Revamping the land in ESMs: Where remote observation and conservation of energy and mass meet ecology

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Computational Design of the Basic Dynamical Processes of the UCLA General Circulation Model

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"To use the general circulation model the following parameters must be prescribed for each grid point:

surface characteristics (open ocean, ice-covered ocean, bare land, and land covered by glacial ice); elevation of the land; surface roughness; thickness of the sea ice; and ocean surface temperature."

(and surface albedo)

No biosphere

Top down

GCM land physics vs. Ecological gap models

- **1D Fluxes** of water & energy
- **2D Area** coupling with atmosphere

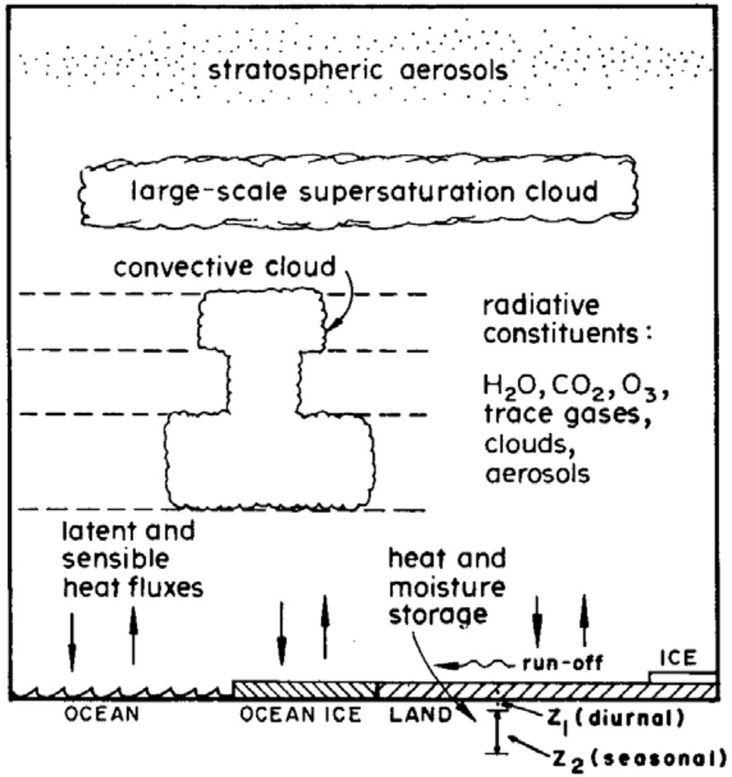
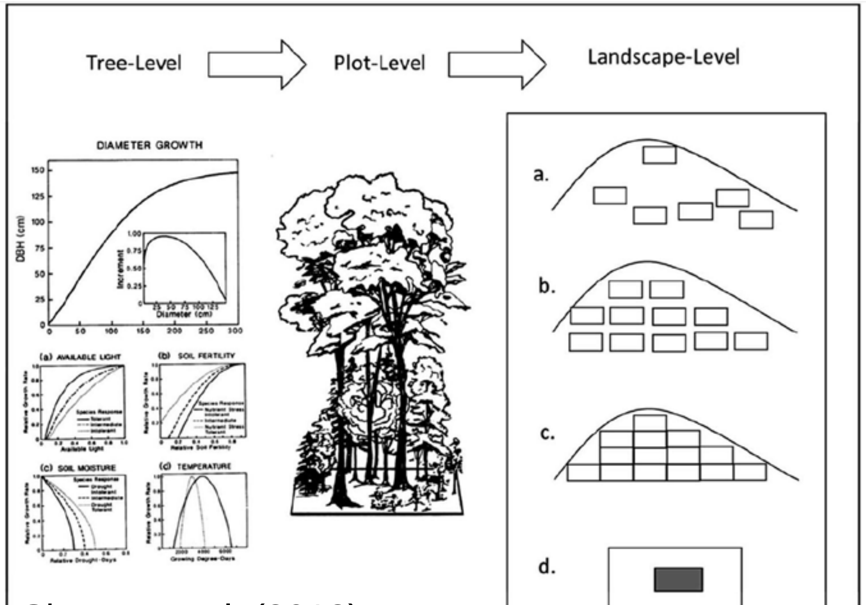


FIG. 3. Schematic illustration of model structure at a single gridbox.

Hansen et al. 1983

Bottom up

- **Quanta**: individual plants
- Stochastic rules, carbon allometry



Shugart et al. (2018)

Figure 2. General functioning of a gap model. As one moves to the right to left, spatial scale increases from an individual tree to a small plot to a landscape. The tree-level response shown here is the elementary growth (or tree ring) equation from the FORET (Shugart and West 1977) model. The magnitude ot the tree-mortality probablity of each tree are also determined at the tree-level depending on tree growth as an index of vigor, species longevieties and other conditions. The form of the growth equation with no constraints is shown at the top and the decrement to this optimal growth equation is found below according to the particular controlling environmental factors (available light, soil moisture, etc). At the plot level, the vertical profile of light, available soil moisture, and other environmental and biogeochemical factors are calculated and tree to tree interactions are computed. Conditions for potential new seedlings for each year are determined factors such as the environmental conditions and seed sources. At the landscape model, a basic gap model can be used to represent the landscape as: (*a*) the summation of a Monte Carlo collection of independent random points; (*b*) gridded points at some spacing, (*c*) a tessellation of adjacent plots; (*d*) a spatially explicit landscape simulation with a spatial map of trees that is 'windowed' or updated for tree birth, growth and death by dropping a gap-model computational window onto the tree-stem map to solve for a subset of a new map. This is repeated to produce the new map. The size of this subset determines the resolution of the spatial map.

Adding vegetation, coupling energy, H_2O, CO_2 - SiB2

Sellers et al. (1985, 1986, 1992, 1996)

with Two-stream canopy radiative transfer

(Dickinson, 1983; Sellers et al. 1985)

$$-\bar{\mu}(dI\uparrow/dL)+[1-(1-\beta)\omega]I\uparrow-\omega\beta I\downarrow=\omega\bar{\mu}K\beta_0\exp(-KL) \quad (1)$$

$$\bar{\mu}(dI\downarrow/dL)+[1-(1-\beta)\omega]I\downarrow-\omega\beta I\uparrow=\omega\bar{\mu}K(1-\beta_0)\exp(-KL) \quad (2)$$

L = cumulative leaf area index (LAI)
μ = cos(θ), θ = solar zenith angle
K = G(μ)/μ = direct beam optical depth per leaf area
G(μ) = relative projected leaf area

How to get K?

How does L(z) vary?

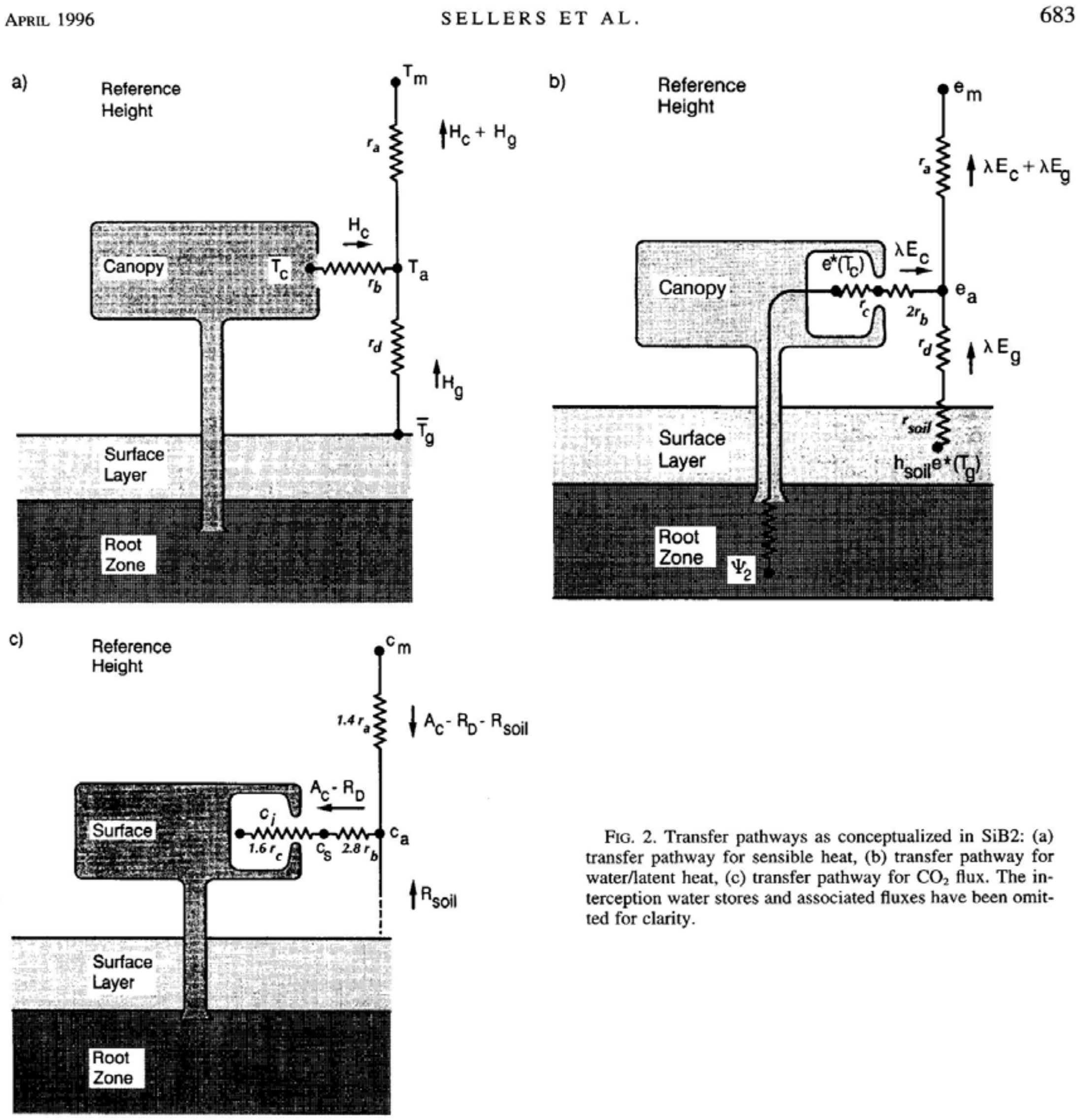
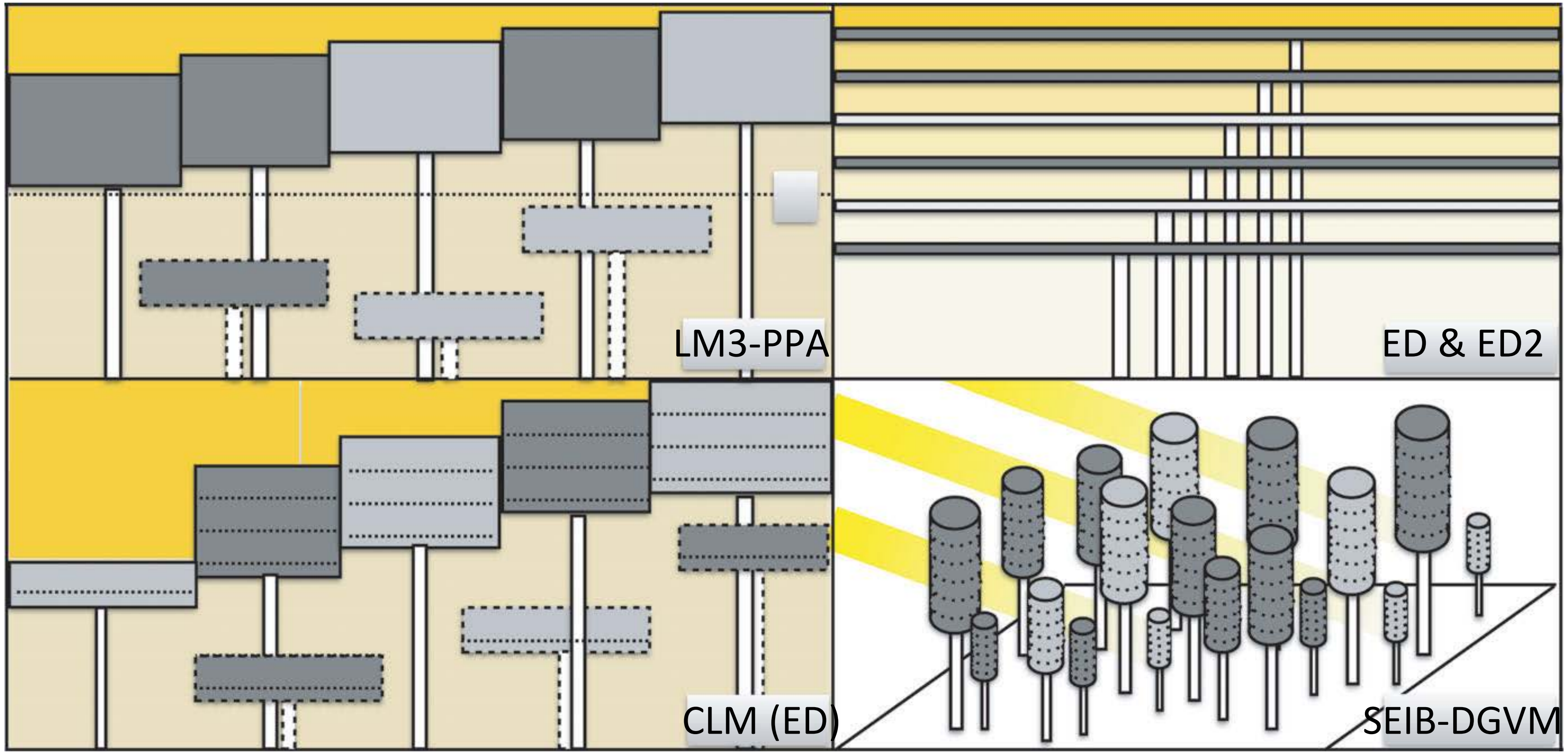


FIG. 2. Transfer pathways as conceptualized in SiB2: (a) transfer pathway for sensible heat, (b) transfer pathway for water/latent heat, (c) transfer pathway for CO_2 flux. The interception water stores and associated fluxes have been omitted for clarity.

Converging toward

Demographic Dynamic Global Vegetation Models



Fisher et al. (2017) GCB DOI: 10.1111/gcb.13910

Problem: No gaps! Or formulated for 30 m scale, fixed solar zenith. Rule-based rather than physics-based canopy radiative transfer.

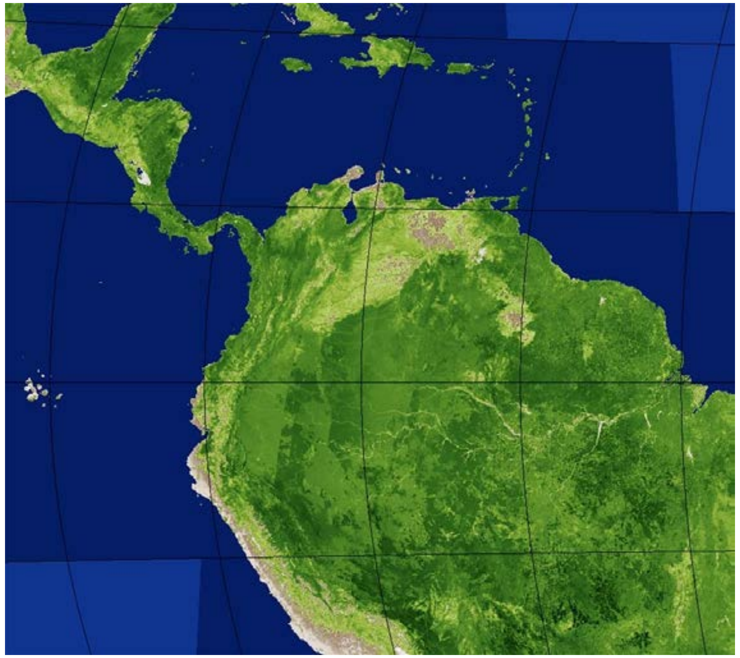
Physics: What does remote sensing see?

Boundary conditions: vegetation structure & quality

<u>Horizontal</u>

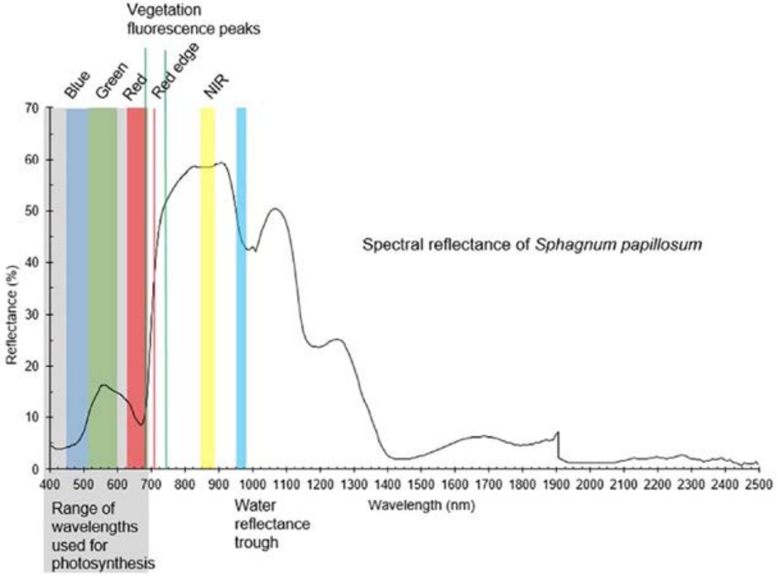
Area (cover, LAI)

Spectra



<u>Spectral</u>

Albedo
Physiological status (NDVI, PRI, etc.)
Activity (SIF, NDVI)
Diversity (PFTs, species)

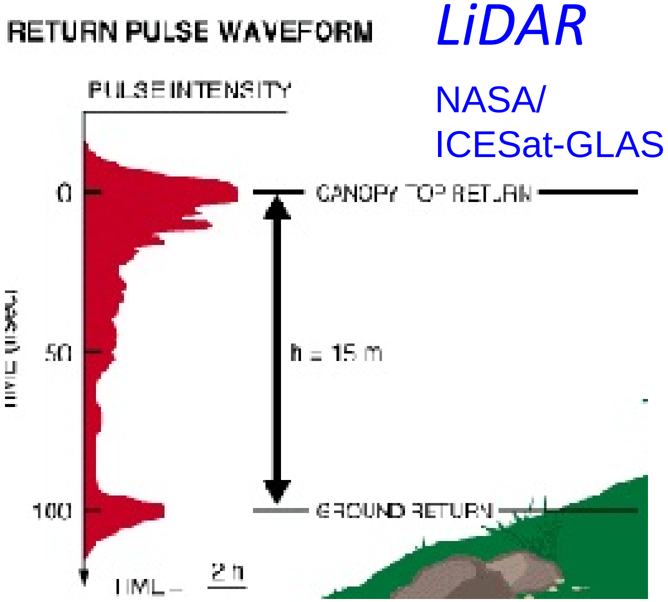


K.J. Lees et al. / Science of the Total Environment 615 (2018) 857–874

<u>Vertical</u>

Height

Shape profiles of foliage/stem density



LiDAR

NASA/ ICESat-GLAS

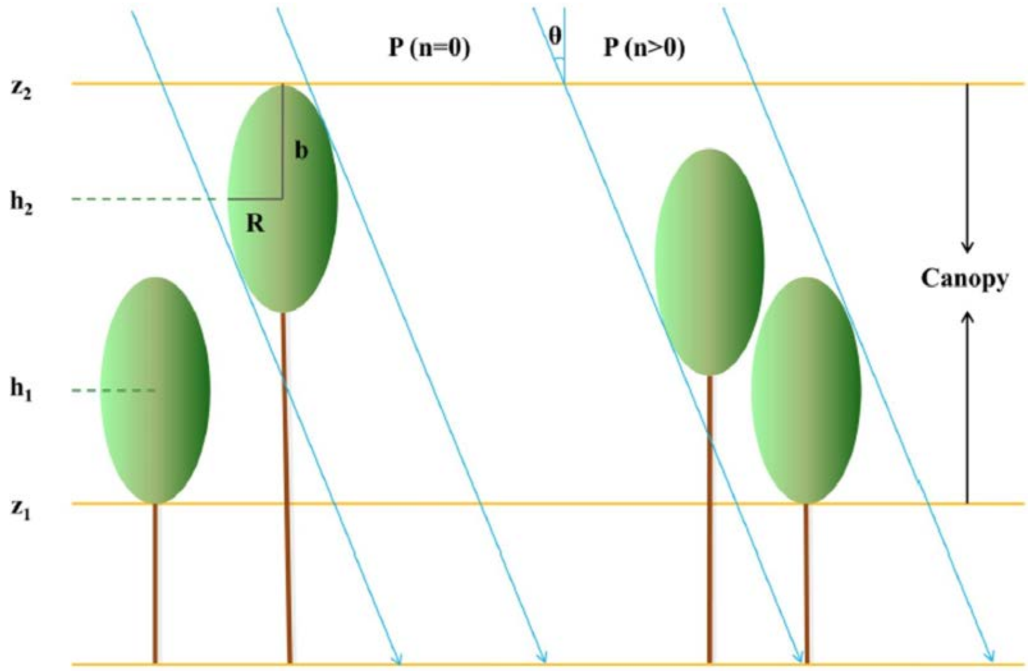
Gap-probability Geometric-Optical radiative transfer (GORT) for demographic DGVMs - consistent with LiDAR

- Ellipsoidal crowns
- Analytical clumping factor for effective two-stream parameters
- LAI layering
- Trunks

FAST

Ent TBM:
Analytical Clumped Two-Stream **(ACTS)**
(Ni-Meister et al., 2010; Yang et al. 2010)

- Non-intersecting crowns
- Optional branch effect



POP-DGVM (after LPJ-GUESS):
Canopy Semi-analytic Pgap And Radiative Transfer **(CanSPART)**
(Haverd et al., 2012, 2014)

- Poisson-distributed crowns

Canopy radiative transfer modeling

RAdiation transfer Model Intercomparison (RAMI)

((Pinty et al., 2001, 2004; Widlowski et al., 2007, 2008, 2011, 2013, 2015)

(shortwave/VIS/NIR/hyperspectral, energy balance,

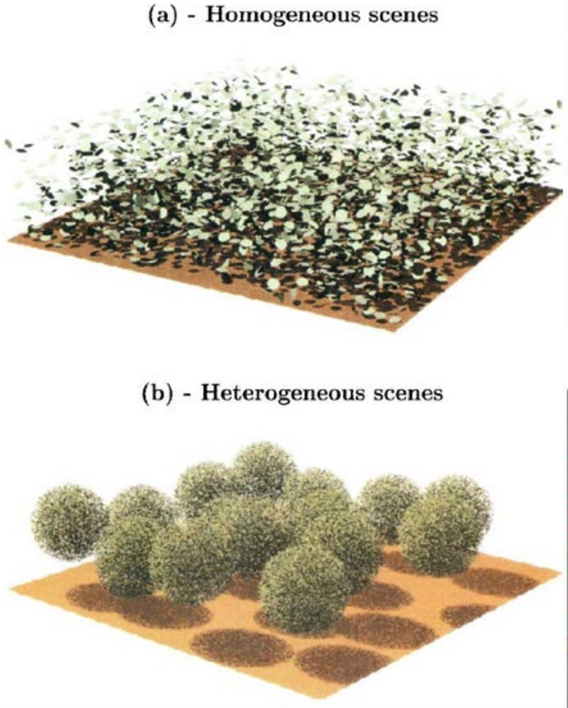
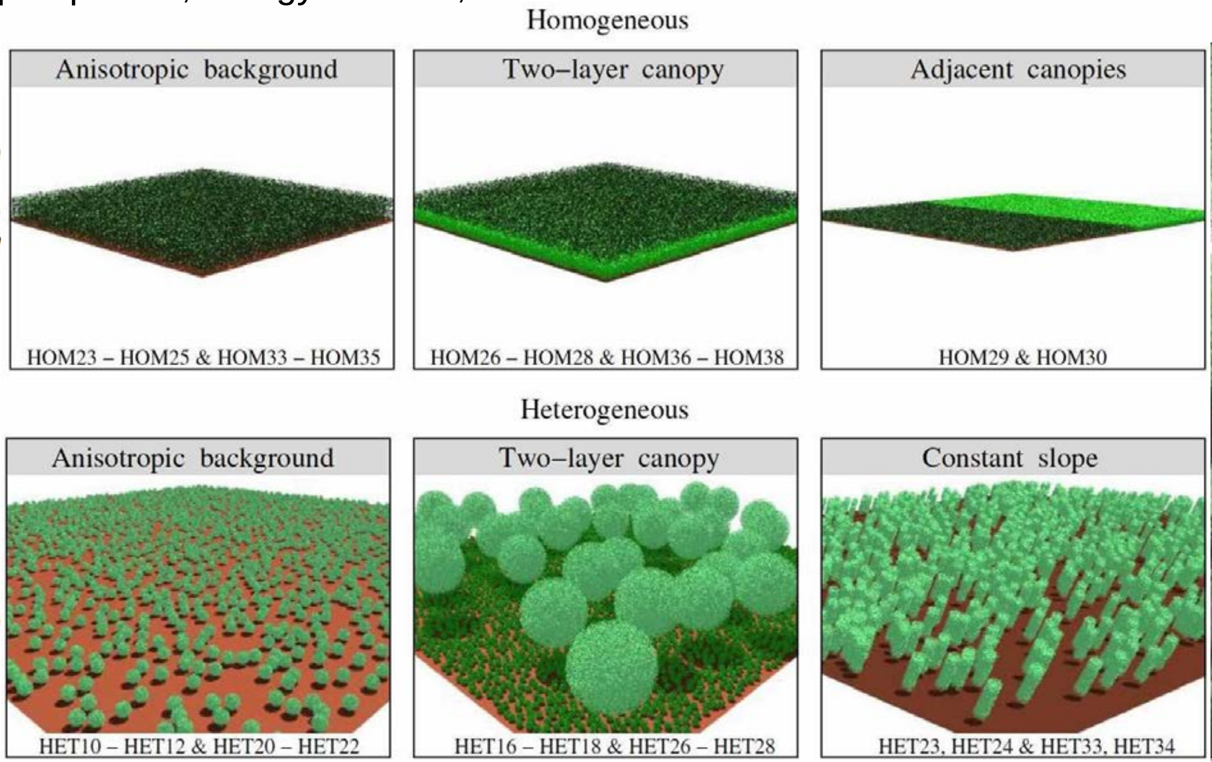
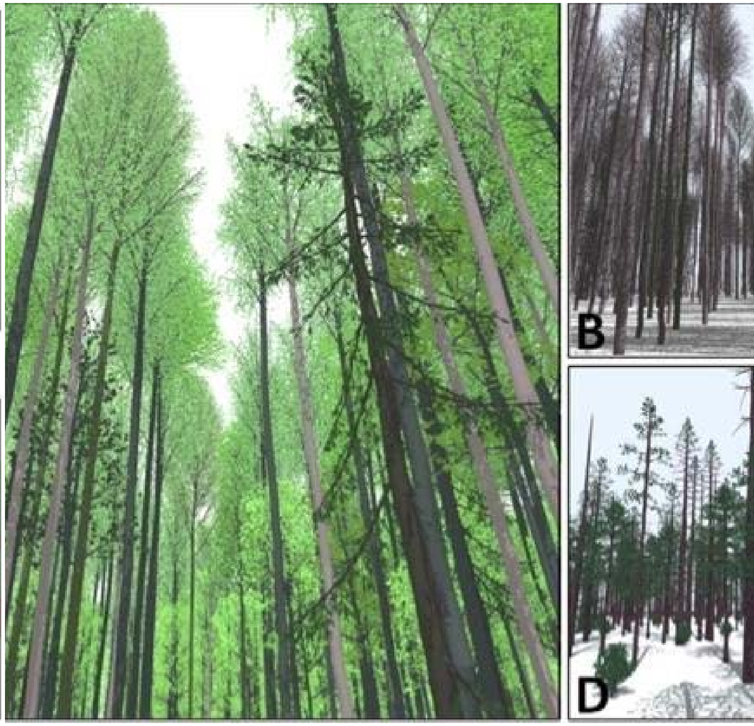


Plate 1. Artist views of the RAMI scenes for discrete (a) homogeneous and (b) heterogeneous scenes.





RAMI-4PILPS

Widlowski et al. (2011)

idealized canopy scenarios

<u>Reference model:</u>
raytran
(Monte Carlo ray-tracing)

G02019 WIDLOWSKI ET AL.: ASSESSING SHORTWAVE FLUXES IN LAND SURFACE SCHEMES G02019

1-D

3-D

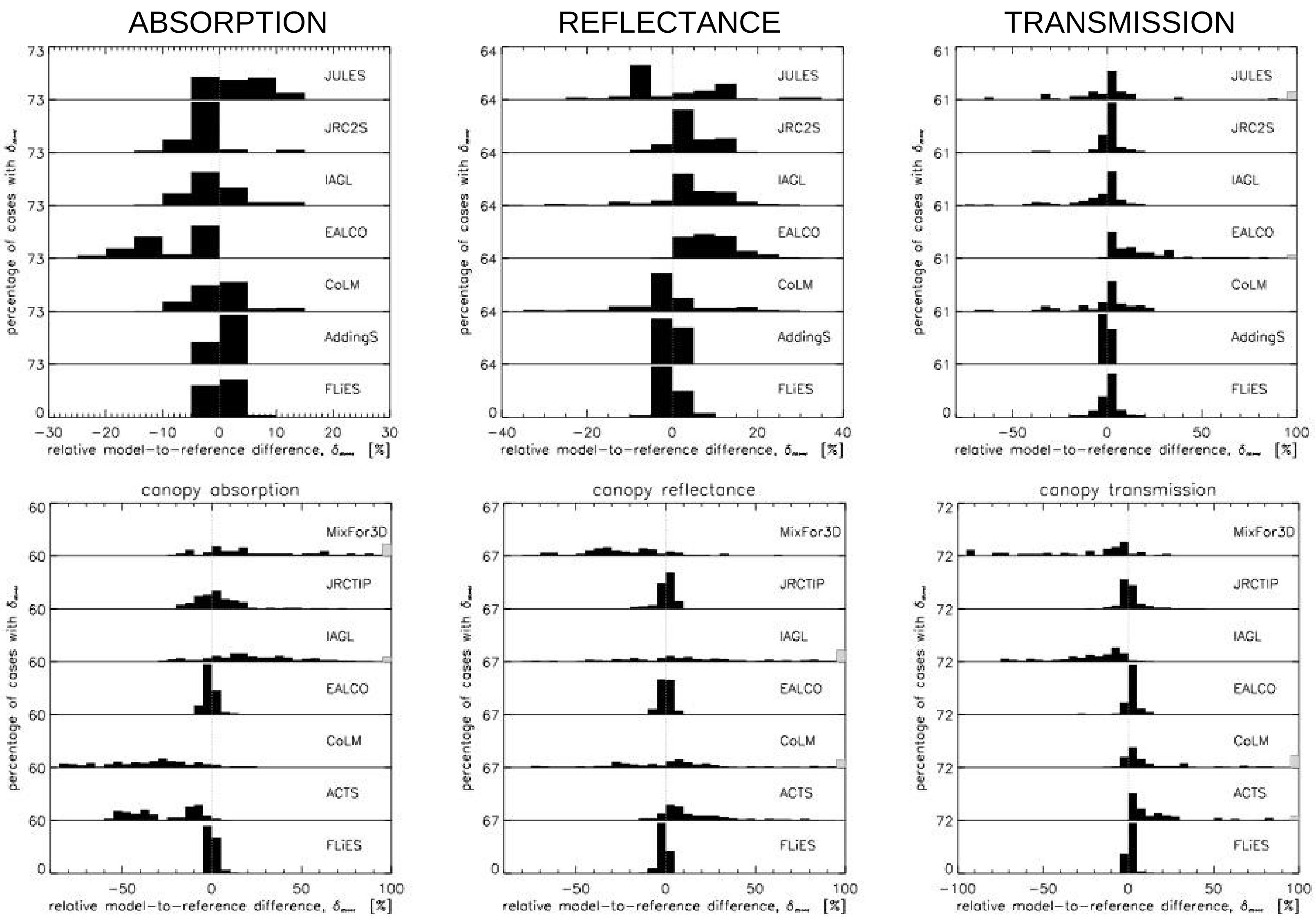


Figure 6. Histogram of relative model-to-reference deviations, $\delta_{m\leftrightarrow r}$ (in percent) for simulation of (left) canopy absorption, (middle) canopy reflectance, and (right) canopy transmission within (top) 1-D and (bottom) 3-D plant environments. The zero deviation line is indicated by a gray vertical line, and all deviations larger than $\delta_{m\leftrightarrow r}$ = 100% are grouped into a single gray-colored bin.

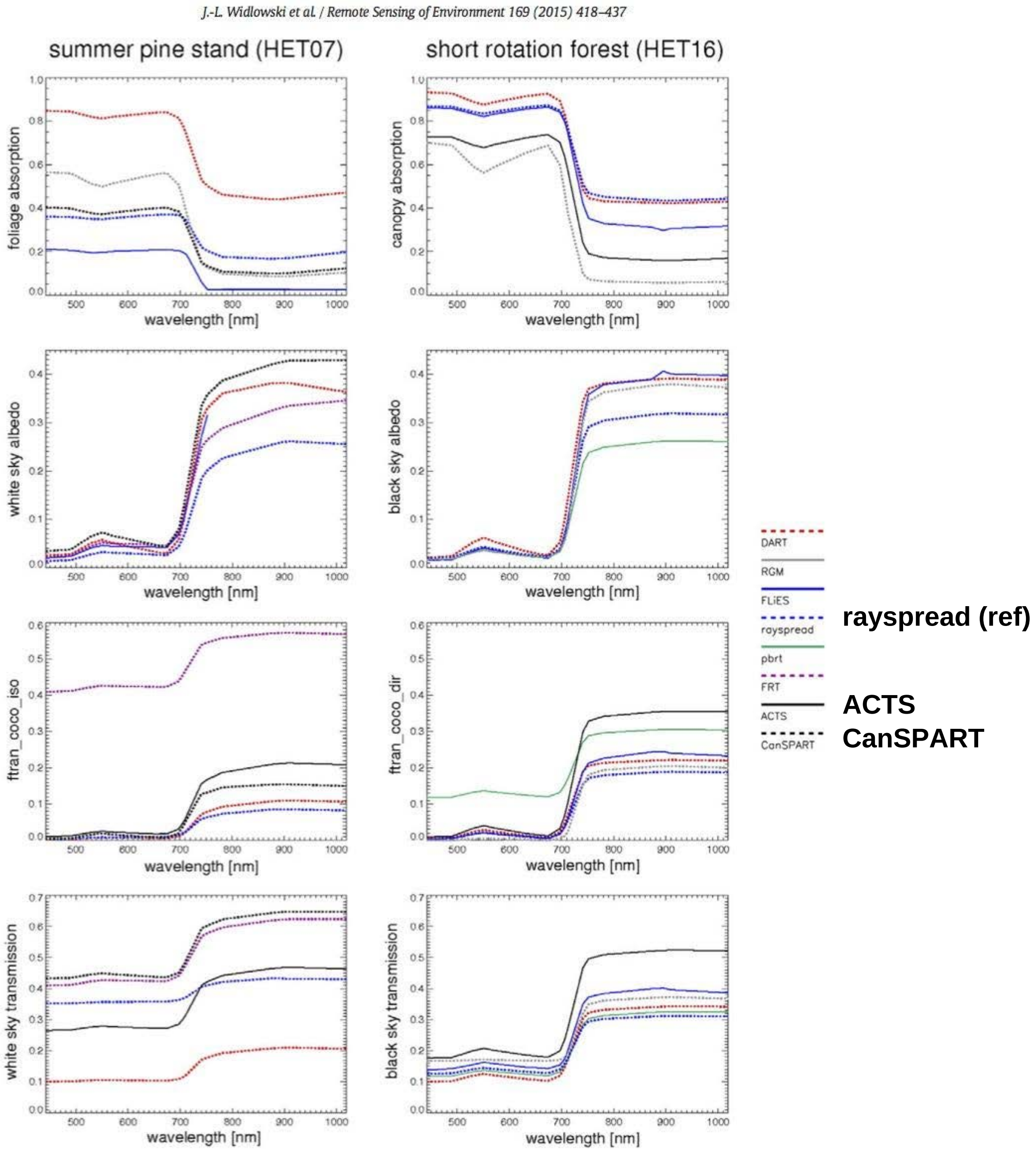
MODEL	GCM/ DGVM	Type
JULES	HadCM	SiB
JR2CS	?	inverse 2-stream
IAGL	?	2-stream
CoLM	CSM/SiB	mosaic 2-stream
AddingS	-	SAIL+ layers
FLiES	-	voxels

MixFor3D	HadCM3	
JRCTIP	?	2-stream
IAGL	?	
EALCO	-	ray-trace
CoLM	CSM/SiB	
ACTS	GISS/Ent	GO 2-stream
FLiES	-	voxels

RAMI-4PILPS

Widlowski et al. (2015)

“actual” canopy scenarios



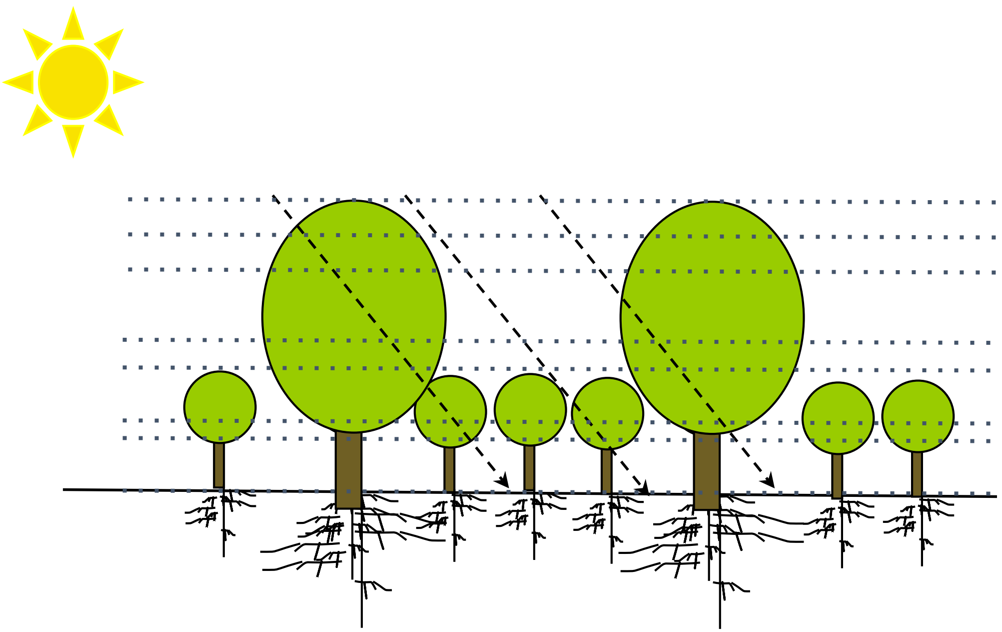
Effective scattering parameters clumping:

Poisson
=
CanSPART
>
Actual canopy clumping?
>
ACTS
>
Uniform

<u>Reference model:</u>
raytran
(Monte Carlo ray-tracing)

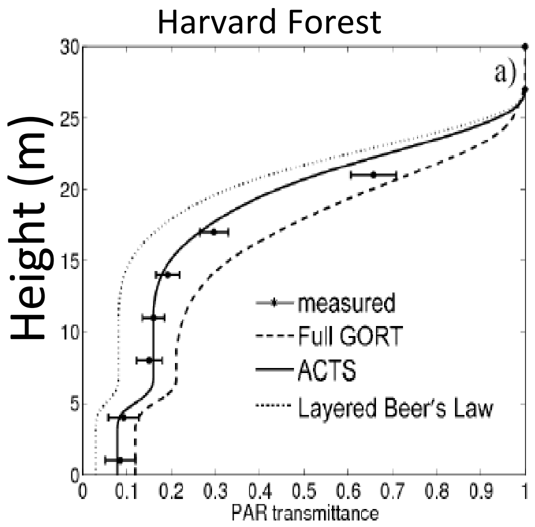
Gap-probability based canopy radiative transfer for demographic DGVMs

Ent: Analytical Clumped Two-Stream (ACTS) (Ni-Meister et al., 2010; Yang et al. 2010)



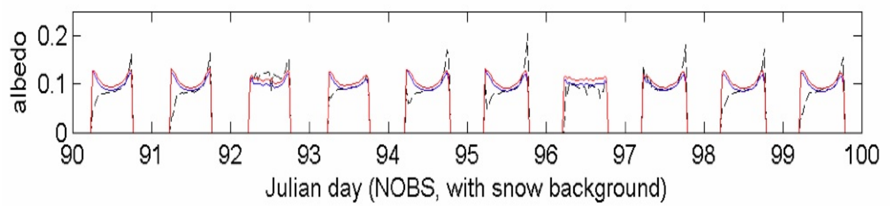
- Cohorts of identical individuals
- Non-intersecting crowns

PAR transmittance

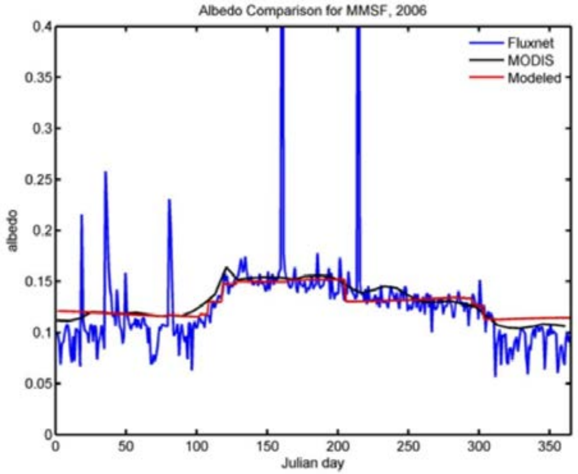


ALBEDO-diurnal

BOREAS diurnal
measured
GORT model
ACTS model



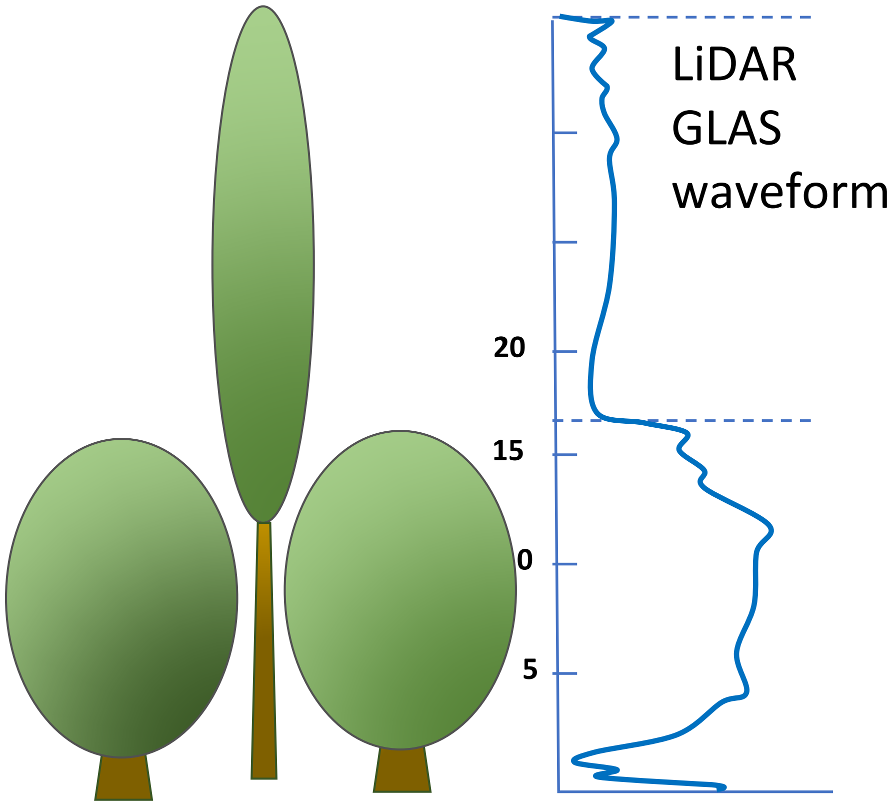
ALBEDO-seasonal



Gap-probability based canopy radiative transfer for demographic DGVMs

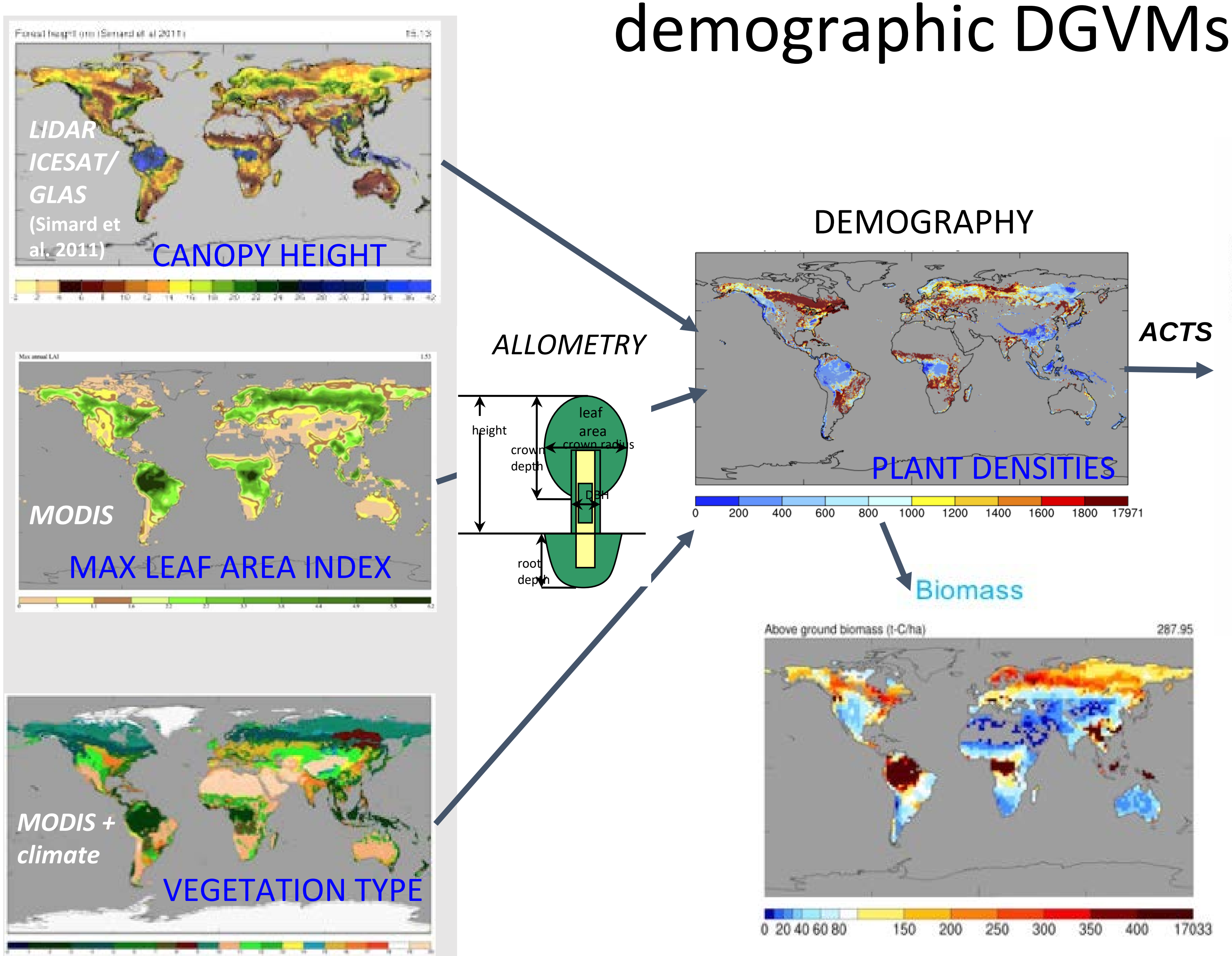
Current challenges:

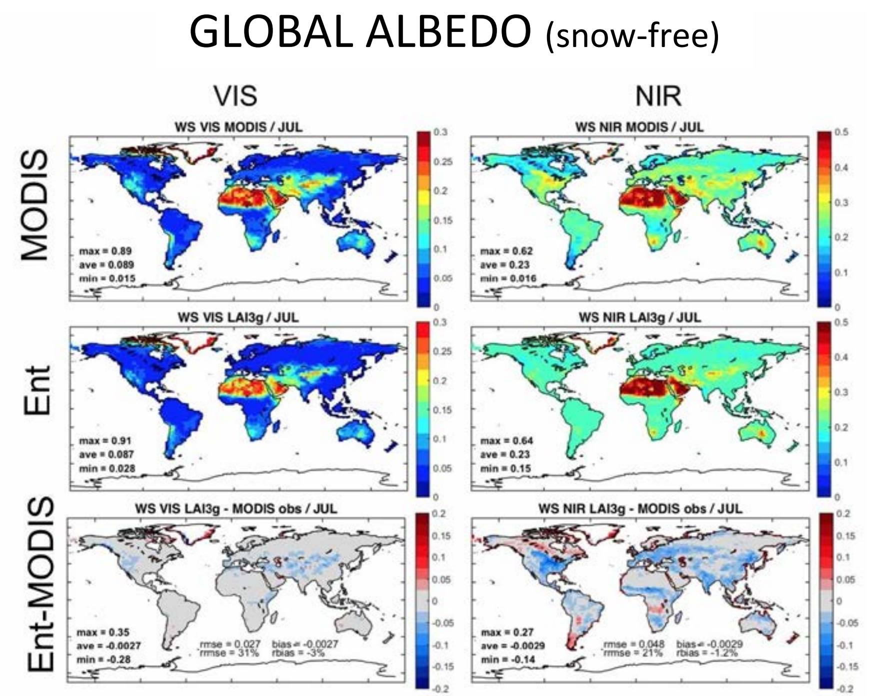
- Cohort structure:
  - Vertical: variable height instead of identical?
  - Horizontal: early->mature : random->uniform
  - Allometry, geometry: ellipticity by age, light status?
  - Branch effect: data
- Optical properties of end members:
  - Data
  - Seasonal variation - prognostic modeling
- RT theory:
  - Vertically heterogeneous optical properties (e.g. tree above grass)
- Spatial scale:
  - Ecology (carbon) vs. Remote Sensing (light)



LiDAR
GLAS
waveform
20
15
0
5

Gap-probability based canopy radiative transfer for demographic DGVMs



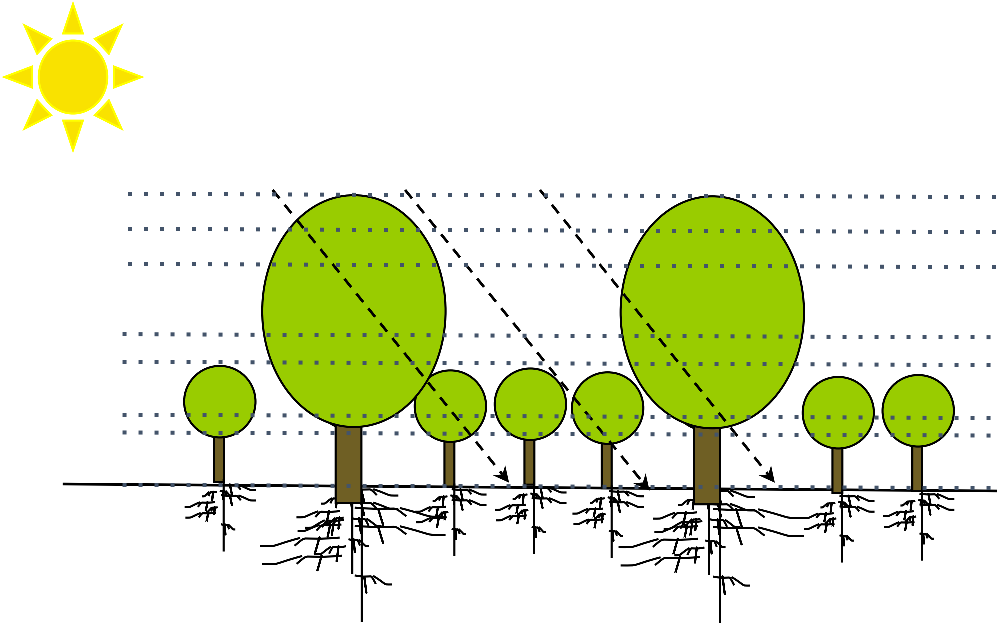


Ent TBM Global Vegetation Structure Data Set (Ent GVSD)

Single-cohort from RH100 ± std. dev.

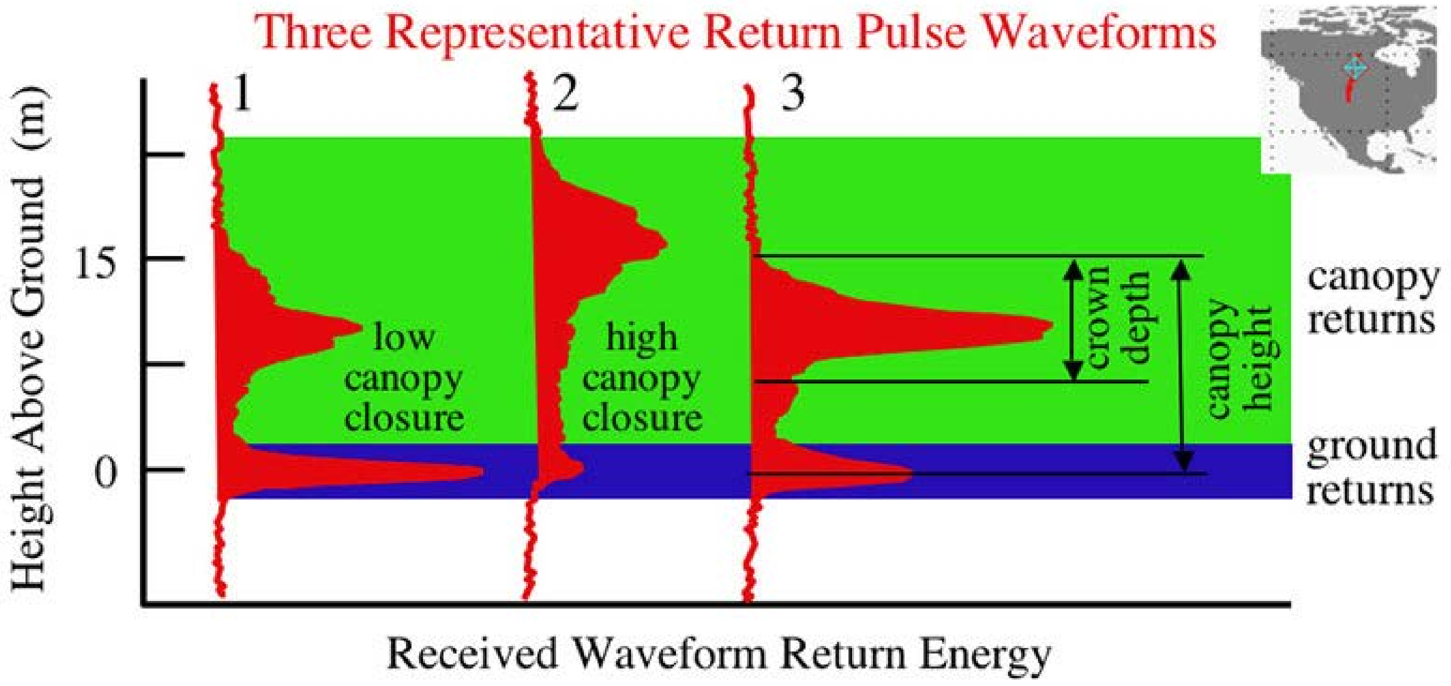
Gap-probability based canopy radiative transfer for demographic DGVMs

Ent: Analytical Clumped Two-Stream (ACTS) (Ni-Meister et al., 2010; Yang et al. 2010)



- Cohorts of identical individuals
- Non-intersecting crowns

LiDAR
Vegetation Height + Foliage Density Profiles



Credit: NASA / ICESat-GLAS

Scaling up Ecology & LiDAR waveforms

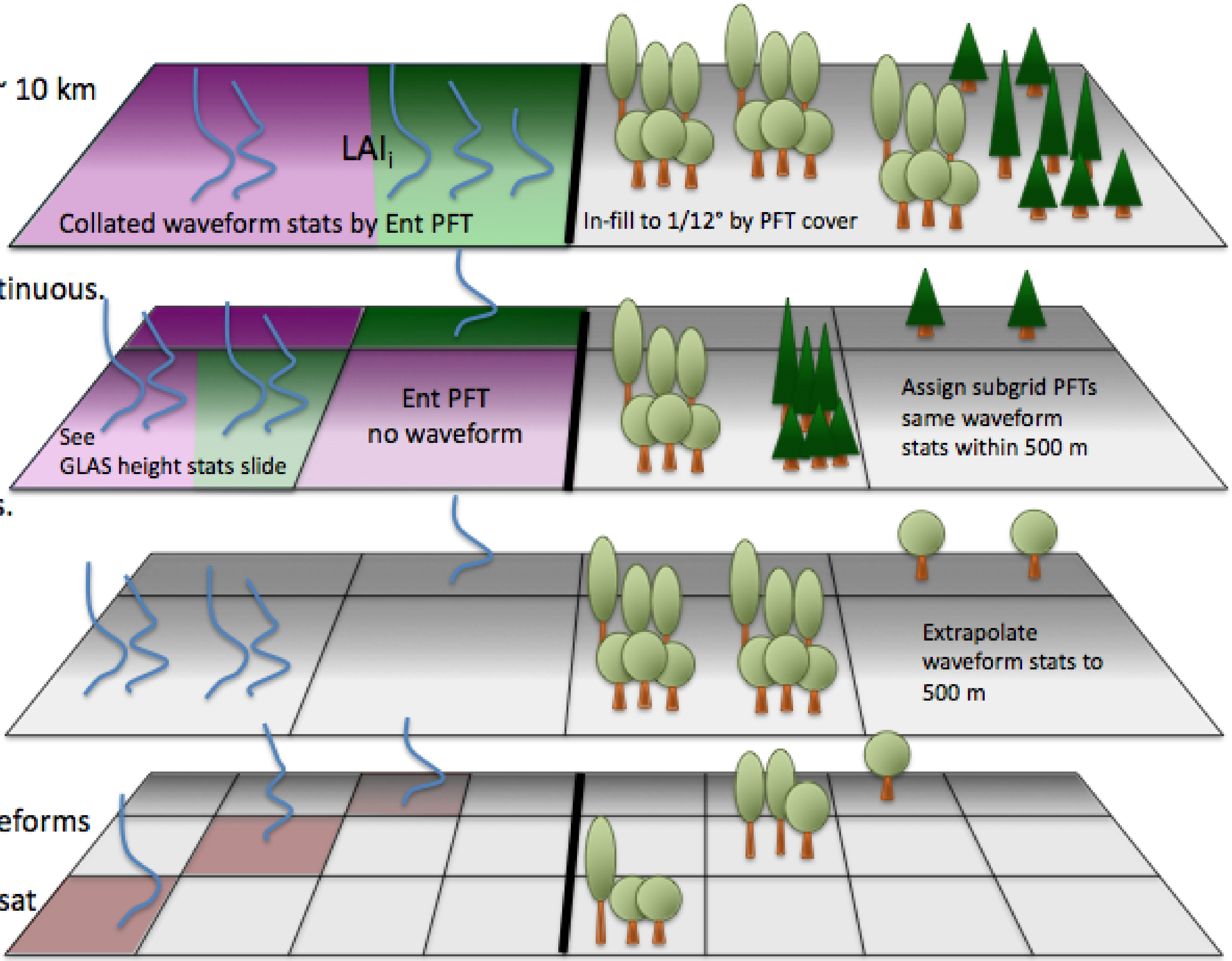
0.5 degree
GCM grid
Subgrid
patches

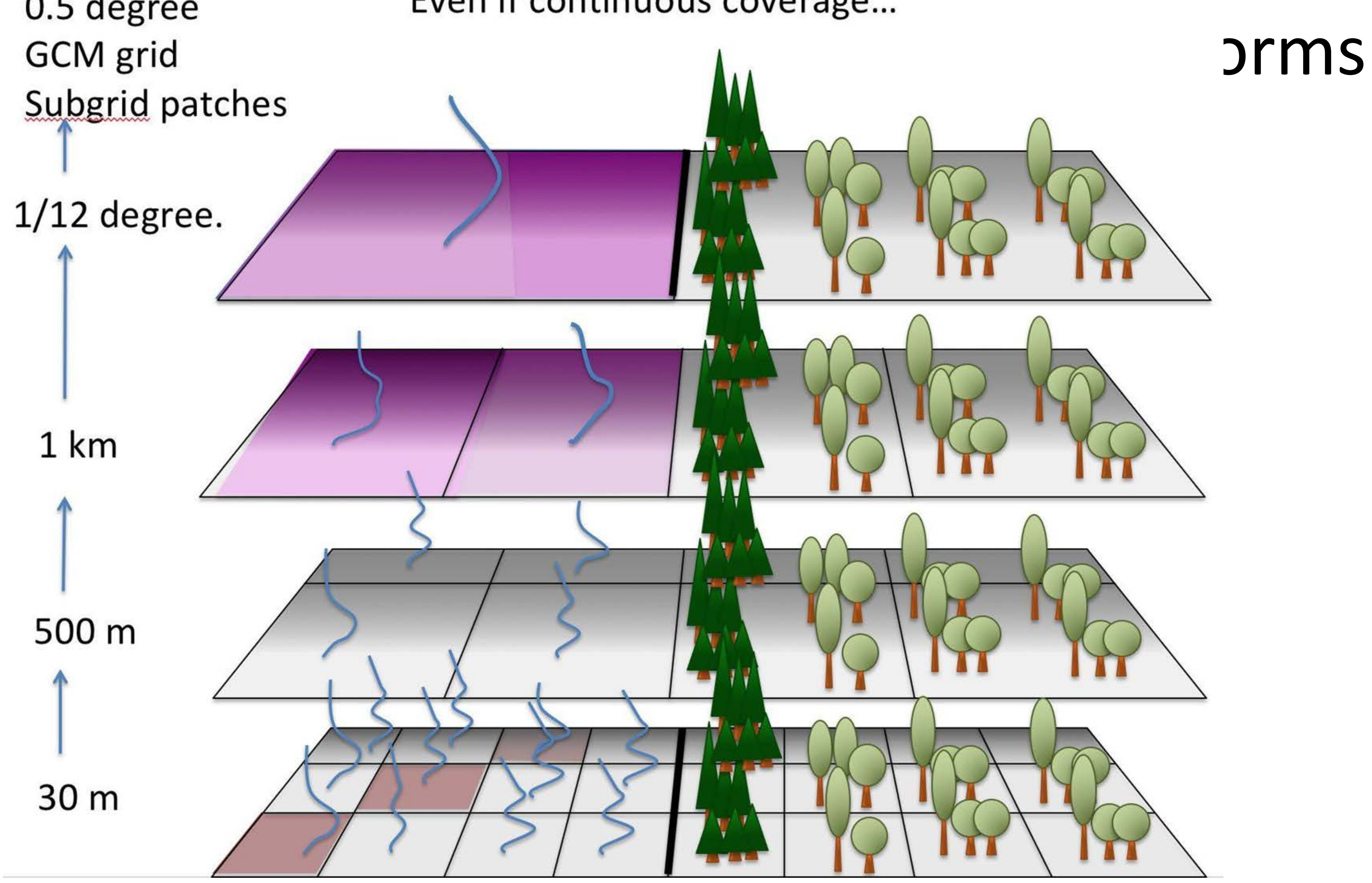
1/12 degree = 5′ ~ 10 km
In-fill heights by
Ent PFT cover
Assign max LAI3g
Partition LAI max
by Landsat. Continuous.

500 m subgrid
Ent 17 PFTs
assigned
Waveforms. Gaps.

Extrapolate
height stats to
500 m. Gaps.

30 m
Gappy GLAS waveforms
and Gaussians
Continuous Landsat
max LAI





0.5 degree
GCM grid
Subgrid patches
1/12 degree.
1 km
500 m
30 m
Even if continuous coverage…
ɔrms

Vertical foliage profiles (VFP) from LiDAR
(Tang et al. 2014, Remote Sensing of Environment, 154:8-18)

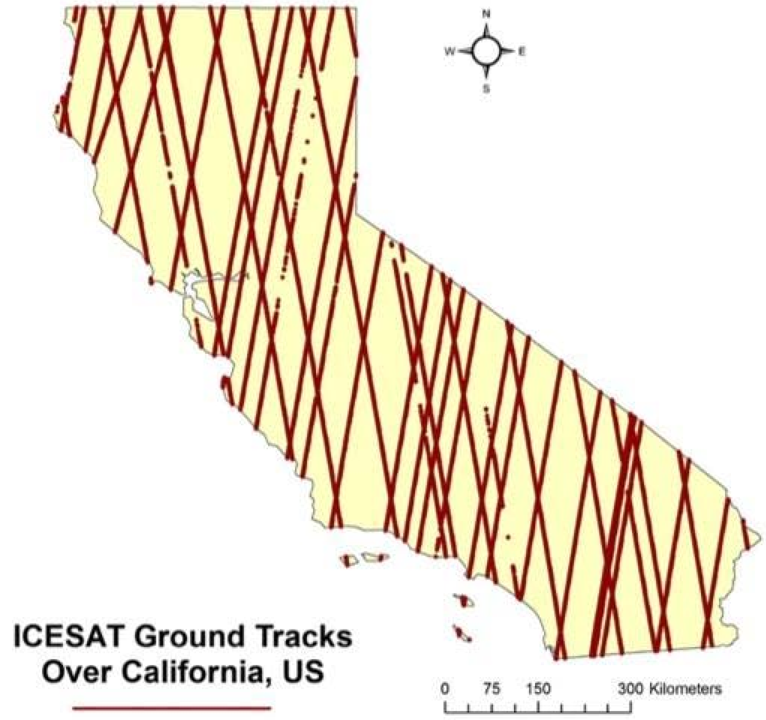


Fig. 1. Location of ICESat ground tracks over California, USA. ICESat did not provide a wall-to-wall coverage but rather data along transects separated by relatively long distances across track at mid-latitudes.

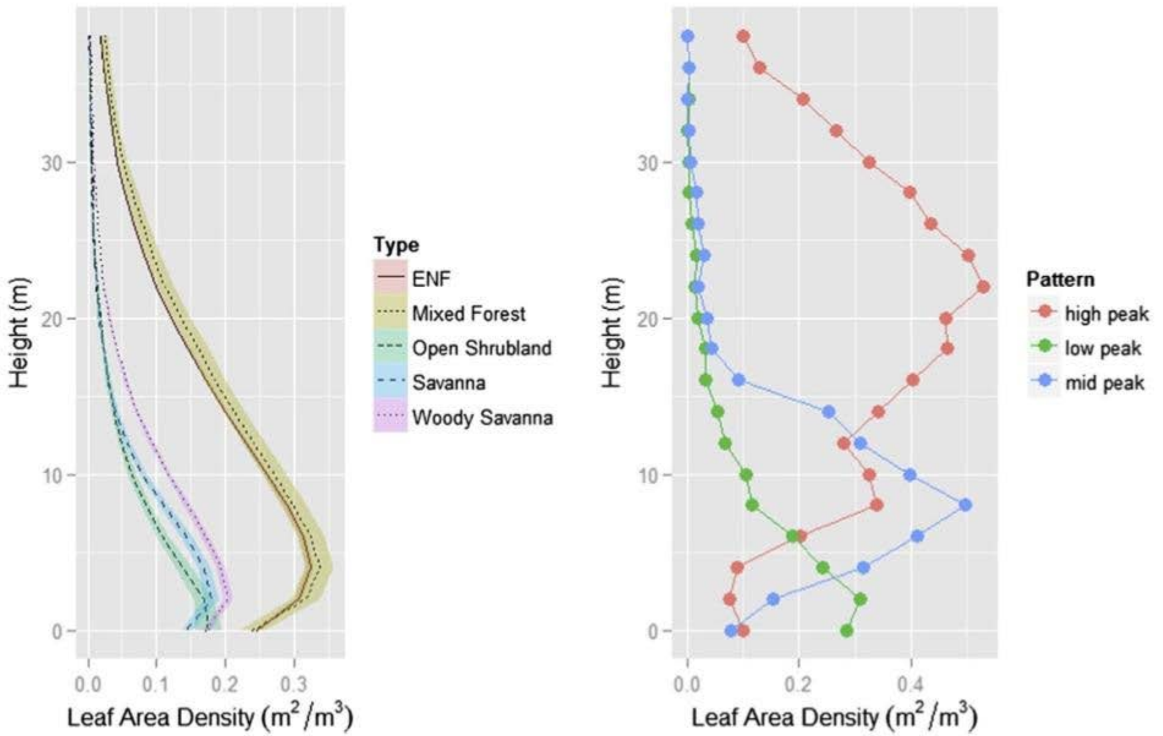
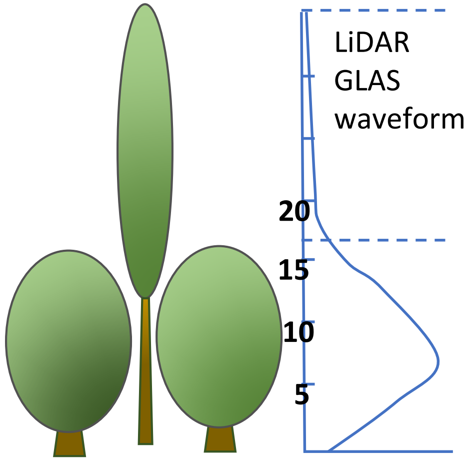


Fig. 6. Left: VFP (vertical resolution of 2 m) averaged for all GLAS shots over California for different land cover types. Each profile represents a single land cover type. Mean values are central lines within the color-filled 95% CI envelope. Note that the low height of peak LAD is because of the averaging process over the land cover type. Individual profiles have much more variable shapes (see right). Right: individual VFP examples with foliage density peak occurring at understory (<5 m), middle-story (~10 m) and up-story (>20 m).

Conclusions



- Accurate vegetation structure boundary conditions

  → Accurate fluxes

  → Better community light competition

- Rethink cohort description in demographic DGVMs
- Global data sets of vegetation community structure possible with LiDAR data -- HOW-TO translate VFP to cohorts bins:
    - Vertical partitioning
    - Horizontal spatial scale
- Data needs: seasonal variation in leaf albedo ~ C, N
- Theory needs:
    - Two-stream RT with systematic heterogeneity in leaf spectra
    - Allometry ~ climate ~ PFT

Acknowledgments

Ent Terrestrial Biosphere Model:

A demographic Dynamic Global Vegetation model

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Software infrastructure, land hydrology, carbon coupling & tracers

Carlo Montes -- formerly NASA Postdoctoral Program

Ensheng Weng – Columbia University
Carbon allocation, ecological dynamics

COLLABORATORS:

Wenge Ni-Meister – CUNY Hunter College
Wenze Yang – Univ. of Maryland
canopy radiative transfer

Yeonjoo Kim – Yonsei University, Seoul
Phenology

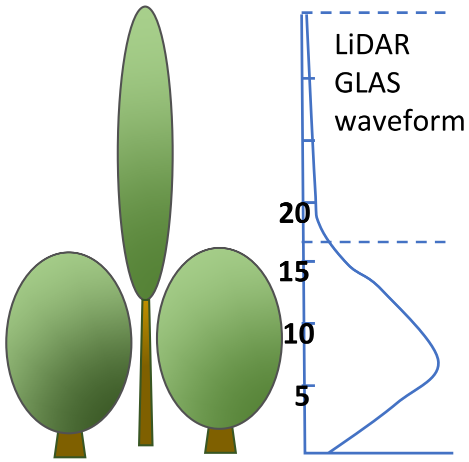
Crystal Schaaf – Univ. of Massachusetts-Boston
Satellite global vegetation structure data sets

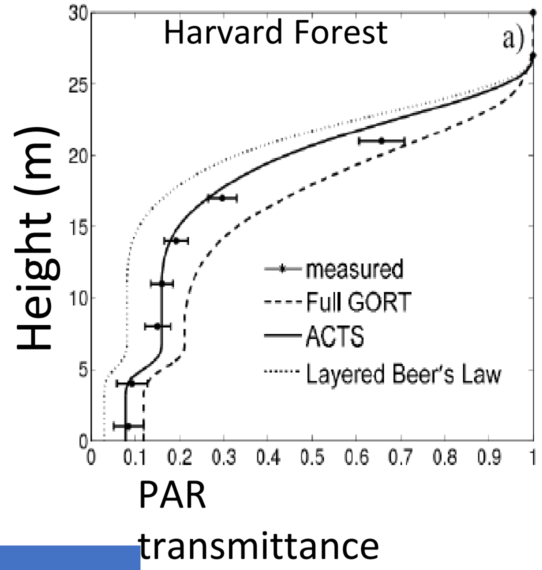
Support: David Considine - NASA Modeling, Analysis, and Prediction (MAP) Program

Ent Canopy Radiative Transfer: Analytical Clumped Two-Stream (ACTS)

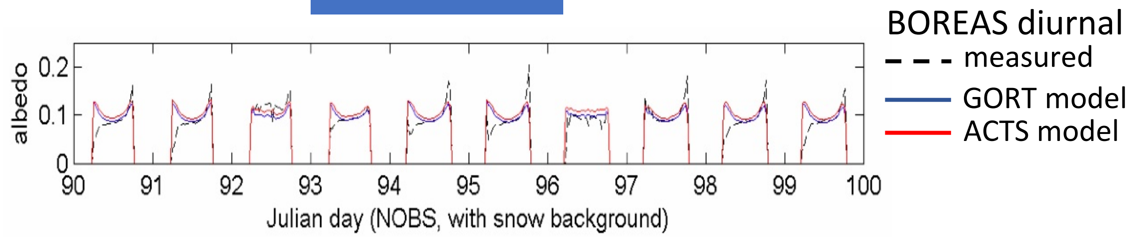
(Ni-Meister et al., 2010; Yang et al. 2010)

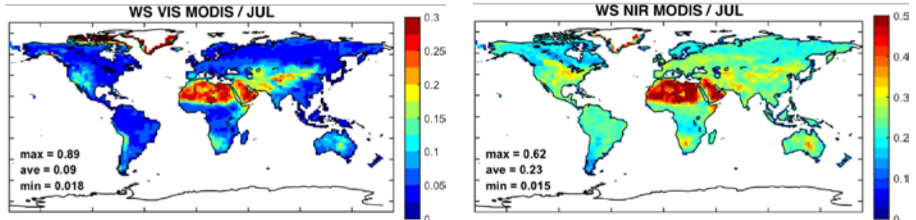
LiDAR Vegetation Structure



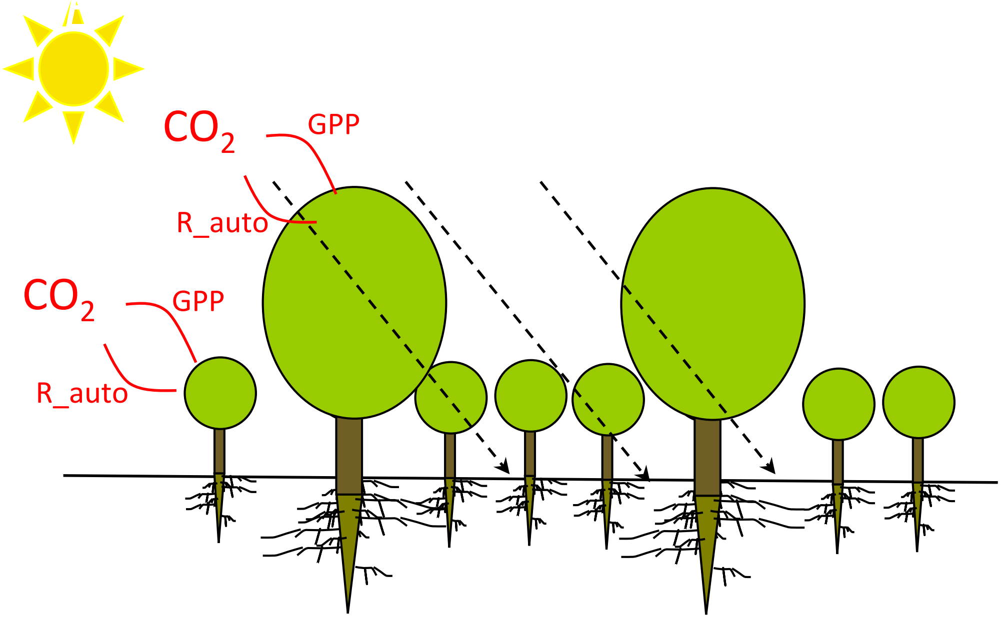


ALBEDO





PHOTOSYNTHESIS/CONDUCTANC



COHORT-COMMUNITY COMPETITION/ECOLOGICAL DYNAMICS

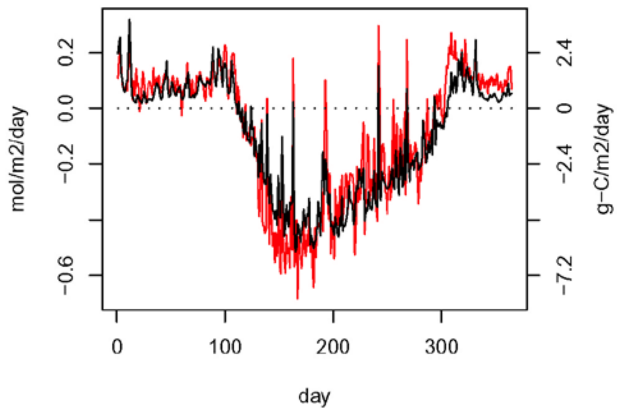
Ent Biophysics: All models can simulate NEE

(GIVEN correct LAI and biophysics tuning)

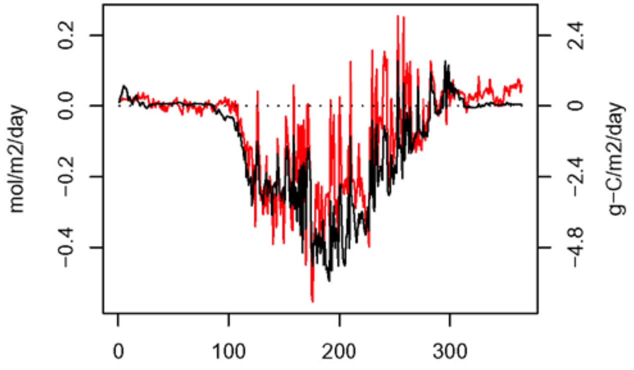
measured

Ent model

Broadleaf deciduous temperate
Morgan-Monroe State Forest, IN

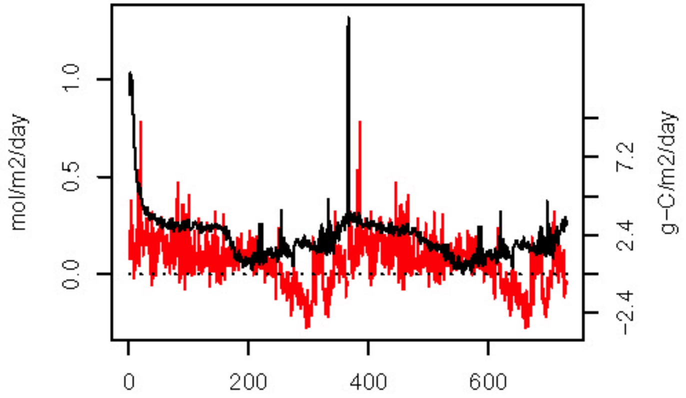


Needleleaf evergreen boreal
Hyytiala, Finland



Annual grassland
Vaira Ranch, CA

Broadleaf evergreen tropical
Tapajo, Brazil



Except in the tropics…

To do:
Photosynthesis and respiration parameter sets for global diversity