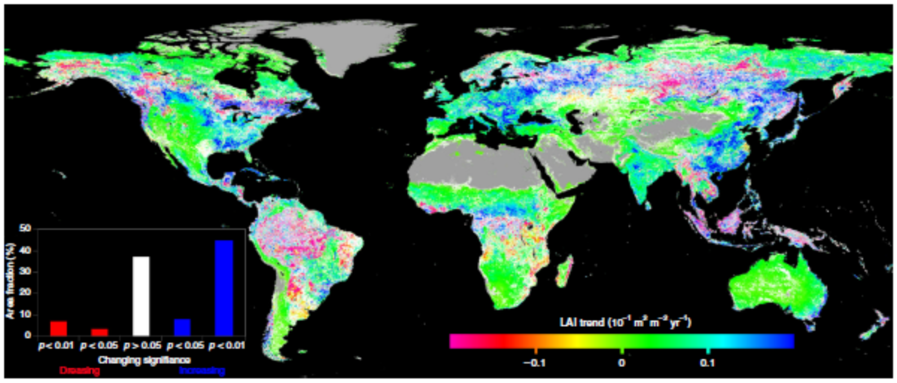


Fig. 1 Global map indicating the trend of LAI from 1981 to 2016. The gray color indicates non-vegetated areas and the white color denotes that the trend is statistically insignificant ($p > 0.05$). Positive values indicate increasing trends of growing season mean LAI and vice versa

Figure 3.35: Global map of LAI trend between 1981 and 2016 based on remote sensing (Chen et al. 2021).

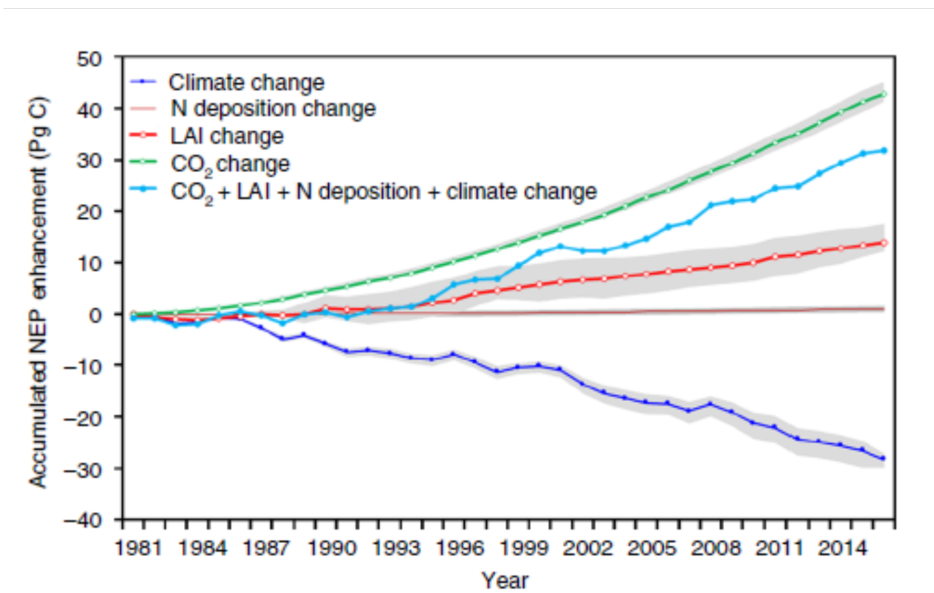


Figure 3.36: Simulated impact of different factors contributing to the increased global land C sink since 1981 (Chen et al. 2021)

Chapter 4

Modelling temporal and seasonal dynamics

4.1 Introduction on temporal dynamics

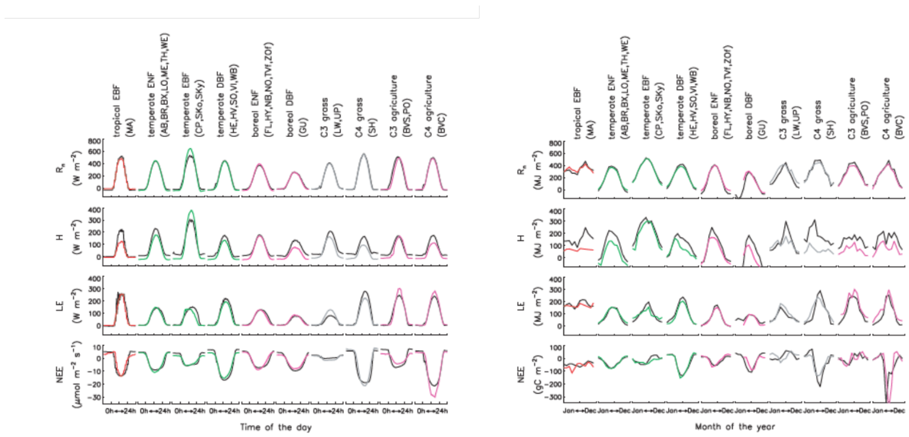


Figure 4.1: Evaluation of the temporal dynamics of fluxes (Rn: Net Radiation, H: sensible heat, LE: latent heat, NEE: net ecosystem exchanges of CO2) simulated by the global model ORCHIDEE. LEFT: measured (color) and modelled "summer" diurnal cycle for each flux and each PFT. RIGHT: measured (color) and modelled seasonal cycle for each flux and each PFT. (Krinner et al. 2005)

4.2 Phenology: the background

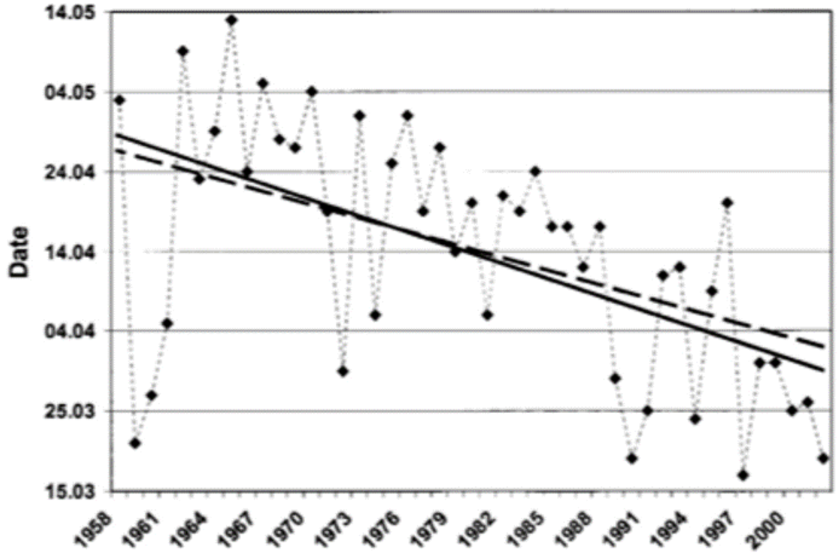


Figure 4.2: Larch needle appearance in Sargans 1958-2002. Dashed line is trend 1958-1999, solid line is trend 1958-2002. (Defilia and Clot 2005)

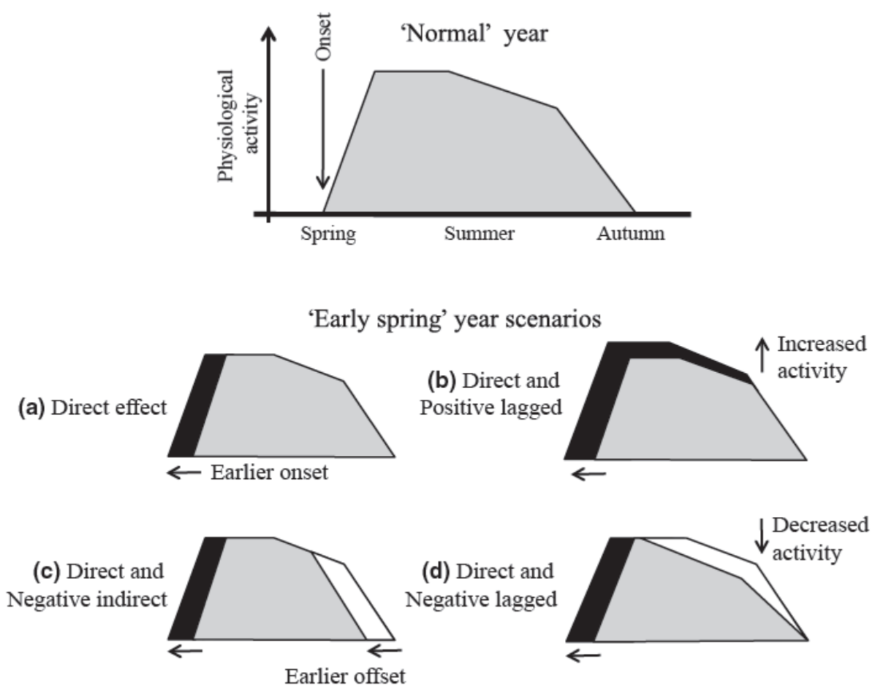


Figure 4.3: Concept of various effect that changing phenology can have on ecosystem processes (e.g. productivity or transpiration). (Polgar and Primack 2011)

4.3 Leaf phenology models

4.3.1 Prescribed phenology

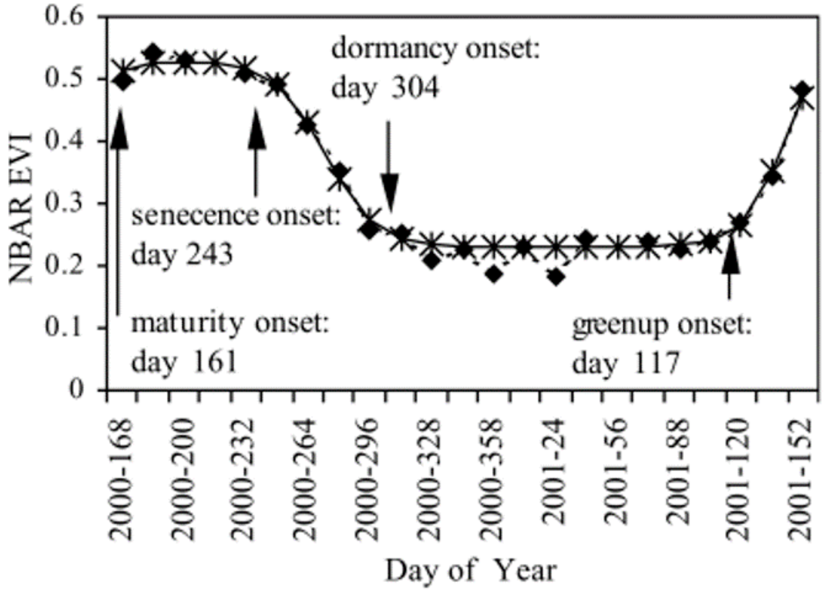


Figure 4.4: Sample time series of MODIS EVI data and estimate phenological transition dates for a mixed forest pixel in New England. Diamonds: EVI data, solid line with stars: fitted logistic model. (Zhang et al. 2003)

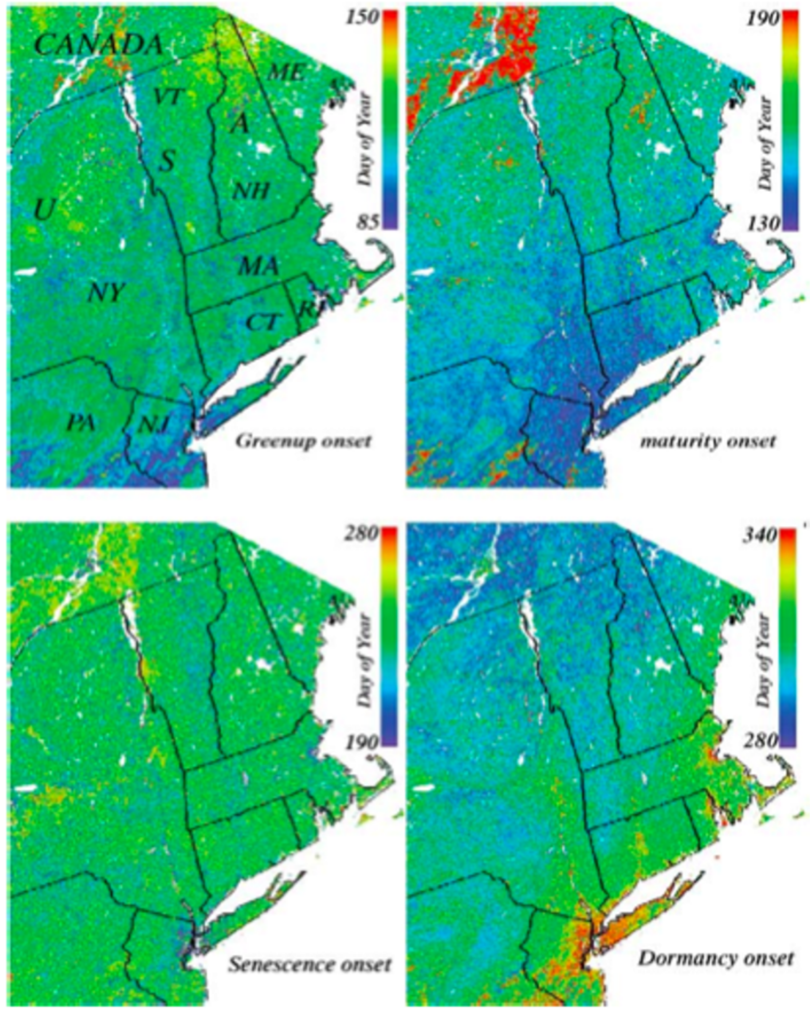


Figure 4.5: Maps of phenological transition dates for New England. (Zhang et al. 2003)

4.3.2 Budburst models

4.3.3 Snescence models

4.3.4 Leaf age

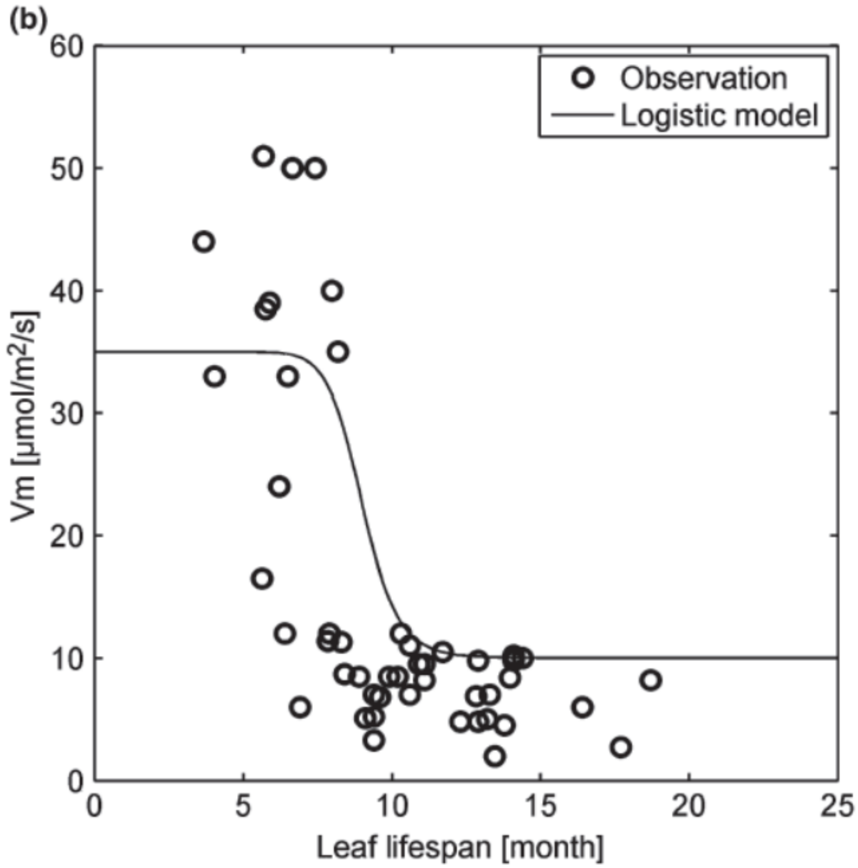


Figure 4.6: Relation between Vcmax and leaf age in the ED2 vegetation model. (Kim et al. 2011)

4.3.5 Phenology in DGVMs

4.3.6 Phenology in the tropics

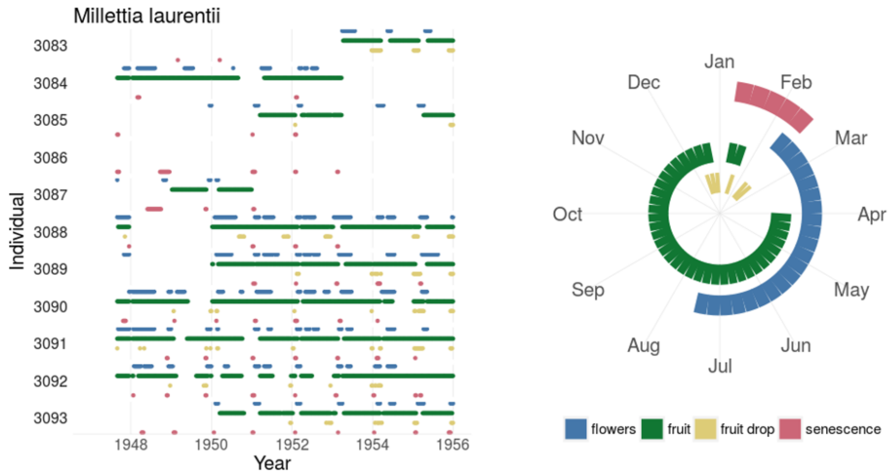
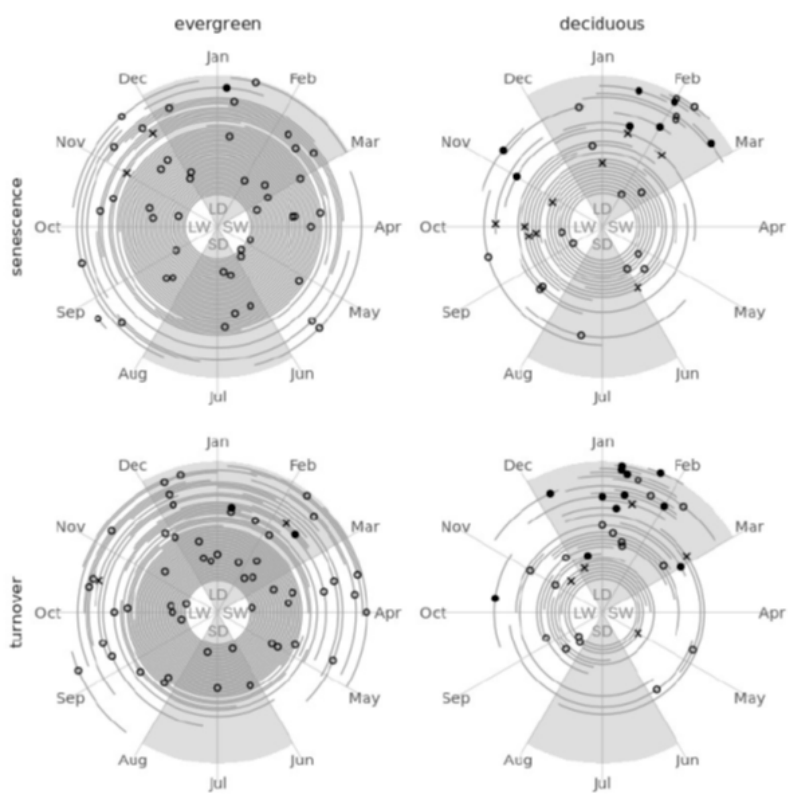


Figure 4.7: Example of how manual historical phenology observations in Yangambi (DR Congo) are trasnlated in a visual phenology pattern for a single tree species. (junglerythms.org))

\begin{figure}



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\caption{Overview of species-specific timing of onset of leaf phenophases for evergreen and deciduous species in tropical forest in Yangambi (DR Congo). The median timing of the onset of leaf senescence and turnover is indicated for each species. Species-specific bootstrapped 95%-confidence intervals are indicated with a line segment. Species are arranged according to the variability in the timing of the phenophase, with species with the lowest uncertainty at the outer edge and continuing towards the center. Species with an annual (full circles) or sub-annual (crosses) fourier-based seasonality are indicated. Grey shaded areas represent the average timing of the long and short dry seasons (LD and SD; monthly precipitation $<$ 150 mm), separated by the long and short wet seasons (LW and SW). (Kearsley et al. 2021))} \end{figure}

4.4 Case studies

4.4.1 Case study 4.1

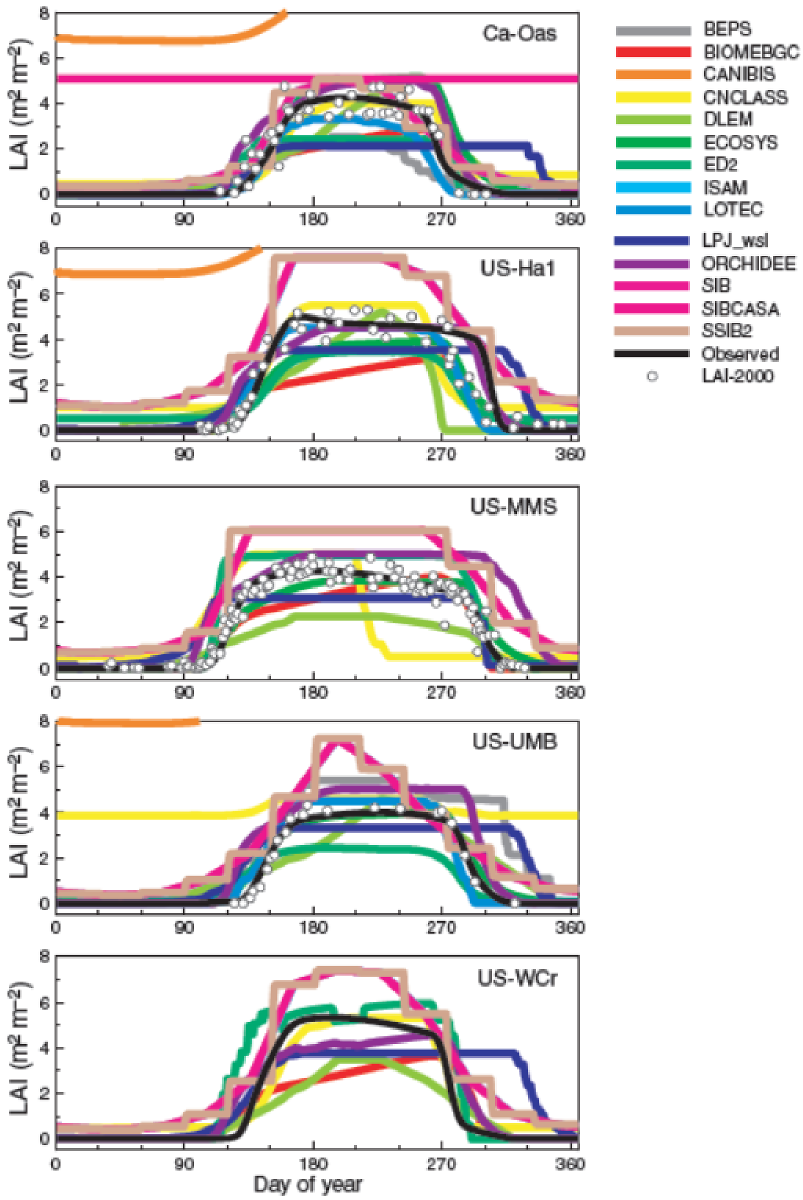


Figure 4.8: Simulated and observed LAI for 5 deciduous forest sites and 14 vegetation models participating to the NACP model intercomparison project. (Richardson et al. 2012)

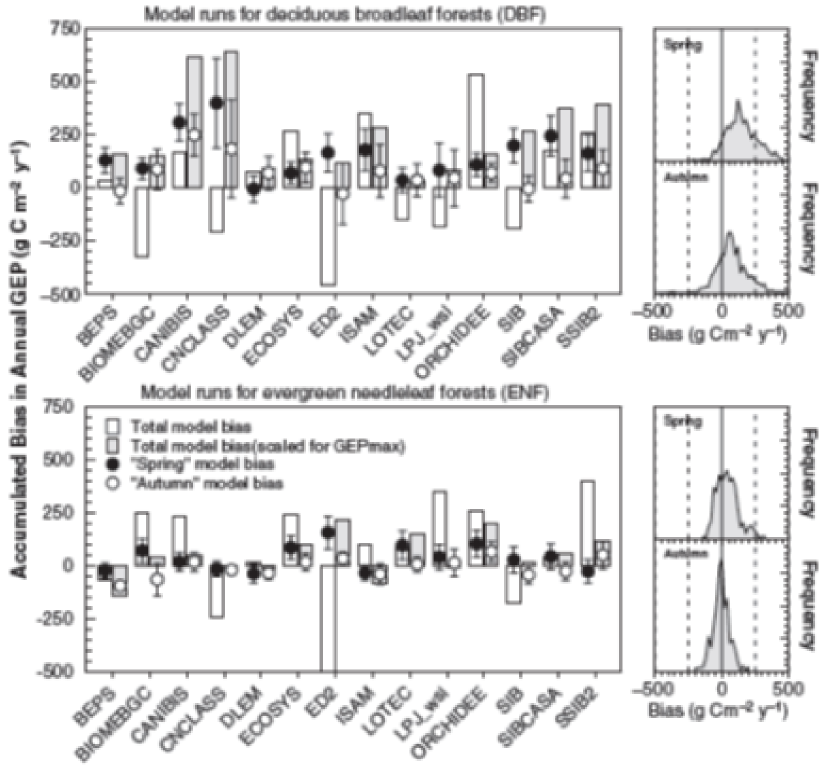


Figure 4.9: Bias in modeled gross ecosystem photosynthesis (GEP=GPP) for deciduous broadleaf (top) and evergreen needleleaf (bottom) forests. Left panels show bias, by model. Right panels show the frequency distribution of these spring and autumn biases in re-scaled model GEP, across all models, sites, and years of data, for each forest type. The sign convention is that positive bias means that modeled GEP > tower GEP. (Richardson et al. 2012)

4.4.2 Case study 4.2

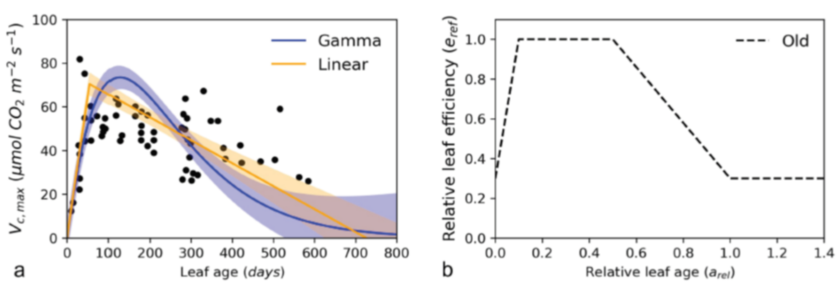


Figure 4.10: Observed and assumed relation between Vcmax and leaf age in the ORCHIDEE global model, for the tropical evergreen PFT. (Chen et al. 2018)

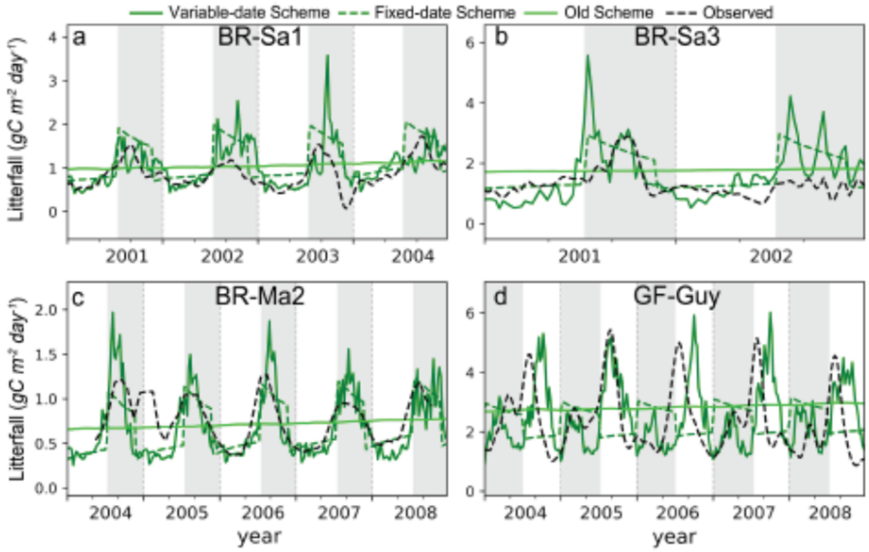


Figure 4.11: Comparison of litterfall data with two new and the old leaf turnover schemes in the ORCHIDEE model for 4 sites in the Amazon. (Chen et al. 2018)

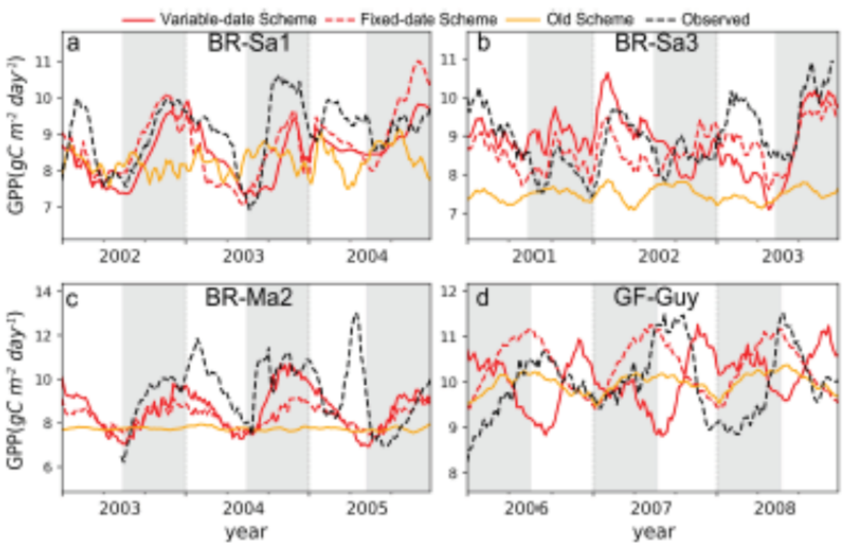


Figure 4.12: Comparison of GPP fluxtower data with two new and the old leaf turnover schemes in the ORCHIDEE model for 4 sites in the Amazon. (Chen et al. 2018)

Part II

Modelling vegetation dynamics

Chapter 5

Modelling plant growth and biogeochemical cycles in vegetation models

- UCL 4.2.2

based on Bonan Chapter 17

5.1 Process-based growth modelling

5.1.1 C-allocation models

- C pools: Allocation to leaf, wood, fruit

5.1.2 Applications of growth modelling in forestry and agriculture

- short, link with inventory course

5.2 Carbon cycle models: stocks and fluxes

This chapter will develop the ecological foundation and mathematics to describe ecosystem carbon dynamics using biogeochemical models. Biogeochemical models abstract an ecosystem as pools of carbon and the flows of carbon among these pools.

Use specific model as an example to illustrate? In Bonan: CASA-CNP model

5.2.1 Model structure

Biogeochemical models simulate processes of allocation of photosynthetic carbon gain to plant parts (e.g., foliage, fine root, wood), turnover of plant biomass as litterfall, transformation of litter to soil organic matter, and carbon loss during respiration.

Principles: - net carbon input is equal to gross primary production minus autotrophic respiration; - carbon flows from donor to receiver pools at a rate that depends on the donor pool size and its chemical quality as modified by the environment; - mass balance is maintained as carbon flows through the system of interconnected pools; - decay of litter and soil organic matter releases CO 2 as heterotrophic respiration.

Models: a system of first-order, linear differential equations to describe carbon pools and fluxes (typically time step of one day)

Pools and fluxes to be included: - Carbon gain from gross primary production minus autotrophic respiration - Allocation of carbon to growth of leaves, wood, and roots pools (partitioning varies with light availability, soil temperature, soil moisture, and nutrients + temporal for leaves (ref to phenology) - Carbon turnover (comprising litterfall, background mortality, and disturbances) + turnover rates depending on the plant material - litter pools: metabolic litter, structural litter, coarse woody debris (vary in chemical quality and turnover rate; base turnover rates are modified for soil temperature and soil moisture (environmental scaling factors)) - decomposition to soil organic matter pools: fast SOM, slow SOM, passive SOM (vary in chemical quality and turnover time) - portion of the decomposition flow lost as heterotrophic respiration

Bonan - Figure 17.2: structure of a typical biogeochemical model - equations 17.1 – 17.10

Additional details? - maintenance respiration and growth respiration - storage pool of nonstructural carbohydrates - some models separate wood into live stems (sapwood) and dead stems, roots into fine roots and coarse roots, and coarse roots into live pools and dead pools to account for the different physiological functioning of these biomass components

5.2.2 Allocation and turnover parameterization

- types of allocation models (see Campioli et al 2013 and work of Fatichi et al.)
- allocation parameters
- fixed allocation and dynamic allocation (specified by biome or based on environmental conditions)
- Optimality models: plants optimally allocate resources to balance light acquisition (foliage), structural support and water transport (stems), and water and nutrient uptake (roots).
- allocation based on scaling relationships among plant components (specified ratios of foliage, root, and wood biomass)
- Turnover rates vary depending on plant material and are specified as a fraction of biomass.
- Turnover rates are commonly estimated as the inverse of residence time or longevity

- biogeochemical models can be applied to any type of ecosystem such as grassland, savanna, forest, shrubland, and tundra

5.3 Nutrient cycle models: soil biogeochemical models

5.3.1 Nitrogen cycle

- Bonan Chapter 17.6 Nitrogen Cycle
- Bonan Figure 17.8: Depiction of the nitrogen cycle
- only ~recently added in most biogeochemical models
- closely coupled to carbon cycle
- important role to limit plant productivity
- similar to carbon with an associated nitrogen pool and transfer.
- cycling of nitrogen can be represented by a system of linear differential equations similar to that for carbon.
- allocation of plant nitrogen uptake up to plant pools
- loss of nitrogen in litterfall + portion is reabsorbed
- soil nitrogen cycle is more complex (various forms)
- decomposition of litter and soil organic matter, (mineralization and immobilization)
- nitrification, denitrification, leaching, ammonia volatilization
- additional inputs from biological nitrogen fixation, atmospheric deposition, and fertilizer
- some examples of models? CLM?
- All models simulate a decrease in plant growth when soil mineral nitrogen is insufficient to meet demand, but they differ in the manner in which this is implemented.
- maybe also more soil oriented model (CENTURY , ….)
- discuss different approaches?

5.3.2 Phosphorus cycle

Not in Bonan - Some models additionally include phosphorus (Wang et al. 2010; Yang et al. 2014; Goll et al. 2017) - ORCHIDEE, CLM-CNP

5.3.3 Other nutrients

- K and Mg in Eucalyptus and other tropical plantations

5.4 Water balance

- focus on the surface energy balance and vertical water movement in the soil–plant atmosphere system (e.g., soil moisture control of evapotranspiration)
- Specific components in terrestrial biosphere models:
  Interception, throughfall, stemflow, infiltration, surface runoff, soil water redistribution, subsurface runoff, snow melt, evaporation, transpiration, plant water uptake, stomatal conductance

5.4.1 A bucket model hydrologic cycle

- refer to hydrology courses in the program
- change in soil water is the difference between precipitation and evapotranspiration, excess runs off
- based on maximum water-holding capacity

Chapter 6

Representing biodiversity in vegetation models

6.1 Why and how representing biodiversity in vegetation models?

We can start with the applications? I think it is more interesting than finishing with the applications. Application: Conservation, ecosystem resilience, vegetation-atmosphere feedbacks

Biodiversity refers here to functional diversity.

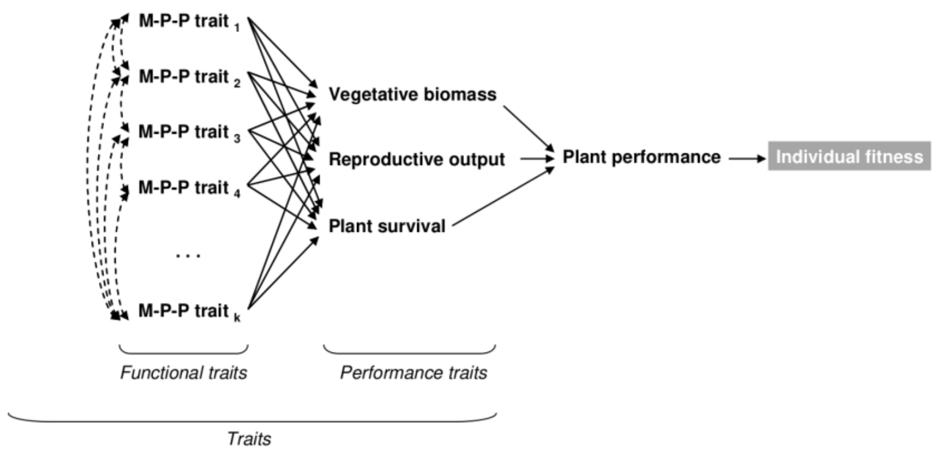
6.2 Functional diversity

- check the book " Terrestrial Ecosystems in a changing world" from P. Canadell (2007)
- Part C: Landscapes under changing disturbance regimes:
  - PFT
  - Fire and disturbances
  - upscalling
  - construction, evaluation and examples of DGVM applications

6.2.1 Definition of funcional diversity and plant functional traits

Any morphological, physiological or phenological feature measurable at the individual level, from the cell to the whole-organism level, without reference to the environment or any other level of organization. It is functional if it affects fitness indirectly via its effects on growth, reproduction and survival.

- Seminal papers from the plant functional trait community Violle 2007, Lavorel, garnier, Shipley, etc...



- Mention here the interesting summer school: http://www.cef-cfr.ca/index.php?n=MEmbres.AlisonMunsonPlantTraits?userlang=en - List of reference papers in the link above - 3 types of traits: dynamic, response & constant, that are linked to the processes we studied in the previous chapter (slow/fast processes)

6.2.2 Representing 400 000 plant species in a single model: the Plant Functional Type approach

Short description in UCL 4.3.2
No description in Bonan

- Lack of observations for every species
- Computing resources problem (refers to the history of DGVMs from the introduction)
- A simplification based on biome description and plant functionning at the ecosystem level
- Different definitions of PFT: statistical classification, etc.
- Table of classical PFTs used in models here.
- PFT mapping: multi-obs approach based on remote sensing.
- First use of PFTs managed to reproduce well the gradients at the global scale, but now it is unsuficcient.

6.2.3 Limits of the PFT representation in the context of global change

- Including acclimation and adaptation processes
- Dynamic vegetation: Accounting for non-random species turnover
- Quantifying vegetation-environment feedbacks
- Quantifying impacts of biodiversity on ecosytem functioning and climate

6.2.4 From model parameters to plant traits

- Reconciliating modelling with functional ecology.
- Existing databases (TRY)
- Empirical approach: More PFTs with traits instead of model-specific parameters, trait-trait, trait-environment relationships
- Trade-offs: modeling plant strategies –> LES, PES, RES, all the ES :D
- Role of data assimilation in regions without data and to assess spatial variability of vegetation properties
- But: requires lots of observations in space and time.

6.2.5 Eco-evolutive optimality approaches

- New generation of models
- PPA, coordination, ect…
- Paper from Oskar.

6.3 Competition models

Not in Bonan nor UCL
In Bonan Chapter 19 on demography, gap models, etc… which is a part of competition.

6.3.1 Representation of PFTs in vegetation models

- Parameterization and calibration of PFTs–> data assimilation, traits, model-specific parameters
- representation by pixels
- shared processes, different processes
- interaction between PFTs
- Depend on the model: individual/cohort/big leaf

6.3.2 Competition for ressources / Plant strategy?

- In fact we can extend the trait based approach and plant strategy (PES, etc) in the competition and community section?
- Mortality, turnover, etc..

6.3.3 Representation of trait distributions

- Trade-offs

6.4 Communities

- Successions and impact on cycles, species composition etc.

6.5 What about crops?

- Not our focus but we don't forget it. A few words to say that specific crop models exists
- Diversity is not a problem anymore
- Plant functional traits are still central to crop modelling, but competition and diversity are no more an issue.
- Other problematics specific to agriculture, such as agro-ecosystems where we have multi layers of vegetation (Trees over crops) –> Very interesting modelling problem and application especially in arid/semi-arid and tropical regions

Chapter 7

Modelling vegetation dynamics and demography

Bonan Chapter 19.2 Another class of models, known as individual plant or ecosystem demography models, retains the complexity of individual plants or cohorts of similar plants. In these models, ecosystem properties such as carbon storage are the outcome of demographic processes.

- plant populations
- community composition
- ecosystem structure
- driven by demographic processes of recruitment, establishment, growth, and mortality

7.1 Gap models, individual and cohort based models

- small scale models; landscape represented as a mosaic of hundreds of independent forest patches, each of which can differ in species composition and stage of development in response to disturbance that creates an opening in the canopy
- models track the establishment, growth, and death of individual trees in an area of land.
- Each tree is characterized by its species, stem diameter, height, and age.
- trees compete for light, soil moisture, and nutrients.
- patch undergoes temporal changes in the density, size, and composition of trees with the formation of a gap in the canopy
- Community composition, biomass, productivity, and biogeochemical cycles are emergent outcomes of individual trees interacting among themselves and with the environment to acquire the resources necessary for growth and survival

- cohort-based models define patches based on age since disturbance and simulate the dynamics of cohorts of similar plant functional types rather than tracking every individual.
- Common to each model is the representation of vegetation demography, with age- and size-dependent growth and mortality and in which growth is constrained by allometric relationships of stem diameter with height, sapwood area, leaf area, and biomass. cohort models –> modelling size distributions

7.2 Allometric relationships

- link with growth modelling of previuous chapter
- allometric relationships are a critical driver of individual tree growth.
- Height is important for its effect on stem diameter increment, both directly through tree volume growth and indirectly through shading.
- Biomass allocation: empirical equations that constrain foliage, stem, and root mass for a given size tree
- relationship between stem diameter and leaf area drives light extinction in the canopy
- annual growth of a tree is calculated from its diameter and height as modified by light, climate, and site conditions. Growth curves figure 19.5

7.3 Competition for light

- critical driver of forest dynamics
- shading of smaller individuals by taller trees
- vertical profile of leaf area in the patch (vertical structure in which trees are arranged into canopy layers)
- height of a tree determines its location in the cumulative leaf area profile
- light extinction coefficient
- figure 19.6: representation of plant canopies

7.4 Seed dispersal and recruitment

- regeneration: stochastic process
- seeds of species are assumed to be present on-site
- available light at the forest floor, climate tolerances, and other site conditions determine which species become established.
- sprouting based on size
- Species are characterized by life history characteristics + maybe add example of herb layer models of FORNALAB

7.5 Mortality

- stochastic process
- Trees die with a constant probability each year
- The probability of mortality increases when tree growth is less than some minimum
- disturbance related mortality : Wildfire and insect outbreaks can be included
- The occurrence of fire is treated stochastically with an annual probability of burning. An individual patch may, for example, have a 1% change of burning in any given year.

Part III

Upscaling and applications

Chapter 8

Spatial heterogeneity, landscape scale, metapopulations

8.1 Patch dynamics

Some references: - Book: The ecology of natual disturance and patch dynamics, Pickett & White, 2013

8.1.1 Spatial heterogeneity: Definitions

- Definition of Patch Dynamics, Perturbation, Disturbance:
- Spatial heterogeneity
- Resilience and shifts

8.1.2 Impact of heterogeneity on ecosystem fonctionning and environmental feedbacks

- Show examples here of the impact of heterogeneity
- Application in the design of nature reserves for example

8.1.3 Heterogeneity is a matter of resolution

- Imbricated levels of heterogeneity depending on spatial and temporal resolution
- Heterogeneity is also a matter of the studied question: important in term of modelling since it will govern how processes are implemented

8.1.4 Representation in Vegetation models: what are the drivers of spatial heterogeneity?

- List here the different drivers
- Heterogeneity is a patchwork of homogeneity in most models
- But we can still represent dynamics in heterogeneity –> mortality, growth and shifts in species composition

8.1.5 Disturbances and Patch dynamics

- We listed the different drivers above, we will now discuss in detail the most important aspects affecting patch dynamics
- Link to land-use and disturbance

8.2 Land-use changes

- Land use is linked to spatial heterogeneity and patch dynamics

8.2.1 Role of Land-use in global emissions and biogeochemicel cycles

- impact C stocks and fluxes
- impact on nutrients (depletion over rotations, etc…)
- important impact on respiration
- vegetation cover and biophysical impact: albedo, etc…
- Specific case of deforestation, one of the most important imapct (make a paragraph on that?)
- How are fluxes attributed to land use in gas emission assessments? –> central role of vegetation modeling

8.2.2 The important role of land use in the water cycle

- Affects regional precipitations
- Affects water routing –> Compared to the local impact on vegetation, here we touch something that will have an impact for the surrounding regions

8.2.3 Monitoring land-use

- remote sensing, rapid link to other courses

8.2.4 How Land-use is represented in vegetation models?

- Compared to vegetation dynamic which is process-based, here land use is imposed.
- management
- urban areas

8.3 Natural and Anthropogenic disturbances

- We provide an overview of disturbances but we will detail only one of each: Fires and Management

8.3.1 Wind and extrem events

- Modelling storms

- Modelling heat and cold waves, frost impact

8.3.2 Herbivory

- Yes herbivory is represented in vegetation models :D
- Palability traits/ fixed fraction/ insects

8.3.3 Modelling fires

- In UCL Practical chap. 6
- For estimating the impact on ecosystems
- To be able to predict fires
- Observation of fires and quantifications of fluxes
- Fires and deposition
- Aerosols
- Modelling "fire" traits, drought and temperature stress in models to simulate fires

8.3.4 Human activity: Management and urban areas

- Forest management: existing models, representation of forestry and use of models
- Fertilization and irrigation in vegetation models
- Urban areas in vegetation models
- Concrete application: Paper of Luyssaert: forest management in Europe did not help in mitigating climate change.

8.3.5 The specific case of CO2 and temperature increase

- conclude the chapter here by refering to climate change, one of the biggest "Continuous" distrubance compared to previous "discrete" disturbances
- Simulating acclimation and adaptation
- refers to chapter 2 for acclimation of processes
- refers to chapter 11 for scenarios

Chapter 9

Upscaling from the leaf to the globe

Some references: - Scalling processes and problems, Jarvis 1995 - upscalling in global change research, Harvey 2000

9.1 Spatial and temporal non-linearities: Cascading effect in the Earth system

- spatial upscalling
- temporal upscalling
- classification of upscalling problems:
- Spatial variability + process nonlinearity
- Minimim scale to observe the process
- Different processes dominate at different scales
- Feedbacks between scales
- Development of emergent properties
- Edge effects
- Temporal lag dependent on spatial scale change
- Collective response with differential effects
- Solutions to upscaling problems:
- Ignore (easy solution)
- Increase model resolution (now more and more possible thanks to computing ressources, and data assimilation)
- etc… ** Nice review in Harvey 2000 **

–> Solution depends on the application, show some examples here

9.2 Land surface models

- Dependence to other disciplines (Biology, ecology, physics, chemistry (VOC, etc), hydrology, pedology, datascience and mathematics, etc…)
- Figure 1.7 from Bonan
- UCL 4.2: Land surface schemes

- Focus on the coupling of different models and what it implies, not the technical aspects ### Soil-Vegetation-Atmosphere-Transer models
- Description of SVAT models, regroups what we studied in Chap1-9

9.3 DVGMs as a part of Earth System Models

- Partially in UCL 4.3.3

9.3.1 One Biosphere

- Chapter 1 of Bonan, specifically 1.5
- Coupling to other components

9.3.2 Atmosphere, Ocean, lakes and urban areas

- Rapid desciption of other models
- Reference here to previous chapter on heterogeneity

9.3.3 Coupling of processes with different time steps and regional scale

9.3.4 Simulating feedbacks

- Nice transition to chap 11 with future scenarii

Chapter 10

Model projections and scenario analysis

10.1 Climate scenarios

10.1.1 Representative Concentration Pathway (RCP scenarios)

- How scenarios are defined
- How current emissions are measured and attributed to different factors?

10.1.2 Different models, different RCP

- The central role of ESM: coupling to Atmosphere and Ocean and feedbacks
- Here refers to preivous Chapter 10
- list some examples and differences: IPSL, HadGEM, etc…

10.1.3 Use of RCP in vegetation modelling

- ENSEMBLE simulations
- IPCC
- Example of applications

10.1.4 How can we evaluate future scenarios?

- FACE
- Rainfall exclusion experiments
- Natural gradient (Iceland and soil temperature based on volcano and geothermy)

10.1.5 The central role of Paleo studies and historical datasets.

- Good performance for past and current conditions is mandatory to evaluate future scenarios
- Here remind the central role of experiments and monitoring

10.2 Land-use scenarios

10.2.1 Construction of Land-use scenarios

- Hyde for historical land-use, https://themasites.pbl.nl/tridion/en/themasites/hyde/
- Scenario for future land-use

–> We can follow the same structure as for RCP?

10.2.2 How can we evaluate land use scenarios?

- Based on historical data
- Remote sensing

10.3 Management scenarios

10.3.1 Construction of Land-use scenarios

10.3.2 How can we evaluate management scenarios?

10.4 Some concrete applications of vegetation models

- As a conclusion of the whole course I see a nice diagram that we constructed throughout the course with small boxes added to each others and we link that to all the possible application

Part IV

Appendix

Contributing to this document

First steps

First, visit the course webpage on https://github.com/femeunier/VegMod_course, and fork it to your own github account. Open a RStudio session and (if it is your first time with git) introduce yourself:

```
git config --global user.name "FULLNAME"
git config --global user.email you@yourdomain.example.com
```

Note that you can do every single step below using the terminal and the git tabs in RStudio. Clone the newly forked folder to your local machine:

```
git clone https://github.com/femeunier/VegMod_course.git
```

or using SSH (to set up it first, see for instance https://help.github.com/en/github/authenticating-to-github/connecting-to-github-with-ssh)

```
git clone git@github.com:femeunier/VegMod_course.git
```

Define upstream

```
cd VegMod_course
git remote add upstream git@github.com:femeunier/VegMod_course.git
```

New pull request

Get the latest code from the main repository

```
git pull upstream master
```

Create a new branch (here new_branch is the new branch's name)

```
git checkout -b new_branch
```

Do some coding, add files and commit them

```
git add filepath
git commit -m "Message"
```

Push your changes to your github (when a feature is working, a set of bugs are fixed, or you need to share progress with others).

```
git push origin new_branch
```

Before submitting code back to the main repository, make sure that book compiles (buikd book). Open the PR online by visiting your github repository. To ease those previous steps you can take advantage of the git GUI in RStudio. To do so, create a new project from an existing directory.

Supporting material

Crash course, basic programming (R), theory about model evaluation etc.

Part V

Practicals

Practical A

PC-room, supervised exercise

Simple model on diurnal variation in solar angle, radiation extinction and photosynthesis in vegetation types with different and canopy structure and LAI: grassland, broadleaved forest, coniferous forest

Scale: aggregated stand level (big leaf model)

Methodological focus: model formulation: translating a few equations into code

Methodological focus: compiling code, running model, reading input-output

Practical B

Group work, report, PC room

Modelling diurnal cycle of carbon and water fluxes for flux tower sites (Savanna's Sahel)

Scale: aggregated stand level

Methodological focus: model-data comparison (goodness-of-fit), simple parameter optimisation

Practical C

PC-room, supervised exercise

Modelling the size structure of a temperate forest (stand diameter distribution)

Scale: forest stand

Methodological focus: initial conditions

Practical D

Group work, report, PC room

Modelling carbon stocks (above and belowground) and fluxes

Scale: ecosystem

Methodological focus: Spinup and sensitivity analysis (testing which climate variables have strongest impact on stocks)

Practical E

PC-room, supervised exercise

Simulating forest succession, meta-analysis of trait dataset to prescribe vegetation functional composition (using PEcAn-framework)

Scale: landscape

Methodological focus: parameter meta-analysis (PFT construction), data assimilation

Practical F

PC-room, group work, microteaching

Climate/land use/management scenario analysis

Scale: site/globe? (Pecan framework) each group choses a question and a model

Methodological focus: sensitivity and uncertainty analysis