UiO : Department of Geosciences
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Representing plants in Land Surface Models

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Outlines

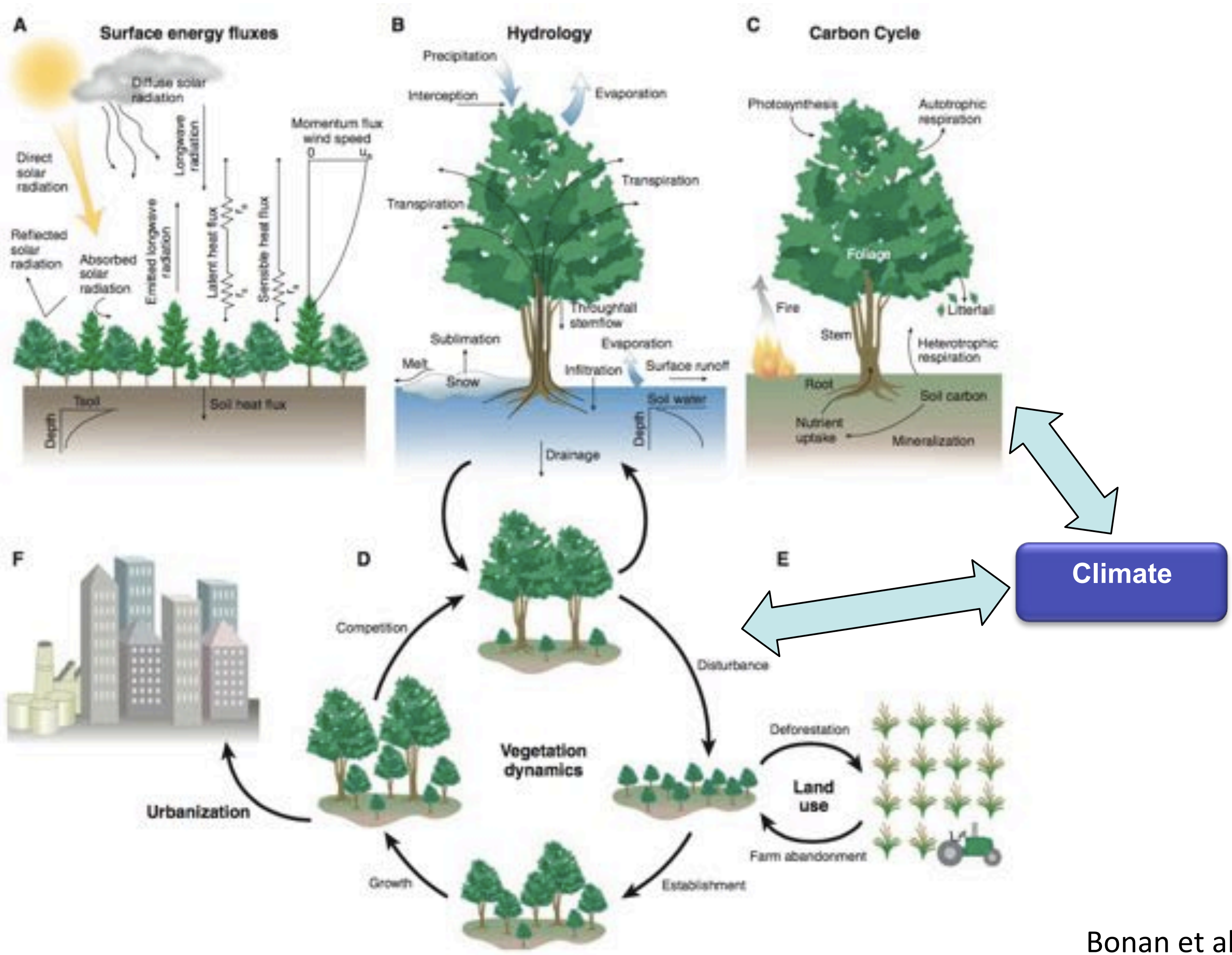
- **Plants as an active player in Earth System**

- **Represent plants in the land surface mode**
  - **From individual plant to a model grid cell**: plant functional types & sub-grid structure
  - **From simple to complex**: different approaches in modeling plant
  - **Biogeophysical processes:** Energy flux, Water, Photosynthesis
  - **Biogeochemical processes:** Carbon allocations, Nitrogen cycle, Phenology
  - **Plant geography & Vegetation dynamics:** Establishment & survival; Disturbance (e.g., fire); Light competition; PFT vs. Trait-Based approach

- **Examples of vegetation simulatons using CLM4.5**
  - Single-column simulation of C3 grass using CLM4.5-BGC
  - Global simulation of vegetation cover over the Arctic using CLM4.5-BGCDV

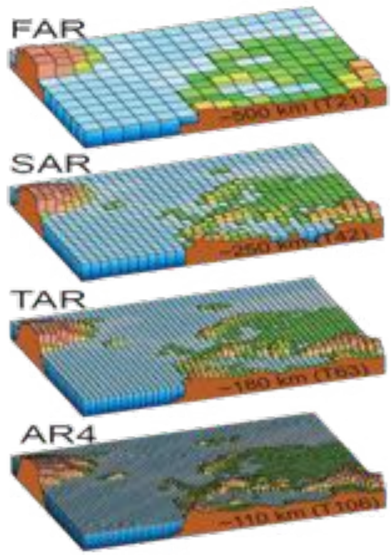
From: http://earthobservatory.nasa.gov/GlobalMaps/index.php

Plant as an active player in Earth System



Bonan et al. 2008

How to represent plants in Land Surface Model?



- **Spatial scale:** From Individual plant (0.1-10 m) to a typical model grid cell (1 - 100 km).
- **Temporal scale:** From 30 min to decades (with or withouth vegetation dynamic)

Model scale

Plant functional types

- **PFT: A classification of plants according to their physical, phylogenetic and phenological characteristics to develop a vegetation model for use in land use studies and climate models.**
- Plants in each PFT are assumed to have the same physical, physiological or phenological characteristics/parameters/traits.

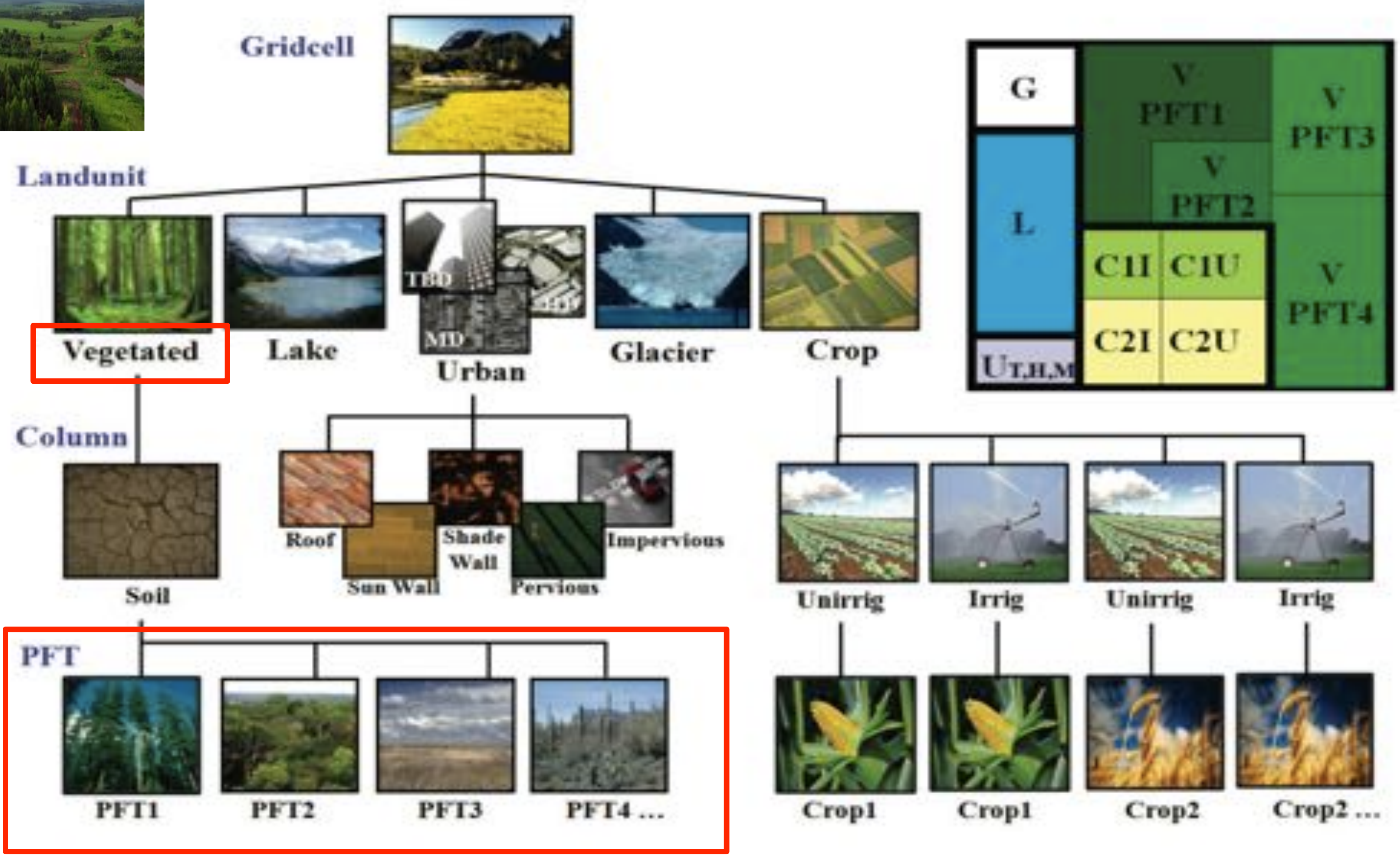
Parameters/traits for different PFTs in CLM4.5

Table 3.1. Plant functional type optical properties

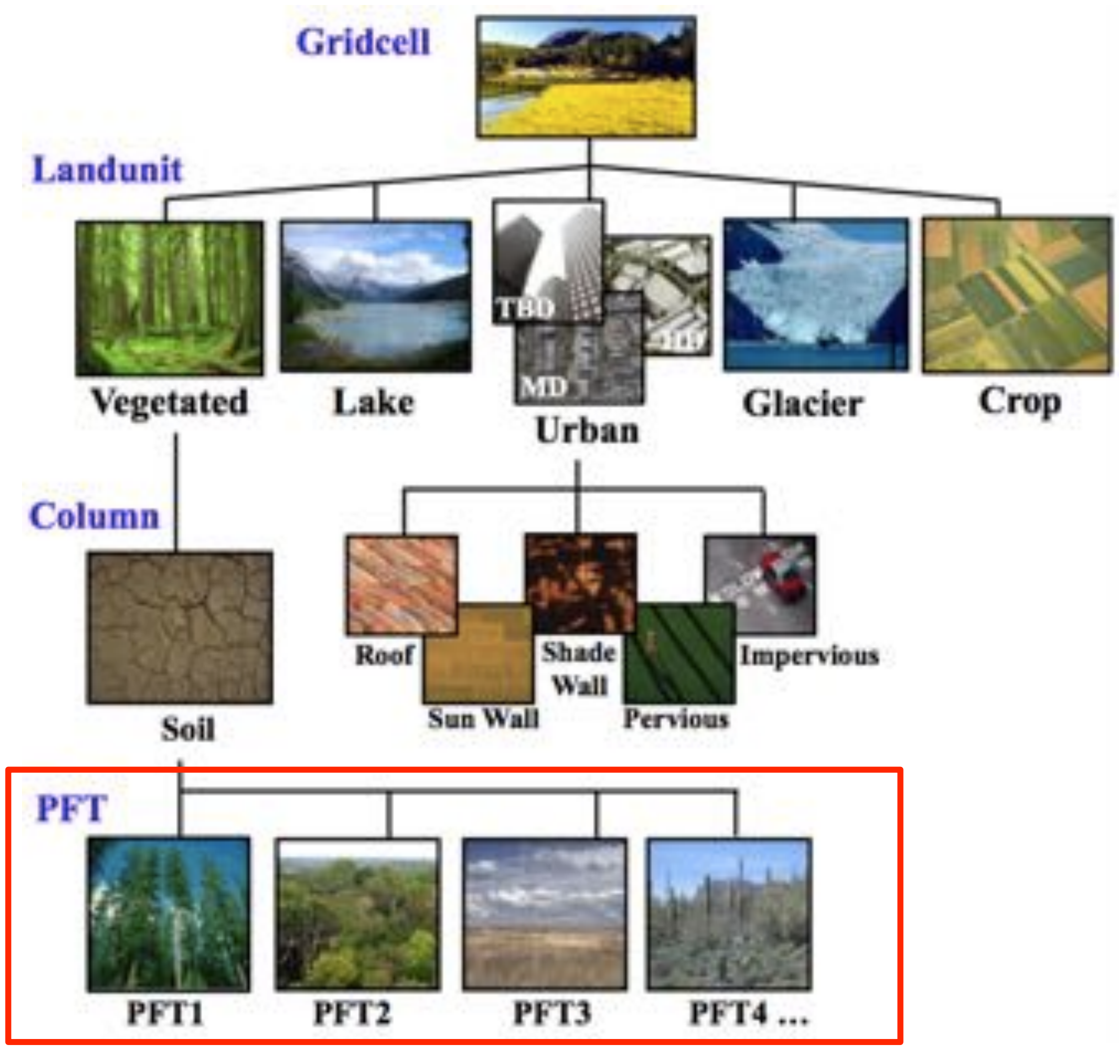
Plant Functional Type	χ_L	α_{vis}^{leaf}	α_{nir}^{leaf}	α_{vis}^{stem}	α_{nir}^{stem}	τ_{vis}^{leaf}	τ_{nir}^{leaf}	τ_{vis}^{stem}	τ_{nir}^{stem}
NET Temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
NET Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
NDT Boreal	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
BET Tropical	0.10	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BET temperate	0.10	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT tropical	0.01	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT temperate	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDT boreal	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BES temperate	0.01	0.07	0.35	0.16	0.39	0.05	0.10	0.001	0.001
BDS temperate	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001
BDS boreal	0.25	0.10	0.45	0.16	0.39	0.05	0.25	0.001	0.001

Oleson et al. 2013

Sub-Model Grid Structures: an example of CLM4.5



Oleson et al. 2013



Plant Functional Types:

0. Bare

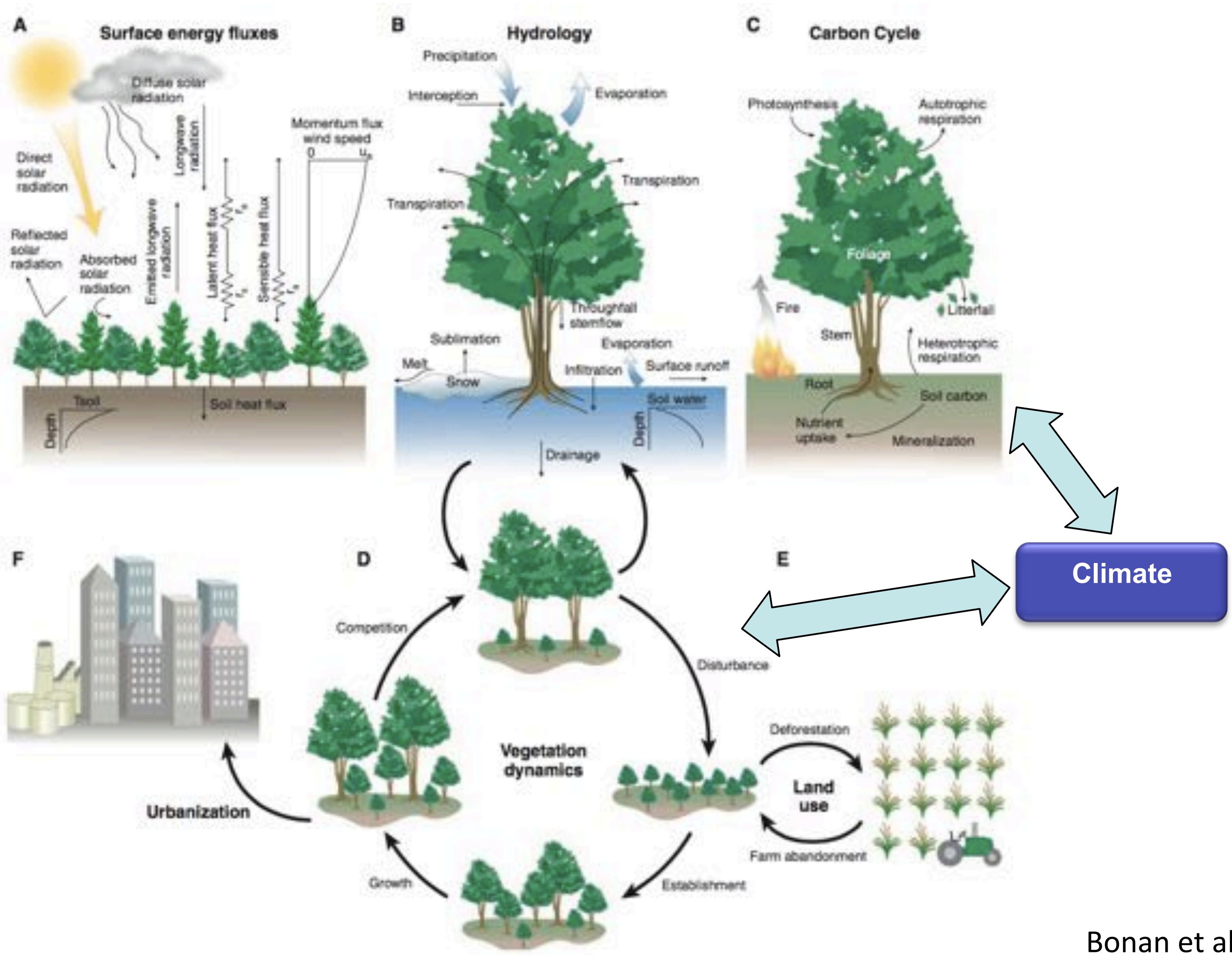
Tree:

1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous / Understorey:

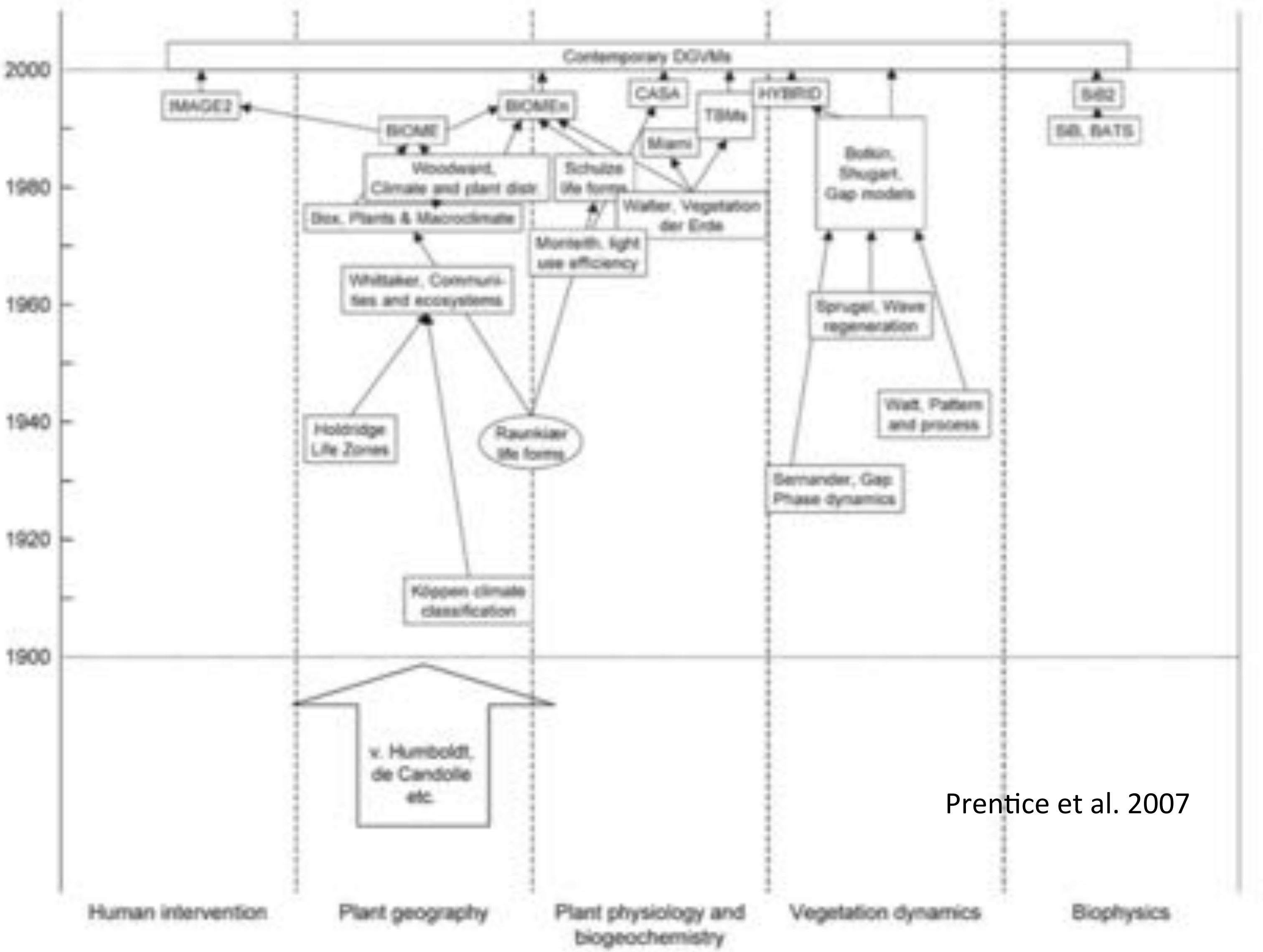
9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. C3 Arctic Grass
13. C3 non-Arctic Grass
14. C4 Grass
15. Crop

Plant as an active player in Earth System



Bonan et al. 2008

Representing plants in the model: from simple to complex



Prentice et al. 2007

Representing plants in the model: from simple to complex

- **Simple fixed parameterization** of a plant property/process based on observation or laboratory findings.

- **Empirical relationships** between a plant property/process and its influencing factors.
  - Large sample of real world
  - Manipulation experiments

- **Mechanistical description** of a plant property/process based on the understanding of plant physiology (e.g., photosynthesis).

- **Optimality theory**: Plants are rational actors, on average.

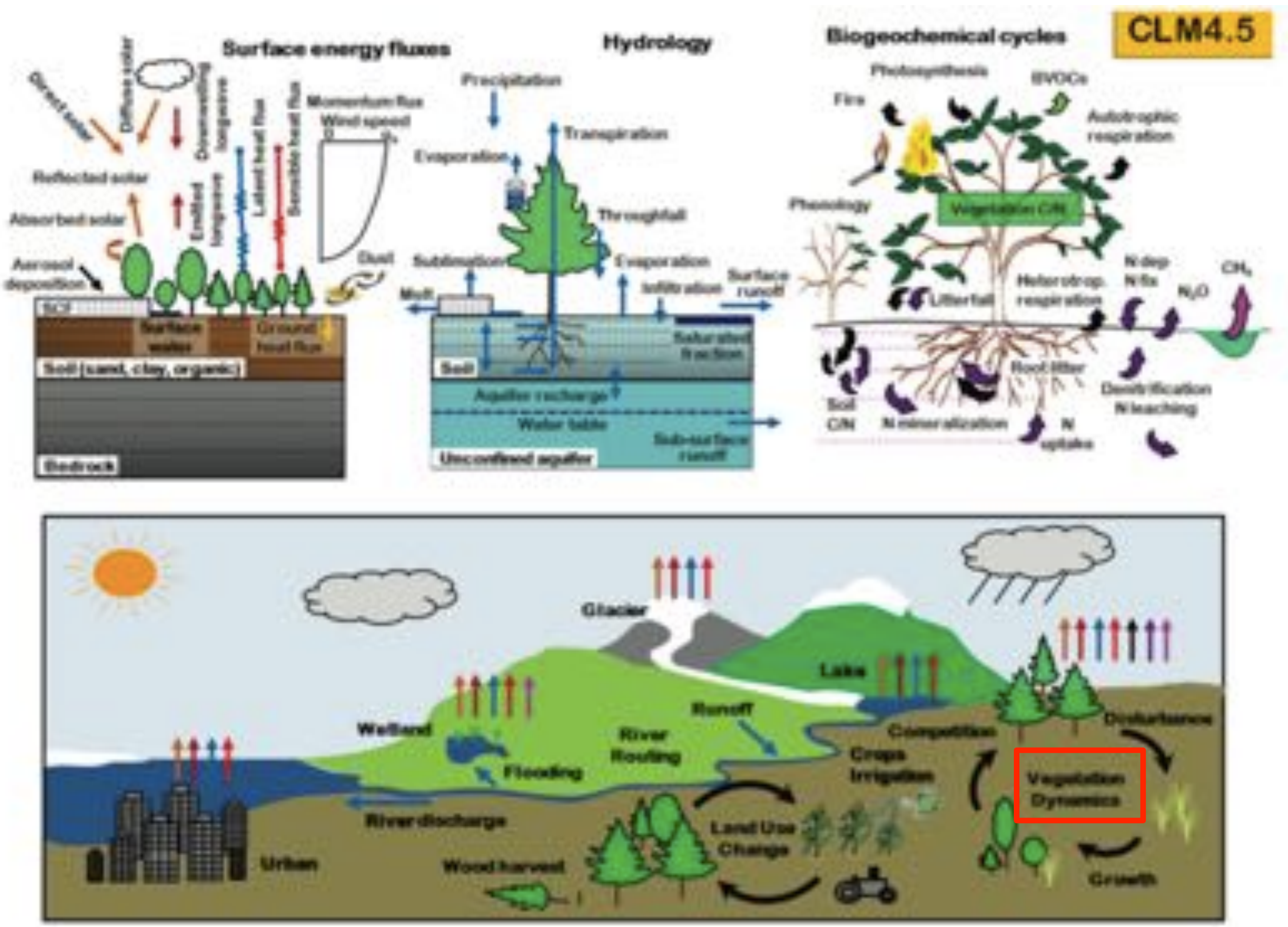
Representing plants in the model: from simple to complex

Options of CLM4.5

- **SP**
- *C only*
- **CN**
- *CNDV*
- *BGC*
- **BGCDV**

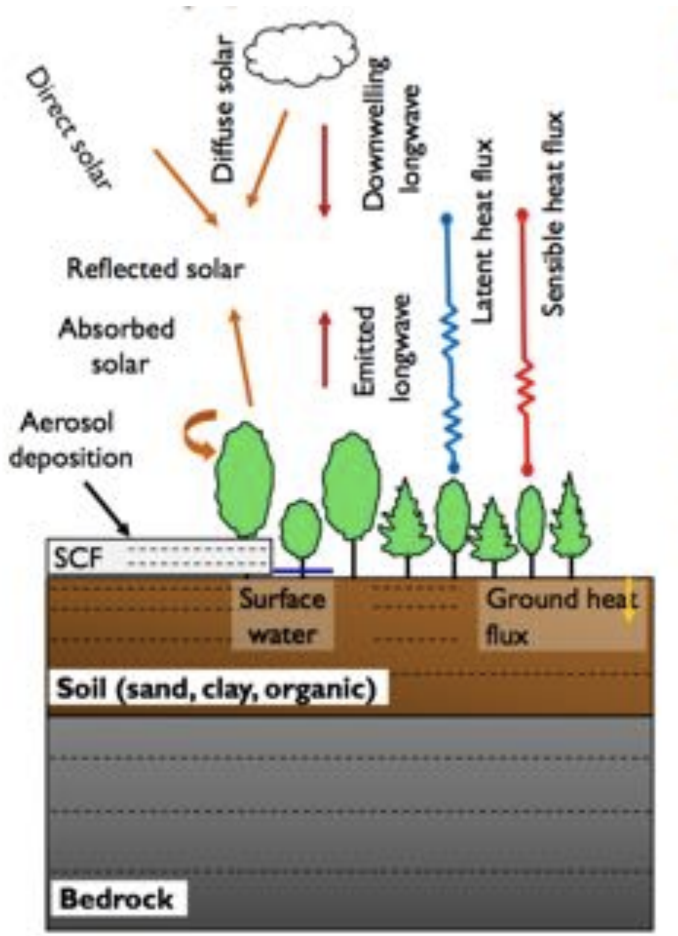
CLM4.5-BGCDV

- CN cycle
- vegetation dynamics
- vertical-layer soil biogeochemistry based on CENTURY model



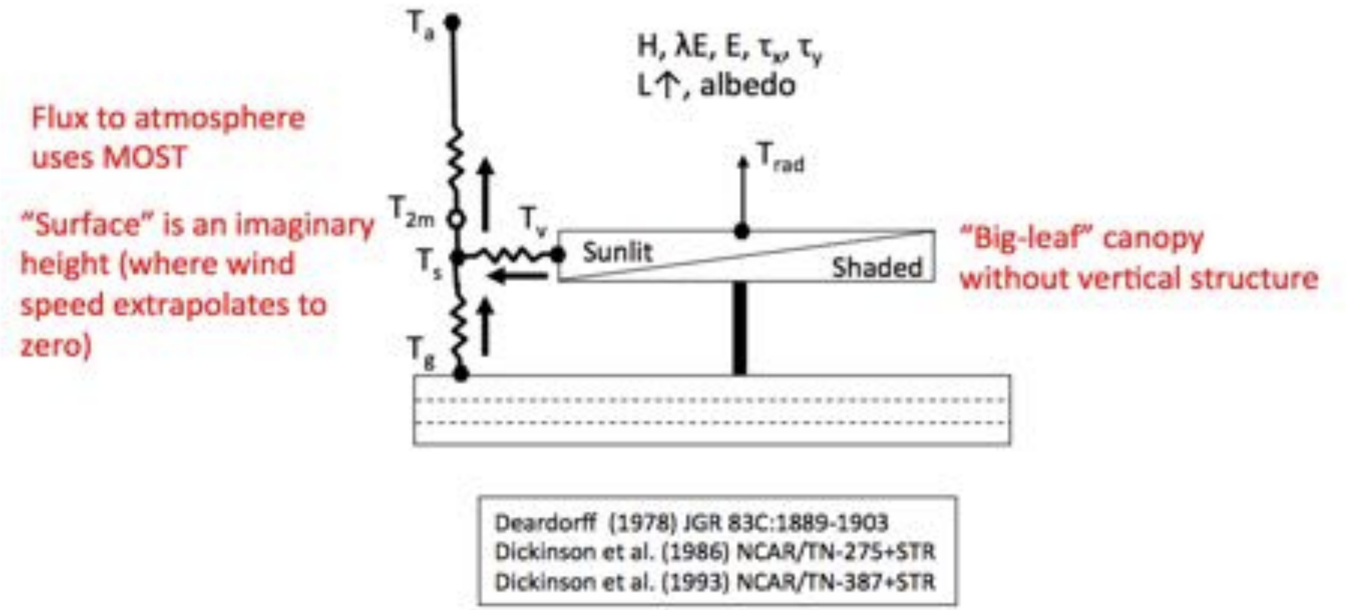
Oleson et al. 2013

Representing plants in the model: Biogeophysical Processes



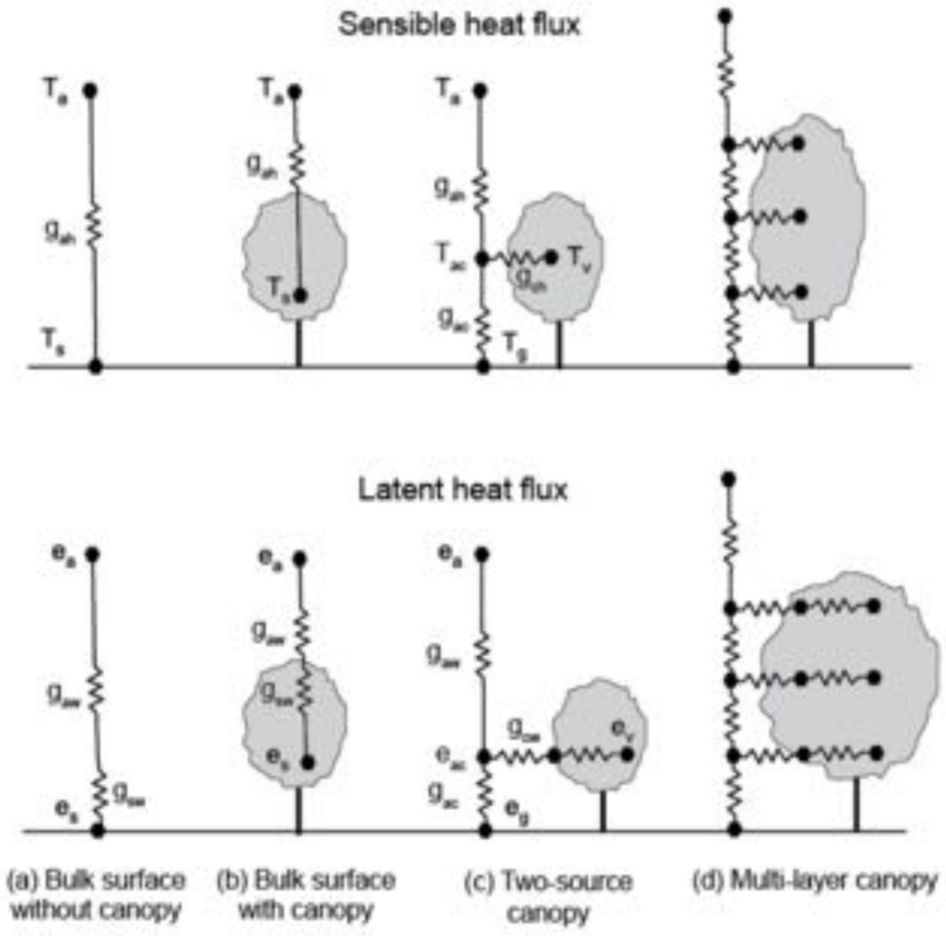
- **Surface energy fluxes:**
  - Albedo, Emitted longwave/short wave radiation
  - Sensible/latent heat flux
  - wind, momentum flux
- Required PFT parameters:
  - Optical properties: e.g., leaf angle, reflectance, transmittance
  - Morphological properties: Leaf area index, stem area index, Roughness length, Canopy top/ bottom height
- Theory/hypothese/assumptions applied:
  - ”Big-leaf” canopy
  - Fourier’s law (heat conduction)

"Big-leaf" Canopy



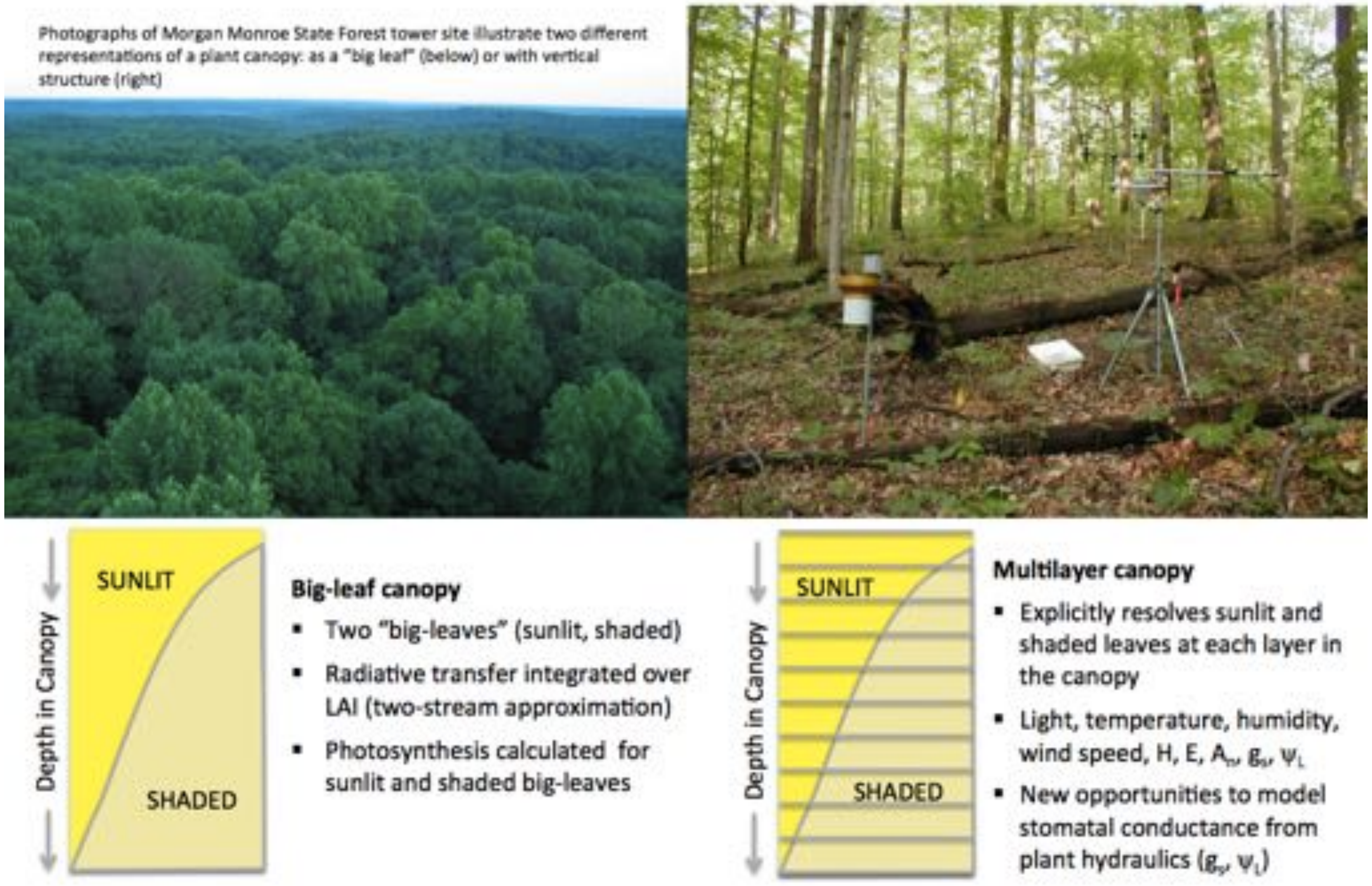
Slide courtesy G. Bonan

”Big-leaf” Canopy vs. ”Multi-layer” Canopy



Slide courtesy G. Bonan

"Big-leaf" Canopy vs. "Multi-layer" Canopy



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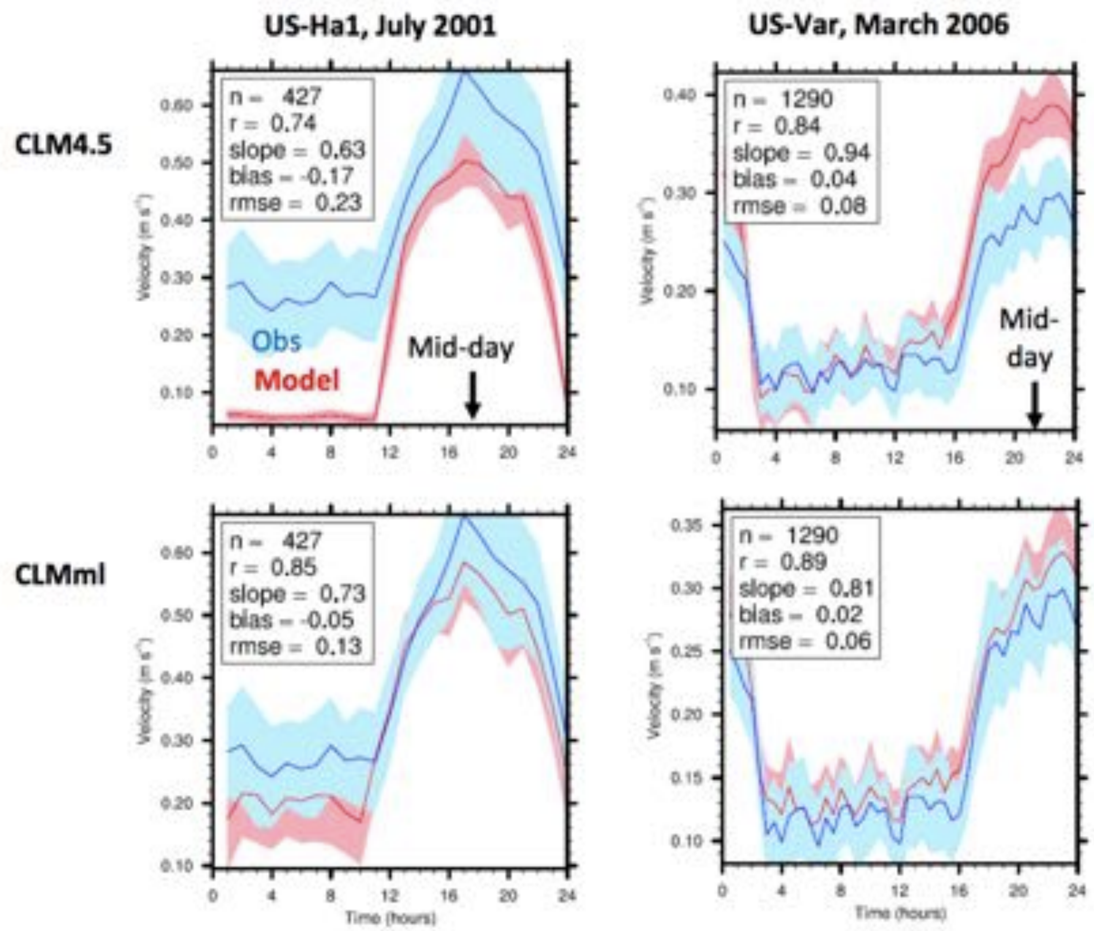
"Big-leaf" Canopy vs. "Multi-layer" Canopy



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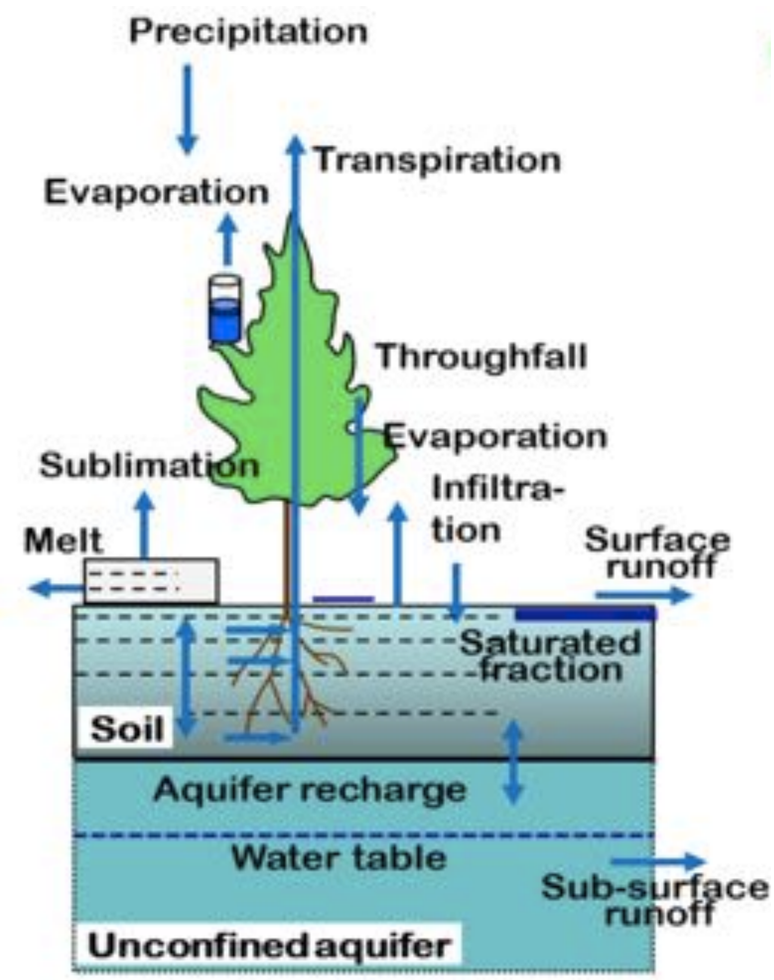
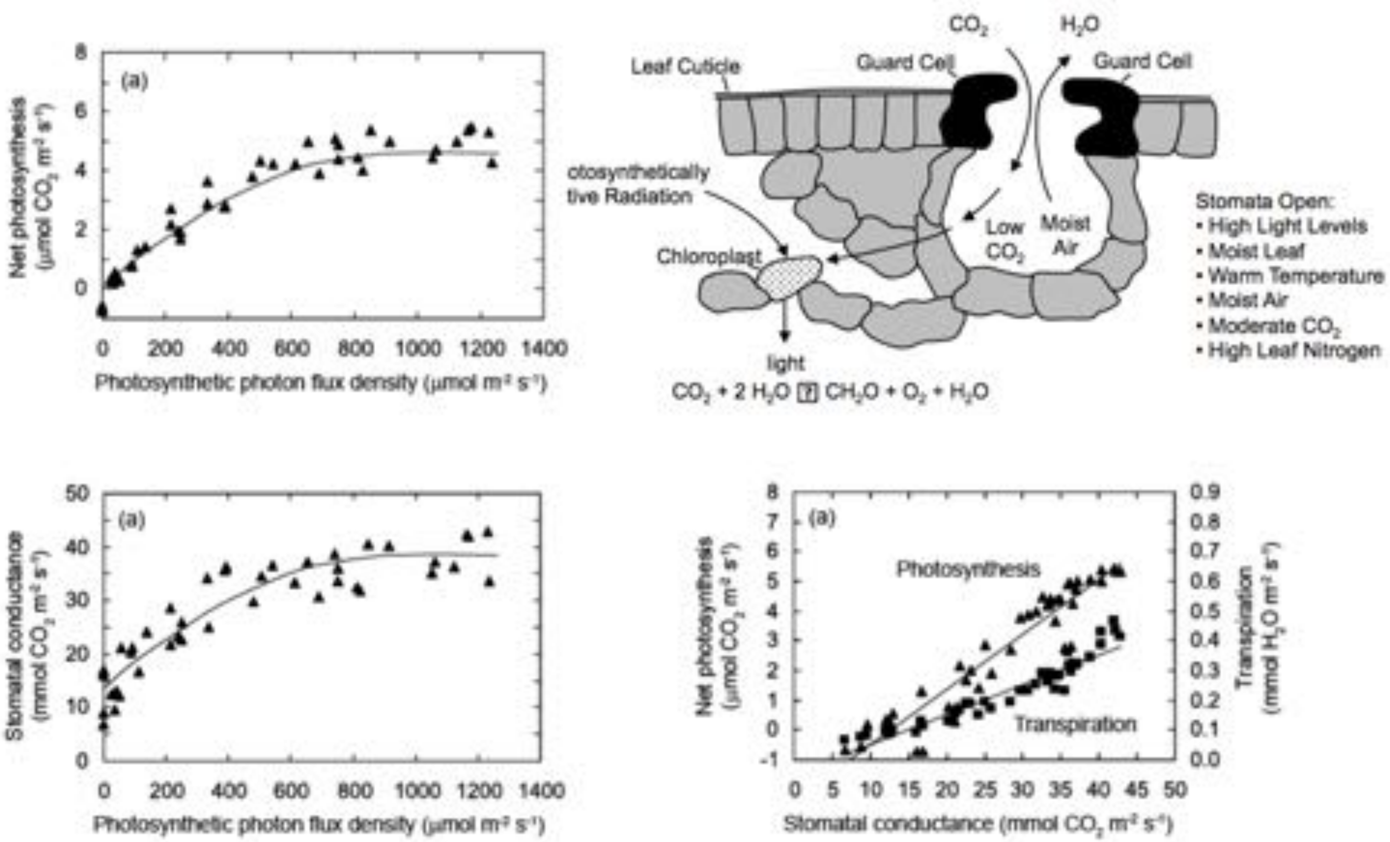
Representing plants in the model: Biogeophysical Processes



- Hydrology
  - stomatal conductance,
  - Evaportranspiration
  - water interception
  - Soil water stress
- Required vegetation parameters:
  - Root depth and distribution
- Theory/hypothese/assumptions applied (Plant physiology):
  - Penman-Monteith equation
  - Ball-Berry stomatal conductance model
- *Photosynthesis*
  - Farquhar model

Stomatal conductance: Ball-Berry model



Slide courtesy G. Bonan

Stomatal conductance: Ball-Berry model

Leaf stomatal conductance is coupled to leaf photosynthesis similar to Collatz et al. (1991, 1992)

$$\frac{1}{r_s} = g_s = m \frac{A_n}{c_s / P_{atm}} h_s + b\,\beta_t$$

- m: PFT dependent parameter
- h_s: Leaf surface humidiy
- c_s: CO2 partial pressure
- β_t: Soil water stress

Table 8.1. Plant functional type (PFT) photosynthetic parameters.

PFT	m	α	CN_L	F_{LNR}	SLA_0	ψ_o	ψ_c	V_{cmax25}
NET Temperate	9	-	35	0.0509	0.010	-66000	-255000	62.5
NET Boreal	9	-	40	0.0466	0.008	-66000	-255000	62.6
NDT Boreal	9	-	25	0.0546	0.024	-66000	-255000	39.1
BET Tropical	9	-	30	0.0461	0.012	-66000	-255000	55.0

Oleson et al. 2013

Root distribution and soil water stress

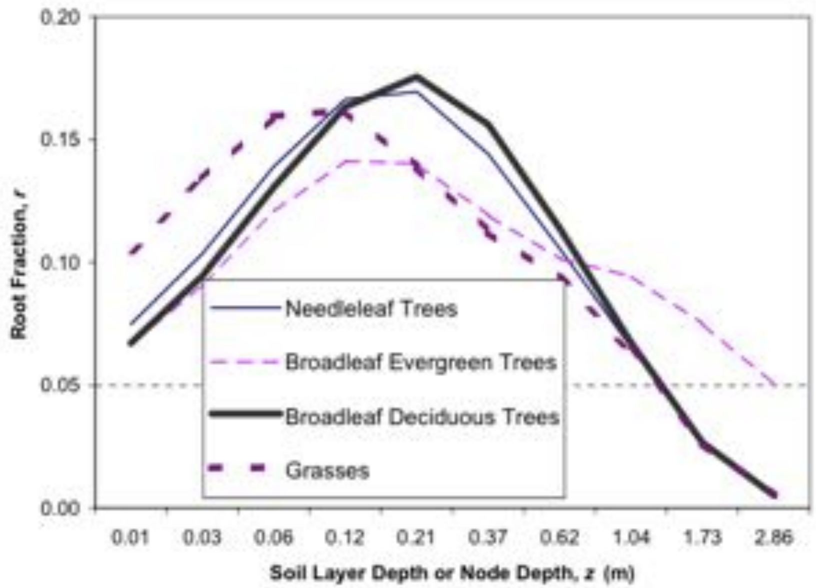


Table 8.3. Plant functional type root distribution parameters.

Plant Functional Type	r_a	r_b
NET Temperate	7.0	2.0
NET Boreal	7.0	2.0
NDT Boreal	7.0	2.0
BET Tropical	7.0	1.0
BET temperate	7.0	1.0

Oleson et al. 2013

Root distribution and soil water stress: BTRAN

- Btran is the CLM4.5 water stress function
- Represents soil water stress
- Linear function relating stress with soil matric potential
- 1=no stress, 0=fully stressed
- Weighted average of each soil layer by root fraction

$$\beta = f(\Psi_{soil})$$

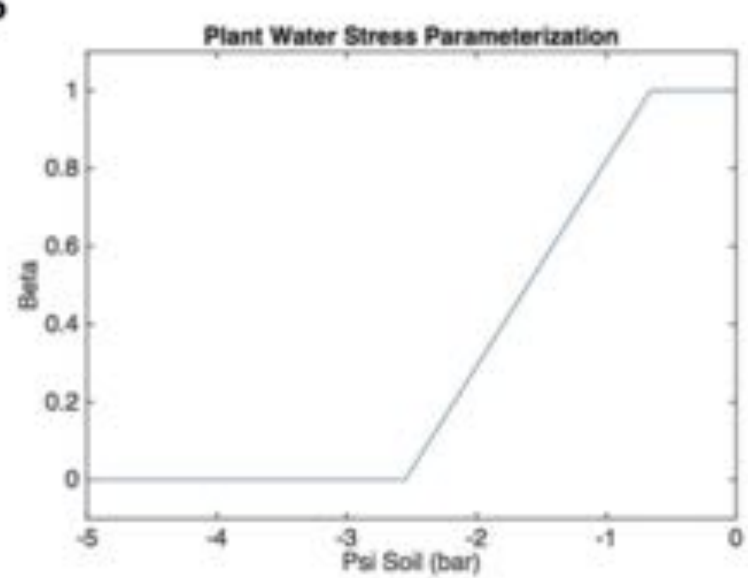
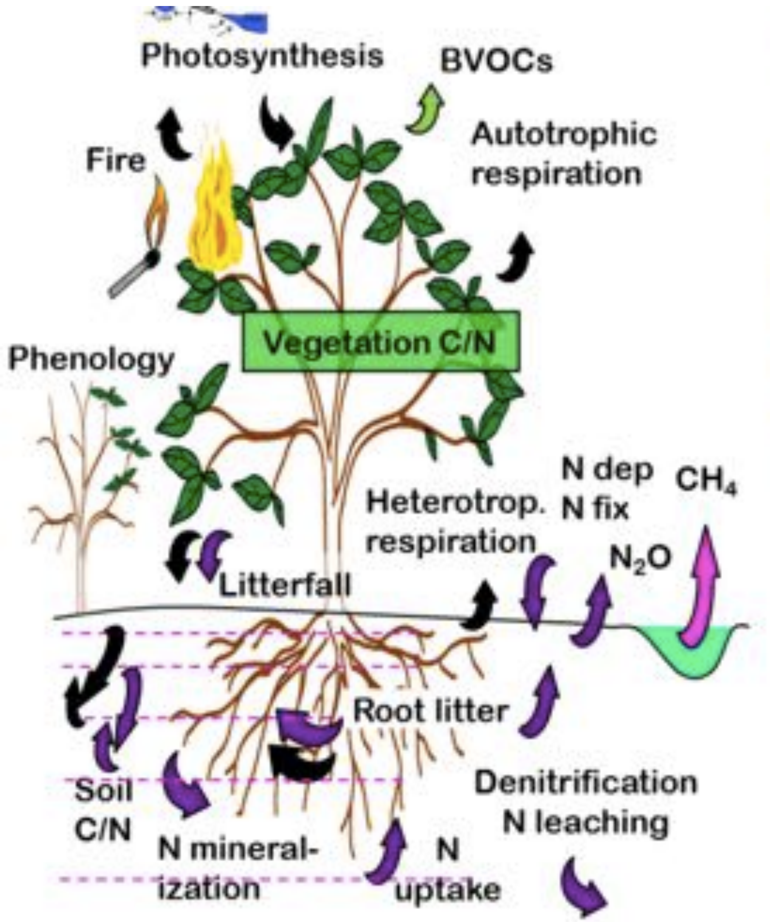


Figure courtesy D. Kennedy

Representing plants in the model: Biogeochemical Processes

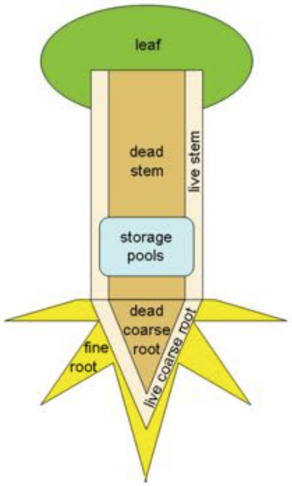


- *Photosynthesis*
- **Carbon/Nitrogen allocation**
- Plant phenology
- *Biogenic VOC emissions*

- Required vegetation parameters:
  - C:N ratios of different parts of plant
  - Allocation ratio of different parts of plant

- Theory/hypothese/assumptions applied:
  - Fixed allocation ratio and N requirement (CLM4.5)
  - Flexibe C:N ratio

Vegetation carbon Pools & Fluxes in CLM



CLM vegetation state variables (pools):

C and N pools for each tissue (structural pools):

- Leaf
- Stem (live and dead)
- Coarse root (live and dead)
- Fine root

Each structural pool has two corresponding storage pools:

- Long-term storage (> 1 yr)
- Short-term storage (< 1 yr)

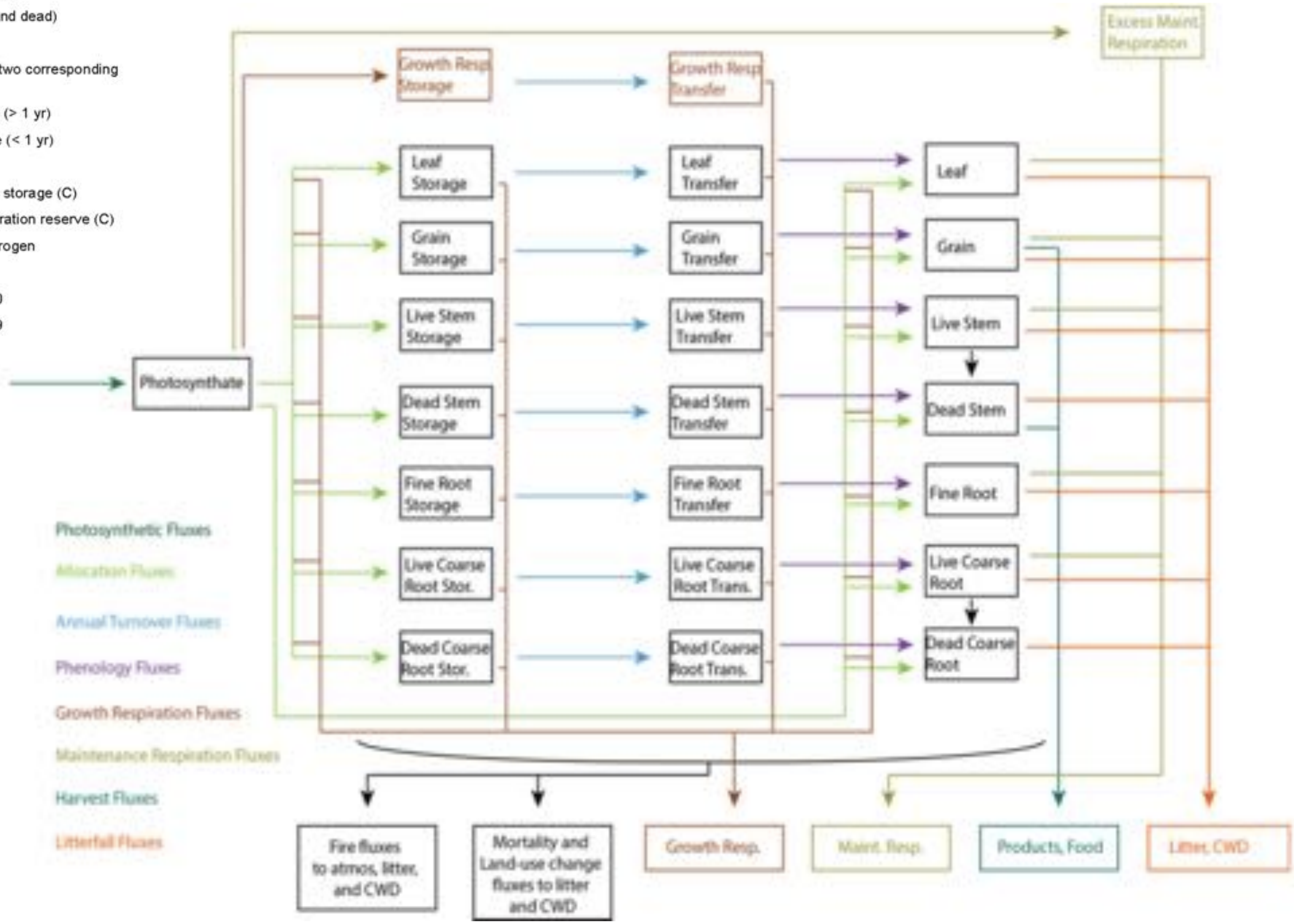
Additional pools:

- Growth respiration storage (C)
- Maintenance respiration reserve (C)
- Retranslocated nitrogen

Total number of pools…

Carbon: 6 + 12 + 2 = 20

Nitrogen: 6 + 12 + 1 = 19



Oleson et al. 2013

Carbon and Nitrogen Allocation in CLM4.5

- **Three steps:**
  - Evaluate the potential allocation of carbon and nitrogen assuming an unlimited nitrogen supply
  - Actual nitrogen supply is compared against the demand.
  - Allocation of carbon and nitrogen are reduced, if necessary, to match nitrogen supply and demand.

- **There are two carbon pools associated with each plant tissue**
  - One represents currently displayed tissue
  - One represents carbon stored for display in a subsequent growth period
  - Separation between the two depends on the parameter f_{cur} (values 0 to 1).

Carbon and Nitrogen Allocation in CLM4.5

Fraction of allocatable carbon to specific pool

Uses ratios

f1 = fine root: leaf
f2 = coarse root : stem
f3 = stem : leaf
f4 = live wood : total wood
f5 = grain : leaf
g1 = growth respiration: total allocation

total = leaf +
leaf*f1 + (__fine roots_)
leaf*f3*f4 + (__stem live wood_)
leaf*f3*f2*f4 + (__coarse wood live wood_)
leaf*f3*(1-f4) + (__stem dead wood_)
leaf*f3*f2*(1-f4) + (__coarse wood dead wood_)
leaf*f5 (__grain_)

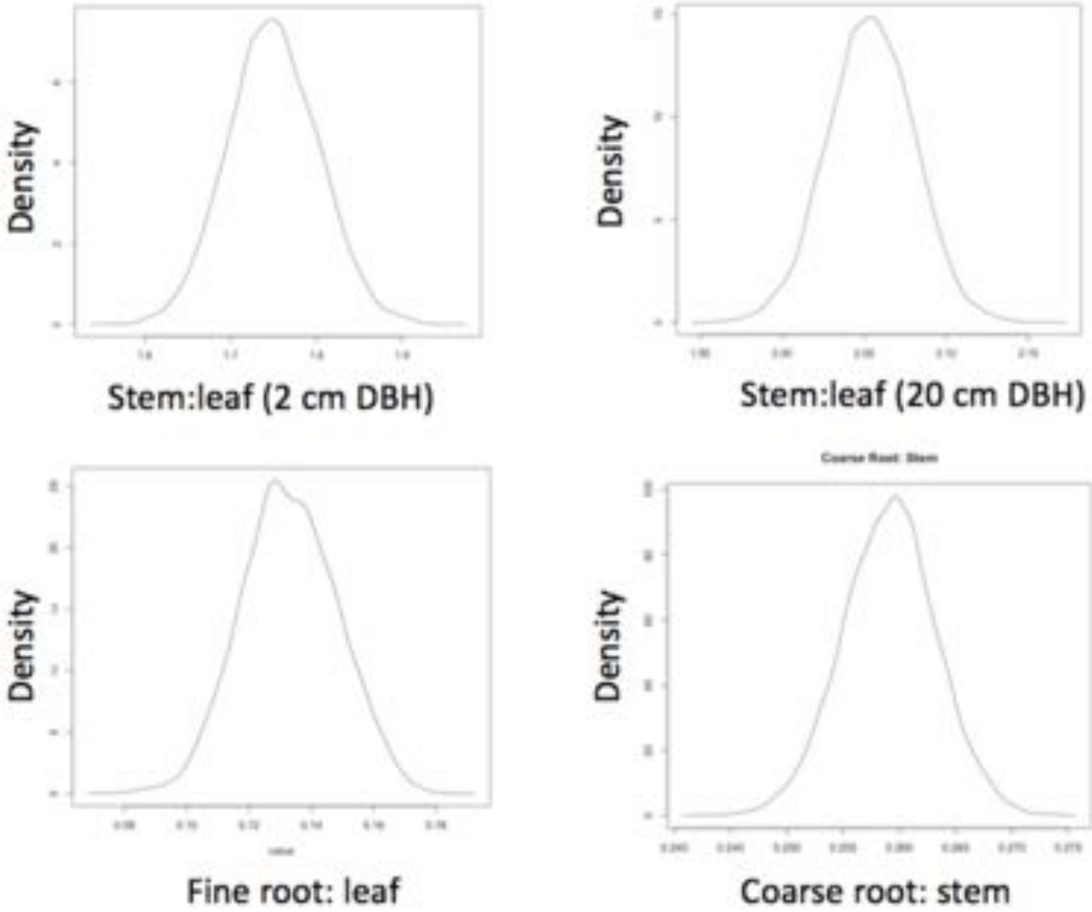
growth respiration = total*g1

Table 13.1. Allocation and carbon:nitrogen ratio parameters

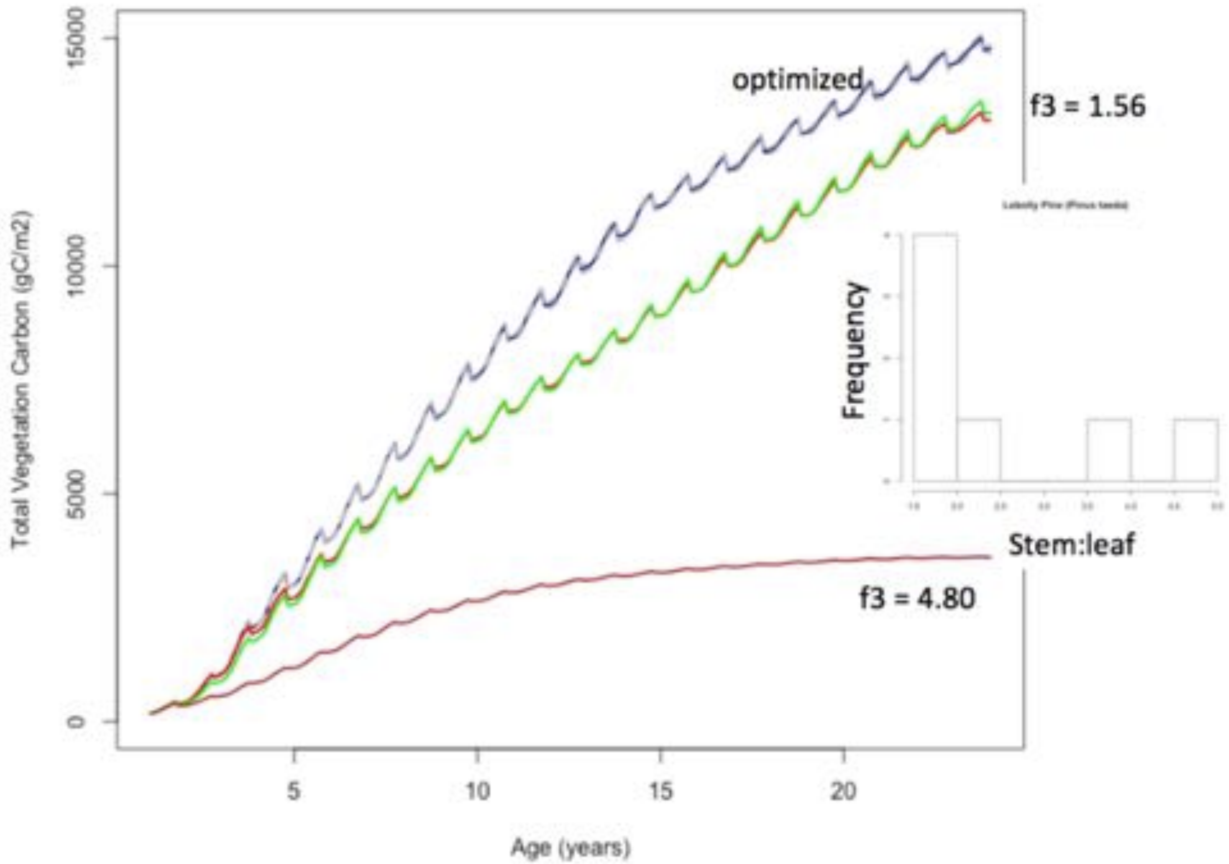
Plant functional type	a_1	a_2	a_3	a_4	CN_{leaf}	CN_{fr}	CN_{lw}	CN_{dw}
NET Temperate	1	0.3	-1	0.1	35	42	50	500
NET Boreal	1	0.3	-1	0.1	40	42	50	500
NDT Boreal	1	0.3	-1	0.1	25	42	50	500
BET Tropical	1	0.3	-1	0.1	30	42	50	500

Oleson et al. 2013

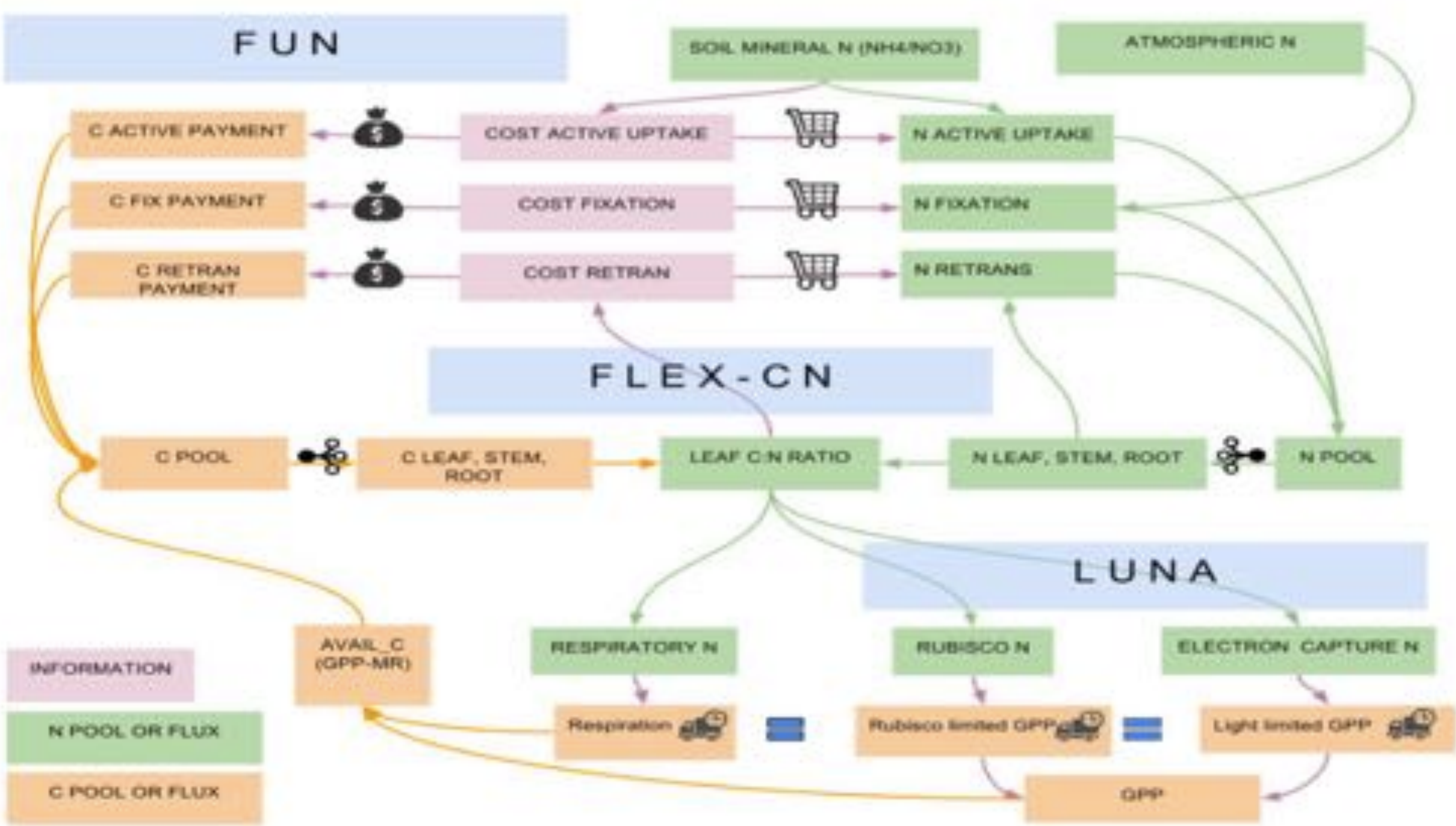
Parameterization example



Slide courtesy R. Q. Thomas


optimized
f3 = 1.56
Frequency
Stem:leaf
f3 = 4.80
Total Vegetation Carbon (gC/m2)
Age (years)
0
5000
10000
15000
5
10
15
20

New carbon and nitrogen allocation in CLM5

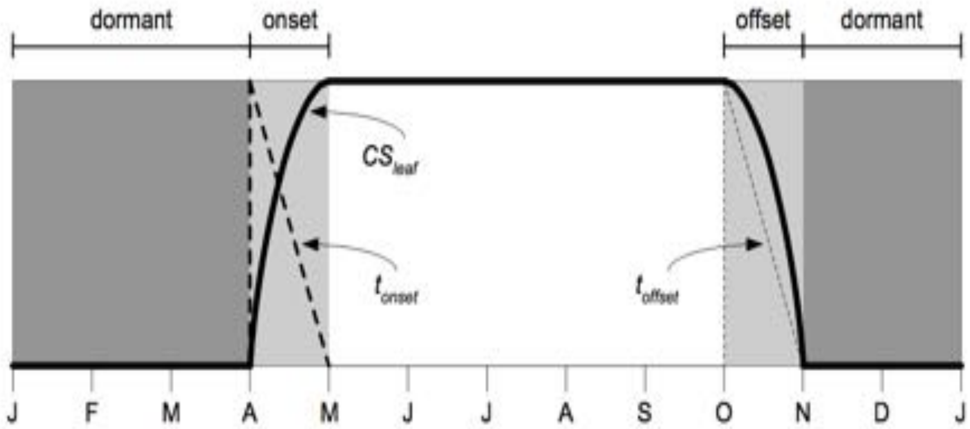


Slide courtesy R. Fisher

Representing plants in the model: Biogeochemical Processes

- **Phenology**: PFTs are classified into three distinct phenological type.
  - **evergreen type**: annual leaf growth persists in the displayed pool for longer than one year
  - **seasonal-deciduous type:** single growing season per year, controlled mainly by temperature and daylength;
  - **stress-deciduous type:** the potential for multiple growing seasons per year, controlled by temperature and soil moisture conditions.

Phenology



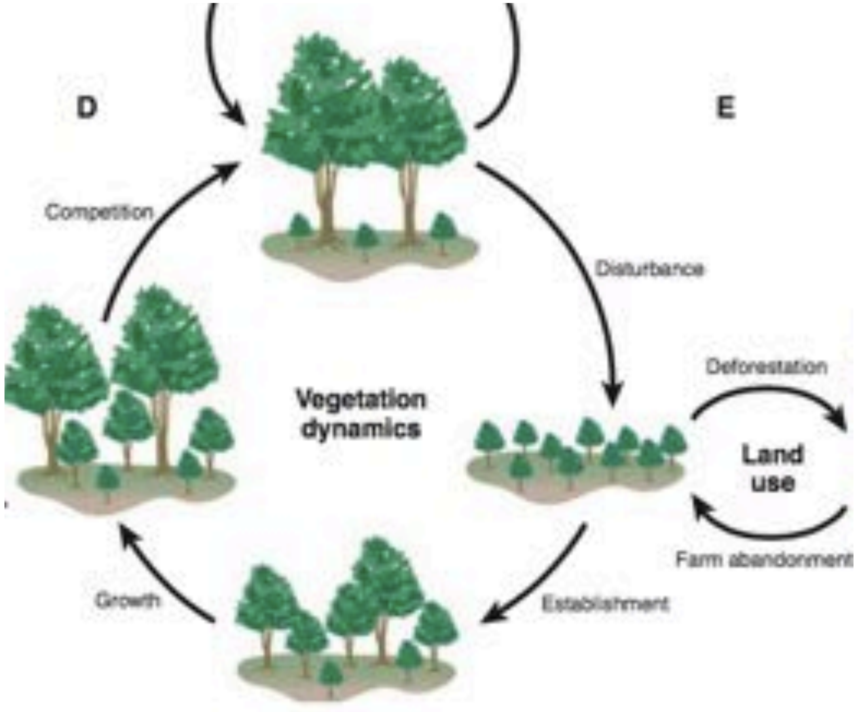
Oleson et al. 2013

$$GDD_{sum\_crit} = \exp\left(4.8 + 0.13\left(T_{2m,ann\_avg} - TKFRZ\right)\right)$$

$$GDD_{sum}^{n} = \begin{cases} GDD_{sum}^{n-1} + \left(T_{s,3} - TKFRZ\right) f_{day} & \text{for } T_{s,3} > TKFRZ \\ GDD_{sum}^{n-1} & \text{for } T_{s,3} \le TKFRZ \end{cases}$$

- **Onset** is triggered when **a common degree-day summation exceeds a critical value**, and **the time is before summer solstice**
- **Offset period** is triggered: sustained period of dry soil, sustained period of cold temperature, or daylength shorter than 6 hours.

Representing plants in the model: Plant geography & Vegetation dynamics



Shorter time scale:

- Disturbances: Vegetation fire, ozone damages
- Mortality

Longer time scale:

- Establishment & survival
- Light competition
- Human activity, land use change

Fire

- **Burned area is affected by climate and weather conditions, vegetation composition and structure, and human activities.**

$$A_b = N_f a$$

$$N_f = N_i f_b f_m f_{se,o}$$

- N_i is the number of ignition sources due to natural causes and human activities
- f_b, f_m is the availability and combustibility of fuel, respectively
- $f_{se,o}$ is the fraction of anthropogenic and natural fires unsuppressed by humans related to the socioeconomic conditions.

$$f_m = f_{RH} f_\theta f_T$$

Table 18.1. PFT-specific combustion completeness and fire mortality factors.

PFT	CC_{leaf}	CC_{stem}	CC_{root}	CC_{ts}	M_{leaf}	$M_{livestem}$	$M_{deadstem}$	M_{root}	M_{ts}	$M_{livestem}$	ξ_l
NET Temperate	0.80	0.25	0.00	0.50	0.80	0.15	0.15	0.15	0.50	0.35	0.15
NET Boreal	0.80	0.25	0.00	0.50	0.80	0.15	0.15	0.15	0.50	0.35	0.15
NDT Boreal	-	-	-	-	-	-	-	-	-	-	-
BET Tropical	0.80	0.22	0.00	0.45	0.80	0.13	0.13	0.13	0.45	0.32	0.13
BET Temperate	0.80	0.22	0.00	0.45	0.80	0.13	0.13	0.13	0.45	0.32	0.13

Establishment and Survival

- **Survival: 20-year running mean of the minimum monthly temperature to exceed pft-dependent value**. Existing pfts cease to exist if they cannot survive or if they drop in density below 10^{-10} individuals m^{-2} of naturally vegetated landunit area

- **Establishment is stricter than survival**, requiring additionally that T_c be less than pft dependent $T_{c,max}$ (prescribed), $GDD_{5°C}$ be greater than pft dependent GDD_{min}, and $GDD_{23°C}$ be equal to 0. **Establishment also requires the 365-day running mean of precipitation be greater than 100 mm yr^{-1}.**

Establishment and survival limits for PFTs in CLM4.5

PFT and PFT number corresponding to the list of PFTs in Table 2.1		Survival $T_{c,min}$ (°C)	Establishment $T_{c,max}$ (°C)	GDD_{min}
Tropical broadleaf evergreen tree (BET)	(4)	15.5	No limit	0
Tropical broadleaf deciduous tree (BDT)	(6)	15.5	No limit	0
Temperate needleleaf evergreen tree (NET)	(1)	-2.0	22.0	900
Temperate broadleaf evergreen tree (BET)	(5)	3.0	18.8	1200
Temperate broadleaf deciduous tree (BDT)	(7)	-17.0	15.5	1200
Boreal needleleaf evergreen tree (NET)	(2)	-32.5	-2.0	600
Boreal deciduous tree	(8)	No limit	-2.0	350
Temperate broadleaf deciduous shrub (BDS)	(10)	-17.0	No limit	1200
Boreal broadleaf deciduous shrub (BDS)	(11)	No limit	-2.0	350
C_4	(14)	15.5	No limit	0
C_3	(13)	-17.0	15.5	0
C_3 arctic	(12)	No limit	-17.0	0

Oleson et al. 2013

Competition for light

- Self-thinning of woody PFTs: the fractional projective cover summed over all tree pfts is limited to 95% of the naturally vegetated landunit

- Tree and grass cover combined cannot exceed 100% of the naturally vegetated landunit

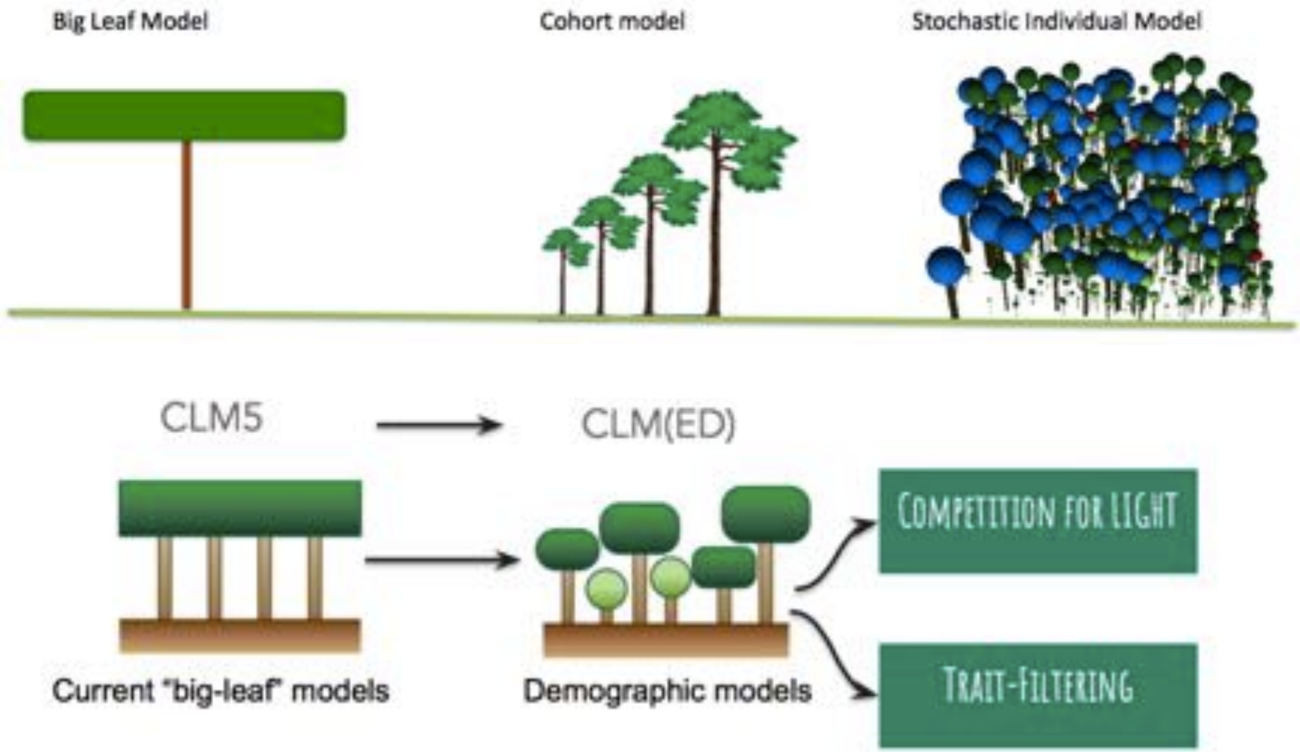
$$FPC_{excess} = (FPC_{woody} - 0.95)\frac{\Delta FPC_{pft}}{\Delta FPC_{woody}}$$

$$FPC_{excess} = \frac{(FPC_{woody} + FPC_{herb} - 1)\,FPC}{FPC_{herb}}$$

- Productive region (forest), less productive (grass), least productive (shrub)

Better represent succession and light competition of plants

- Agent-based, size-and-age structured, cohortized population models of trees



See Fisher et al. "Taking off the training wheels..." Geoscientific Model Development 2015

Figure courtesy R. Fisher

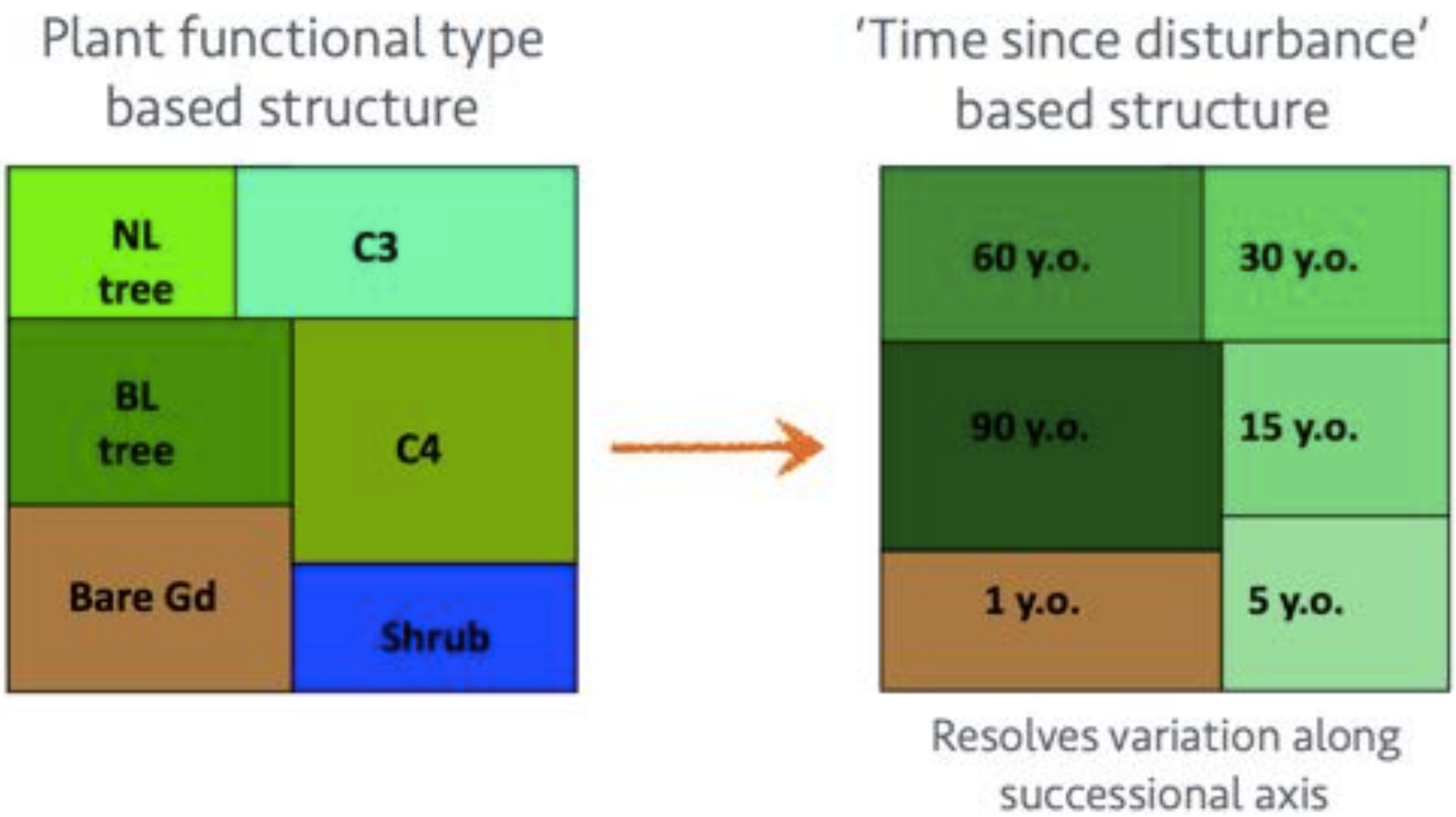


Figure courtesy R. Fisher

Individual or trait based vegetation model

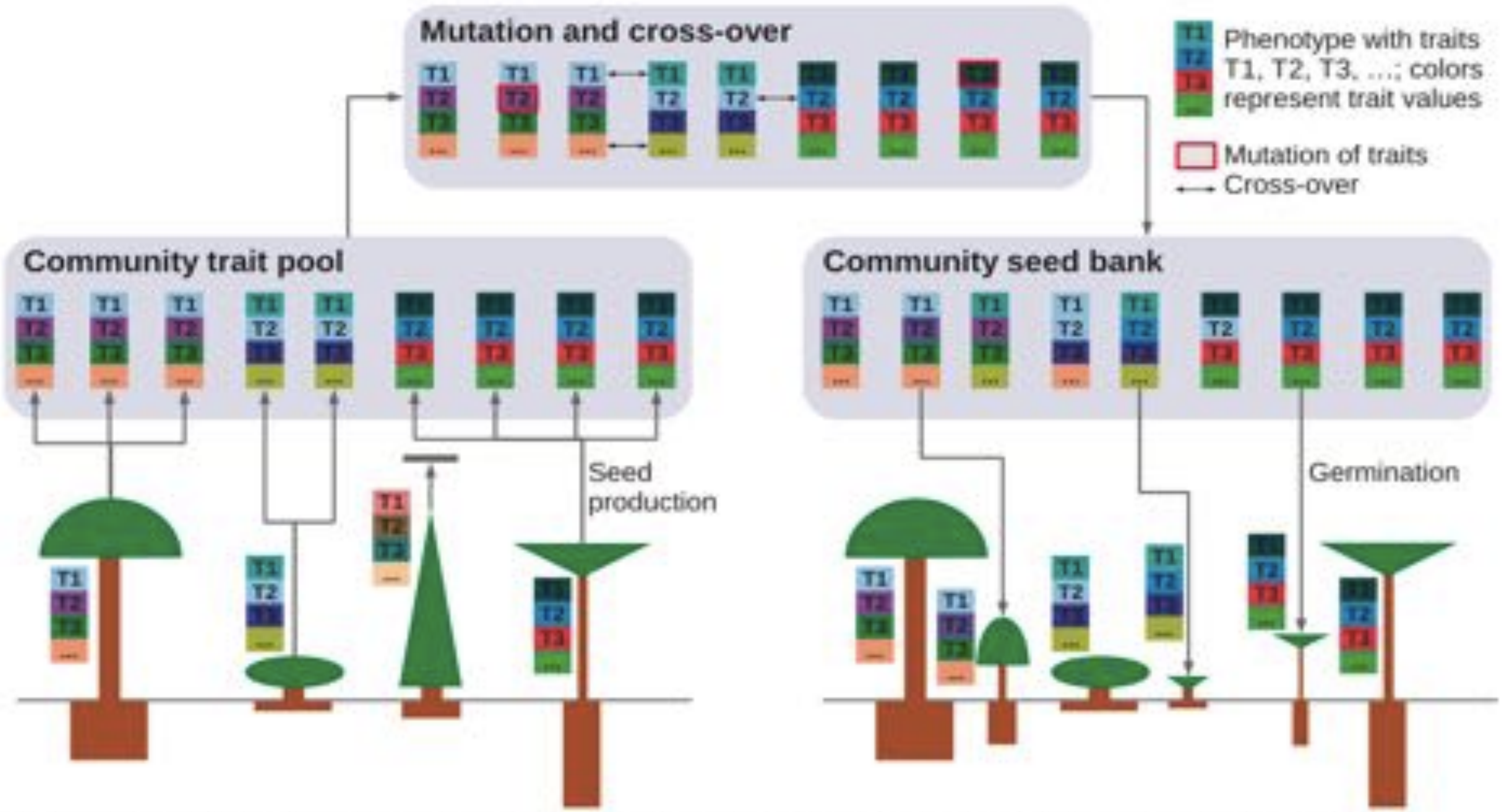
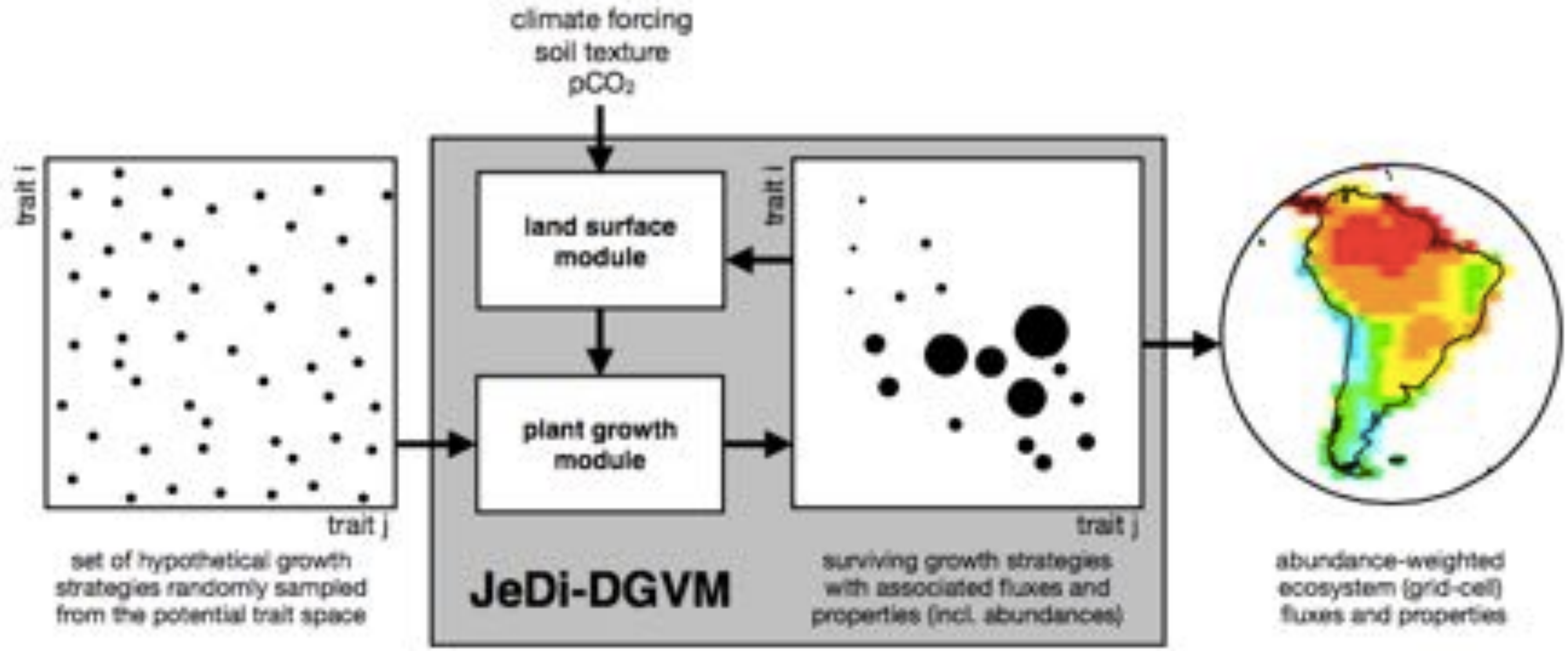


Fig. 4 Seed bank model in a next-generation dynamic global vegetation model (DGVM). Each plant is characterized by a unique trait combination. Reproducing individuals add their seeds to the community trait pool. In the community trait pool, mutation and crossover of seeds generate new trait combinations, which constitute the community seed bank. Randomly selected seeds can germinate, which means that they are added to the plant community as seedlings.

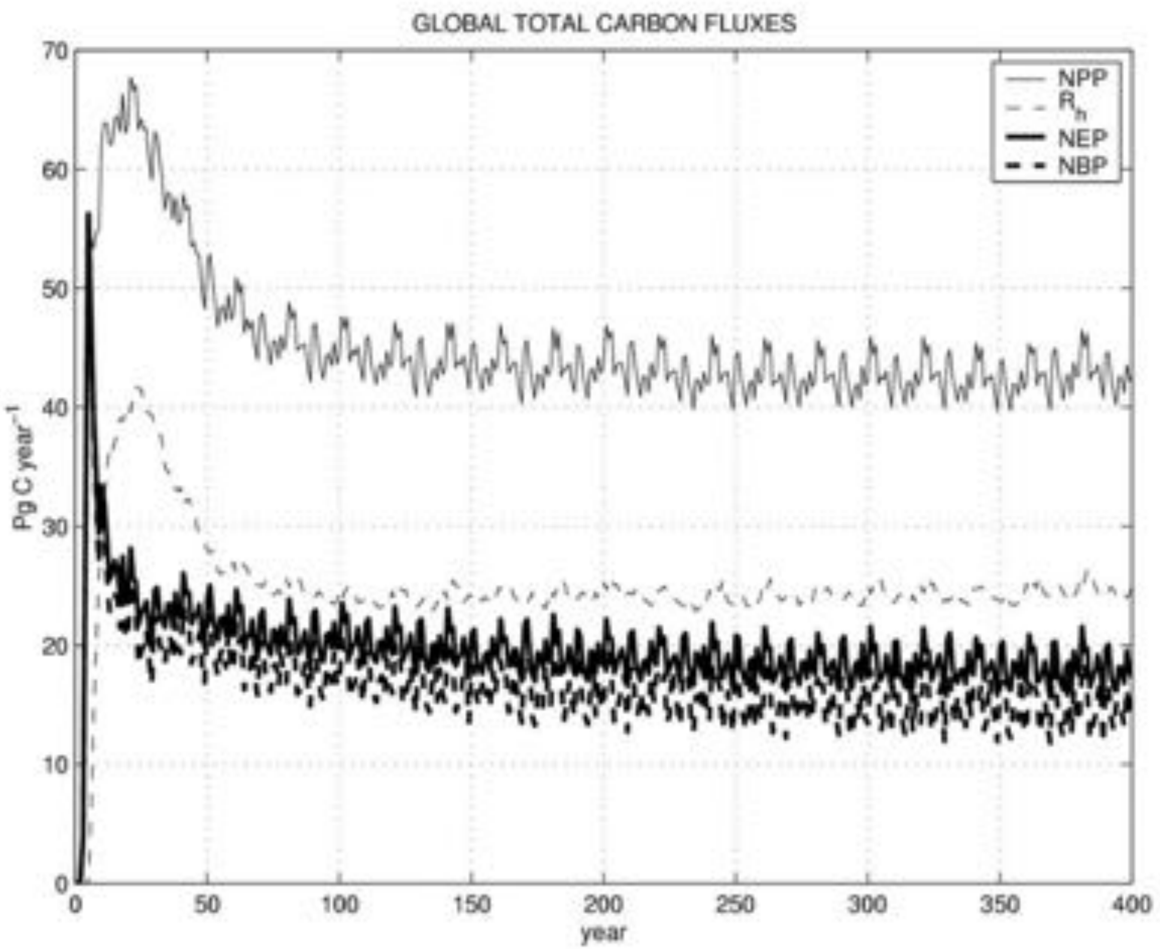
Sheiter et al. 2013

Individual or trait based vegetation model



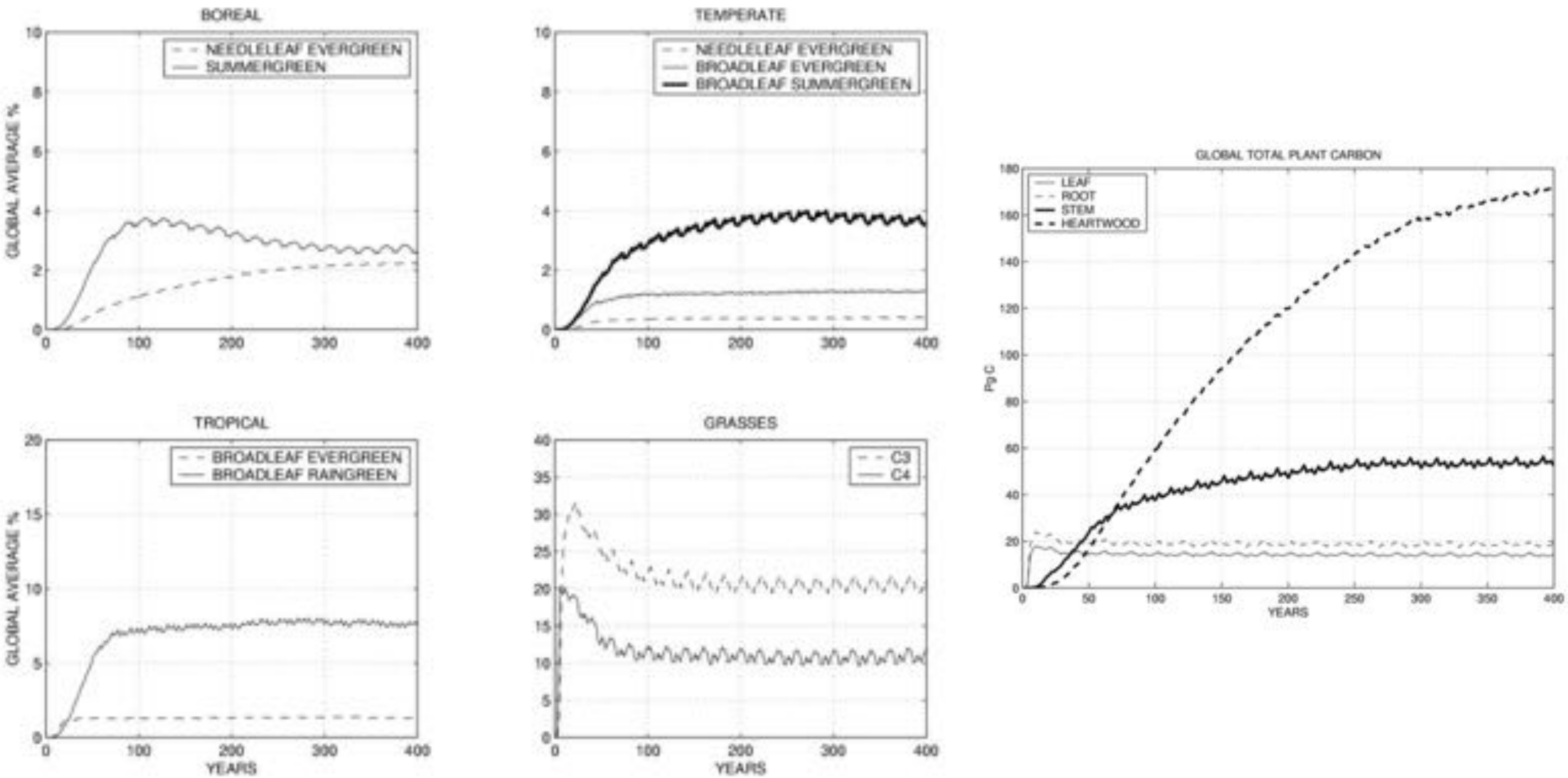
Pavlick et al. 2013

Model Spinup for vegetation



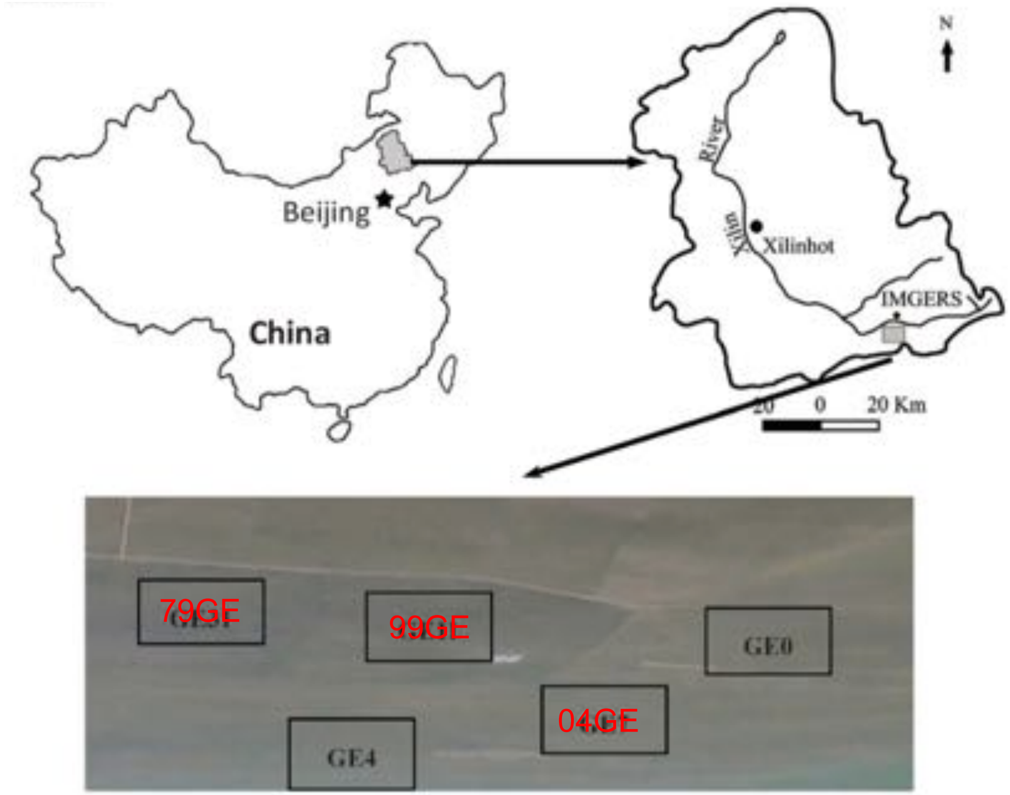
Levis et al. 2003

Model Spinup for vegetation



Levis et al. 2003

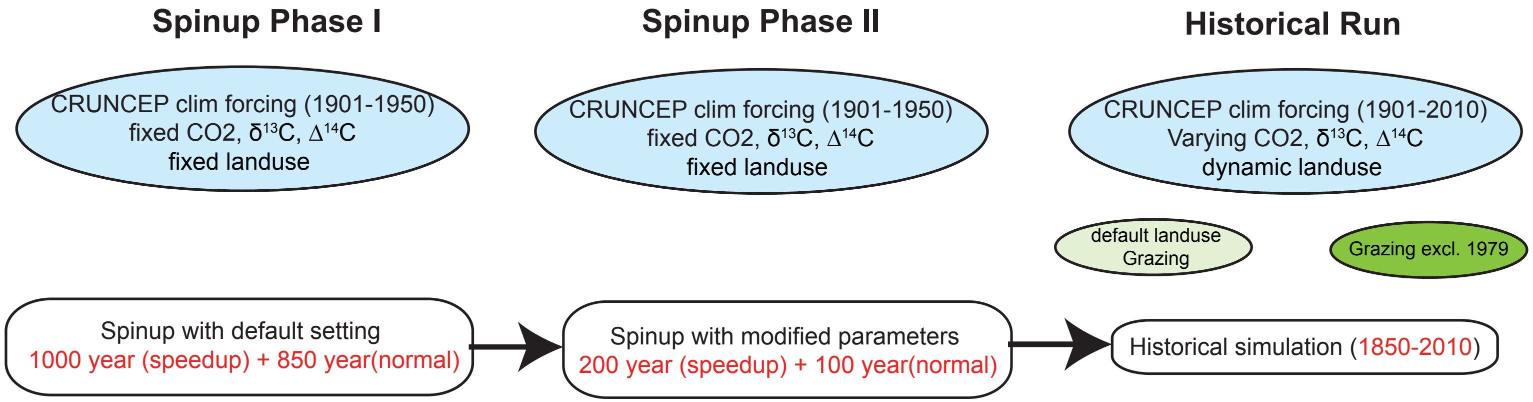
Case Study 1: single-column site



Wen et al. 2016

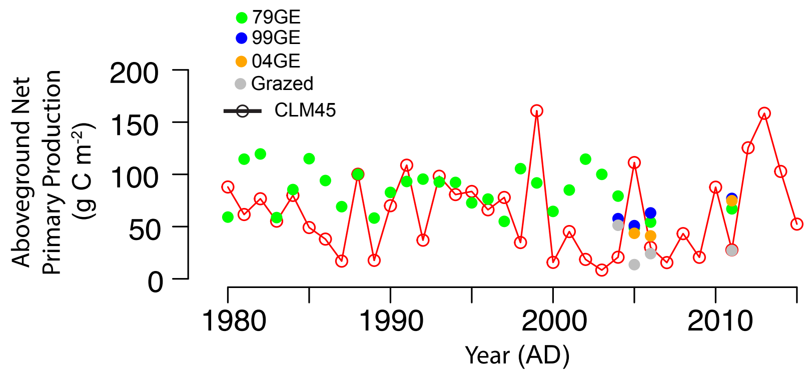
- IMGERS, Inner Mongolia Grassland Ecosystem Research Station (43°33’N, 116°40’E)
- Three fenced plots primarily investigated.

Case Study 1: Experimental design



- Site simulation using isotope-enabled CLM4.5-BGC
- No Nitrogen limitation, No Fire, and only C_3 grass exists in the site

Case Study 1: Validation of model results: GPP, AGPP, Leaf δ^{13}C

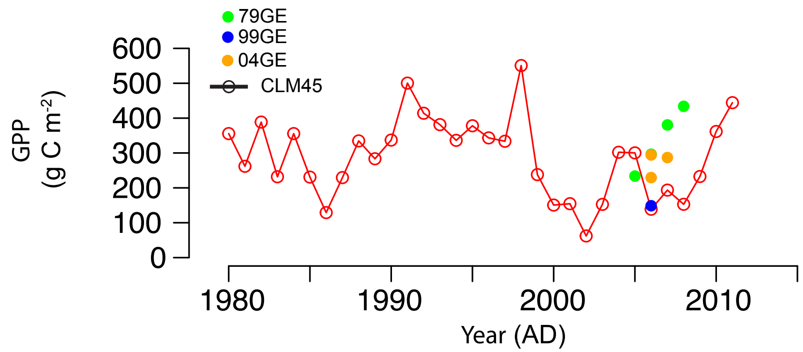


Average (1980-2003)

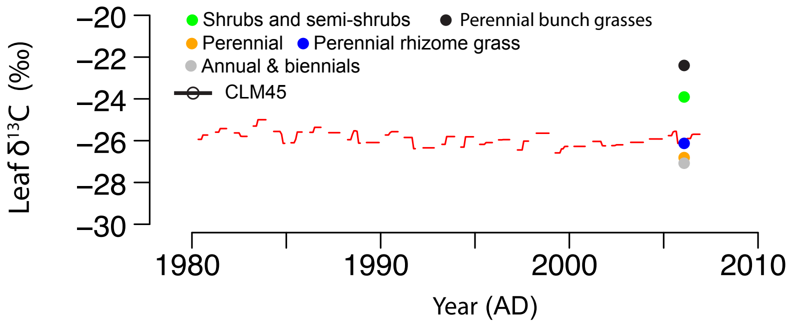
Obs. GE79: 87 g C/m^{-2}

Model: 62 g C/m^{-2}

Observation from *Bai et al. 2004*



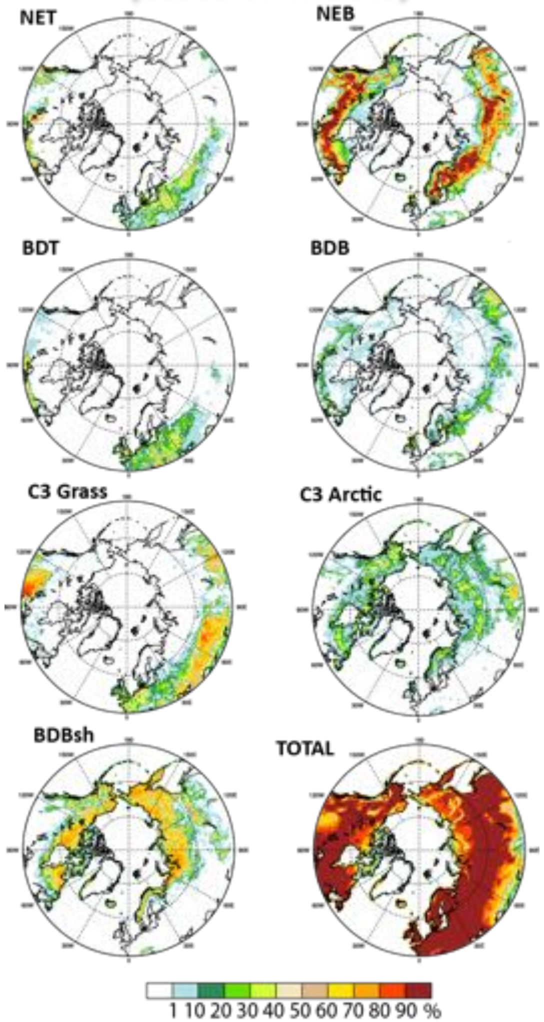
Observation from *Wang et al. 2016*



Observation from *Bai et al. 2004*

Case study 2: Modelling Arctic plant cover fraction (%)

Observation (based on MODIS)



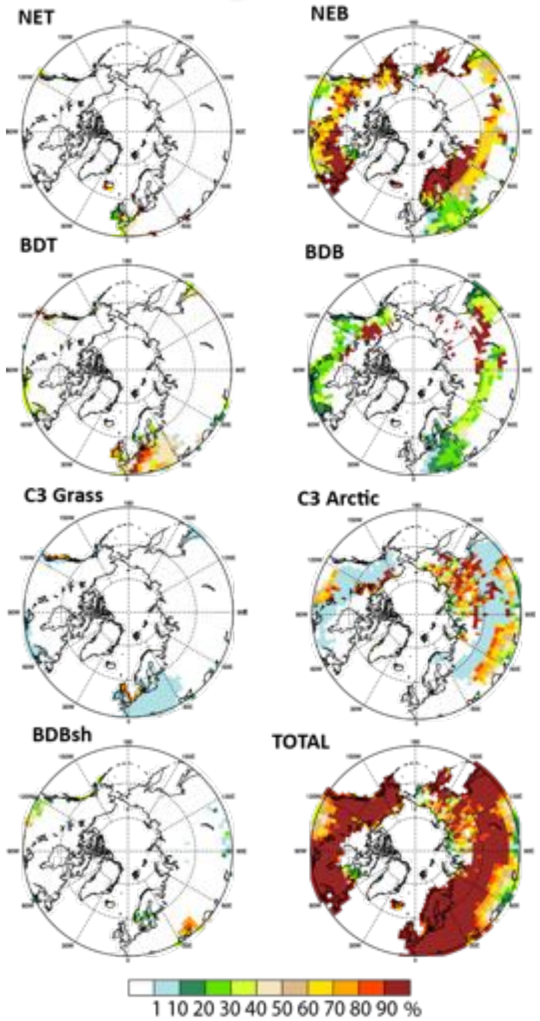
NET: Needleleaf evergreen temperate tree
NEB: Needleleaf evergreen boreal tree

BDT: Broadleaf deciduous temperate tree
BDB: Broadleaf deciduous boreal tree

C3 grass
C3 Arctic Grass

BDBsh: Broadleaf deciduous boreal shrub
Total: Total plant cover

Veg run



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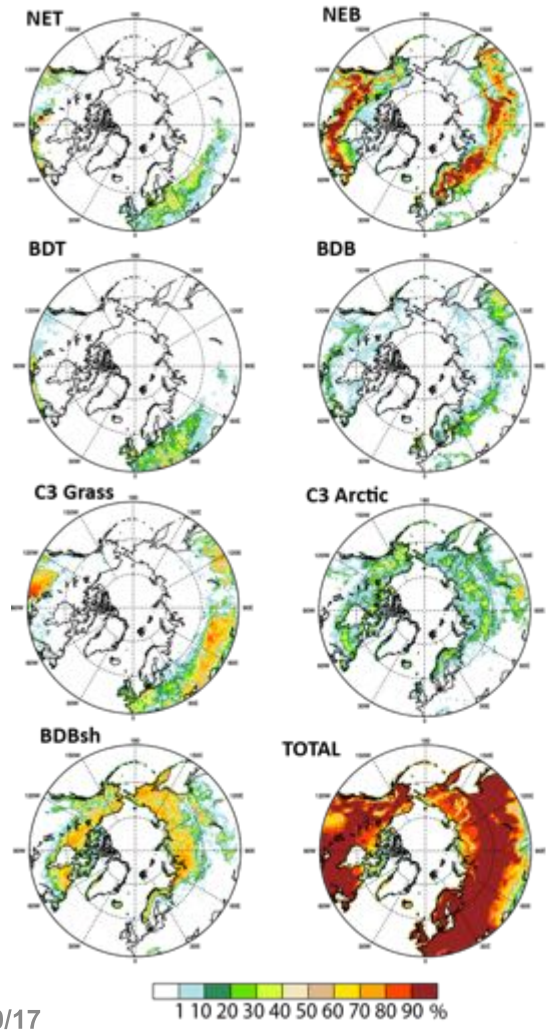

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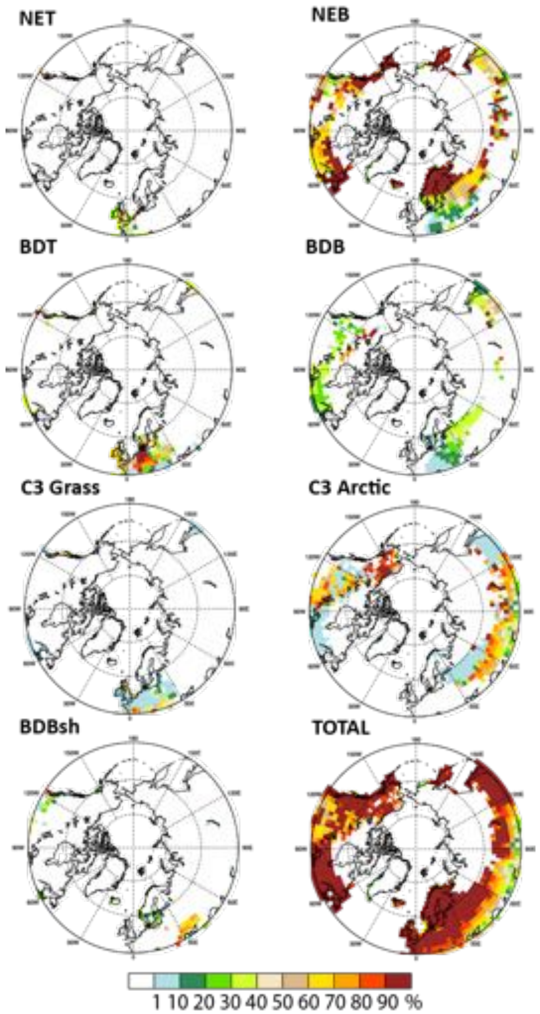
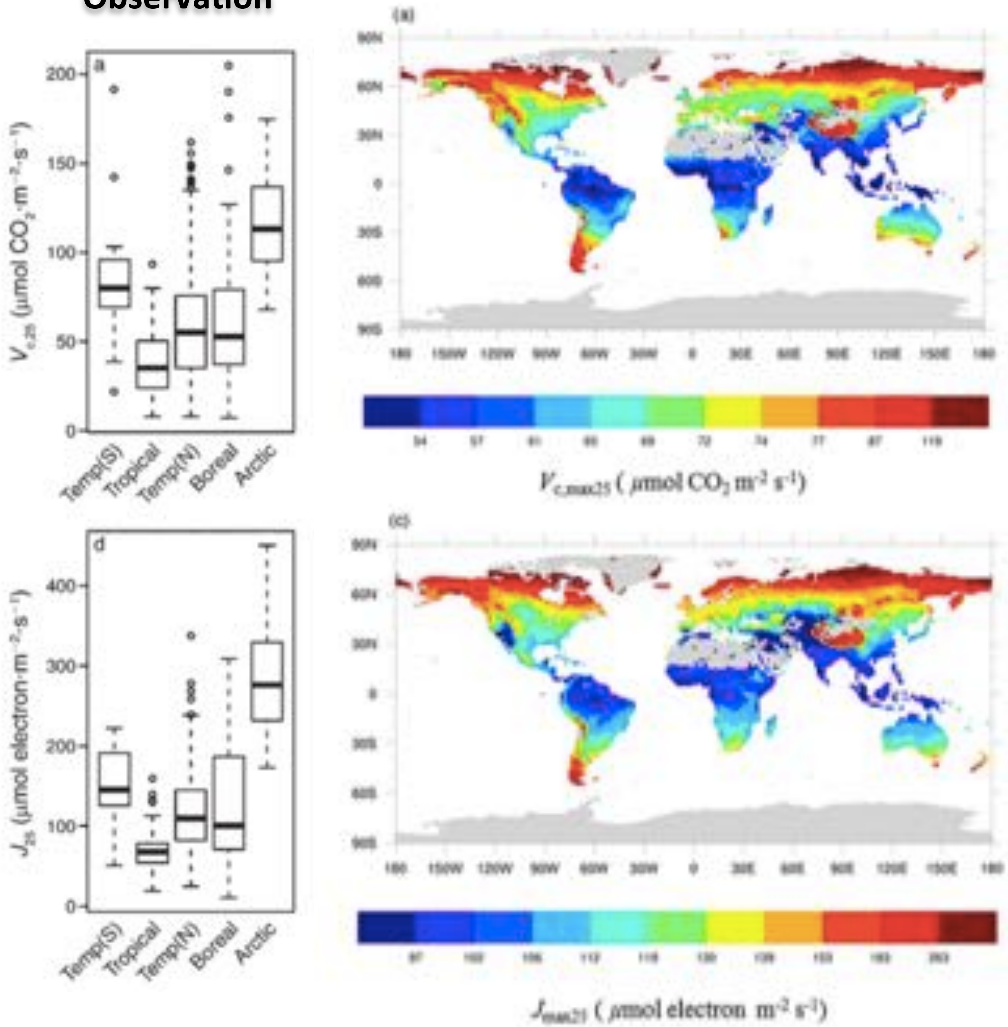
AtmVeg run

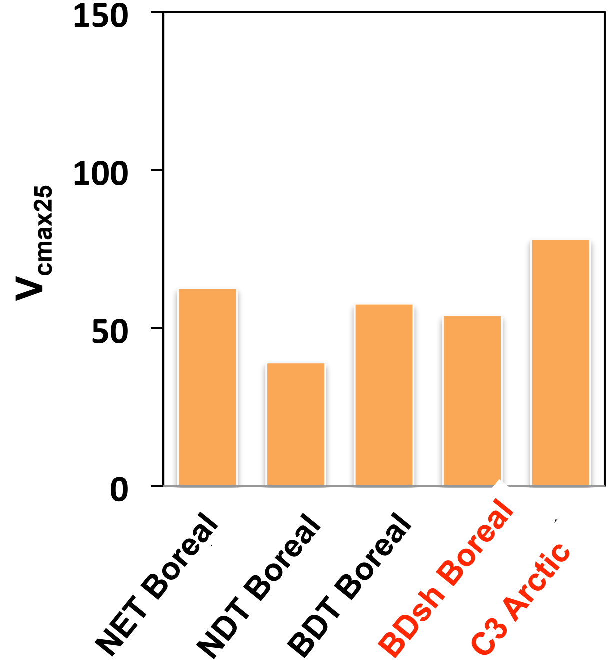


Parameterization of photosynthetic capacity (V_{cmax25}, J_{max25})

Observation



CLM4.5 Default



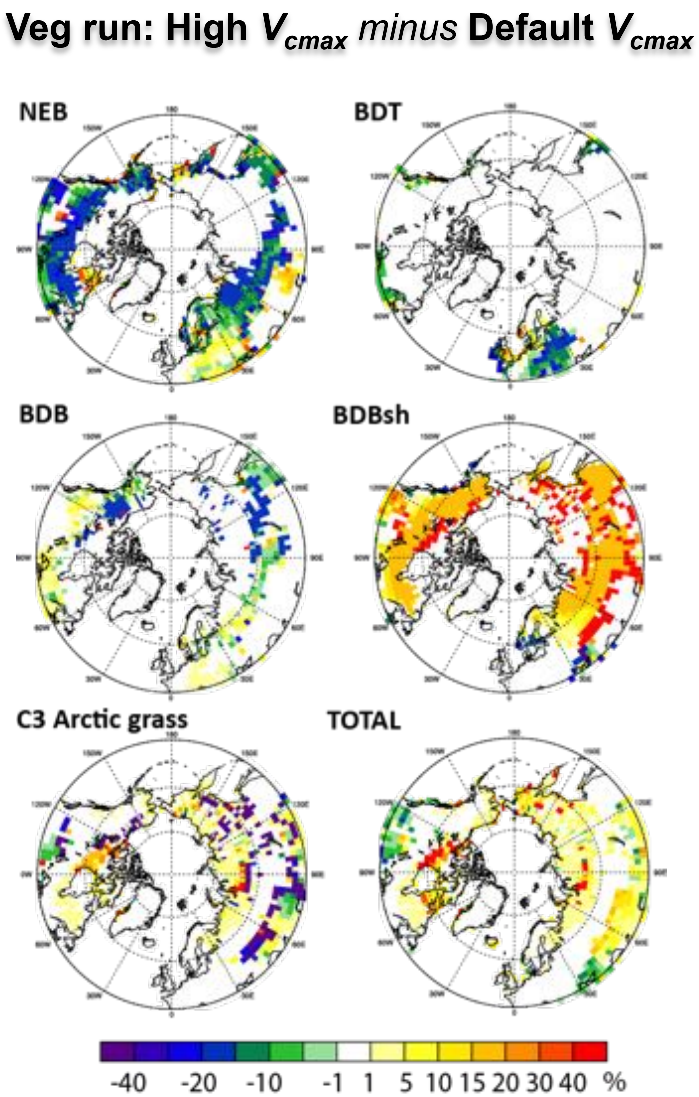
Ali et al. 2015, 2016

Plant cover changes (% points) due to increased V_{cmax25}

NEB: Needleleaf evergreen boreal tree
BDT: Broadleaf deciduous temperate tree

BDB: Broadleaf deciduous boreal tree
BDBsh: Broadleaf deciduous boreal shrub

C3 Arctic Grass
Total: Total plant cover

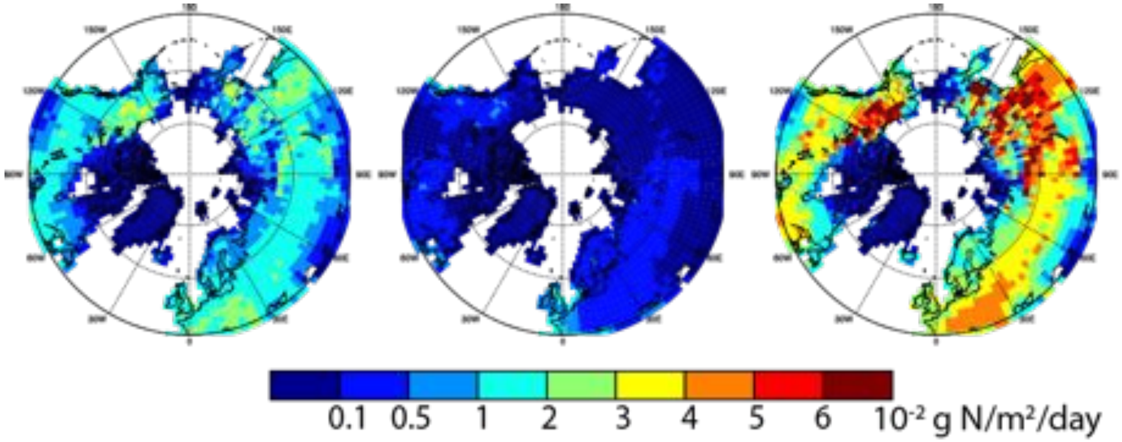


Nitrogen limitation in the Arctic region

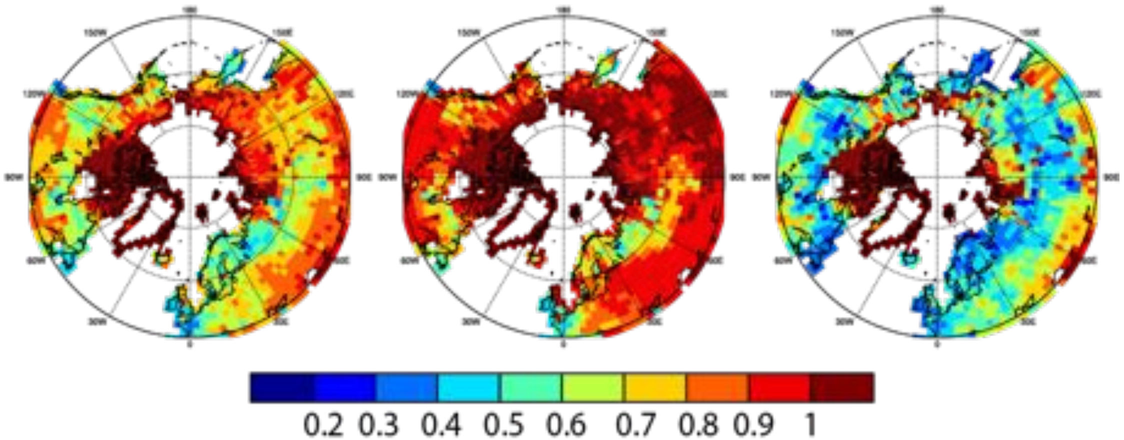
Veg run

Annual **DJF** **JJA**

Net rate of soil N mineralization



N limitation factor for plant



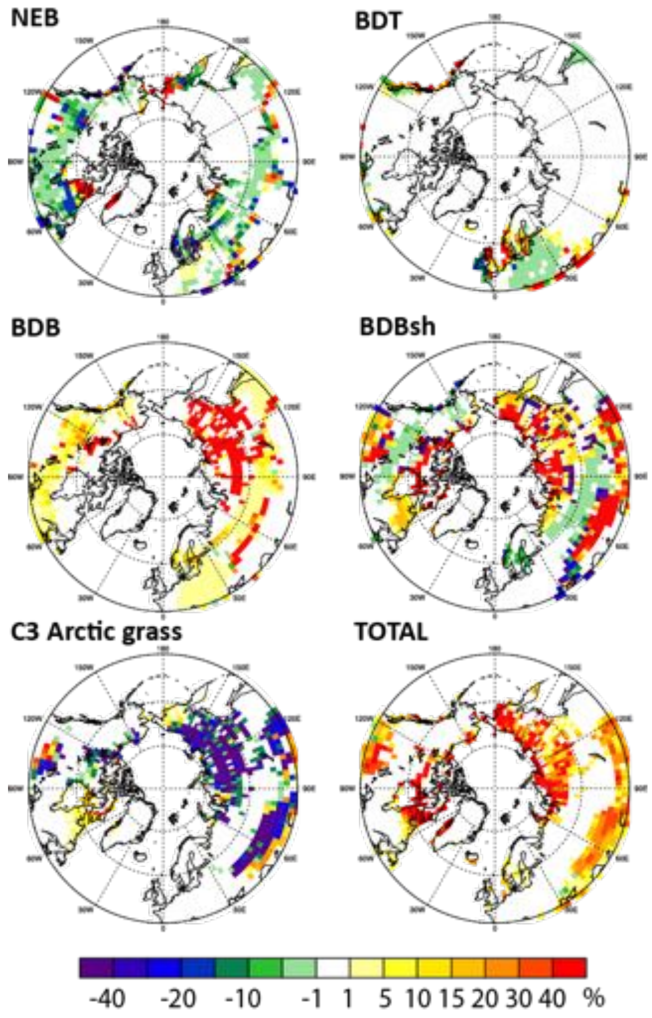
Plant cover changes (% points) due to removal of N limitation

NEB: Needleleaf evergreen boreal tree
BDT: Broadleaf deciduous temperate tree

BDB: Broadleaf deciduous boreal tree
BDBsh: Broadleaf deciduous boreal shrub

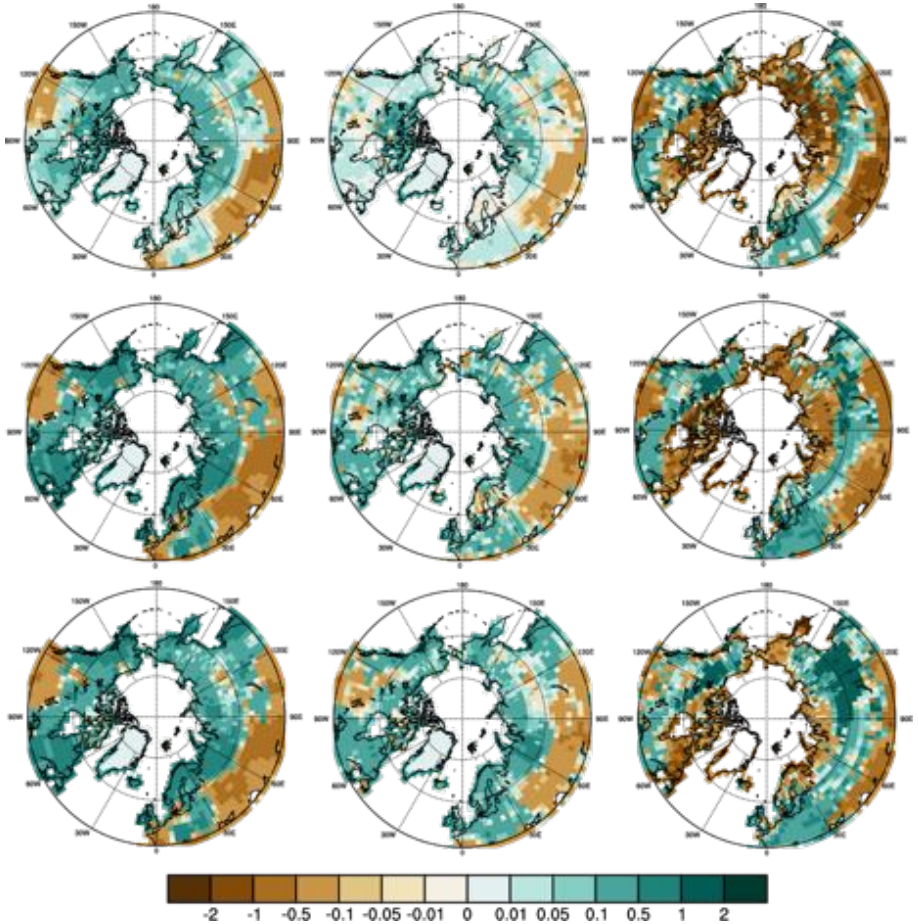
C3 Arctic Grass
Total: Total plant cover

Veg Run: No N-limitation *minus* N-limitation



Change of feedbacks between Arctic vegetation and temperature

	Temp. – Photosyn. rate	Temp. – LAI	LAI – Albedo
Veg run (Default V_{cmax})			
Veg run (High V_{cmax})			
Veg run (High V_{cmax} & No N-limation)			



Regression coefficiency (standardized)

Feedback loop: Increase temp. ->Vegetation growth -> **LAI -> Albedo** -> Increase Temp.

Take home messages:

- To represent plants in a land surface model grid, a generalization of plants (e.g., PFTs vs. Cohorts, Big-leaf vs. Multilayer Canopy) is necessary, while to represent the heterogeneity of plants in a model grid, a sub-grid tiling has to be used.

- Plant models are parameter heavy, but more and more processes are described mechanistically or using optimal theories.

- Choose vegetation model with a complexity to suitable for your reserach questions (spatial-temporal scale). Complex model is not always the better one.

- Vegetation module cannot tell you what the real world should be, but help you better understanding the processes.

Questions to think or discuss

- What are the major defeciencies of the current land surface model (e.g., CLM) in representing vegetation? Any missing processes?

- What are the key parameters/traits of plant in the model?

- How can observation and experements be conducted to improved the parameteration of plants in the model?

- How to better describe plant heterogeneity or diversity in the model? More PFTs, varying parameters for PFTs, or trait-based/individual based approach?

Tusen Takk!