Geogg124
Terrestrial Ecosystem Modelling

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Aims of lecture

In this lecture, we will consider:

1. Land surface schemes
2. Global vegetation modelling
3. Production efficiency models
4. Phenology
5. Modelling Photosynthesis

1. Land surface schemes

- LS schemes, implemented as LS models
- LS component of climate / earth system models
- Purpose:
  - Model energy and (carbon, water) fluxes at land-atmosphere interface

Main driver: energy

$$Rn = S\downarrow(1-\alpha) + L\downarrow - L\uparrow$$

- Rn = net radiation; $S\downarrow$ = downwelling s/wave; α = albedo; $L\downarrow$, $L\uparrow$ down/upwelling longwave
- terms balance globally over the long term
  - But short term /spatial variations drive earth system

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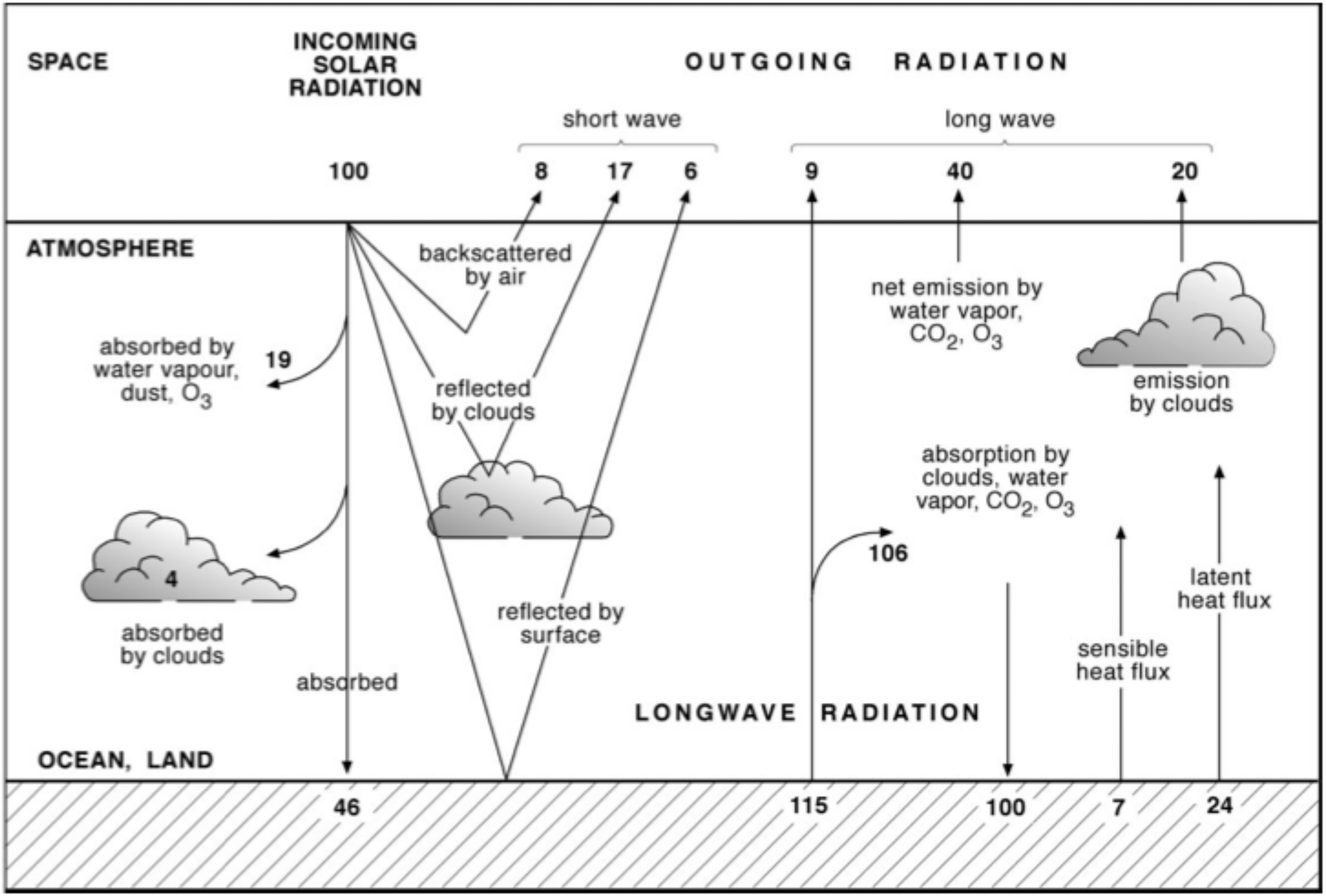

Figure 1. Schematic diagram of the annual mean global energy balance. Units are percentage of incoming solar radiation. The solar (shortwave) fluxes are shown on the left-hand side and the terrestrial (longwave) fluxes are on the right-hand side (redrawn from Rosen, 1999)

Balance by heat & chemical fluxes

$Rn=H+\lambda E+G+F$

H = sensible heat flux; λE = latent heat flux; G = soil flux; F = chemical energy flux stored in photosynthesis

Latent heat – heat absorbed/released by change of state at constant T (eg liquid to vapour)

Sensible heat – causes solely change in T

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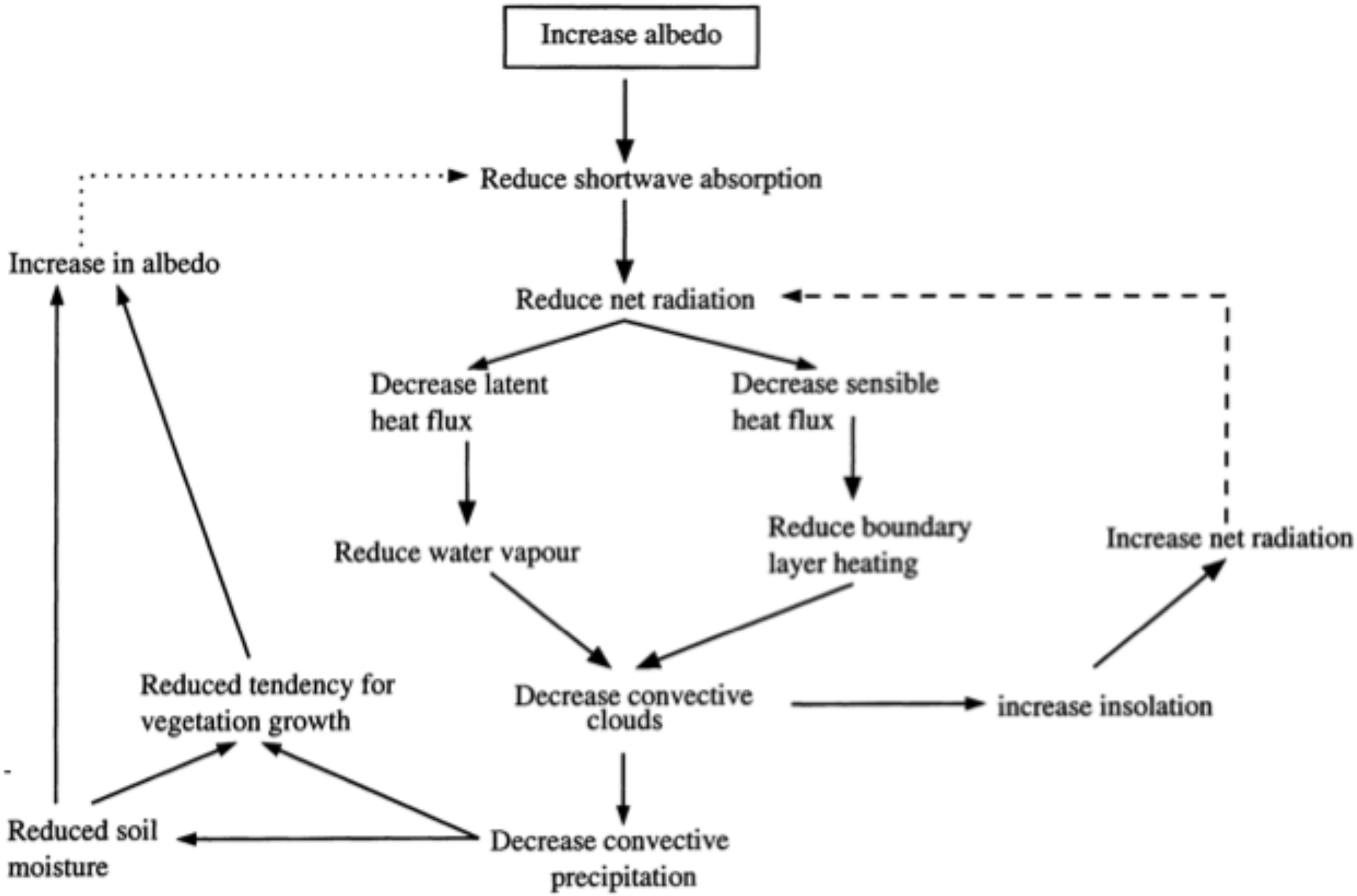

Figure 2. Conceptual diagram of the impact an increase in albedo has on the land surface and some elements of the boundary-layer climate. The dotted line represents a positive feedback and the dashed lines represent a negative feedback

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Changing albedo

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Partitioning latent & sensible heat

- Partitioning important as controls flux of water vapour to the atmosphere
  - Influence on cloudiness, rain
- *H* and *λE* are turbulent heat fluxes

$$H = \frac{T_s - T_r}{r_a} \rho c_p \qquad \lambda E = \left(\frac{e^*(T_s) - e_r}{r_s + r_a} \right) \frac{\rho c_p}{\gamma}$$

- T_s = surface T; T_r = ref. temp. above surface; r_a = aerodynamic resistance; ρ = density of air; c.r = specific heat of air. $e^*(Ts)$ is saturated vapour pressure at Ts; e_r = vapour pressure at ref height; v = psychometric constant; r_s = bulk surface resistance to transfer of water to air.

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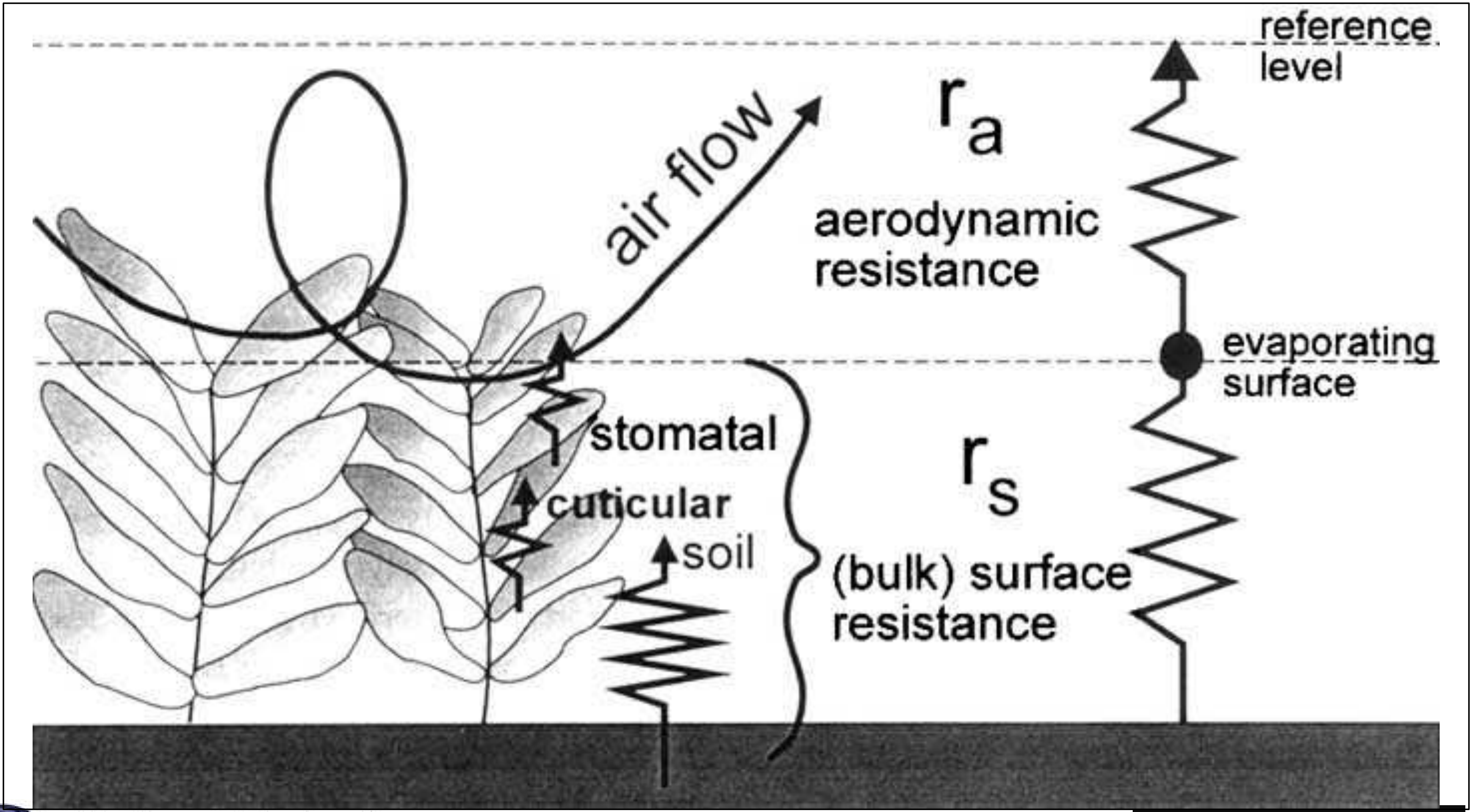
surface and aerodynamic resistances for water vapour flow



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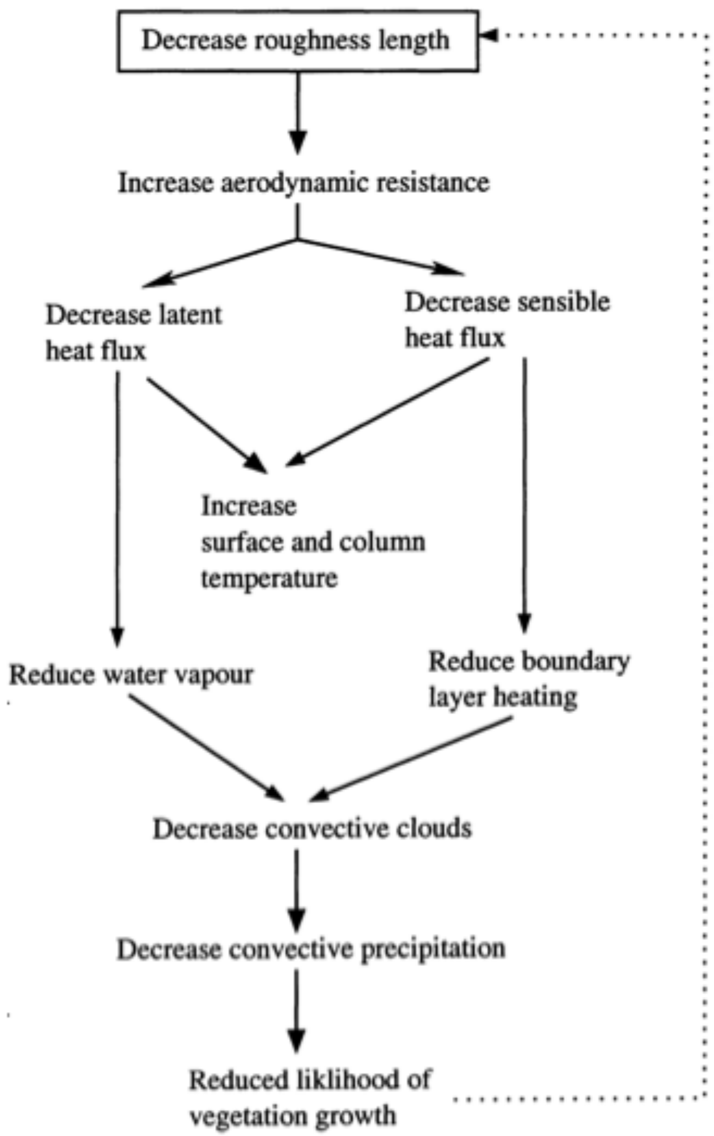

Figure 5. As Figure 2, but for the aerodynamic roughness length

Roughness length depends on vegetation height

Removal of vegetation can have feedback effect

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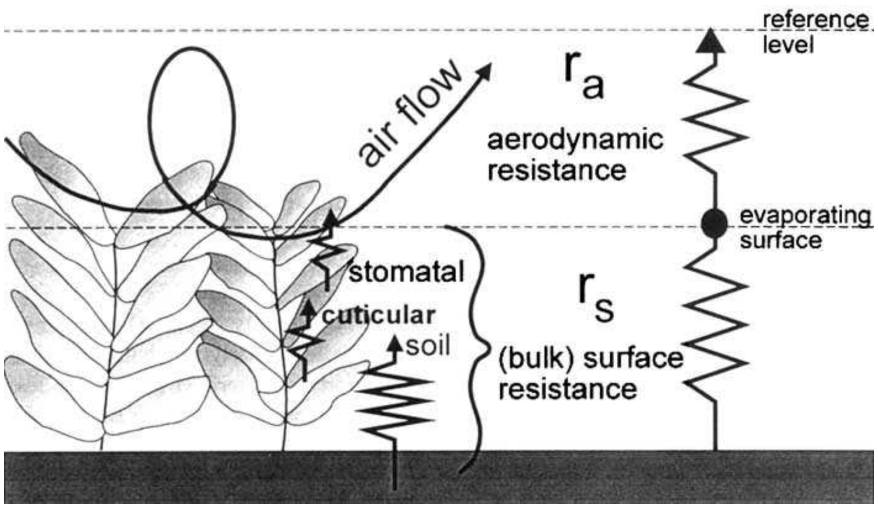
Other fluxes

Turbulence also affects other fluxes e.g. CO2

$$F = \frac{c_i - c_a}{r_{st} + r_a}$$



So we can relate internal and ambient CO2 to stomatal and aerodynamic resistance

Approx.

$$r_s = \frac{r_{st}}{LAI_{active}}$$

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Water balance

$$P = E - Rdrain - Rsurf - \Delta S$$

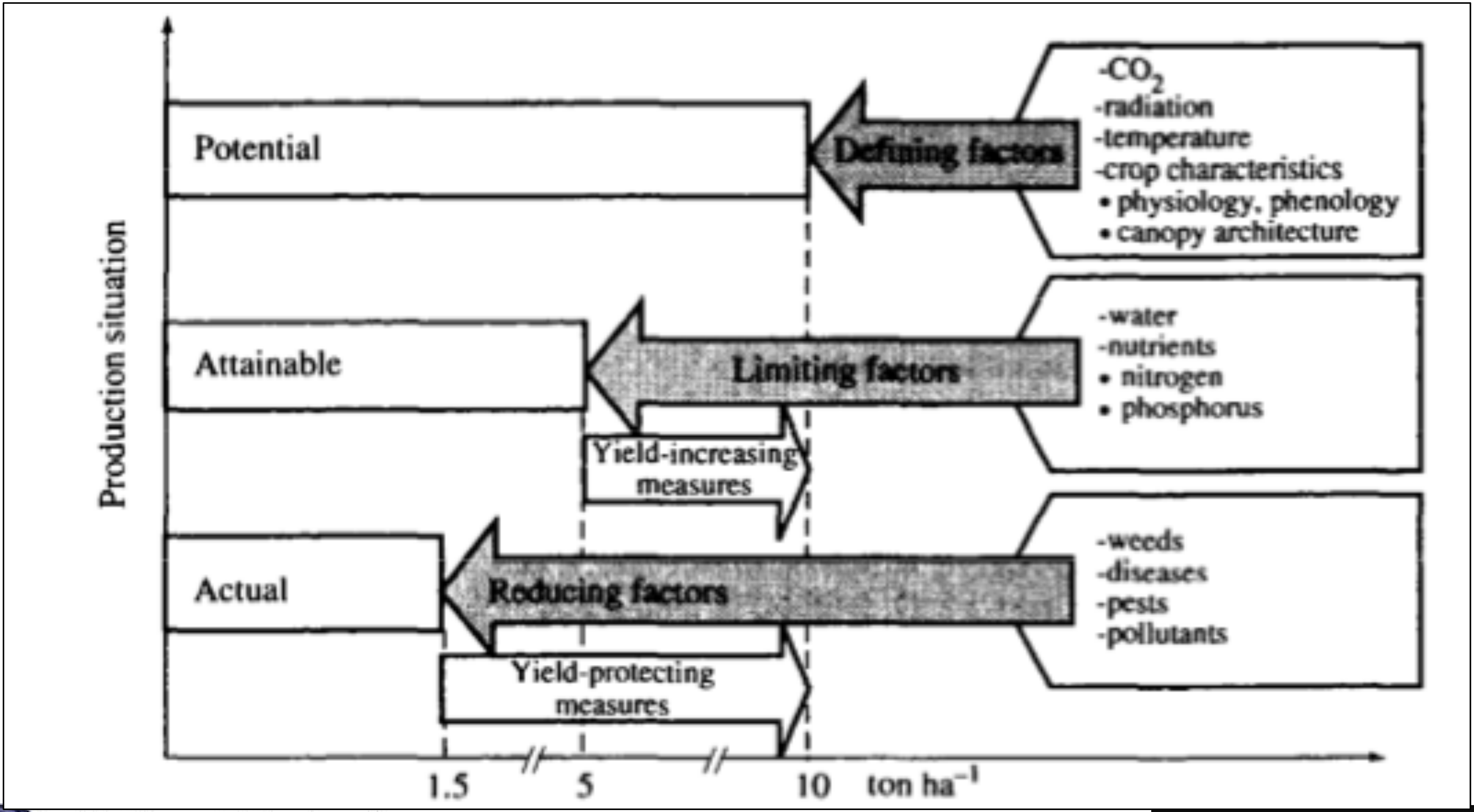
So we can relate evapotranspiration to runoff, change in soil water storage and water inputs (precip., snowmelt)

P = water input; E = evapotransp.; Rdrain = slow drainage; Rsurf = surface runoff; ΔS = change in soil moisture storage

Land Surface Model

- Models energy and water fluxes (++) at the land surface
- provides an interface of these to atmospheric modelling.
- Usually, this will be done for a set of grid cells, where inputs and outputs of each cell are considered separately
- Lateral transport of water (e.g. snow, river)

Basic vegetation growth



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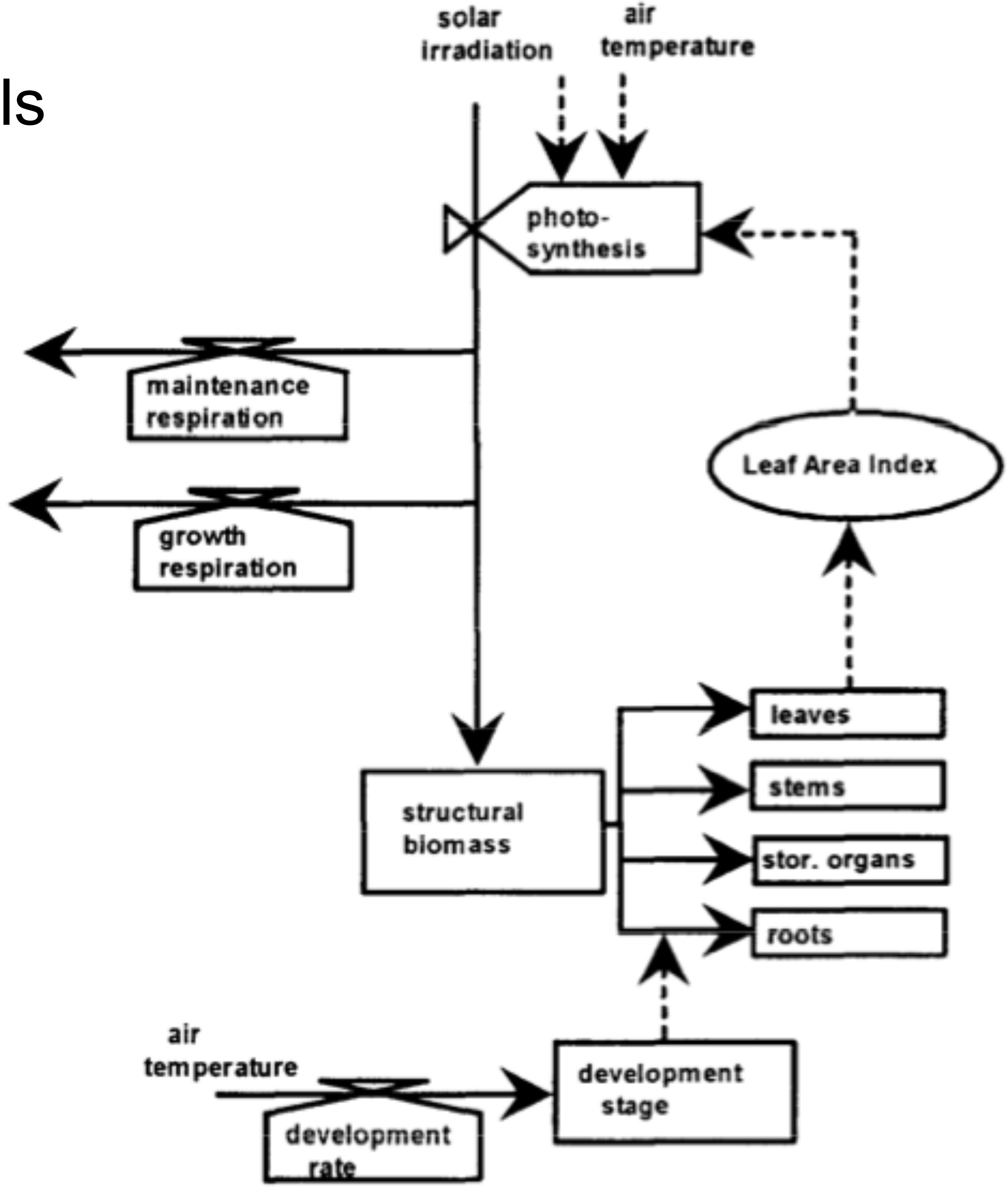
Structure of most models similar



Some land surface schemes: Third generation LSMs

- 1990s+
- Advance LSM by connecting leaf stomatal conductance and carbon assimilation
  - Farquhar et al. (1980) and Farquhar and von Caemmerer (1982)
  - Can dynamically model vegetation
  - Examine climate feedbacks

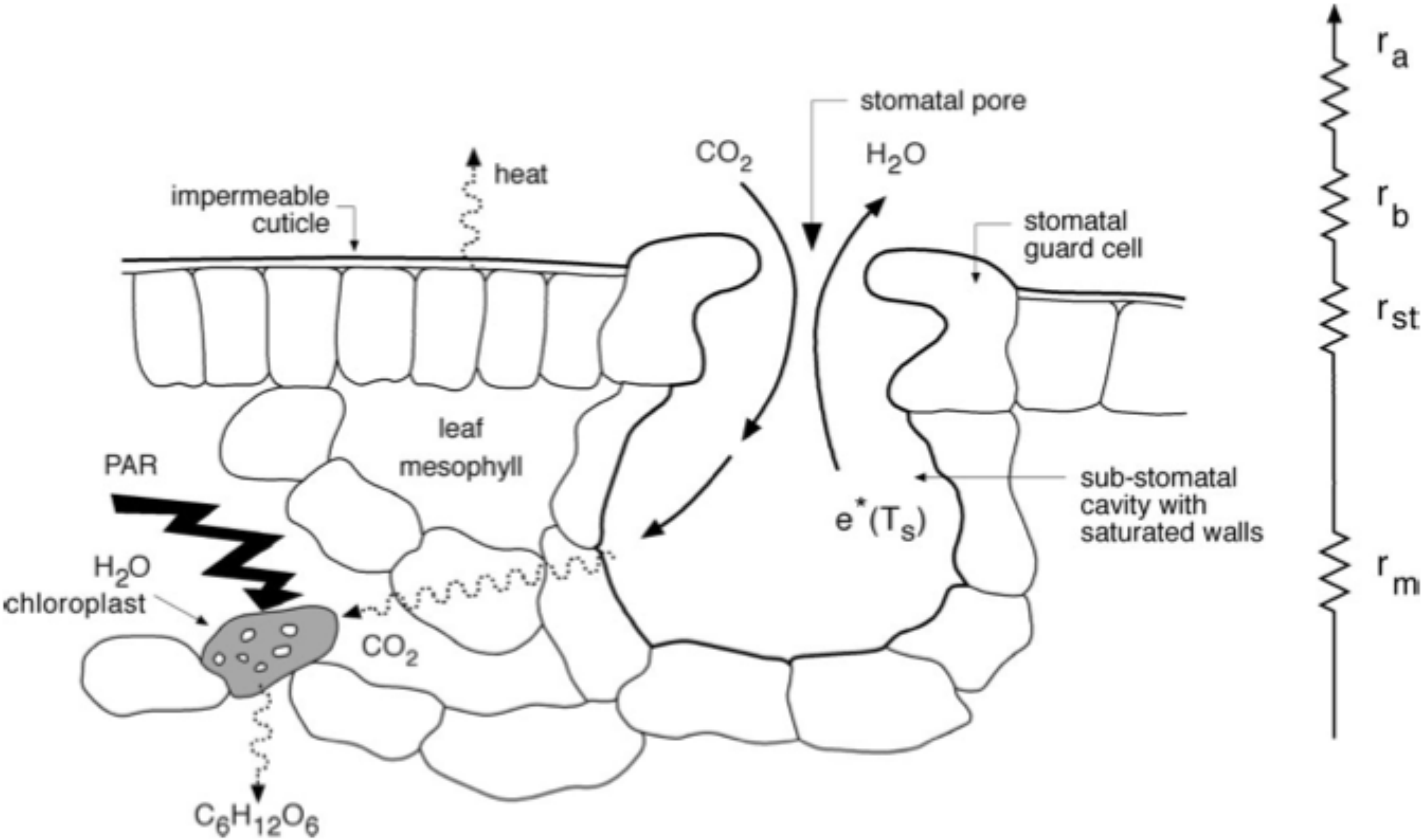


Figure 10. Schematic of a cross-section of a leaf. The resistance not defined in the text is the mesophyll resistance (r_m)

1. Land surface schemes

Summary

- outlined the main processes in land surface schemes and models and highlighted the interplay of radiation and water.
- introduced some core concepts in vegetation processes
  - vegetation growth can be modelled as a potential amount of carbon assimilation that is then limited by factors such as water and nutrient availability as well as being reduced by pests, disease etc.
- Looked at some features of 3rd generation LSMs
  - Include carbon

2. Global vegetation modelling

- Focus on linking measurements from Earth Observation and other sources with models of terrestrial carbon at regional and global scales.
- motivation for models
  - to express current understanding of the controls on carbon dynamics as embedded in Earth System / Terrestrial Ecosystem models.
- The role of observations is to test and constrain these models to enable:
  - (i) monitoring of terrestrial carbon dynamics;
  - (ii) improved prognostic models.
- The main focus of the modelling and monitoring is on Net Primary Productivity (NPP).

Types of models

- TEMs
  - Static vegetation representation
- DGVMs
  - Dynamic vegetation
- PEMs
  - Simplifications for ‘data driven’ model

Dynamic Global Vegetation Models

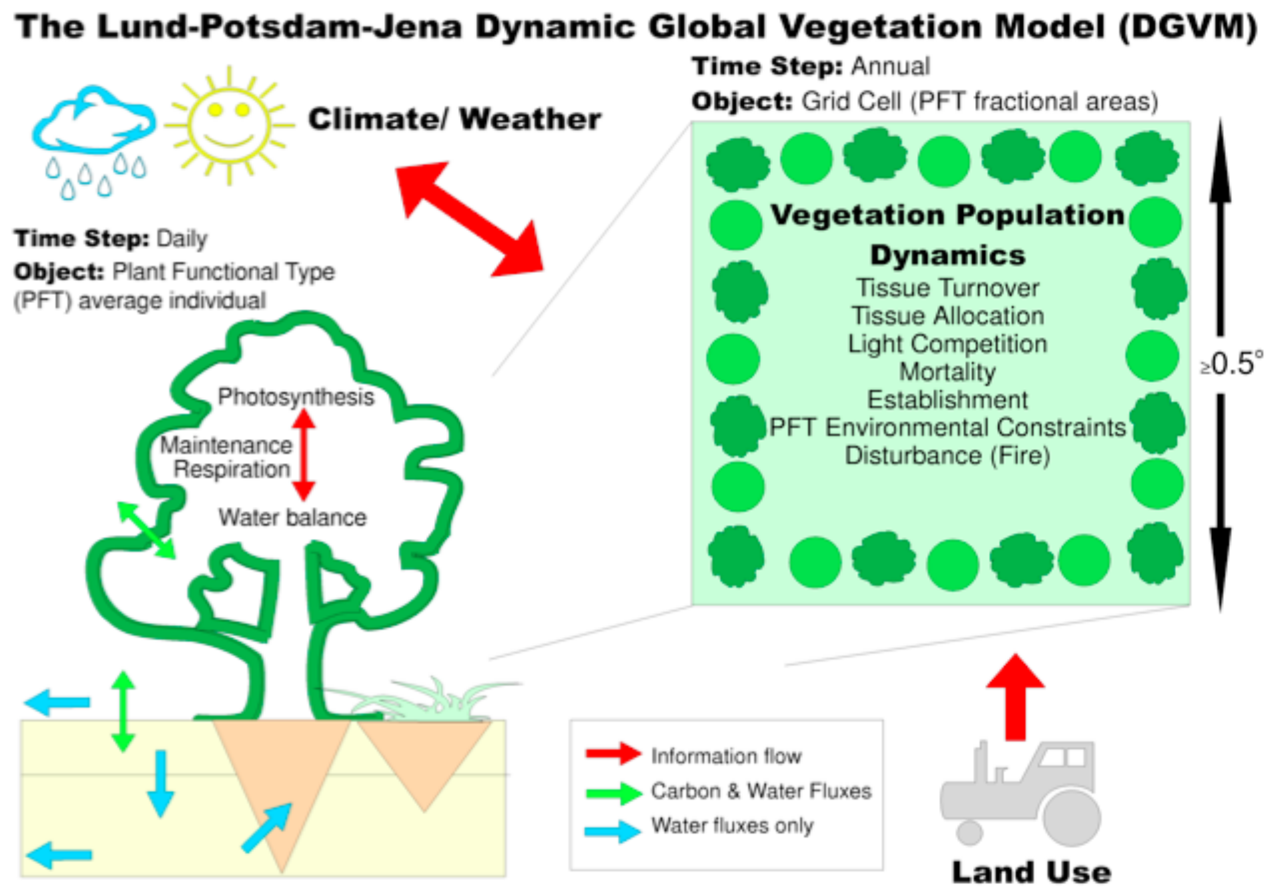


Fig. 1: Scaling from the average individual plant to a grid cell in the LPJ-DGVM

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DGVMs

- Main components:
  - establishment,
  - productivity and competition for resources,
  - resource allocation,
  - growth,
  - disturbance and mortality

DGVMs

- Key features:
  - allows for prognostic and paleo use
  - geared towards modelling *potential* vegetation
    - anthropogenic influences e.g. changes in land use incorporated by forcing these effects
      - e.g. prescribing land cover/PFT

Table 1 Characteristics of the Dynamic Global Vegetation Models (DGVMs)

	HyLand (HYL)	Lund–Potsdam–Jena (LPJ)	ORCHIDEE (ORC)	Sheffield-DGVM (SHE)	TRIFFID (TRI)
Shortest time step	1 day	1 day	0.5 h	1 day	1/2 h
Physiology					
Photosynthesis	Farquhar *et al.* (1980)	Farquhar *et al.* (1980)/ Collatz *et al.* (1992)	Farquhar *et al.* (1980)/ Collatz *et al.* (1992)	Farquhar *et al.* (1980)/ Collatz *et al.* (1992)	Collatz *et al.* (1991)/ Collatz *et al.* (1992)
Stomatal conductance	Jarvis (1976)/Stewart (1988)	Haxeltine & Prentice (1996)	Ball *et al.* (1987)	Leuning (1995)	Cox *et al.* (1998)
Canopy scaling	Optimum N_{leaf} distribution	Optimum N_{leaf} distribution	Optimum N_{leaf} distribution	Optimum N_{leaf} distribution	Optimum N_{leaf} distribution. Sellers *et al.* (1992)
Sapwood respiration	f(Assimilation) Gifford (1995)	Dependent on sapwood mass and C : N ratio (Lloyd & Taylor, 1994)	Dependent on temperature, sapwood mass and C : N ratio	Annual sapwood increment, C : N f(T)	Pipe model to diagnose sapwood volume, then Q_{10} relationship
Fine root respiration	f(Assimilation)	$f(T,C_{root})$	$f(T,C_{root})$	$f(T,C_{root})$	$f(T,N_{root})$
Evapotranspiration	Penman–Monteith transpiration (Monteith & Unsworth, 1990)	Total evapotranspiration (Monteith, 1965)	Transpiration, interception loss, bare ground evaporation and snow sublimation are computed using Monteith–type formulations (Ducoudré *et al.*, 1993)	Penman–Monteith transpiration (Monteith, 1981) + interception + evaporation from soil surface	Penman–Monteith transpiration (Monteith, 1981) + interception (fixed fraction)
Water balance	One soil layer Bucket model (dynamic water holding capacity)	Two soil layers Modified bucket model from Neilson (1993) Surface runoff + drainage Snow pack	Two soil layers (deep bucket layer and upper layer of variable depth) Surface runoff + drainage Snow pack	Three soil + one litter layer Modified Bucket model Drainage Snow pack	Four soil layer Darcy's law
Canopy temperature	Canopy energy balance (Friend, 1995)	n/a	n/a	n/a	Diagnosed from energy balance
Aerodynamics	n/a	n/a	Log-wind profile	Log-wind profile	Neutral transfer coefficients using z_0 proportional to height
Radiation	Beer's Law (applied to PFTs)	Beer's Law (applied to vegetation fraction)	Beer's Law (applied to vegetation fractions)	Beer's Law (applied to total vegetation)	Beer's Law (applied to vegetation fractions)
Ecosystem structure					
Phenology					
Cold deciduous	n/a	GDD requirement Temperature threshold	GDD requirement Temperature threshold	Temperature threshold	Temperature sum with threshold
Dry deciduous	n/a	Soil moisture threshold	Soil moisture threshold	Soil moisture threshold	n/a

Grass	n/a	Soil moisture and carbon balance threshold	Dependent on climate zone. Botta *et al*. (2000)	Growth threshold	n/a
Litter fall	Daily litter carbon balance	Annual litter carbon balance		Monthly litter carbon balance	Monthly litter
Decomposition	CENTURY (Parton *et al*., 1993), modified by Comins & McMurtrie (1993)	f(T,θ_{top},tissue type)	Based on Parton *et al*. (1988)	Similar to CENTURY (Parton *et al*., 1993)	f(T,θ,C_{soil}) McGuire *et al*. (1992)
C allocation	Allometric relationships	Annual allometric relationship for individuals	Based on resource optimization (Friedlingstein *et al*., 1998)	Daily allocation by demand in order of priority LAI > roots > wood	Partitioning into 'spreading' and 'growth' based on LAI leaf : root : wood partitioning from allometric relationships
N uptake	n/a	n/a	n/a	Based on soil C and N decomposition also dependent on soil T and moisture	n/a
N allocation	Fixed C : N	Implicit, dependent on demand	n/a	Variable N with light	Fixed C : N
Plant functional types (PFTs)					
Trees evergreen	Broadleaf evergreen	Tropical evergreen Temperate broadleaf evergreen	Tropical broadleaf evergreen Temperate broadleaf evergreen Temperate needleleaf evergreen	Broadleaf evergreen	Broadleaf
	Needleleaf evergreen	Temperate needleleaf evergreen Boreal needleleaf evergreen	Boreal needleleaf evergreen	Needleleaf evergreen	Needleleaf
Trees deciduous		Tropical raingreen Temperate summergreen Boreal summergreen	Tropical broadleaf raingreen Temperate broadleaf summergreen Boreal broadleaf summergreen Boreal needleleaf summergreen	Broadleaf deciduous Needleleaf deciduous	
Shrubs	n/a	n/a	n/a	Shrubs	Shrubs
Grasses/forbs	C3 herbaceous	C3 herbaceous C4 herbaceous	C3 herbaceous C4 herbaceous	C3 herbaceous C4 herbaceous	C3 herbaceous C4 herbaceous

Dynamics, Establishment & Mortality

	HyLand (HYL)	Lund–Potsdam–Jena (LPJ)	ORCHIDEE (ORC)	Sheffield-DGVM (SHE)	TRIFFID (TRI)
Vegetation dynamics					
Competition	Competition between PFTs for light	Nonhomogeneous area-based competition for light (1-layer), H_2O (2 layers)	Nonhomogeneous area-based competition for light (1-layer), H_2O (2 layers)	Nonhomogeneous area-based competition for light (1-layer), H_2O (3 layers)	Lokta-Volterra in fractional cover
Establishment	All PFTs establish uniformly as small individuals	Climatically favoured PFTs establish in proportion to area available, as small individuals	Climatically favoured PFTs establish in proportion to area available, as small individuals	Climatically favoured PFTs establish in proportion to area available, as small individuals	Minimum 'seed' fraction for all PFTs
Mortality	Dependent on carbon pools	Deterministic baseline self-thinning carbon balance Fire Extreme temperatures	Deterministic baseline self-thinning carbon balance Fire Extreme temperatures	Carbon balance, Age Wind throw Fire Extreme temperatures	Prescribed disturbance rate for each PFT

Plant Functional Types

- Key simplification in DGVMs: PFTs
- Group plant types by responses to resources and climate
- Simplification allows global modelling
  - Limits number of parameters required
- PFTs should:
  - represent the world's most important plant types;
  - characterize them through their functional behavior;
  - provide complete, geographically representative coverage of the world's land areas

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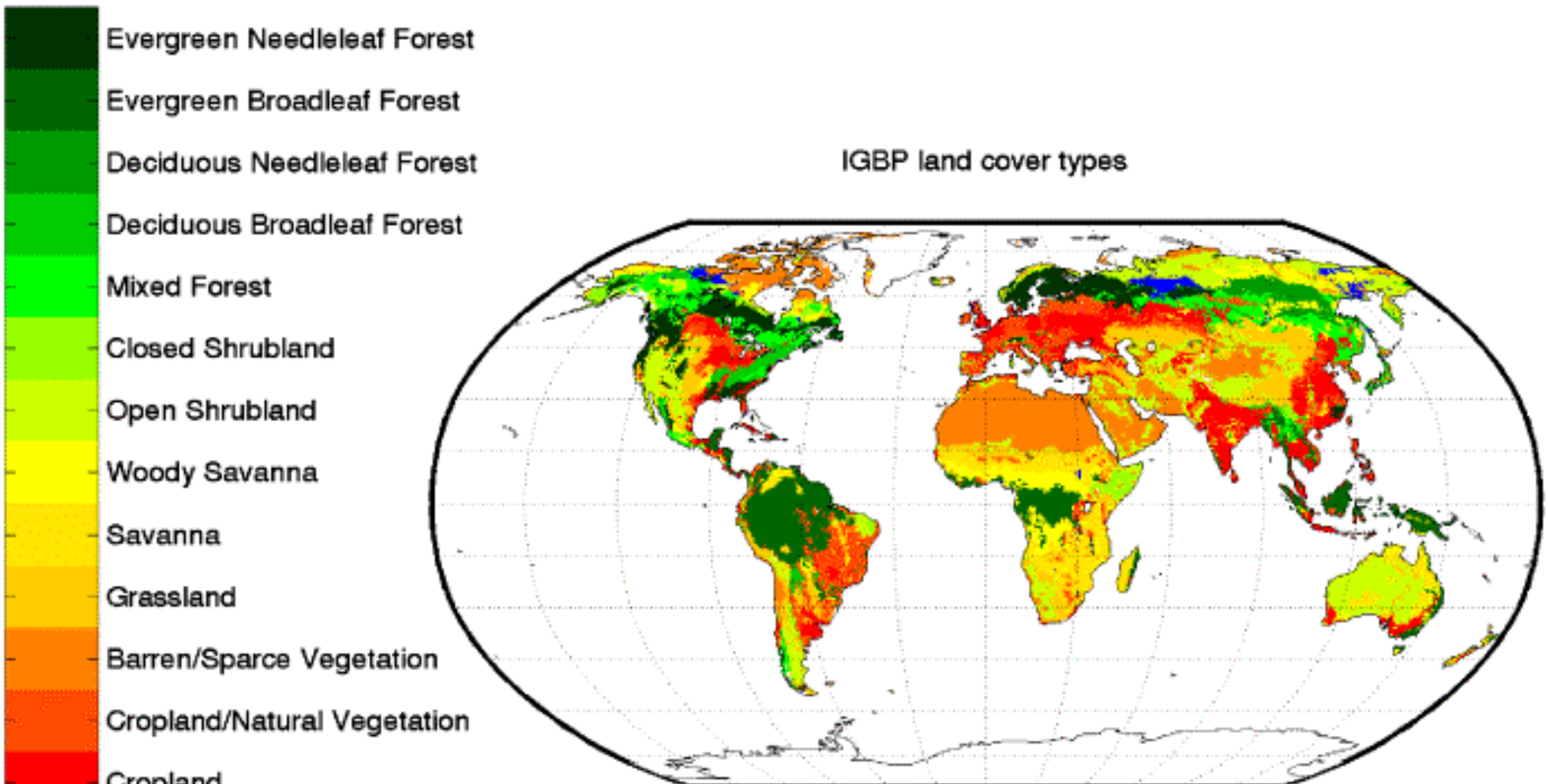
Biome Representation Of Land Cover



<u>Biomes determine</u>:

- Plant physiology (e.g., Vmax)
- Leaf and stem optical properties
- Roughness length
- Leaf and stem area index

Table 8. Dominant plant types suggested by pheno-physiognomic biome types with structural and functional characteristics.

Dominant plant type	Biome type(s)	Structure	Habit	Other
1. Tropical evergreen broad-leaved trees	Tropical rainforests	Tall woody determinate	Evergrowing	Mesomorphic
2. Tropical deciduous broad-leaved trees / arborescents	Raingreen forests, woodlands, scrub	Woody determinate	Deciduous (facultative?)	
3. Extra-tropical evergreen broad-leaved trees (mainly laurophyll)	Evergreen broad-leaved forests, Temperate rainforests	Woody determinate	Evergreen (seasonal)	Mesomorphic, shade-tolerant
4. Temperate deciduous broad-leaved trees	Summergreen broad-leaved forests and woodlands	Woody determinate	Deciduous (obligate)	Winter-dormant
5. Temperate/boreal needle-leaved evergreen trees	Needle-leaved evergreen forests/open woodlands	Woody monopodial	Evergreen (seasonal)	Winter-dormant (cold-tolerant)
6. Boreal/cool-temperate deciduous needle-leaved trees	Deciduous boreal needle-leaved forests/open woods	Woody monopodial	Deciduous (obligate)	Winter-dormant (cold-tolerant)
7. Sclerophyll trees/ arborescents	Subhumid woodlands/scrub	Short woody determinate	Evergreen/ semi-evergreen	Xeromorphic, light-demanding
8. Sclerophyll/coriaceous shrubs/dwarf-shrubs	Shrublands, krummholz, semi-deserts	Basally determinate	Evergreen/ semi-evergreen	Xeromorphic light-demanding
9. Deciduous shrubs/ dwarf-shrubs	Shrublands, krummholz, semi-deserts	Basally determinate	Deciduous	Rapid growth, seasonally dormant
10. Short-season broad-leaved dwarf-shrubs	Tundra: dwarf-shrub, graminoid, etc.	Basally ramifying	Evergreen/ deciduous	Winter-dormant (cold-tolerant)
11. Diurnally active tuft-arborescents/ frutescents/forbs	Tropical alpine scrub	Monopodial rosettes	Evergreen (diurnal)	Tolerant to diurnal frost, high UV, etc.
12. Grasses and related graminoids	Grasslands and savannas	Herbaceous (marcescent)	Opportunistic	Rapid growth, spreading
13. Stress-tolerant succulents	Semi-desert scrub	Stem/leaf/ root-succulents	Evergreen	Slow growth, water storage in tissue
14. Ephemeral herbs	Semi-desert scrub	Annual/ perennial	Ephemeral	Short life cycle/ growing season
15. Stress-tolerant lower plants, especially mosses, lichens	Tundra, cold-desert	Non-vascular cryptogams (small)	Seasonal/ stable	Winter-dormant; very slow growth; cold-tolerant

The plant types in the left column are (co)dominants or other important constituents of the pheno-physiognomic biome types in the second column and thus represent potentially the most important plant types in world vegetation, in a geographic as well as ecological sense. These plant types could then constitute an initial minimal global set of PFTs able to represent the main global vegetation types. Important functional characteristics are shown at the right and include, in particular: (1) permanence and potential height growth, as indicated by woodiness vs. herbaceousness, and by multiple branching (determinate) vs. monopodial (indeterminate) development of above-ground structure; (2) seasonal or other temporal activity pattern (evergreen vs deciduous, etc.); and (3) other characteristics such as stress-tolerance, dormancy, light/shade relationships, etc. The biome types resulted from a global model of potential dominant vegetation types needed to cover the physiognomic, seasonal, and geographic variation in global terrestrial vegetation (Box 1995b).

Box et al. PFTs

Table 3. Plant Functional Types and Their Derivation From 1-km Land Cover Data and Climate Rules[a]

Plant Functional Type	1-km Land Cover Data	Climate Rules
Needleleaf evergreen tree, temperate	needleleaf evergreen tree	$T_c > -19°C$ and GDD > 1200
Needleleaf evergreen tree, boreal	needleleaf evergreen tree	$T_c \leq -19°C$ or GDD $\leq$ 1200
Needleleaf deciduous tree	needleleaf deciduous tree	none
Broadleaf evergreen tree, tropical	broadleaf evergreen tree	$T_c > 15.5°C$
Broadleaf evergreen tree, temperate	broadleaf evergreen tree	$T_c \leq 15.5°C$
Broadleaf deciduous tree, tropical	broadleaf deciduous tree	$T_c > 15.5°C$
Broadleaf deciduous tree, temperate	broadleaf deciduous tree	$-15°C < T_c \leq 15.5°C$ and GDD > 1200
Broadleaf deciduous tree, boreal	broadleaf deciduous tree	$T_c \leq -15°C$ or GDD $\leq$ 1200
Broadleaf evergreen shrub, temperate	shrub	$T_c > -19°C$ and GDD > 1200 and $P_{ann} > 520$ mm and $P_{win} > 2/3\ P_{ann}$
Broadleaf deciduous shrub, temperate	shrub	$T_c > -19°C$ and GDD > 1200 and ($P_{ann} \leq 520$ mm or $P_{win} \leq 2/3\ P_{ann}$)
Broadleaf deciduous shrub, boreal	shrub	$T_c \leq -19°C$ or GDD $\leq$ 1200
C_3 grass, arctic	grass	GDD < 1000
C_3 grass[b]	grass	GDD > 1000 and ($T_w \leq 22°C$ or $P_{mon} \leq 25$ mm and for months with $T > 22°C$)
C_4 grass[b]	grass	GDD > 1000 and $T_c > 22°C$ and driest month $P_{mon} > 25$ mm
Crop	crop	none

[a] T_c, temperature of coldest month. T_w, temperature of warmest month. GDD, growing-degree days above 5°C. P_{ann}, annual precipitation. P_{win}, winter precipitation (Northern Hemisphere, November through April; Southern Hemisphere, May through October). P_{mon}, monthly precipitation.

[b] A 1-km grid cell is assumed to be 50% C_3 and C_4 if GDD > 1000 and neither the C_3 nor C_4 criteria are met.

Or Bonan et al., biome/climate rules

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PFTs

- Some issues:
  - Uncertainty from land cover
  - Variations in mappings to PFTs
  - Assume parameters describing functioning constant over PFT
    - New evidence from traits databases

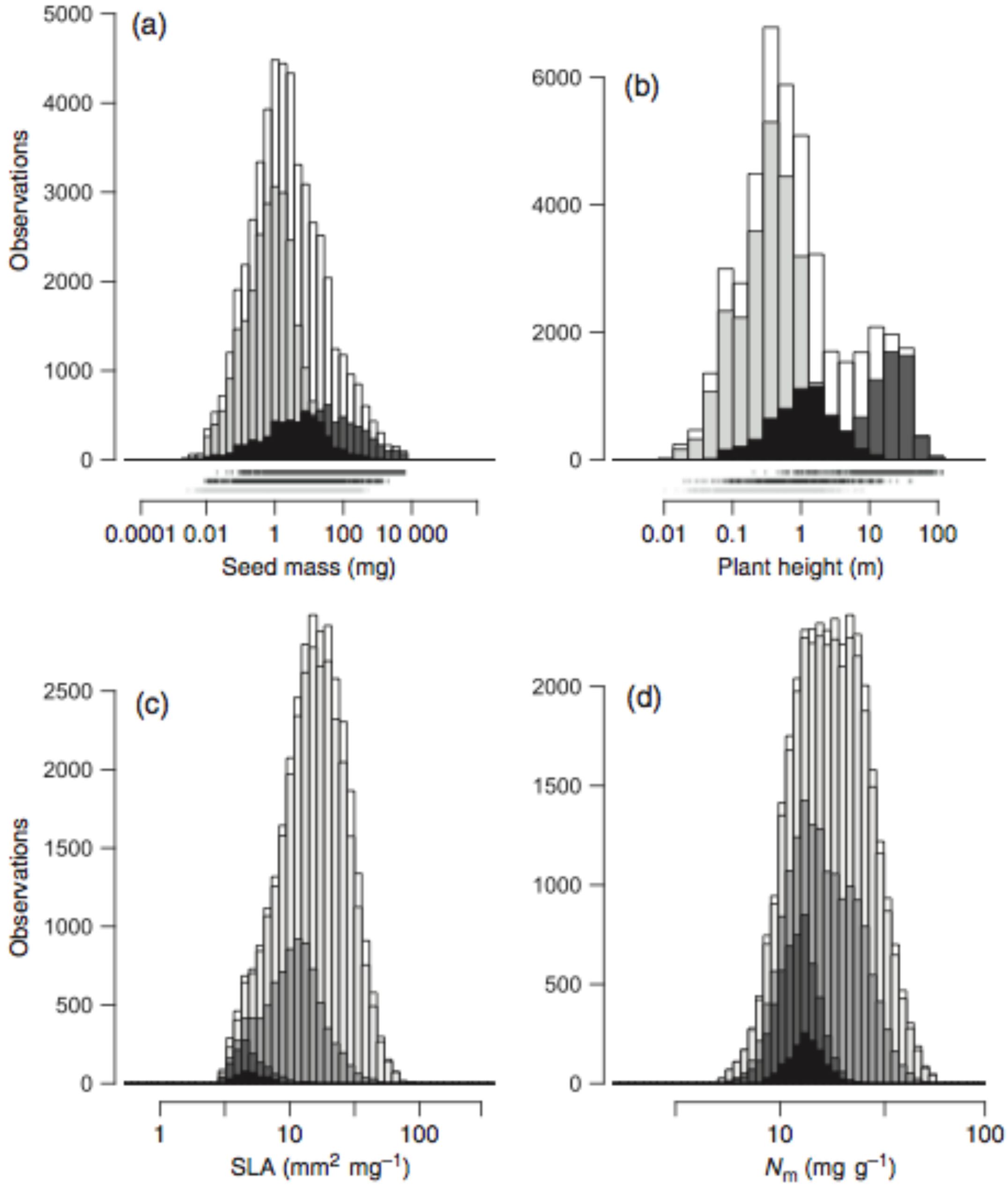

Fig. 4 Examples of trait frequency distributions for four ecologically relevant traits (Westoby, 1998; Wright *et al*., 2004). Upper panels: (a) seed mass and (b) plant height for all data and three major plant growth forms (white, all database entries; light grey, herbs/grasses; dark grey, trees; black, shrubs). Rug-plots provide data ranges hidden by overlapping histograms. Lower panels: (c) Specific leaf area (*SLA*) and (d) leaf nitrogen content per dry mass [N_m, white, all database entries excluding outliers (including experimental conditions); light grey, database entries from natural environment (excluding experimental conditions); medium grey, growth form trees; dark grey, PFT needle-leaved evergreen; black, *Pinus sylvestris*].

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Analysis of species/PFT in TRY

http://try-db.org/pmwiki/index.php

Kattge et al. (2011) GCB

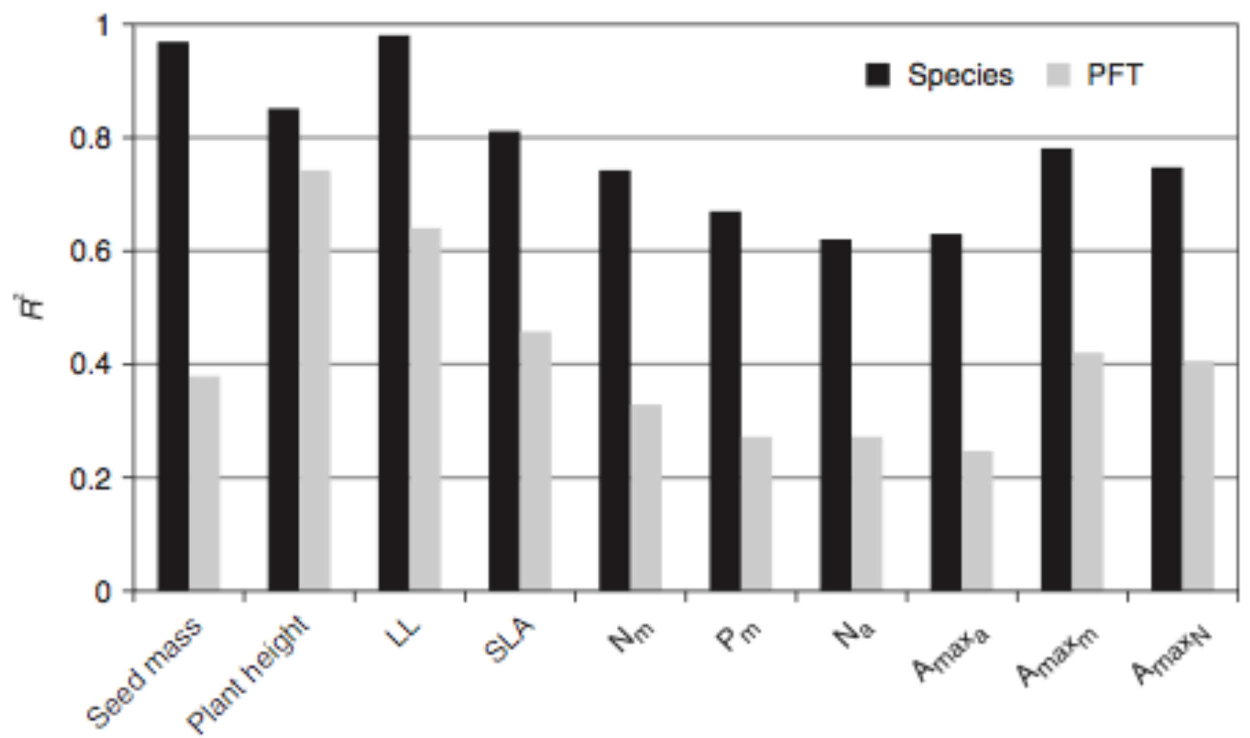

Fig. 5 Fraction of variance explained by plant functional type (PFT) or species for 10 relevant and well-covered traits. R^2, fraction of explained variance; Traits: *Seed mass*, seed dry mass; *Plant height*, maximum plant height; *LL*, leaf longevity; *SLA*, specific leaf area; N_m, leaf nitrogen content per dry mass; P_m, leaf phosphorus content per dry mass; N_a, leaf nitrogen content per area; A_{max_a}, maximum photosynthesis rate per leaf area; A_{max_m}, maximum photosynthesis rate per leaf dry mass; A_{max_N}, maximum photosynthesis rate per leaf nitrogen content.

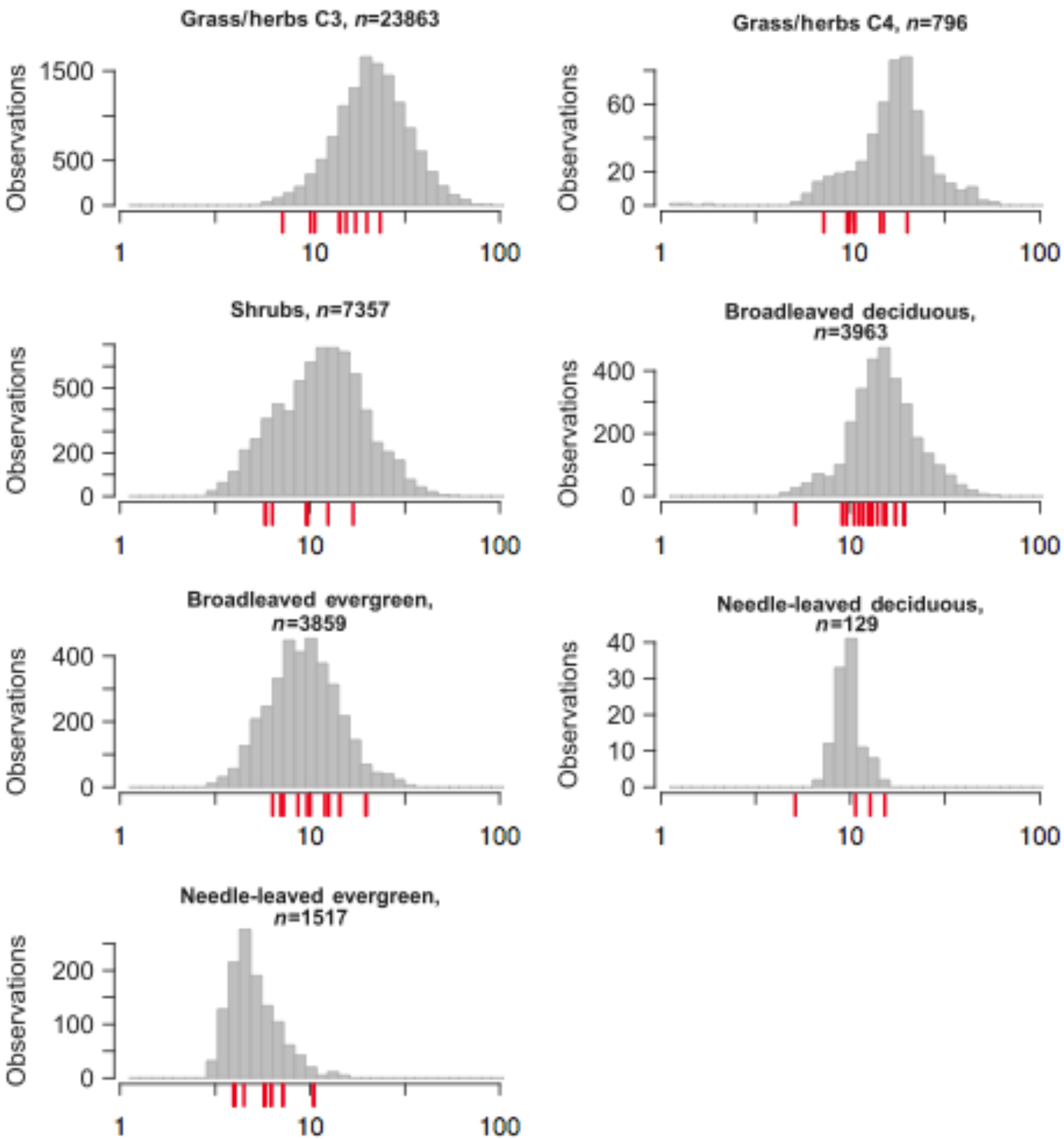

Fig. 7 Frequency distributions of specific leaf area (*SLA*, $mm^2\,mg^{-1}$) values (grey histograms) compiled in the TRY database and parameter values for SLA (red dashes) published in the context of the following global vegetation models: Frankfurt Biosphere Model (Ludeke *et al.*, 1994; Kohlmaier *et al.*, 1997), SCM (Friend & Cox, 1995), HRBM (Kaduk & Heimann, 1996), IBIS (Foley *et al.*, 1996; Kucharik *et al.*, 2000), Hybrid (Friend *et al.*, 1997), BIOME-BGC (White *et al.*, 2000), ED (Moorcroft *et al.*, 2001), LPJ-GUESS (Smith *et al.*, 2001), LPJ-DGVM (Sitch *et al.*, 2003), LSM (Bonan *et al.*, 2003), SEIB–DGVM (Sato *et al.*, 2007). *n*, number of SLA data in the TRY database per PFT.

How ‘good’ are these models?

- Current benchmarking efforts
  - International Land Model Benchmarking – iLAMB
- Previous (more limited)
  - Carbon-Land Model Intercomparison Project - C-LAMP
  - 2 models (CASA’, CN)
  - global carbon sinks for the 1990s differed by a factor of 2
  - magnitude of net carbon uptake during the growing season in temperate and boreal forest ecosystems was under-estimated

How 'good' are these models?

- Model intercomparisons (e.g. Sitch et al., 2008)

Table 2 Global land carbon budgets for the 1980s and 1990s, expressed as decadal mean land–atmosphere exchange (Rh-NPP), units are $Pg\,C\,yr^{-1}$, and the simulated cumulative land uptake from 1958 to 2002 in Pg C

	1980s	1990s	1958–2002
IPCC Residual Land Sink Prentice *et al.* (2001)	−1.9 (−3.8 to 0.3)	−2.6 (−4.3 to −1.0)	
Model			
HyLand (HYL)	−1.67	−2.39	71.5
Lund–Potsdam–Jena (LPJ)	−1.32	−1.52	67.7
ORCHIDEE (ORC)	−1.58	−2.21	81.4
Sheffield-DGVM (SHE)	−1.80	−2.75	85.3
TRIFFID (TRI)	−1.62	−2.47	110.1

IPCC, Intergovernmental Panel on Climate Change.

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How ‘good’ are these models?

- models estimates within range of current knowledge of C budgets and relatively close to the mean IPCC values.
- The models in general agreement about the cumulative land uptake over the last 50 years.
- Models simulated the correct sign of response to ENSO events but differed markedly in magnitude.
- have similar response of productivity to elevated atmospheric CO2 in agreement with field observations
- The DGVMs are in less agreement in the way they respond to changing climate.
- suggest a release of land carbon in response to climate
  - implying a significant positive climate-carbon cycle feedback in each case. This response is mainly due to a reduction in NPP and a decrease in soil residence time in the tropics and extra-tropics, respectively.

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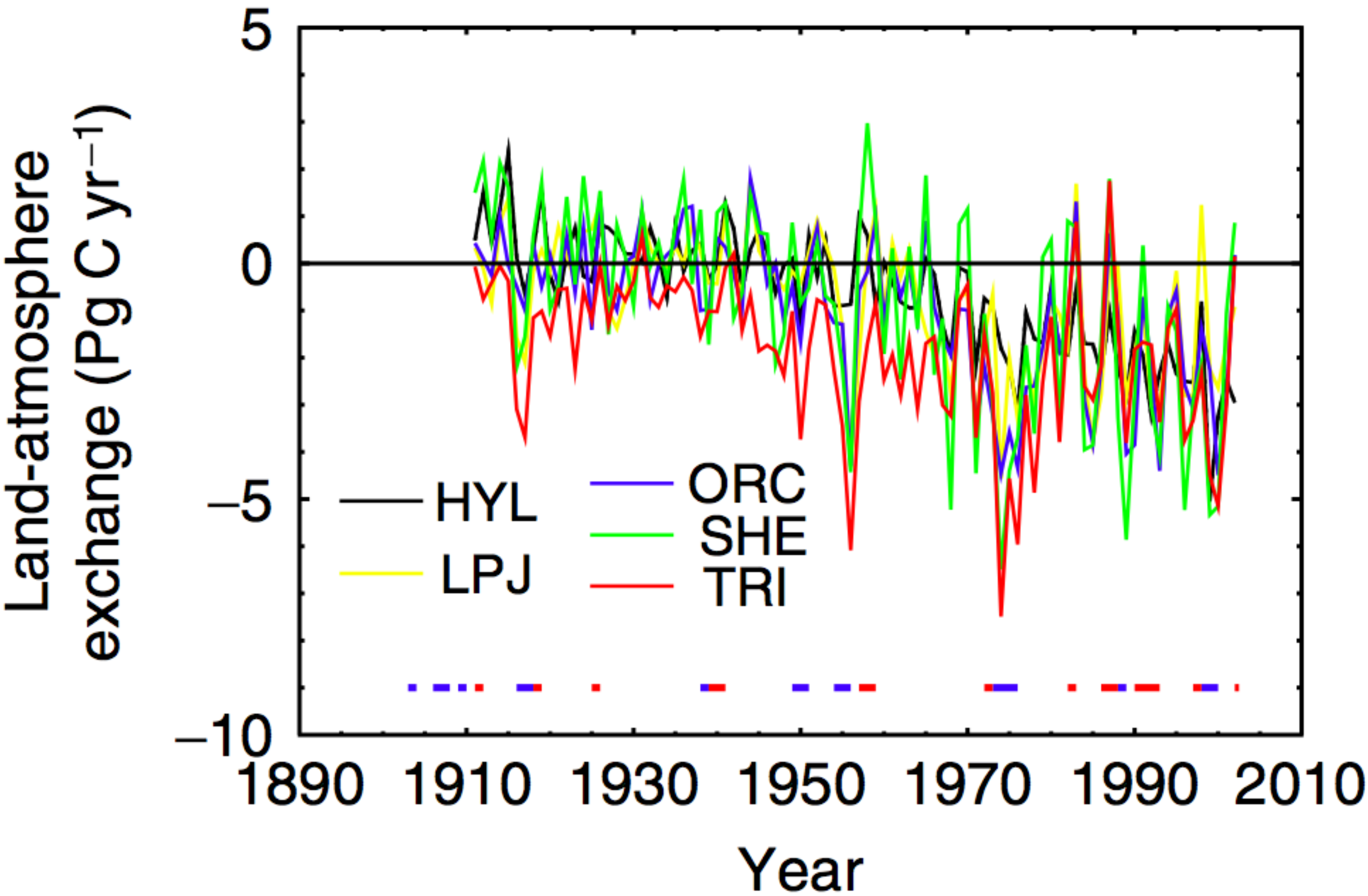
Land-atmosphere exchange (Pg C yr⁻¹)
5
0
–5
–10
1890
1910
1930
1950
1970
1990
2010
Year
HYL
LPJ
ORC
SHE
TRI

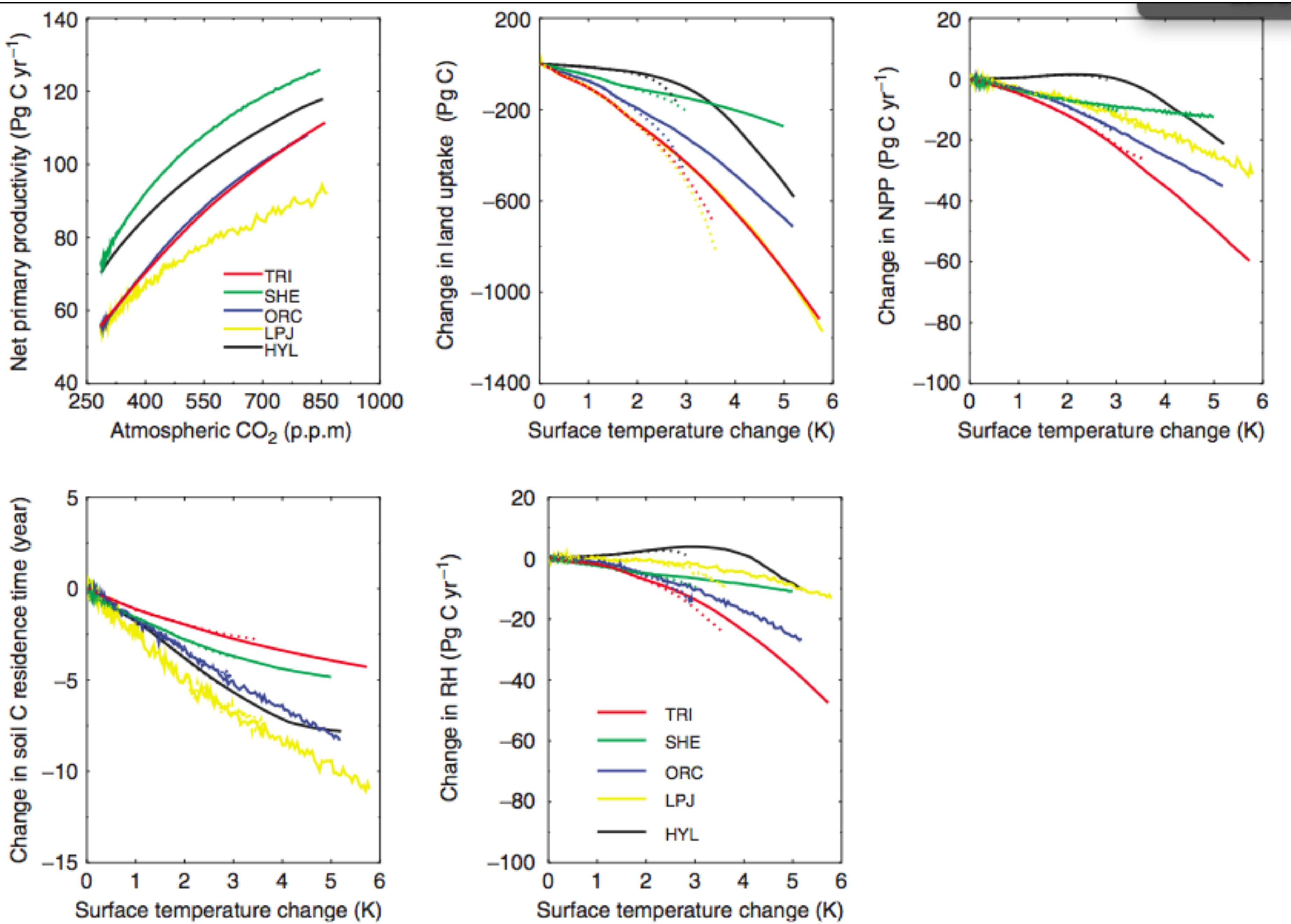

Fig. 9 Simulated net primary productivity (NPP) sensitivity to atmospheric CO_2 (prescribed climate simulation). Simulated land uptake sensitivity, net primary productivity (NPP), heterotrophic respiration (RH) (coupled-prescribed climate) and soil residence time (from the coupled simulation) to global mean temperature change for two Special Report Emission Scenarios (SRES) emission scenarios, A1FI (solid line) and B1 (dashed line) for five Dynamic Global Vegetation Models (DGVMs), HyLand (HYL, black), Lund–Potsdam–Jena (LPJ, yellow), ORCHIDEE (ORC, blue), Sheffield (SHE, green) and TRIFFID (TRI, red).

2. Global vegetation modelling

In this section,

- noted that the two main types of model we are interested in are DGVMs and PEMs.
- Outlined some of the main features of DGVMs and discussed some of the concepts they employ, such as PFTs.
    - Traits databases
- We have also considered how we can tell how good these models are.

3. Production efficiency models

'Monteith' approach

$$GPP = PAR \times f_{PAR} \times (\epsilon \times C_{drm}) \times scalars$$

$$NPP = GPP - R_a$$

The scalars represent multiplicative environmental constraints that are typically meteorologically derived (i. e. limiting factors).

PEMs

- Attractions:
  - simple and
  - captures the ‘main effect’
    - C assimilation increases with increasing PAR absorption in the absence of limiting factors
      - including such limits as scalars
  - fAPAR is potentially accessible from satellite data, so a major part of the model can be driven by observations globally.

Some PEMs

Table 1: Attributes and results of six global PEMs available from the literature.

PEM	*Study period*	*Timestep*	*Cell-size*	*LUE Scalars*	*LUE-GPP (g C MJ⁻¹)*	*NPP (Pg C yr⁻¹)*	*Reference*
CASA	1982-1998	Month	0.5°	T, AET, PET	0.39[e]	48.0[c]	[46]
GLO-PEM	1981-2000	10 days	8 km	T, SW, VPD	1.03-1.64[a]	69.7[b]	[48]
TURC	1998	Month	1°	No Scalars	1.10	64.0	[49]
C-Fix	1998-2008	10 days	1 km	T, CO_2, SW, EF	1.10	NA[f]	[14]
MOD17	2000-2008	Day/Year	1 km	T, VPD	0.68-1.159	56.0[d]	[18]
BEAMS	1982-2000	Month	1°	T, h, SW	0.0-1.0		[53]

[a] [13]; [b] [31]; [c] [78]; [d] [51]; [e] based on NPP; [f] NA (globally not available in published literature)
T Temperature; SW Soil Water; VPD Vapour Pressure Deficit; AET Actual Evapotranspiration; PET Potential Evapotranspiration; CO_2 fertilization factor; EF Evaporative Fraction; h Relative Humidity

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PEM requirements

- LUE often assumed constant
  - e.g. constant globally in CASA or
  - per biome via a land cover map as in MOD17.
  - GLO-PEM does not assume a constant LUE.
- make use of satellite data (fAPAR),
  - But most also require climate data
    - (for APAR and to drive limiting scalars).
    - Only GLO-PEM runs on only satellite data (with the exception of attribution of C3 and C4 plants).

Some issues

- LUE should not be assumed constant, but should vary by PFTs
- Results are strongly dependent on the climate drivers used for particular models (which also complicates intercomparison)
- Further use of satellite data would alleviate the need for many or all climate drivers.
- PEMs should consider incorporating diffuse radiation, especially at daily resolution
- PEMs should also consider the need to account for GPP saturation when radiation is high

How good are these models?

Cramer et al. (1999) intercomparison

PEMs & other models

	Selected inputs[a]			Selected outputs		
	Vegetation distribution[b]	Satellite FPAR	Other satellite data[c]	Biogeo-chemical fluxes	Leaf Area Index (LAI)[d]	Vegetation Distribution
Satellite based models						
CASA	X	X		X		
GLO-PEM		X	X	X		
SDBM		X		X		
TURC	X	X		X		
SIB2	X	X	X	X		
Models for seasonal biogeochemical fluxes						
HRBM				X		
CENTURY	X			X		
TEM	X			X		
CARAIB	X			X	X	
FBM	X			X	X	
PLAI	X			X	X	
SILVAN	X			X	X	
BIOME-BGC	X			X	X	
KGBM	X		X	X	X	
Models for seasonal biogeochemical fluxes and vegetation structure						
BIOME3				X	X	X
DOLY				X	X	X
HYBRID				X	X	X

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How good are these models?

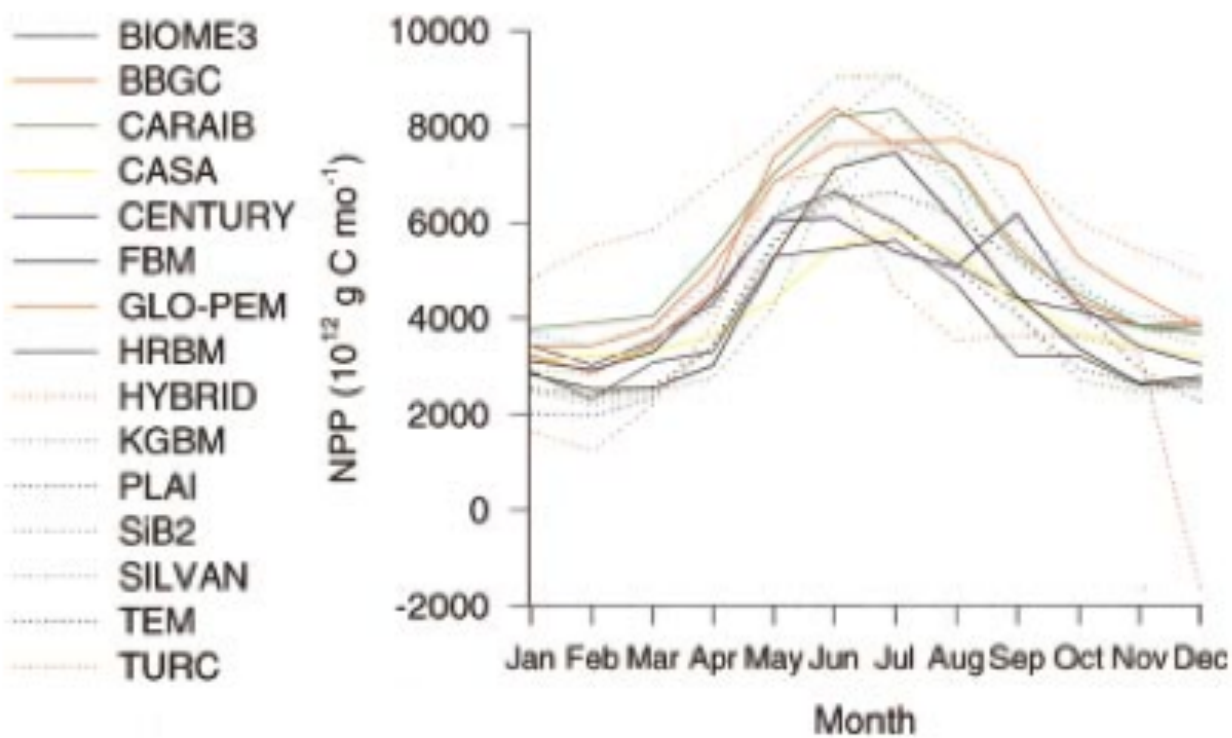

Fig. 3 Comparison of seasonal variations in global net primary productivity among all models except DOLY, which simulated only annual totals.

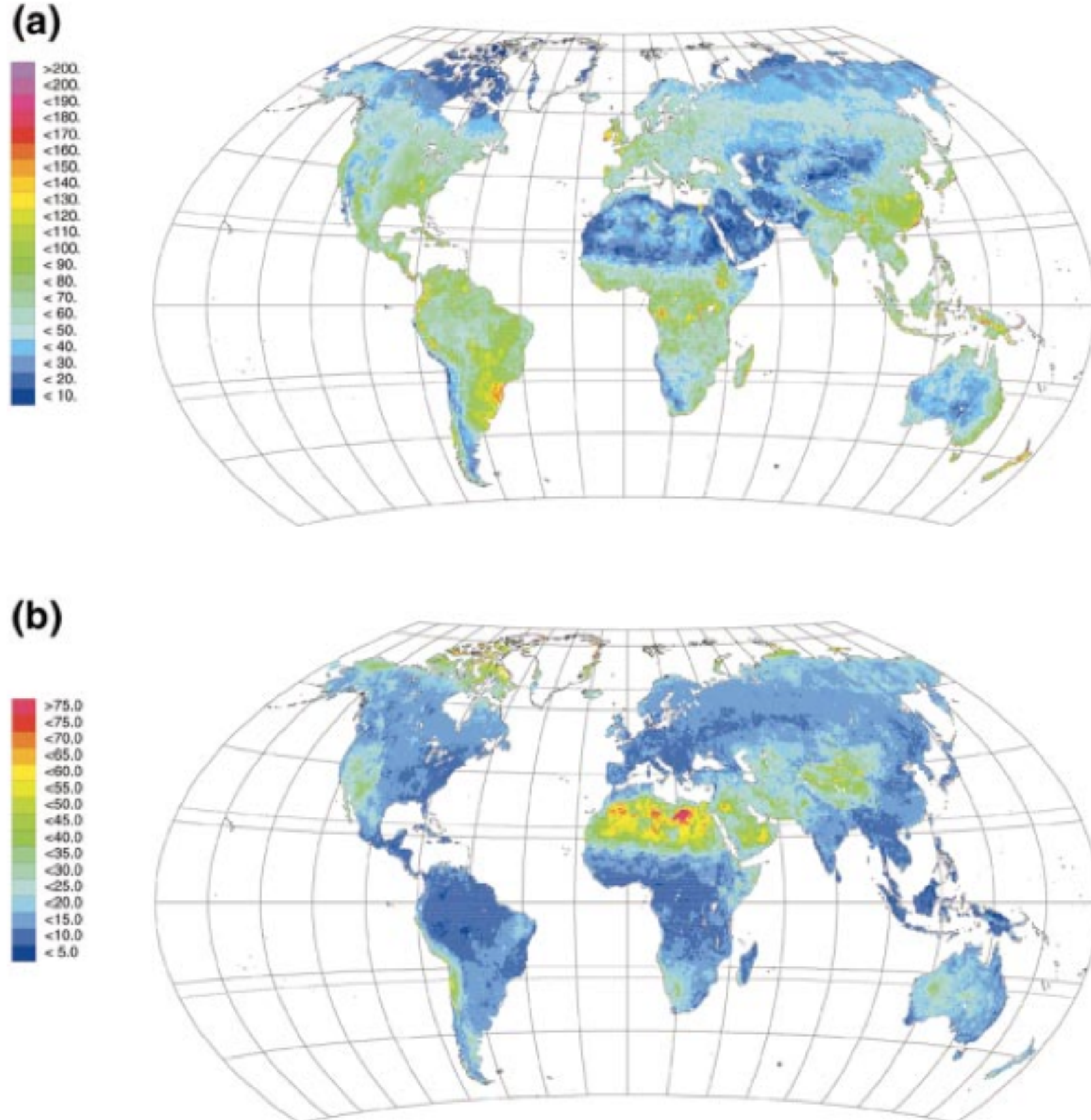

Fig. 2 Spatial distribution of the variability in NPP estimates among the models as represented by (a) the standard deviation of model NPP estimates in a grid cell; and (b) the coefficient of variance of model NPP estimated in a grid cell. The coefficient of variance is determined by dividing the standard deviation by the mean of the model NPP estimates within a grid cell.

3. Production efficiency models

Summary

- overview of PEM approach.
    - The key idea that non-limited carbon assimilation can be assumed a linear function of the capacity of a canopy to absorb shortwave (specifically PAR) radiation and the amount of downwelling PAR.
- Models particularly useful as they can be largely driven by observations (or rather fAPAR, derived from satellite observations).
- Several key issues in the use of such models are highlighted, but these models seem to perform ‘quite well’ in comparison to mechanistic approaches.
- Since these models are driven by observations, they cannot directly be used in prognostic mode.

4. Phenology

Phenology

- plants experience daily and seasonal variations in environmental conditions.
  - tend to adjust their behaviour to these variations.
  - diurnal variations in light, temperature and water.
    - Many plants then exhibit cirdadian rhythms (24 hour cycles) for example in stomatal opening

Phenology

- temperate climate plants: strong seasonal variations in environment
  - generally exhibit a predictable pattern of phenology
  - put more resources into leaf production at certain times, flowers at others etc.
  - E.g. leaf senescence timing from photoperiod
    - Cues onset of winter
    - shift resources (nutrients, carbohydrates, water) from leaves to other organs to prevent their loss from the plant

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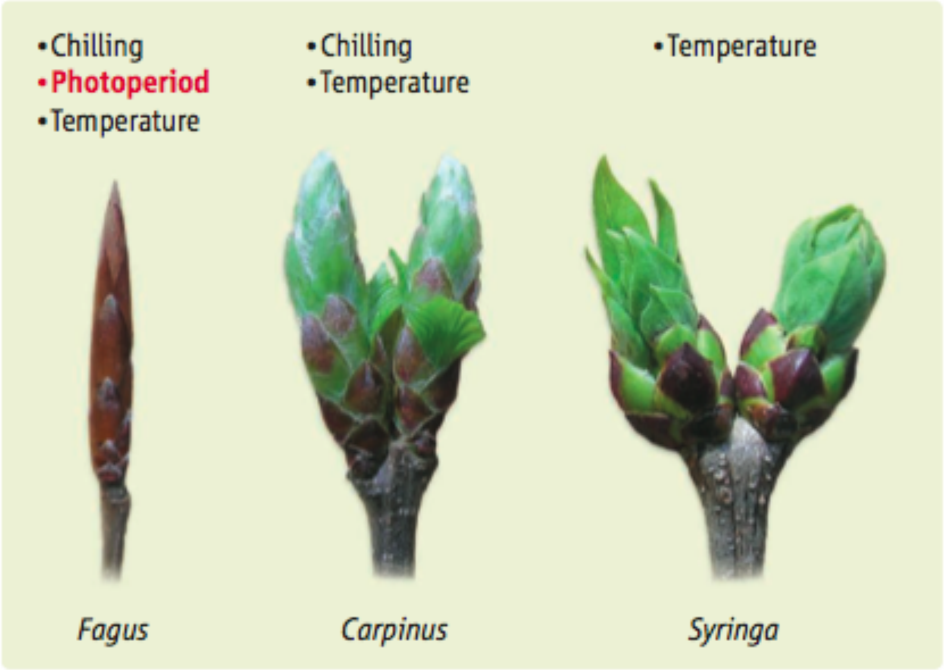
Extratropics (outside tropics)

- Photoperiod same in winter and autumn,
    - plants need a cue that winter is over.
    - This is often obtained from the dose of low T … a ‘chilling’ requirement by some plants before spring bud burst



Not just temperature. Spring development in many ornamental plants from warm regions, such as lilac (*Syringa*), is primarily controlled by temperature, whereas early successional species native to temperate latitudes, such as hornbeam (*Carpinus*), only become temperature-sensitive once their chilling demand has been fulfilled. Late successional taxa, such as beech (*Fagus*), are photoperiod controlled, with temperature only exerting a limited modulating effect once the critical day length has passed. This mechanism prevents such taxa from sprouting at the “wrong” time.

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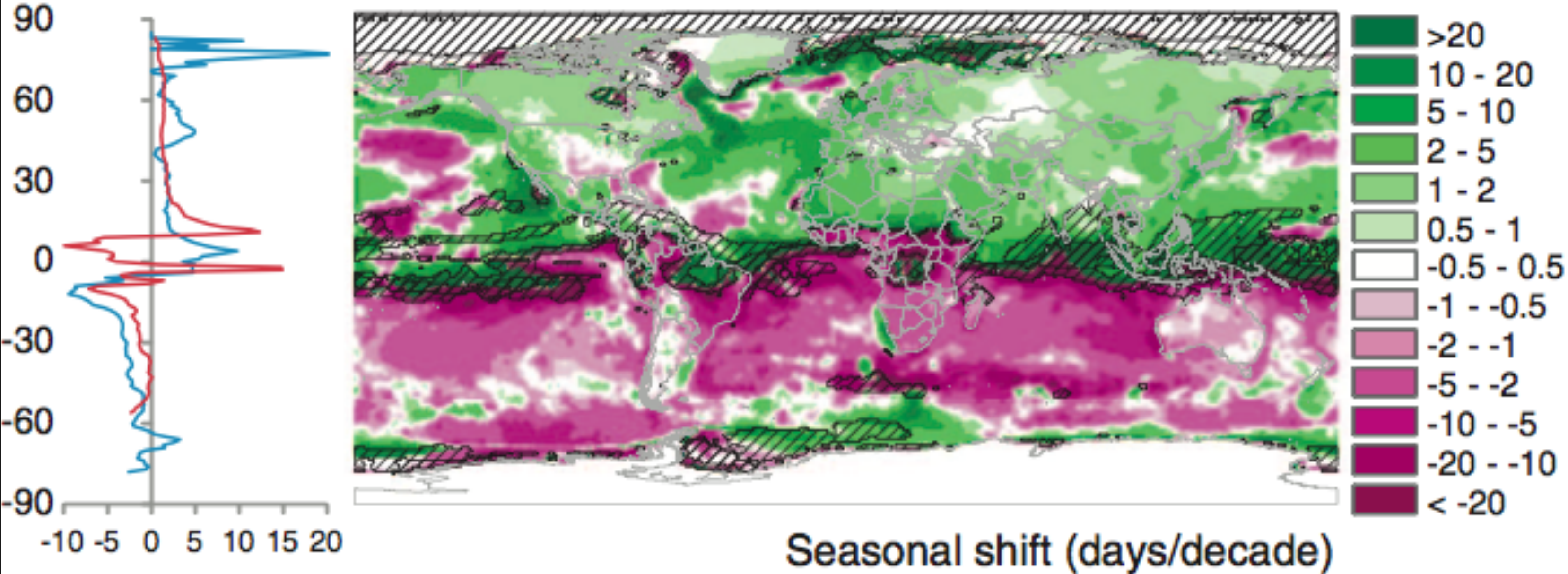
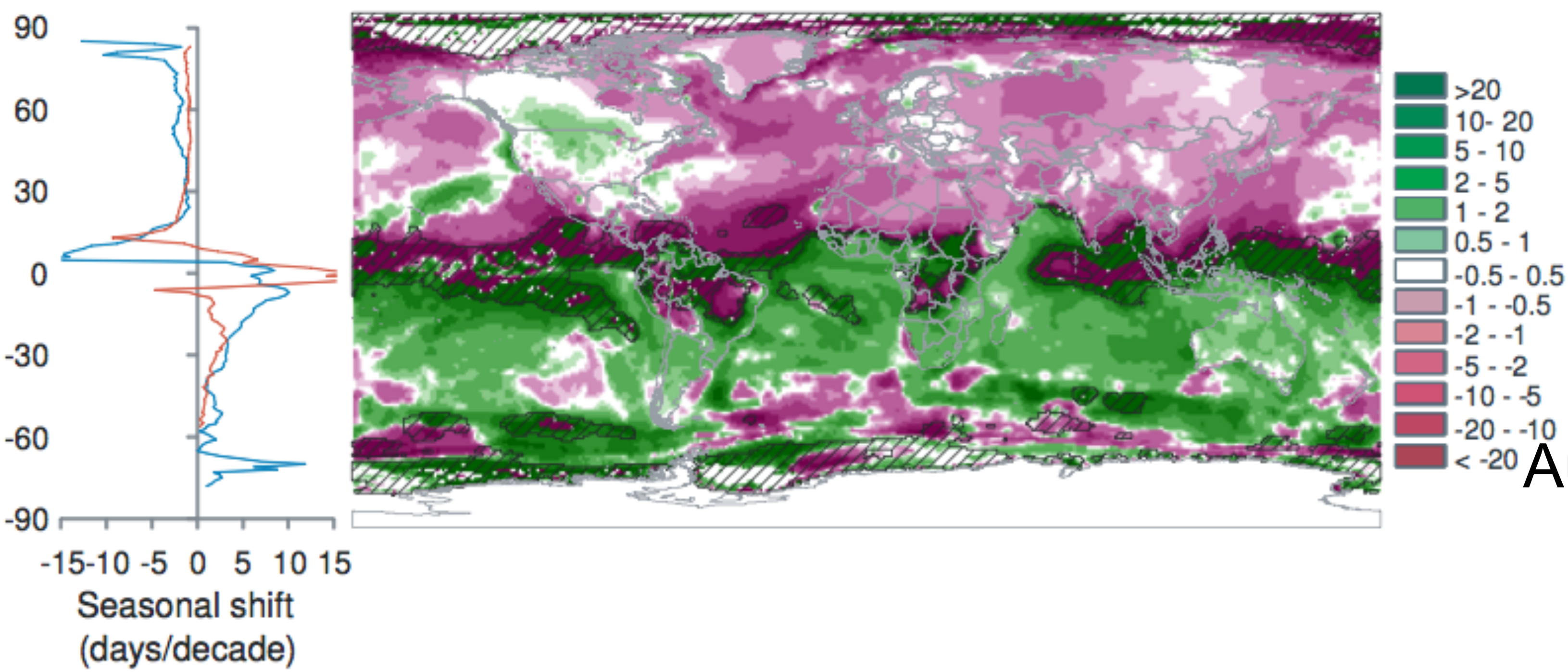


Spring Temp.

Seasonal shift in temp. 1960-2009



AutumnTemp.

phenology

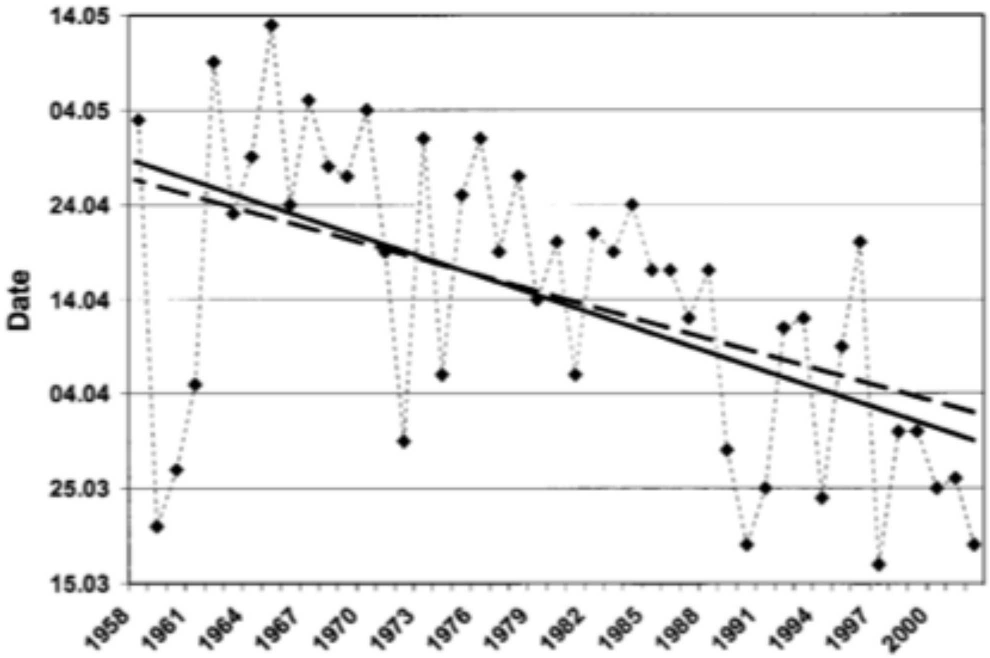


Figure 2: Example of trend reinforced by the early occurrence dates during the years 1999–2002: larch needle appearance in Sargans, 1958–2002. Earlier occurrence of 28 days over 50 years for the period 1958–1998 (dashed line), and of 33 days over 50 years for the period 1958–2002 (solid line).

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Models of phenology

Simplest: logistic fn of time

$$y(t) = \frac{c}{1 + e^{a+bt}} + d$$

e.g. Zhang et al., 2003 MODIS phenology

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Track features of phenology

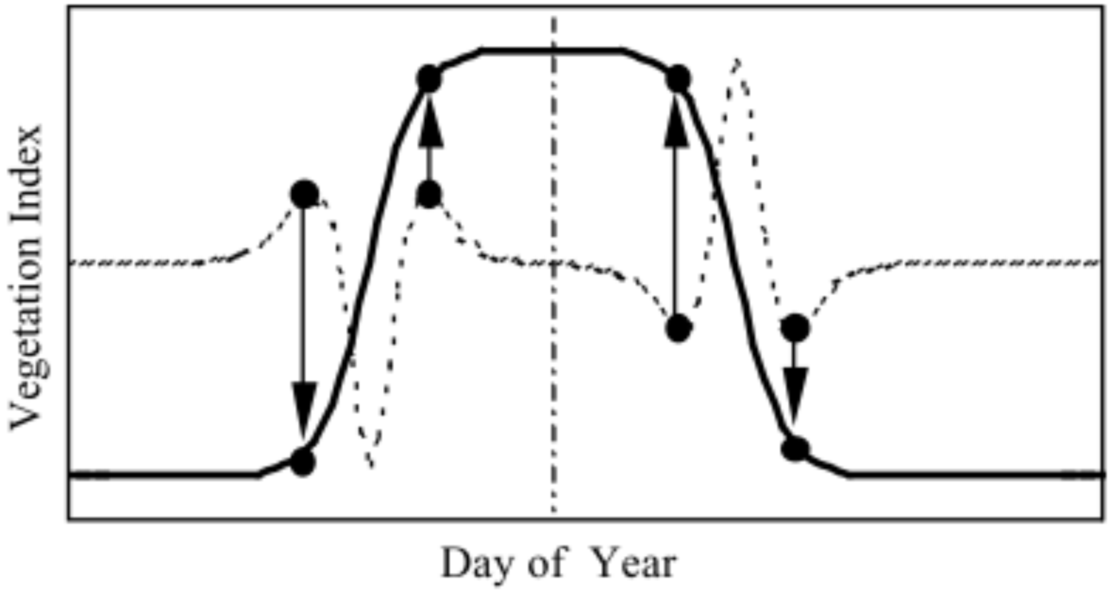

Fig. 2. A schematic showing how transition dates are calculated using minimum and maximum values in the rate of change in curvature. The solid line is an idealized time series of vegetation index data, and the dashed line is the rate of change in curvature from the VI data. The circles indicate transition dates. The extreme values located between each circle indicate the point at which the rate of change in curvature changes sign.

Track features of phenology

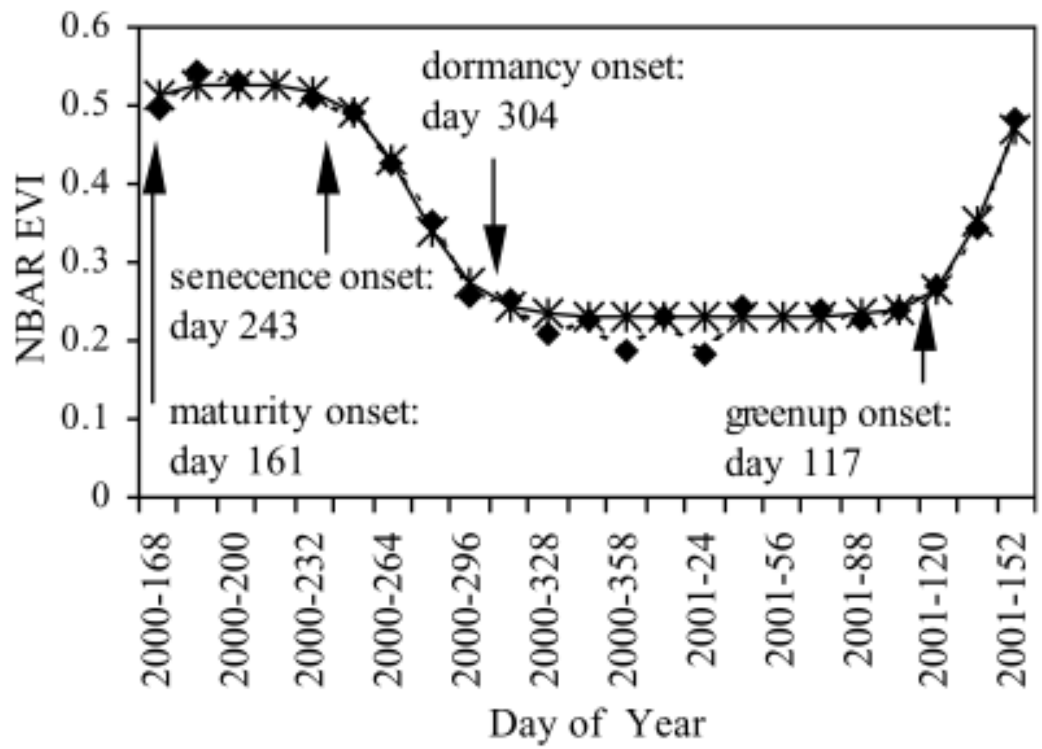

Fig. 3. A sample time series of MODIS EVI data and estimated phenological transition dates for a mixed forest pixel in New England. The dashed line with diamonds is the original EVI data and the solid line with stars is the fitted logistic models.

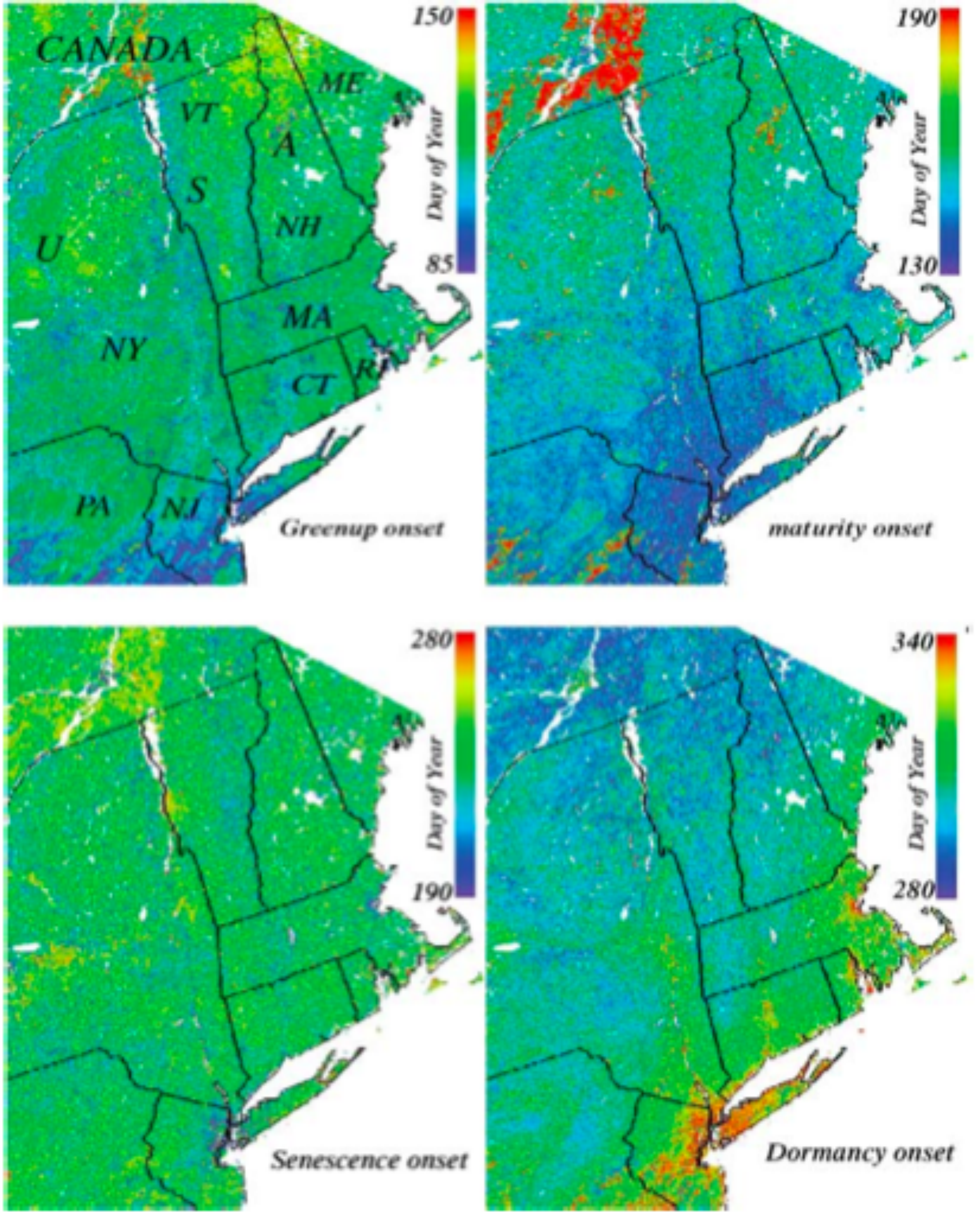

Fig. 4. Maps of phenological transition dates estimated using the method described in Section 2.

Such processing provides valuable spatial datasets of information related to phenology and allows the tracking of dynamics of the phenology metrics over time.

model of this sort is used to derive *data* that are then used to model phenology.

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(Growing) Degree day model

- simplest form of model that can be used prognostically
- only really appropriate where temperature is a limiting factor in plant growth (the extratopics).

$$GDD = \sum_{T>T_{base}} (T - T_{base})$$

- identify some threshold value of GDD $F*$ that corresponds to the metric of interest.
- So essentially 2 parameters (Tbase & F*)

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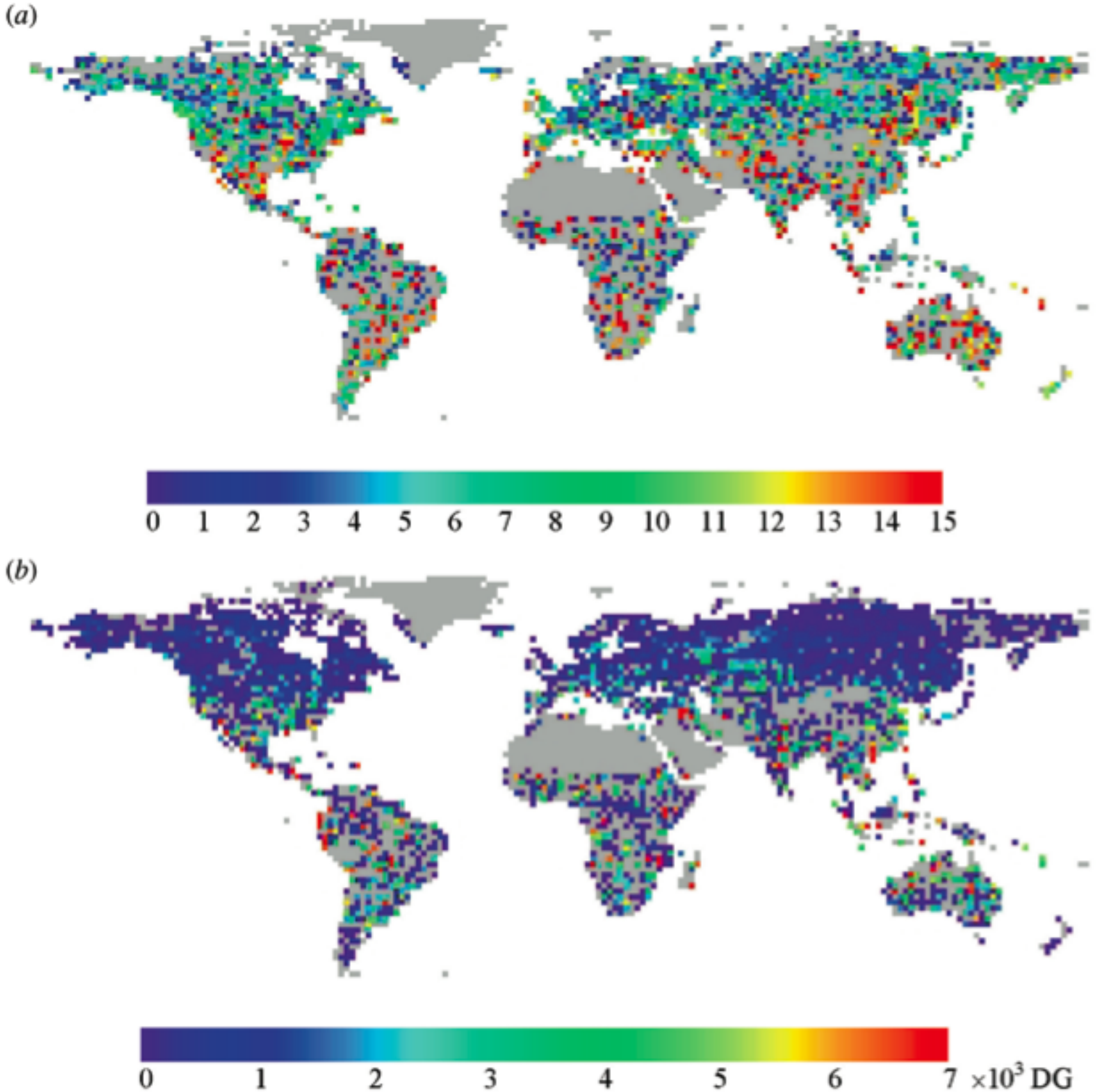

Figure 5. Retrieved thresholds for spring date estimation from degree-days: (*a*) T_0 – daily threshold (in °C); (*b*) DG – total degree-day amount (cf. equation (3)).

Model calibration

- Take data (e.g. satellite VI) and T dataset
- Extract phenology metric (e.g. bud burst) from VI
- Work out which Tbase & F* give best fit to this
  - Over long time series per location
  - Or assuming parameters constant spatially

Chilling

Can incorporate chilling:

- sequential models:
  - forcing only starts when the chilling requirement is met
- parallel models:
  - chilling and forcing accumulated in parallel and critical values then applied to both
- alternating models:
  - the temperature $F*$ is a decreasing function of chilling.

Picard et al. (2005) use NDWI to track chilling for Siberia

Use to calibrate DVGM

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Tables

t_0	starting date for counting, set to 1st of January
t_{bb}	day of year of bud-burst
t_{rc}	day of year when the chilling requirement is first fulfilled.
R_c	chilling rate function
R_f	forcing rate function
$C(t)$	rate of chilling
C	critical value of rate of chilling
F	critical value of rate of forcing
T_b	base temperature
T_c	optimal temperature for chilling
b	rate of reduction of forcing required per unit of chilling
Forcing rate:	$R_f(\theta) = \max(\theta - \theta_b, 0)$
Chilling rate:	$R_c(\theta) = \begin{cases} 0 & \theta \le -3.4 \text{ or } \theta \ge 10.4 \\ \dfrac{\theta + 3.4}{\theta_c + 3.4} & -3.4 < \theta < \theta_c \\ \dfrac{\theta - 10.4}{\theta_c - 10.4} & \theta_c < \theta < 10.4 \end{cases}$
Spring Warming:	t_{bb} such that $\sum_{t=t_0}^{t_{bb}} R_f(\theta) \ge F^*$
Sequential model:	t_{cr} such that $\sum_{t=t_0}^{t_{cr}} R_c(\theta) \ge C^*$ and t_{bb} such that $\sum_{t=t_{cr}}^{t_{bb}} R_f(\theta) \ge F^*$
Parallel model:	$C(t) = \sum_{t'=t_0}^{t} R_c(\theta)$ and t_{cr} such that $C(t) \ge C^*$ t_{bb} such that $\sum_{t=t_0}^{t_{bb}} \min(C(t)/C^*, 1) R_f(\theta) \ge F^*$
Alternating model:	$C(t) = \sum_{t'=t_0}^{t} R_c(\theta)$ and t_{cr} such that $C(t) \ge C^*$ t_{bb} such that $\sum_{t=t_{cr}}^{t_{bb}} R_f(\theta) \ge F^* \exp[-b.C(t))]$

Table 1. Notation and formulation of the major types of phenology model (spring warming, alternating, sequential, parallel) tested in this paper. Some slight variations can be found in the

tropics

- simulating and understanding phenology is complicated
- Mainly water constraint
  - But complicated as not just dept. on precipitation
    - Plants may have deep or shallow roots

- The state of phenology models in DGVMs for tropical areas then is at present rather weak and an area of active research.

4. Phenology

Summary

- Phenology important concept in monitoring, modelling and understanding vegetation dynamics and its response to climate variations.
  - growing amount of observational data on phenology at various scales and more recent attempts to reconcile measures at different scales.
- likely that for some areas at least, species specific (or slighly broader groupings of species) parameterisations of phenology need to be considered rather than just broad PFT definitions.
- Most phenology analysis is done using simple degree day models, although some analyses also consider chilling requirements.
- Phenology models in DGVMs may be phrased rather differently to those used in most analyses. Whilst maintaining a required ‘mechanistic approach’, current DGVM phenology models are not entirely satisfactory.

5. Modelling Photosynthesis

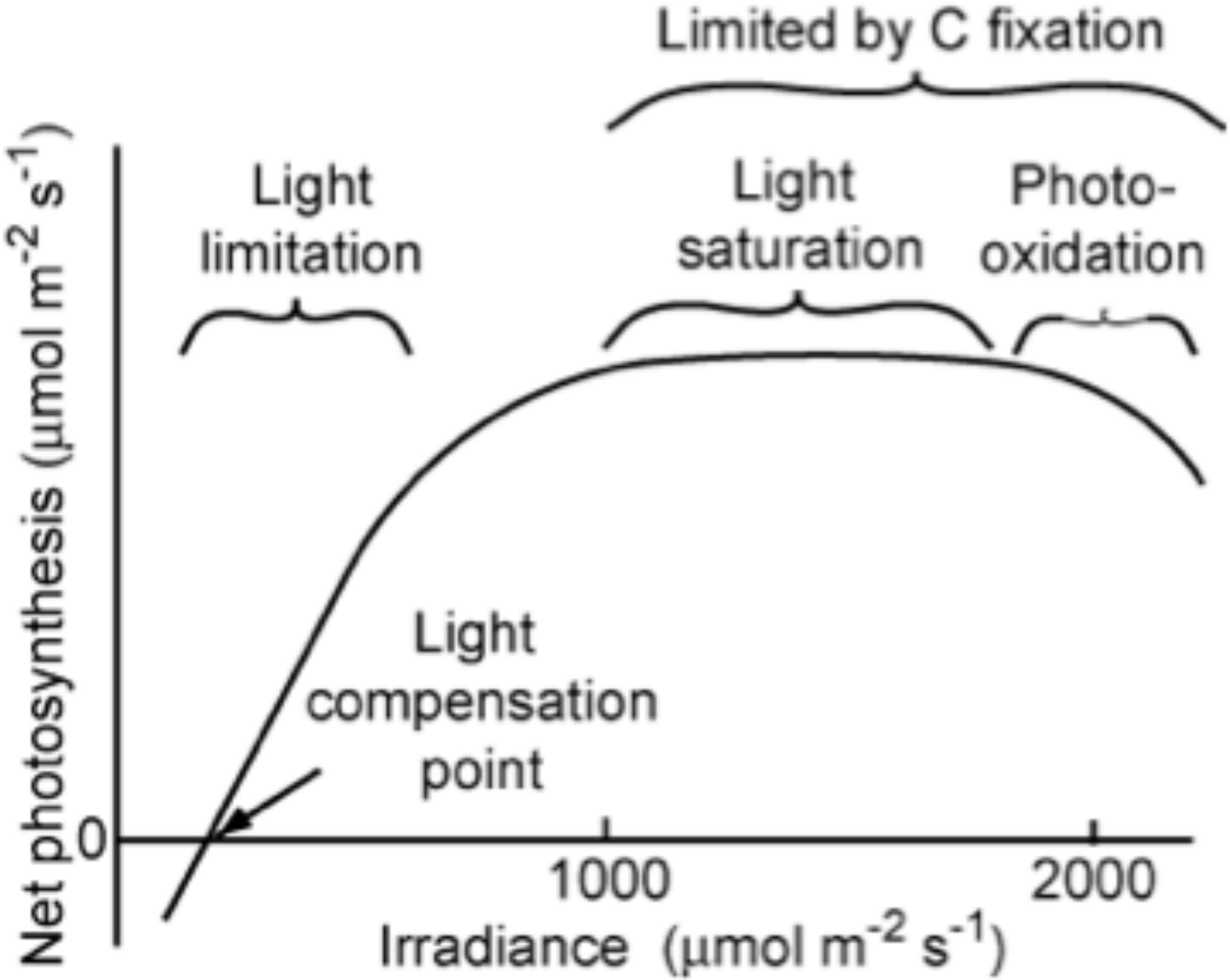
Farquhar approach:

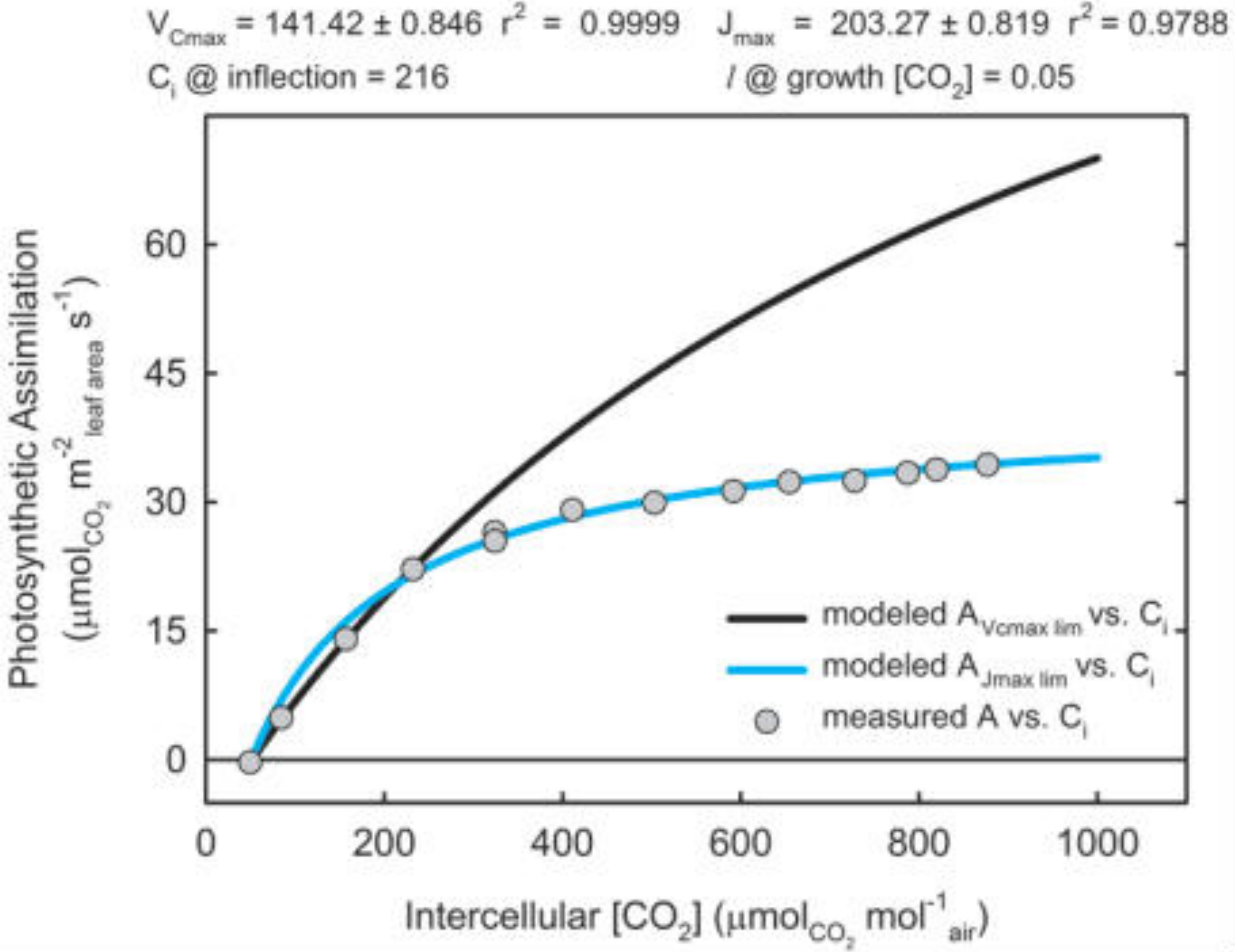
$$A = min\{J_C; J_E\} - R_d$$

Assim. Rate = min of electron transport limited rate and carboxylating rate JE, JC, & leaf dakr resp Rd; Gamma* is CO2 compensation point without leaf resp.

$$J_C = V_m \frac{C_i - \Gamma_*}{C_i + K_C(1 + \frac{O_x}{K_O})}$$

$$J_E = J \frac{C_i - \Gamma_*}{4(C_i - 2\Gamma_*)}$$


Limited by C fixation
Light limitation
Light saturation
Photo- oxidation
Light compensation point
Net photosynthesis (µmol m-2 s-1)
0
1000
2000
Irradiance (µmol m-2 s-1)



V_{Cmax} = 141.42 ± 0.846 r^2 = 0.9999 J_{max} = 203.27 ± 0.819 r^2 = 0.9788
C_i @ inflection = 216 / @ growth [CO_2] = 0.05
Photosynthetic Assimilation (μmol_{CO_2} $m^{-2}_{leaf\ area}$ s^{-1})
60
45
30
15
0
0
200
400
600
800
1000
Intercellular [CO_2] (μmol_{CO_2} mol^{-1}_{air})
modeled $A_{Vcmax\ lim}$ vs. C_i
modeled $A_{Jmax\ lim}$ vs. C_i
measured A vs. C_i

Electron transport rate

$$J = \frac{\alpha I J_{max}}{\sqrt{J_{max}^2 + \alpha^2 I^2}}$$

depends on I, alpha, Jmax

$I=IPAR/EPAR$ where $IPAR$ ($Wm-2$) is the PAR absorption rate $EPAR$ the energy content of PAR quanta (220 $kJmol-1$), $Jmax$ the maximum electron transport rate, ($mol(CO2)m-2s-1$ and α the efficiency of photon capture (0.28).

$NSCL$ is a Nitrogen scaling factor at maximum carboxylation rate and maximum electron transport rate.

$$J_{max} = E_{transport} * NSCL * (T - 273.15)/25.$$

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Exploring Farquhar’s Eqn

- An IPython notebook you can use to familiarise yourself with the Farquhar Photosynthesis model:

http://bit.ly/1eAm2xz

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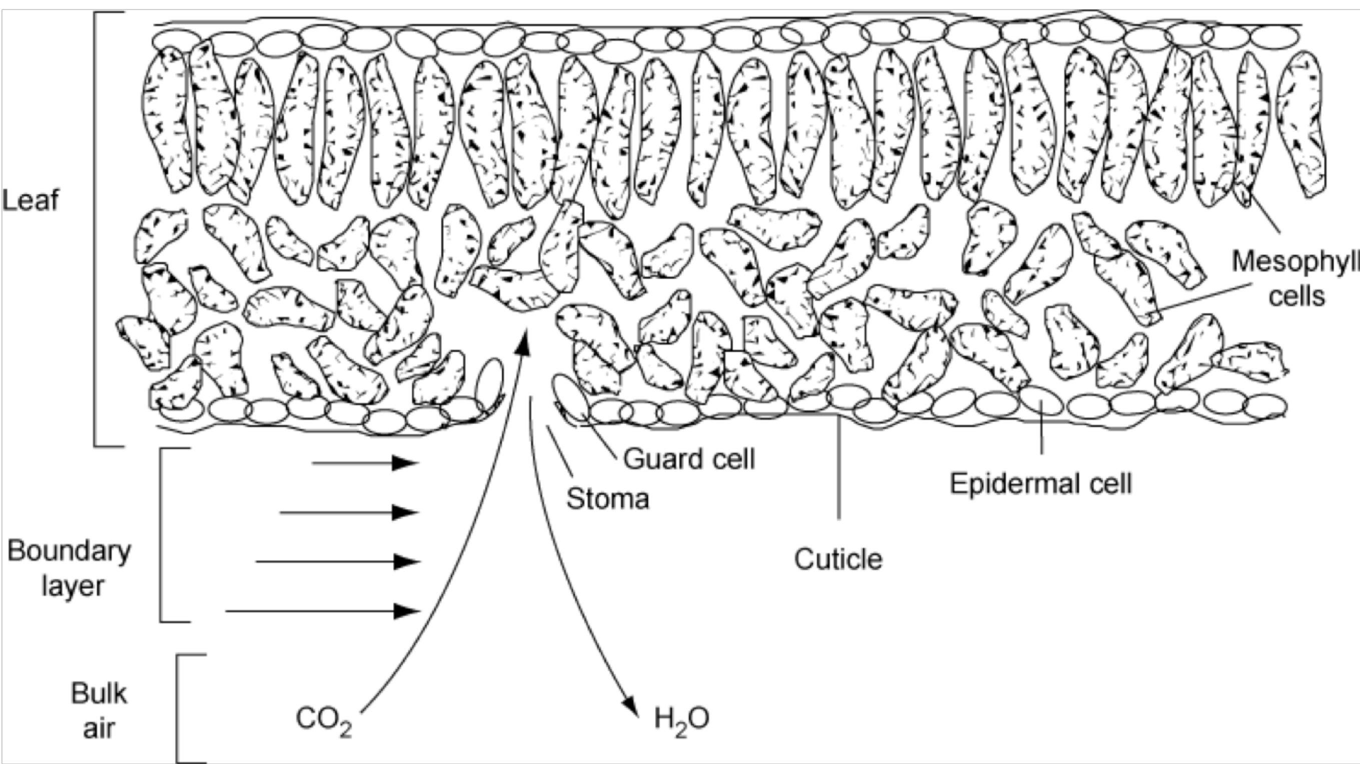
Stomatal conductance

when plants decrease stomatal conductance (increase resistance) to minimise water loss, photosynthesis declines redcuing the efficiency at which plants convert light to carbohydrates



Model of stomatal conductance

Non water stressed:

$$G_{c,0} = \frac{1.6 A_{c,0}}{C_a - C_{i,0}} \frac{R T_K}{p}$$

Often strong relationship between $G_{c,0}$ and assimilation:

$$G_{c,0} = 0.883 A_{c,0}$$

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5. Modelling Photosynthesis

Summary

- outlined the 'Farquhar' approach to modelling photosynthesis, that is used in this or related forms in most DGVMs.
- Relates carbon assimilation rate to the minimum of two potentially limiting factors
  - the electron transport limiting rate and
  - a carboxylating rate,
  - with leaf 'dark' respiration subtracted.
- it relates carbon assimilation to ambient CO2 concentrations.
- outlined some concepts about what controls stomatal conductance.
  - important concept because it can limit carbon assimilation and relates to water use by the leaf (transpiration).

Summary

- more detail considering processes in vegetation canopies (and their interface to the atmosphere and soils).
- outlined land surface schemes and models as the ‘containers’ (in e.g. an Earth system model) for models of vegetation process.
  - considered carefully energy and water balances.
- outlined some basic concepts in vegetation growth, and reviewed the development of current LSMs, highlighting the inclusion of carbon fluxes in the current generation.
- reviewed the structure of DGVMs, and considered in detail PFTs and parameterisation of DGVMs, highlighting trait databases as a useful source of information on this .
  - looked into how well we can tell DGVMs are operating, concluding that the current generation show a significant amount of scatter, but they agree broadly in some key areas.

Summary

- PEMs as a viable (more data-driven) approach to modelling NPP.
  - We saw that again there is a lot of scatter in NPP estimates, but those produced by the PEMs are broadly in agreement with those from the DGVMs and other more mechanistic approaches.
- phenology in some detail, highlighting the mechanisms and modelling approaches.
- some of the basic equations for photosynthesis and stomatal conductance as used in most DGVMs

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