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IAEA International Atomic Energy Agency

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Workshop on Theoretical Ecology and Global Change

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Developing a Predictive Science of the Biosphere

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Developing a predictive science of the biosphere

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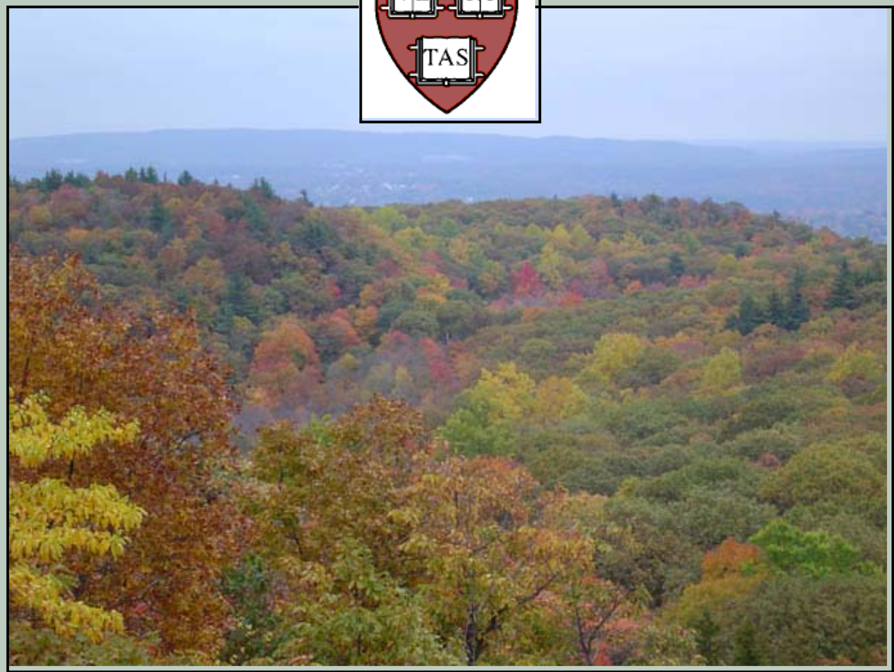
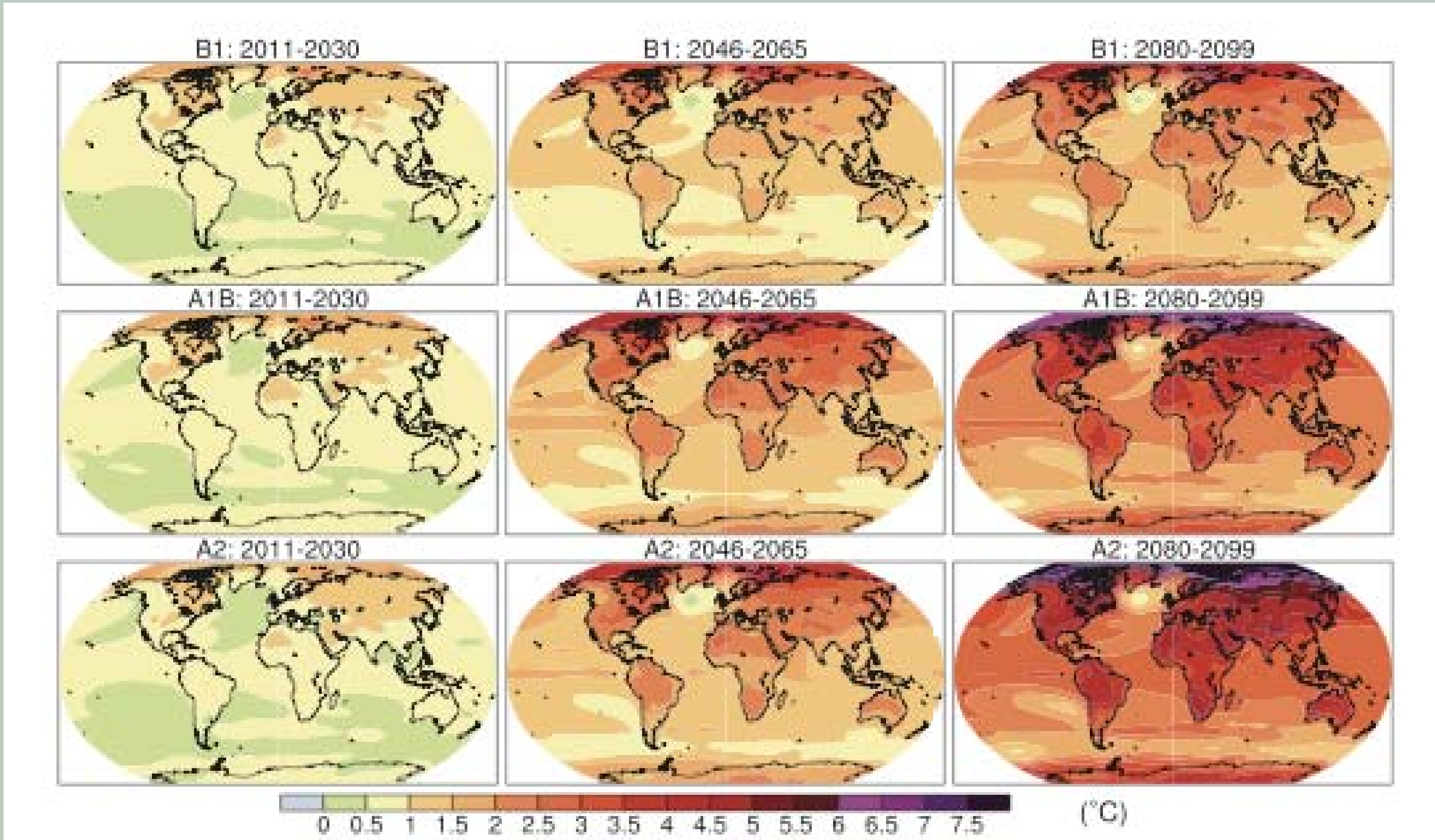
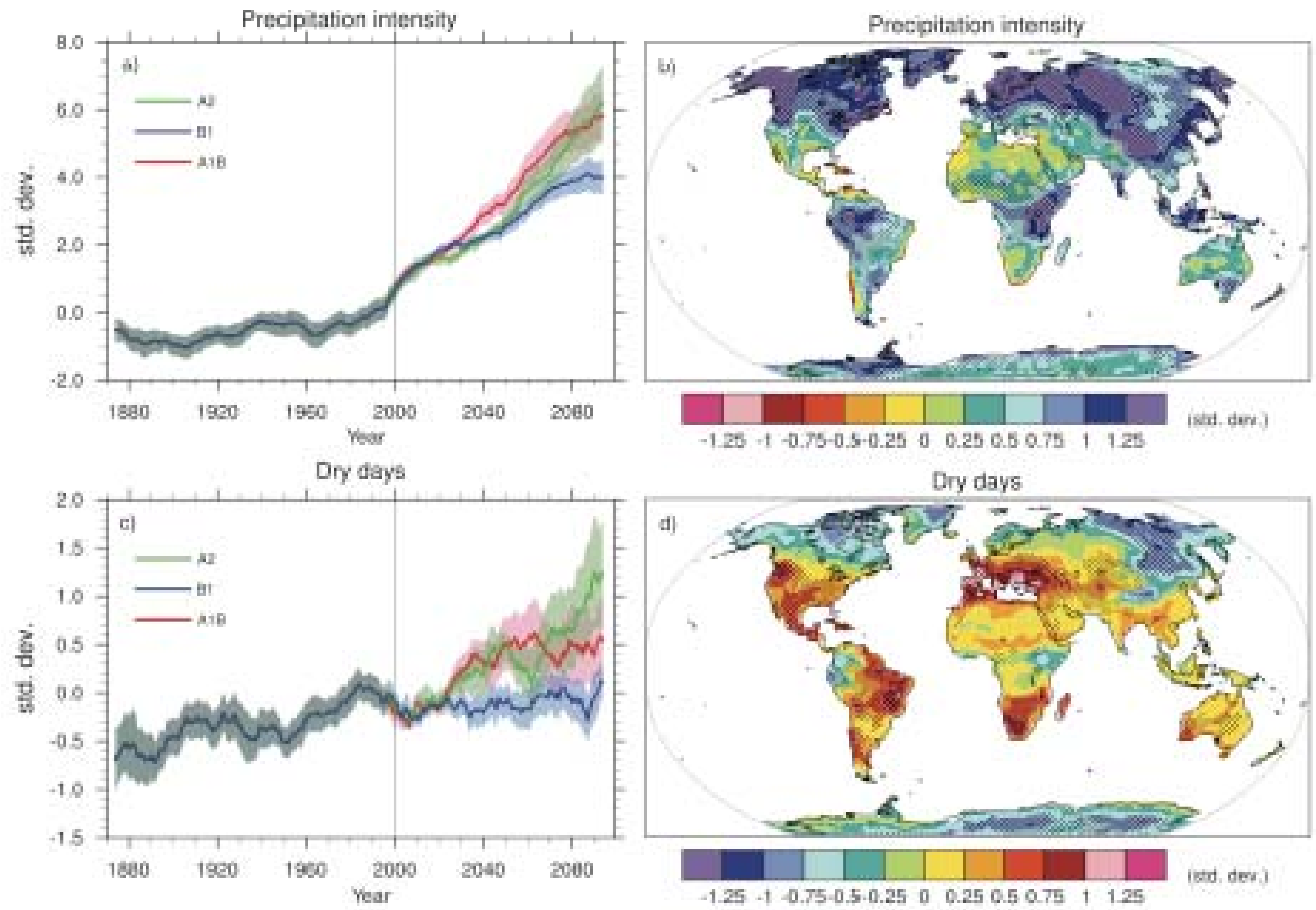


Overview

- Background
- Approaches to modeling the terrestrial biosphere
- Structured ecosystem models

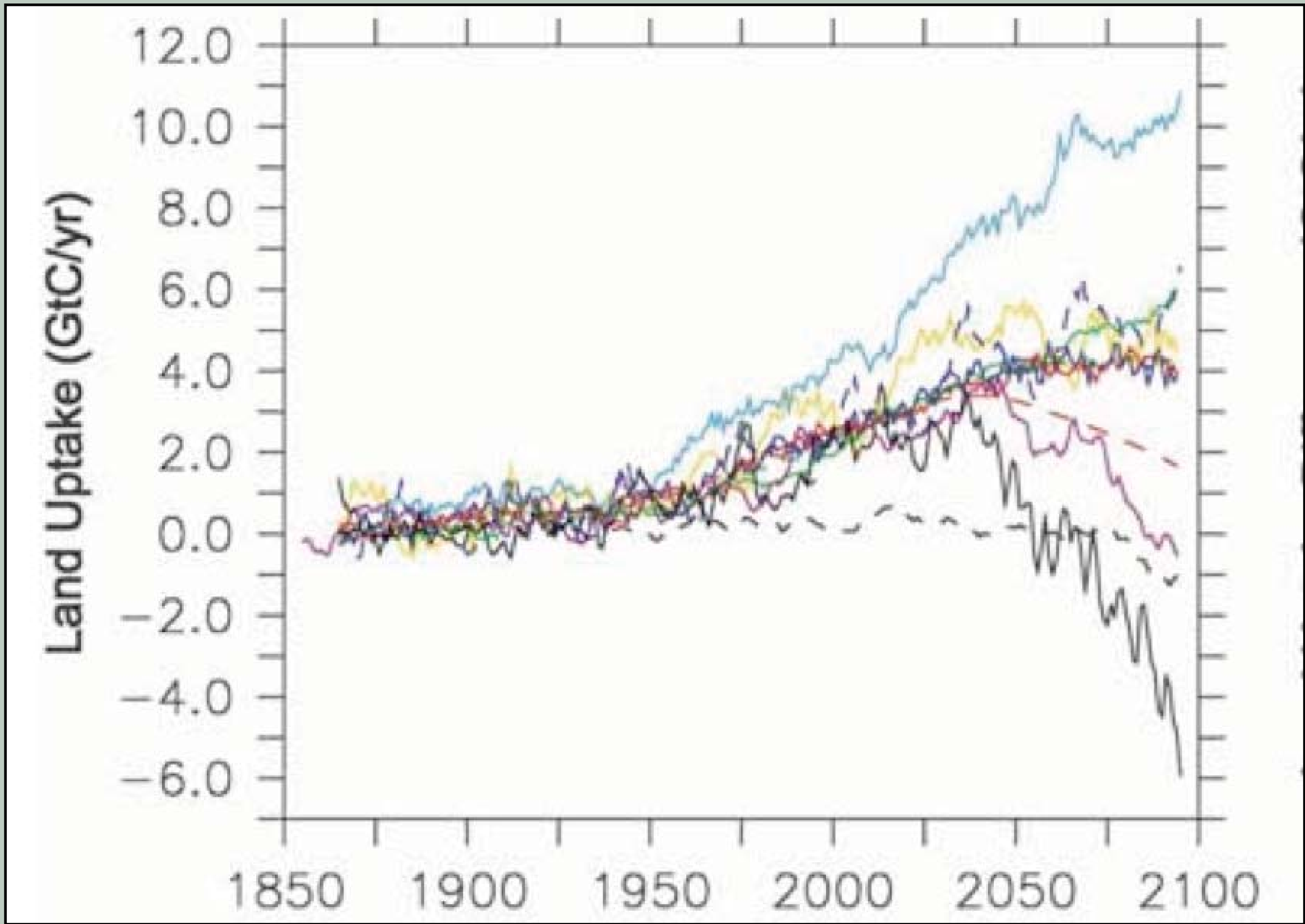
Predicted temperature changes over the coming century





Precipitation intensity
a)
A2
B1
A1B
std. dev.
8.0
6.0
4.0
2.0
0.0
-2.0
1880
1920
1960
2000
2040
2080
Year
Precipitation intensity
b)
-1.25
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
1.25
(std. dev.)
Dry days
c)
A2
B1
A1B
std. dev.
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1880
1920
1960
2000
2040
2080
Year
Dry days
d)
-1.25
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
1.25
(std. dev.)

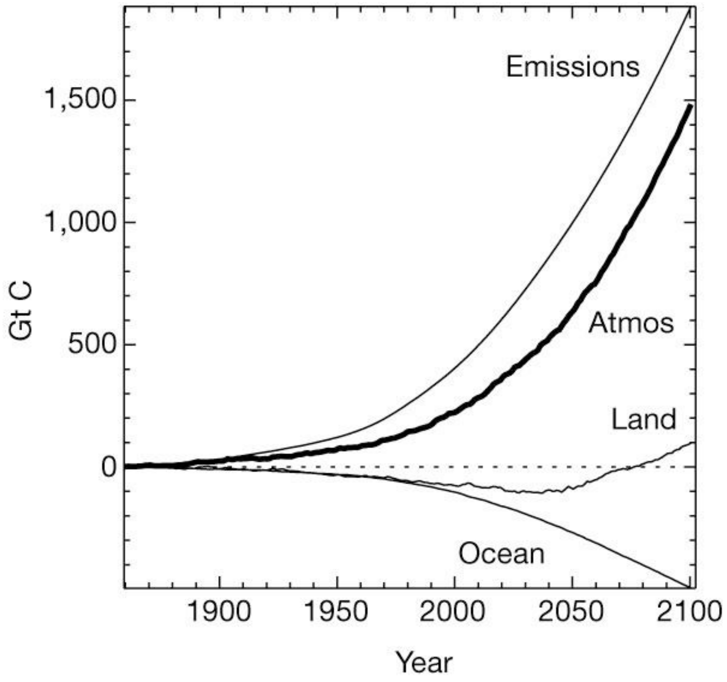
Predictions for the long-term responses of terrestrial ecosystems to climate change (IPCC 2007)

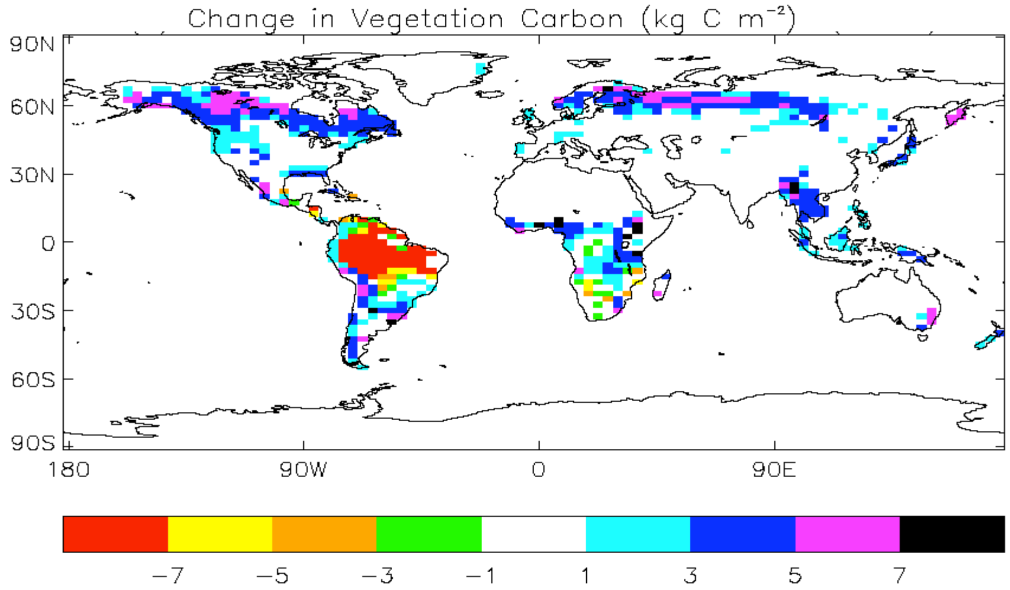


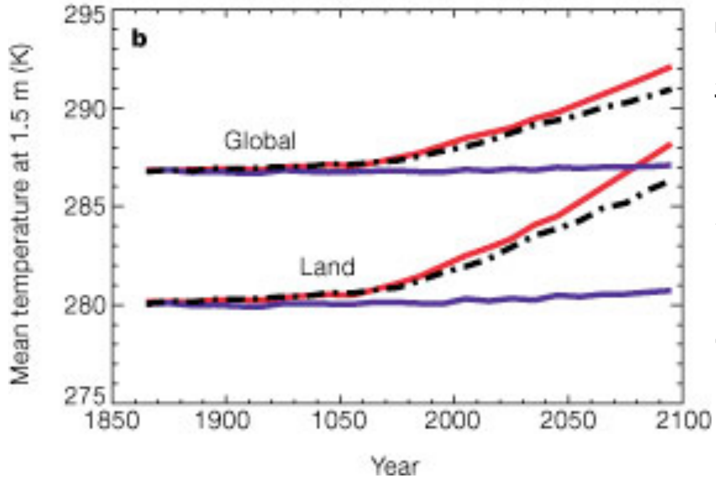
HadCM3LC (solid black), IPSL-CM2C (solid red), IPSL-CM4-LOOP (solid yellow), CSM-1 (solid green), MPI (solid dark blue), LLNL (solid light blue), FRCGC (solid purple), UMD (dash black), UVic-2.7 (dash red), CLIMBER (dash green), and BERN-CC (dash blue).

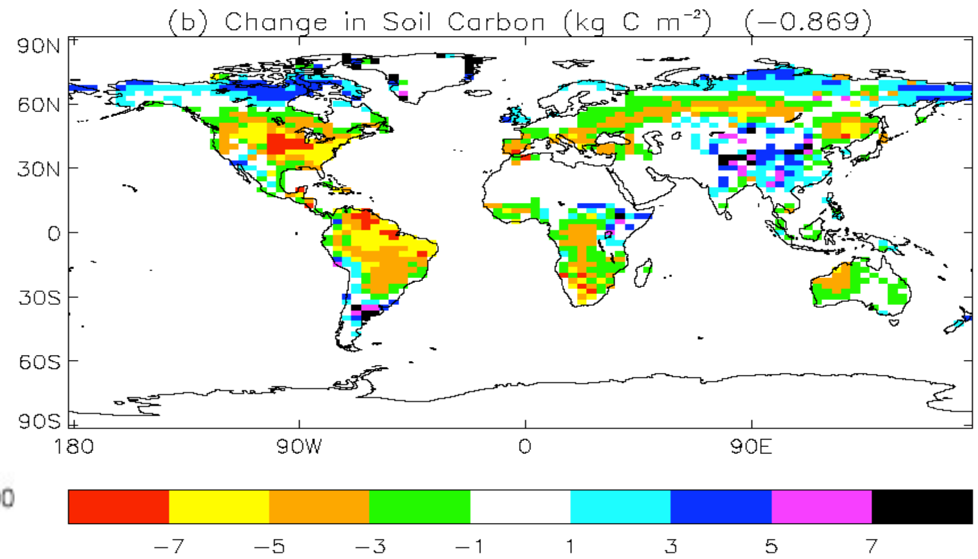
(Cox et al. 2000)

HadCM3LC: Predicted collapse of Amazon ecosystems in response to rising CO_2



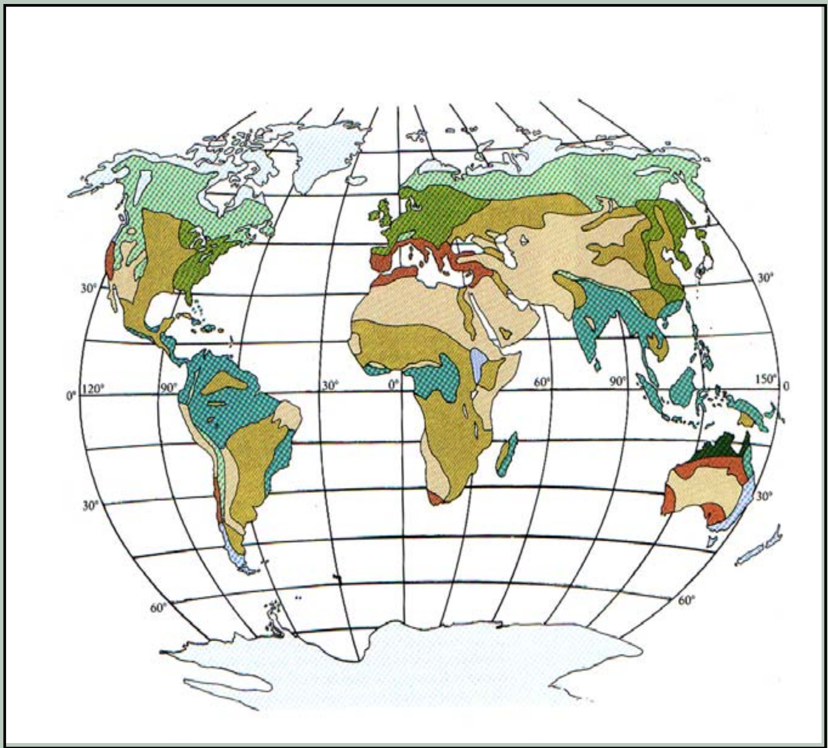


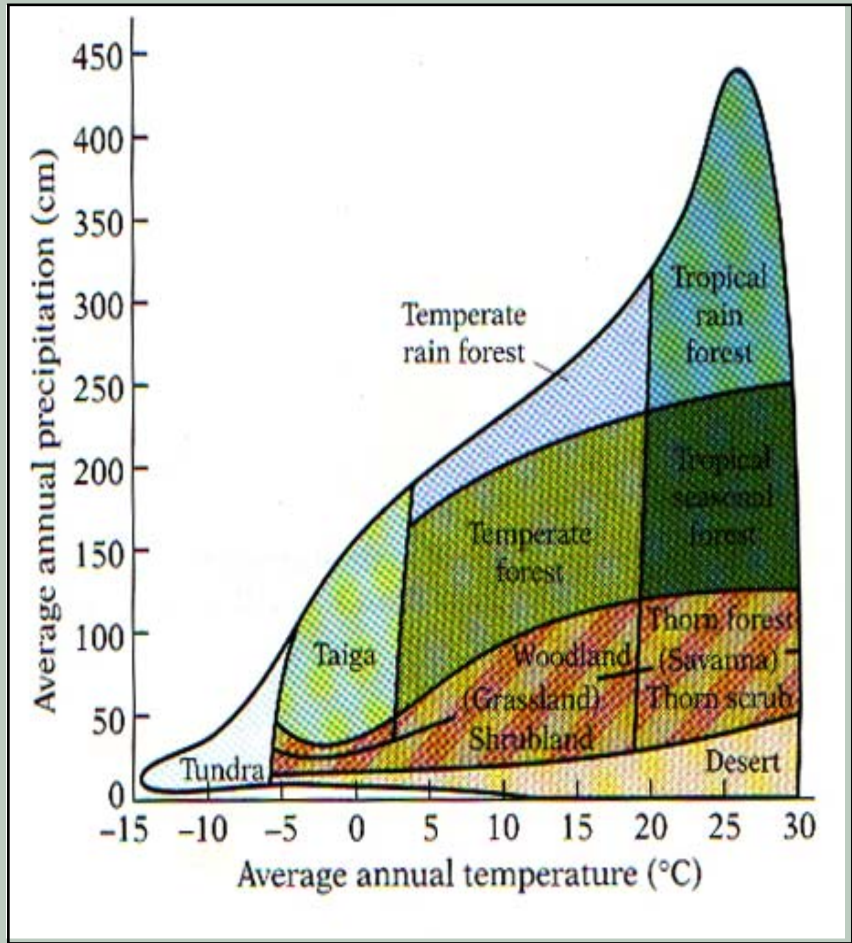




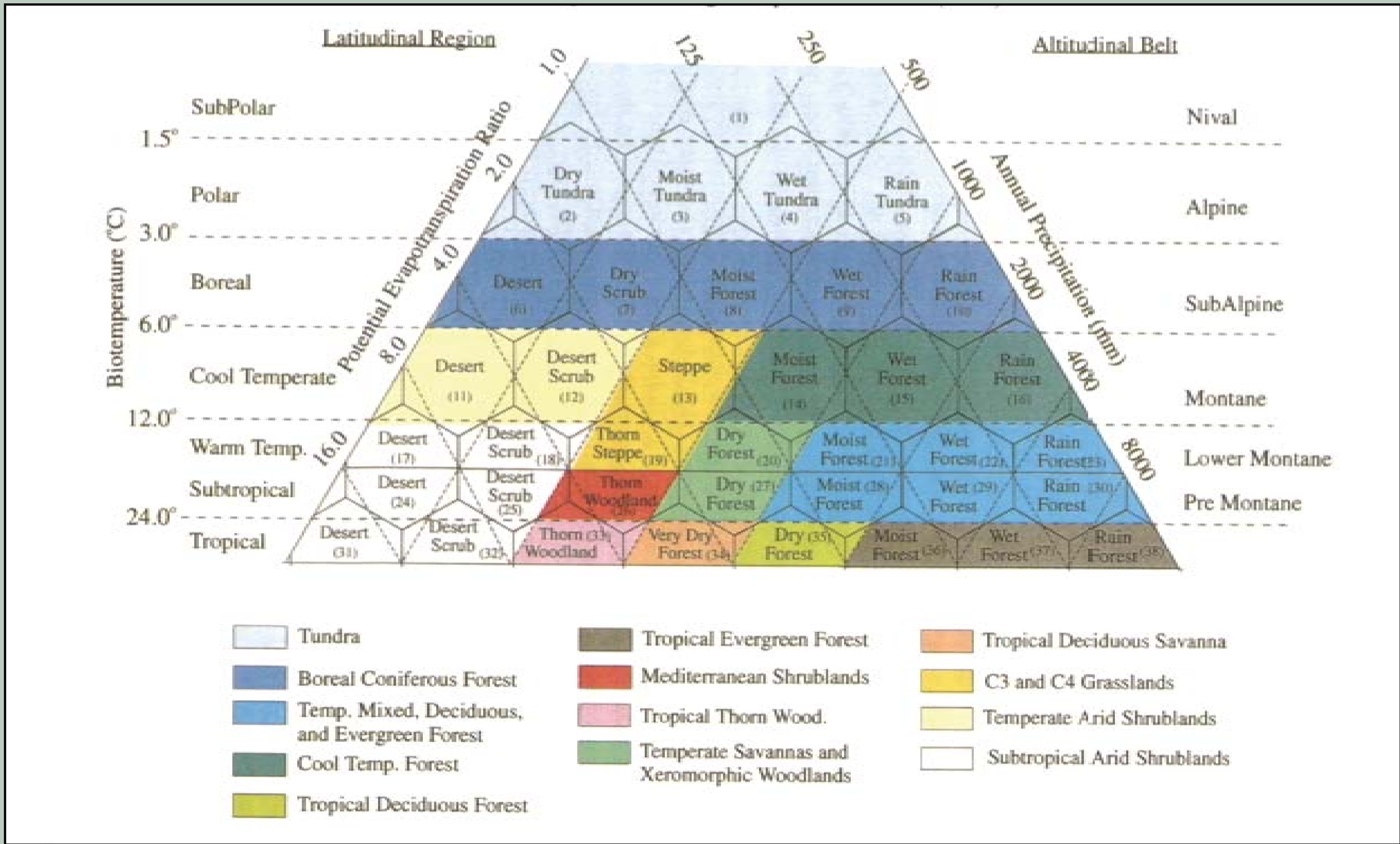
• Biogeographic models

Whittaker biogeographic scheme: biome type in relation to average annual temperature & precipitation





Holdridge classification scheme



Potential Evapotranspiration Ratio = potential evapotranspiration/precipitation

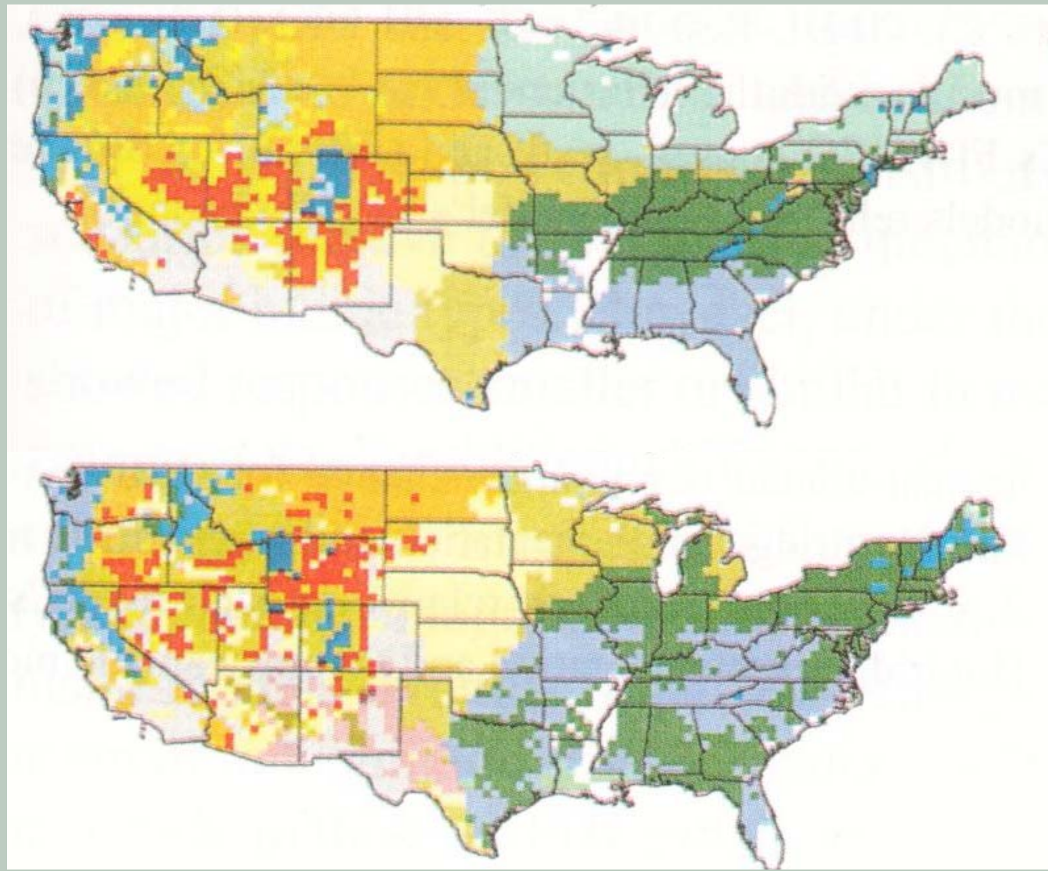
Biotemperature = Average of temperatures > 0^oC

“Vegetation is crystallized, visible climate” (Koppen, 1936)

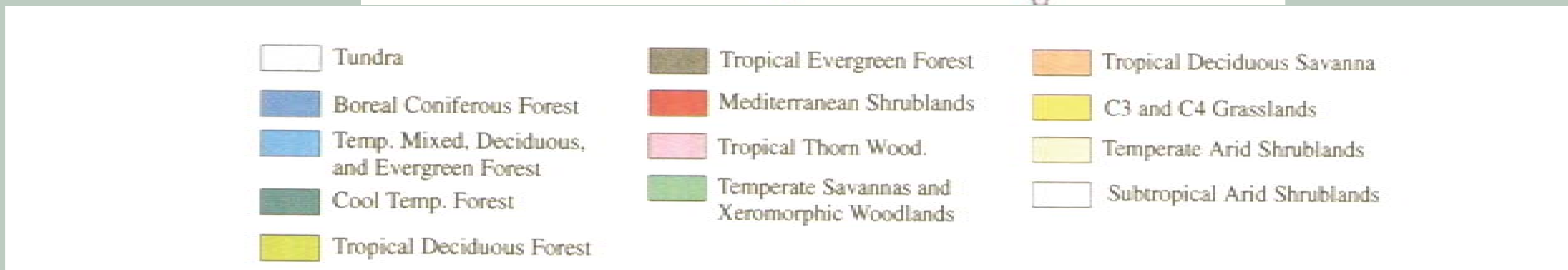
Using Biogeographic Vegetation Models to predict the effects of climate change

1 x CO_2

2 x CO_2



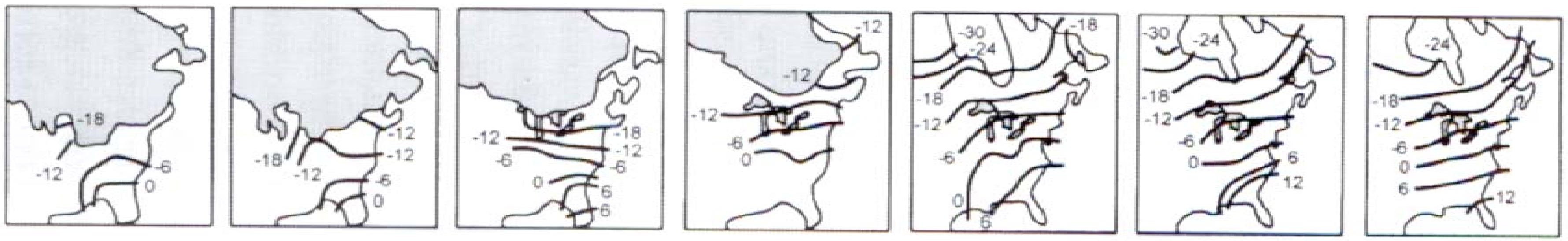
(Holdridge classification Scheme)

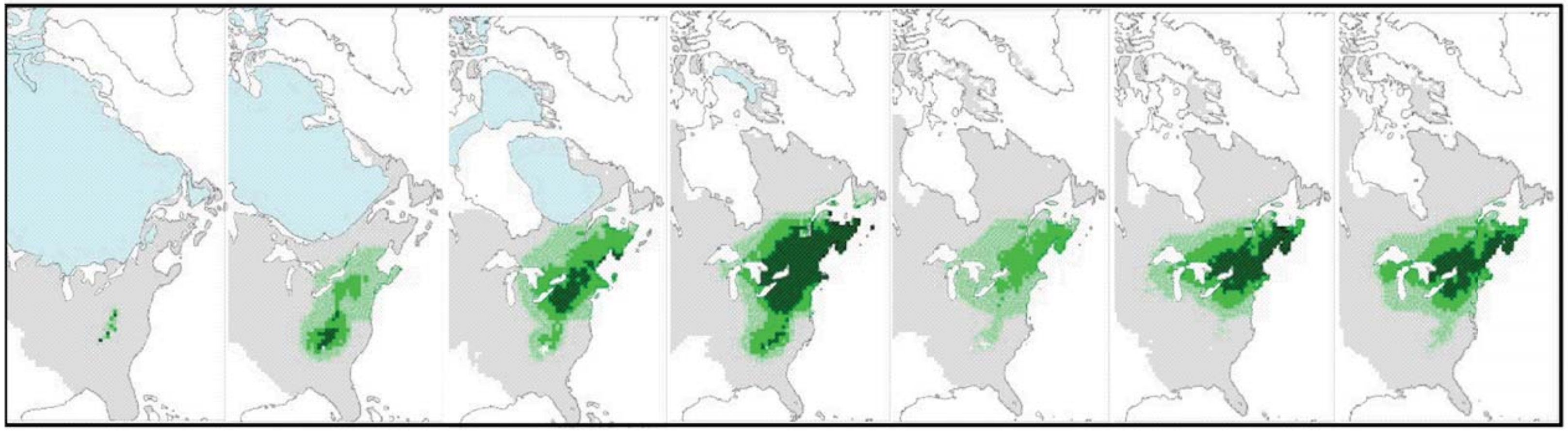


Problems with the Biogeographic approach

Issue #1: assumes ecosystems are in equilibrium with climate, both now & in the future.

Mean January Temperature (°C)





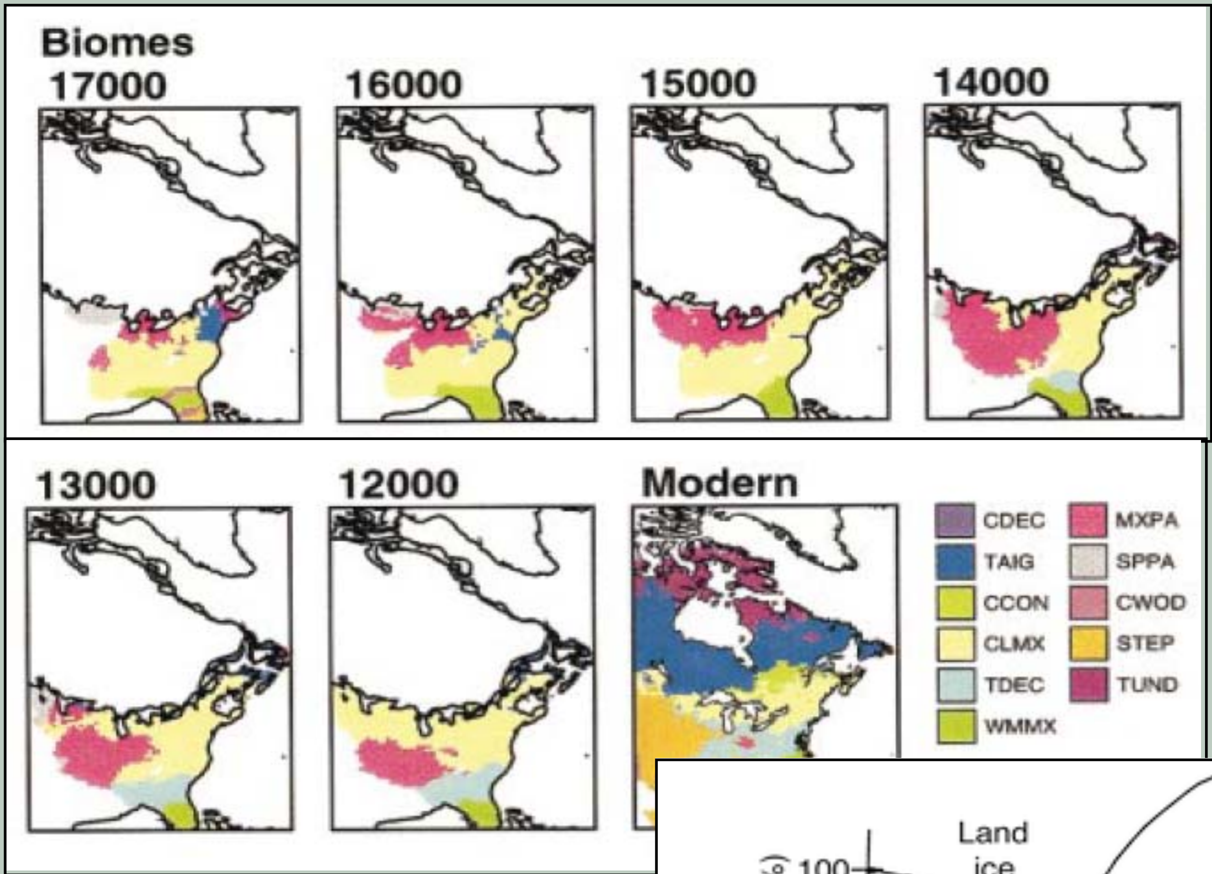
14,000 10,000 8,000 6,000 4,000 2,000 500

Years before present

Hemlock abundance: 0 to 1 | 1 to 5 | 5 to 10 | 10 to 100

(Williams et al 2001)

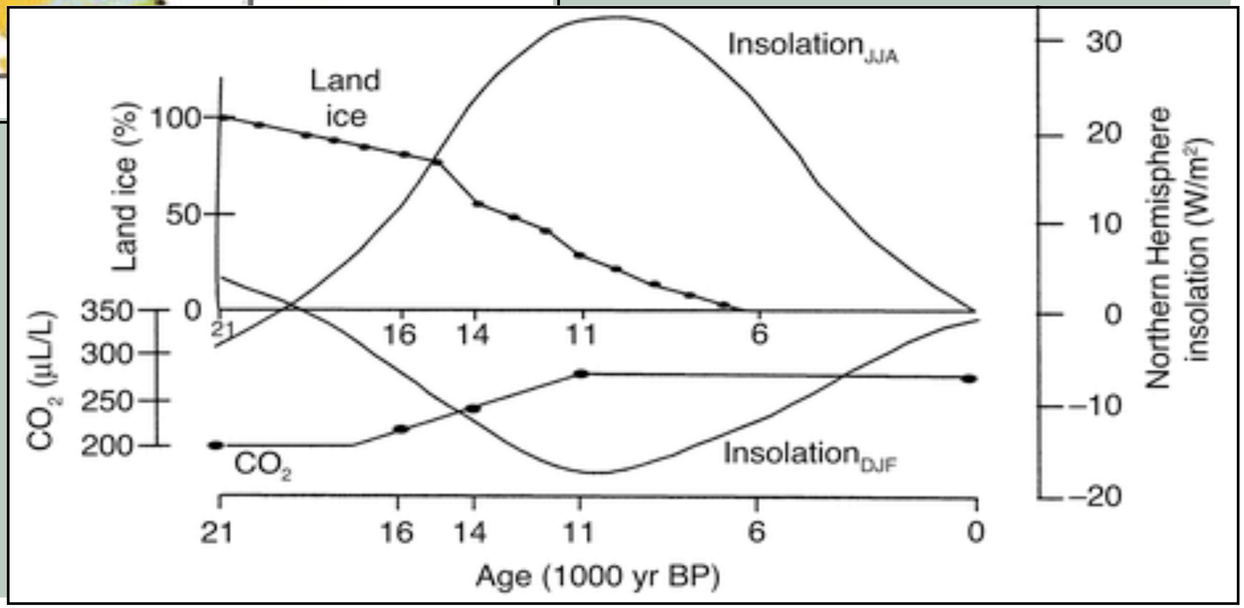
Issue #2: “No-analog communities”



<u>MXPA= Mixed Parkland</u>
[spruce, larch, ash, hornbeam, poplar, willow, sedge, and sage]

MXPA termed a a ‘no-analog community’ because these species are not found together in any present-day vegetation community.

i.e. Distribution of biomes is a macroscopic pattern arising from the responses of the constituent species to climate forcing.



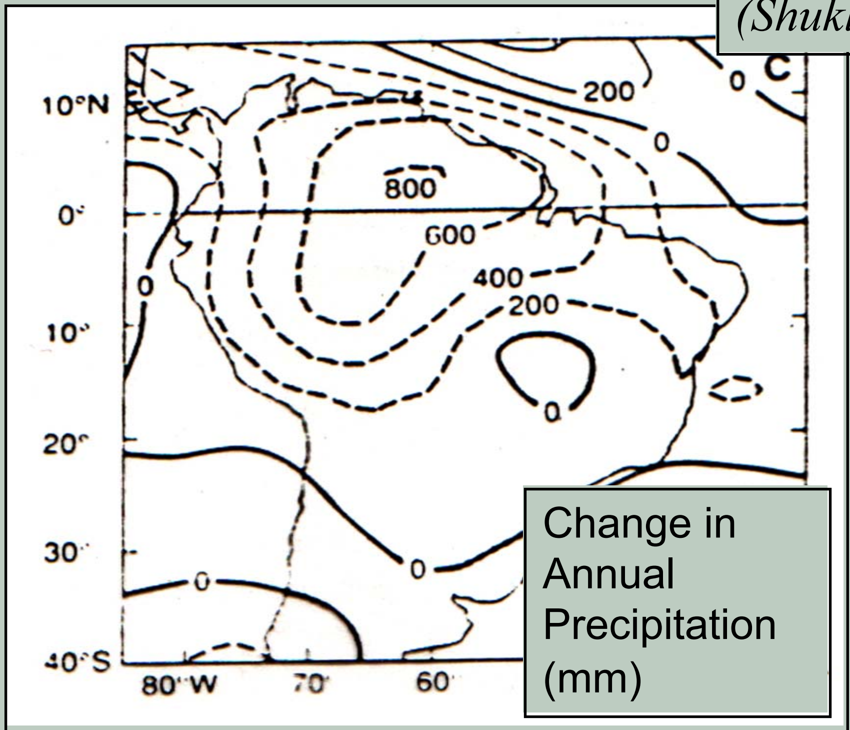
Issue #3: Biosphere-atmosphere feedbacks

- the biogeographic approach implicitly assumes a unidirectional relationship between ecosystems and climate:

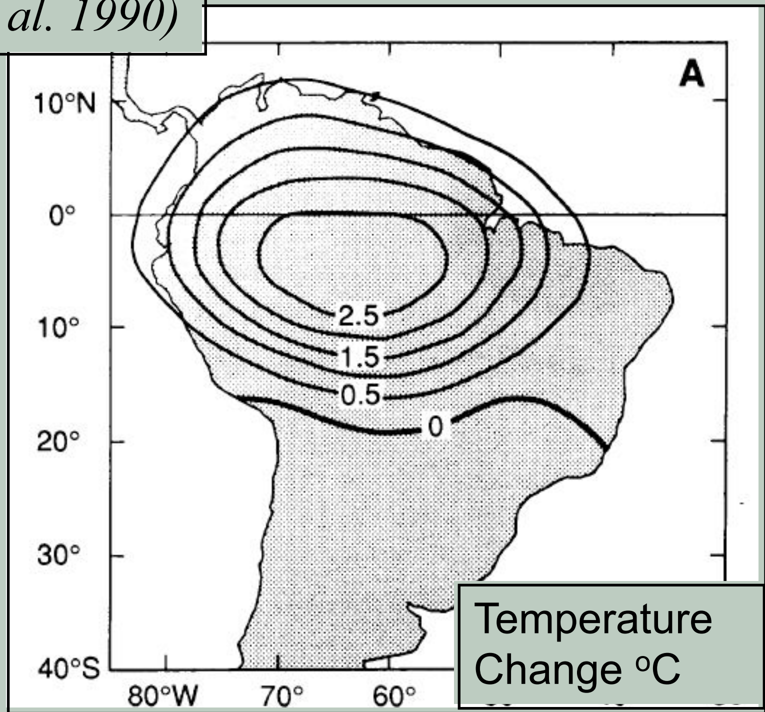
- now know that this relationship is bi-directional.

e.g: Amazonian deforestation predicted to change South American climate

(Shukla et al. 1990)

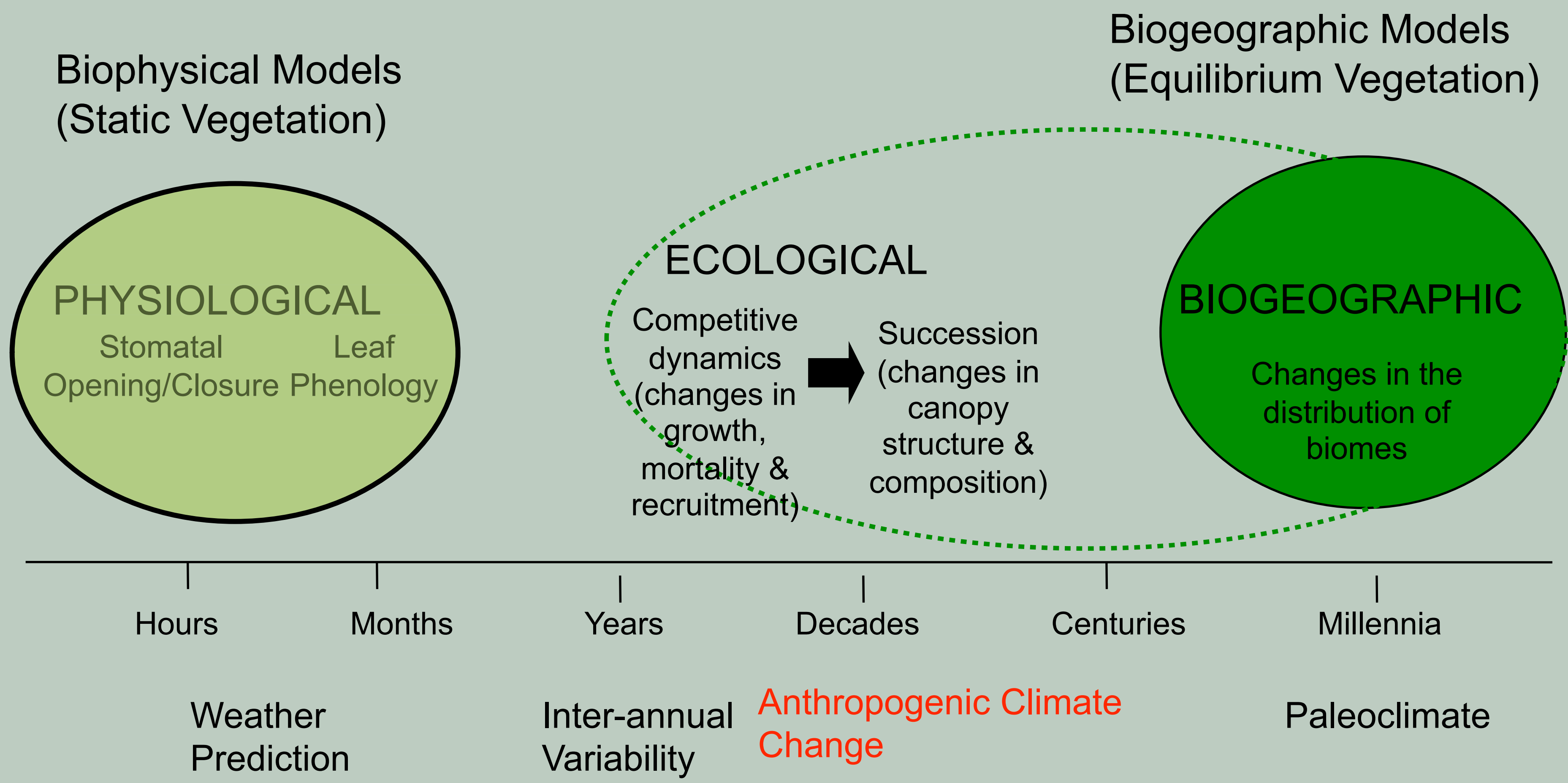


Change in Annual Precipitation (mm)

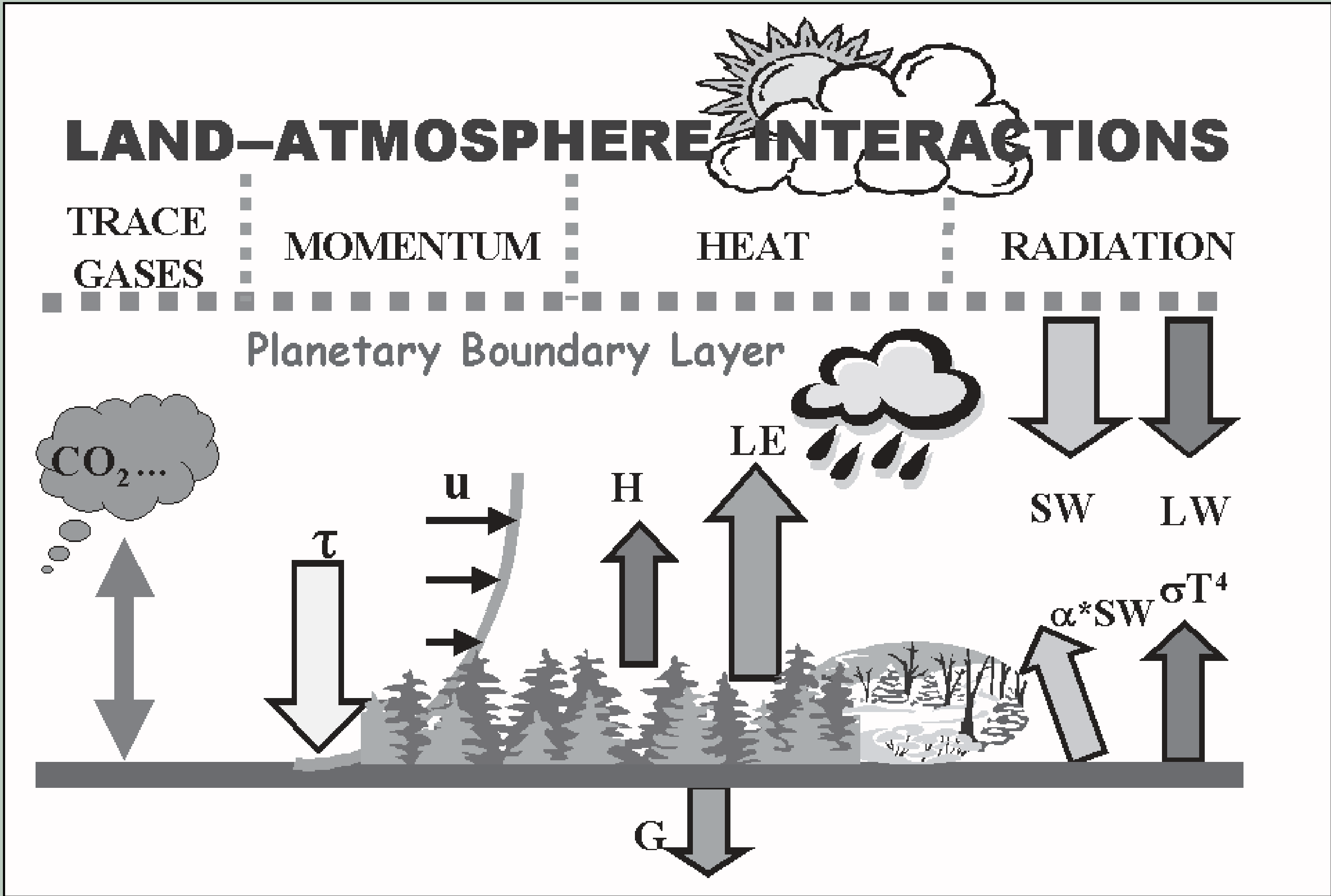


Temperature Change °C

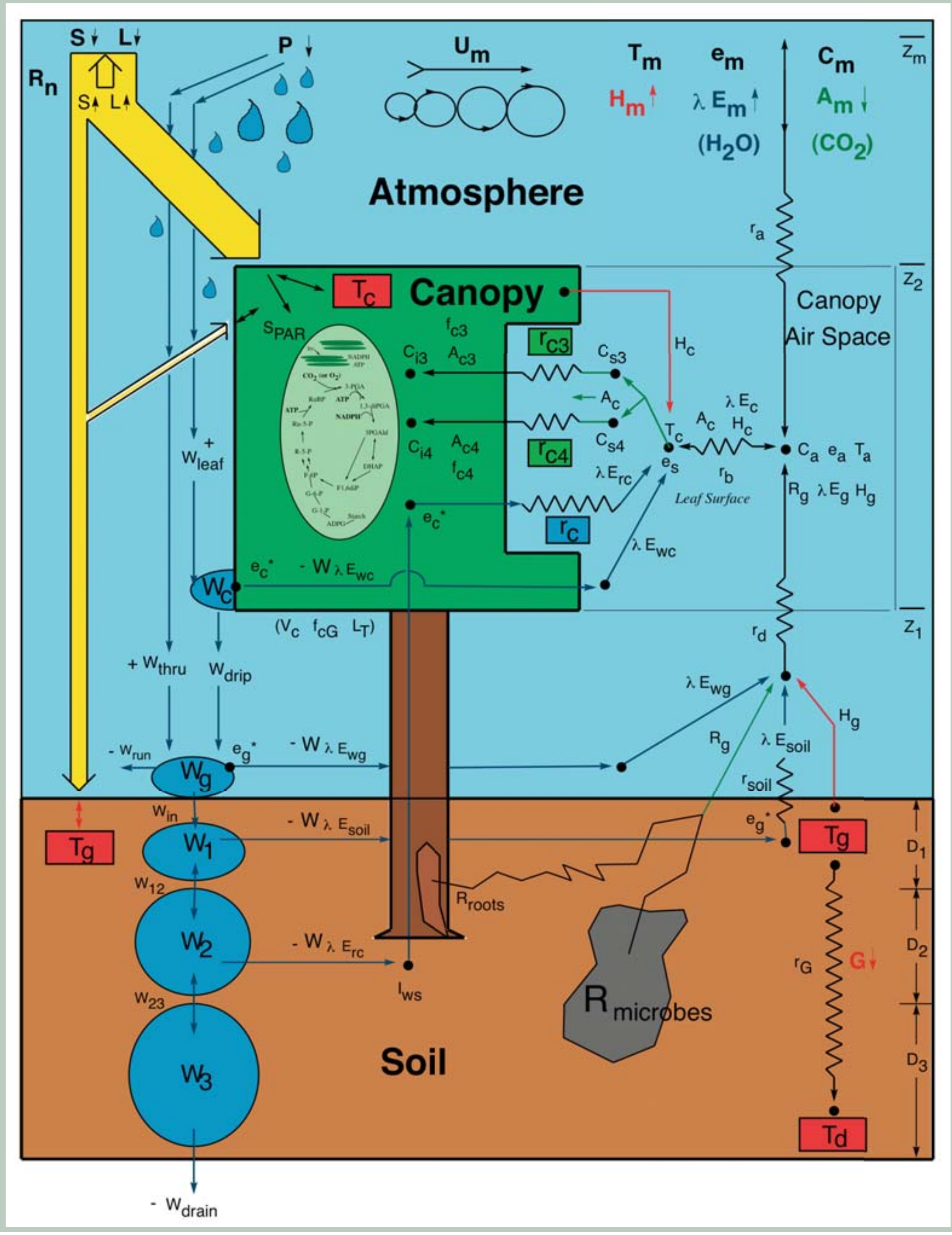
Timescales of Terrestrial Ecosystem Responses to the Atmosphere



Biosphere-Atmosphere Feedback Processes

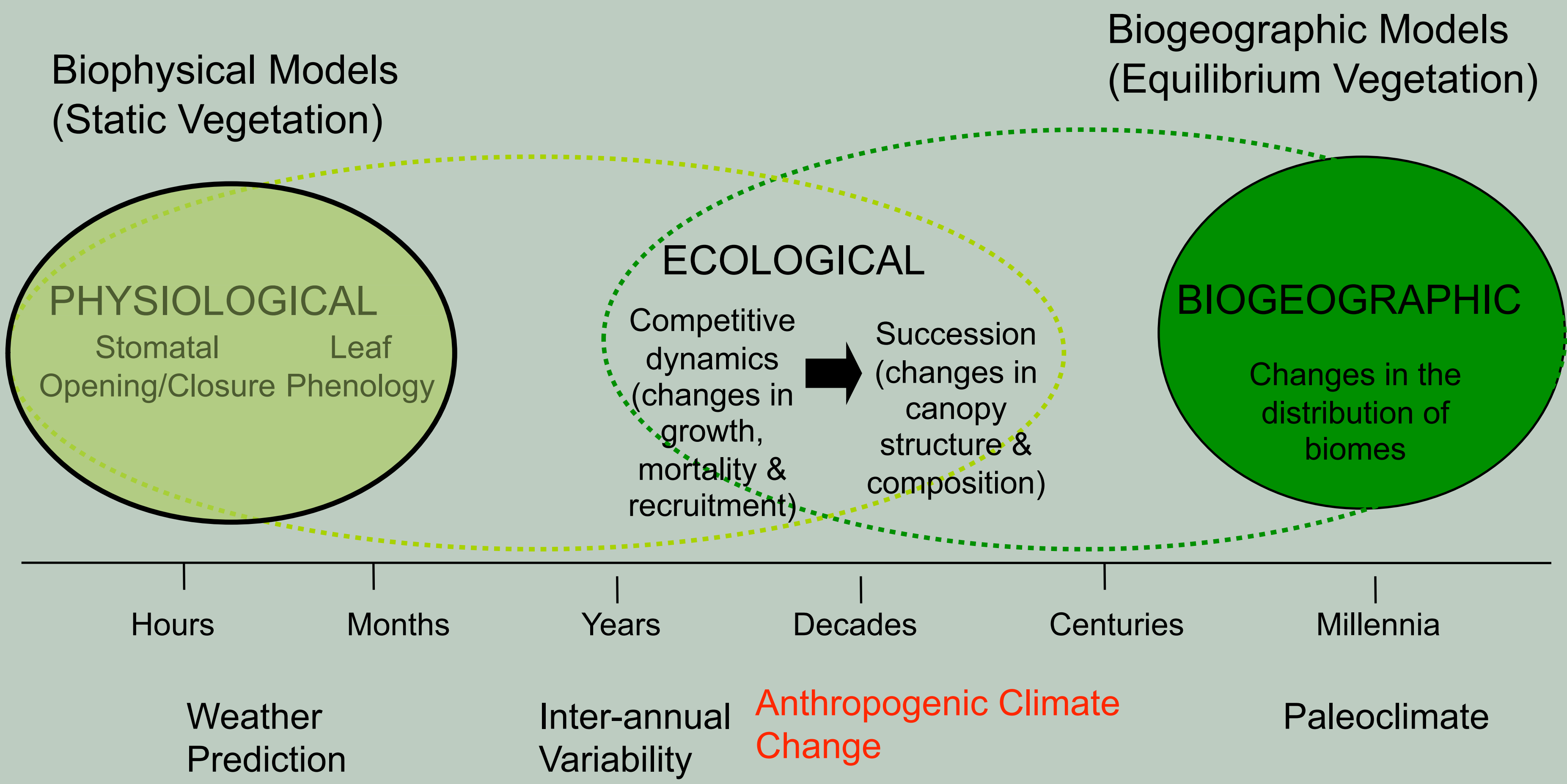


e.g. The Simple Biosphere Model, version 2 (SiB2) (Sellers et al. 1996)



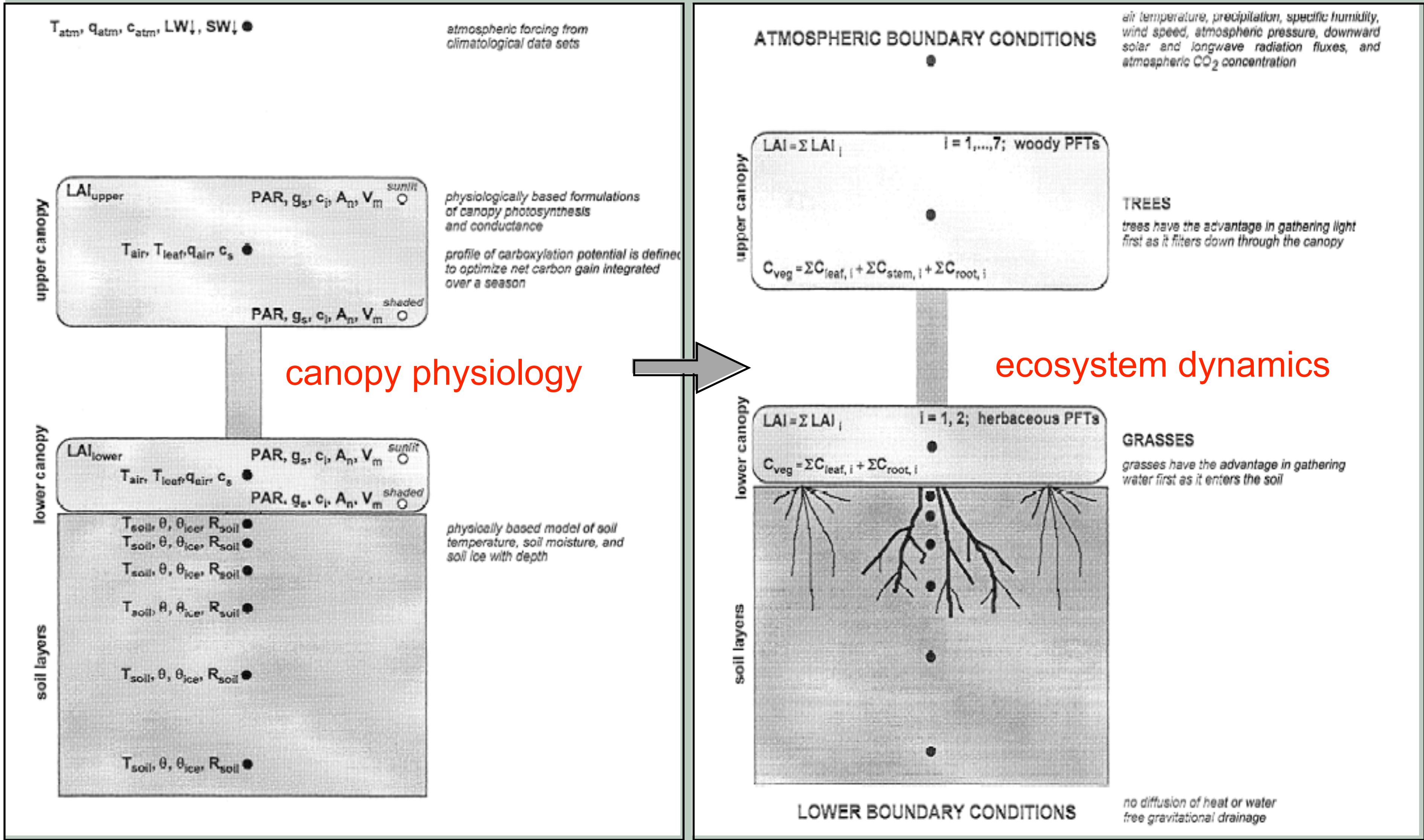
SiB2 was one of the first terrestrial biosphere models to explicitly link canopy biophysics with a biological of photosynthesis

Timescales of Terrestrial Ecosystem Responses to the Atmosphere



The Integrated Biosphere Simulator (IBiS) (Foley et al., 1996)

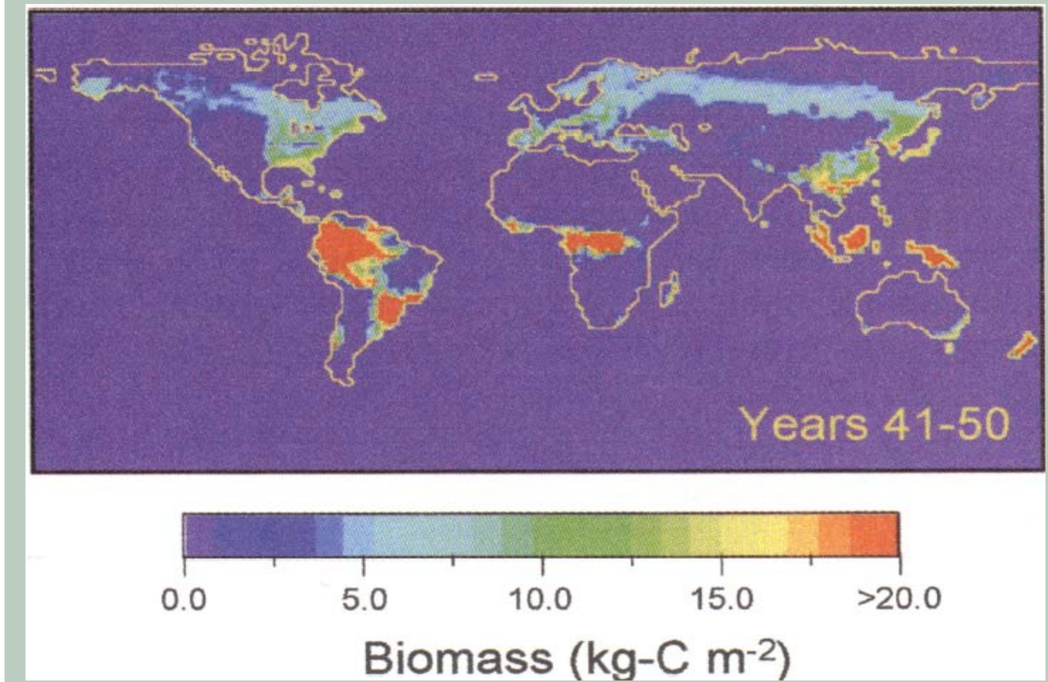
- IBiS was the first biosphere model to incorporate long-term ecosystem dynamics



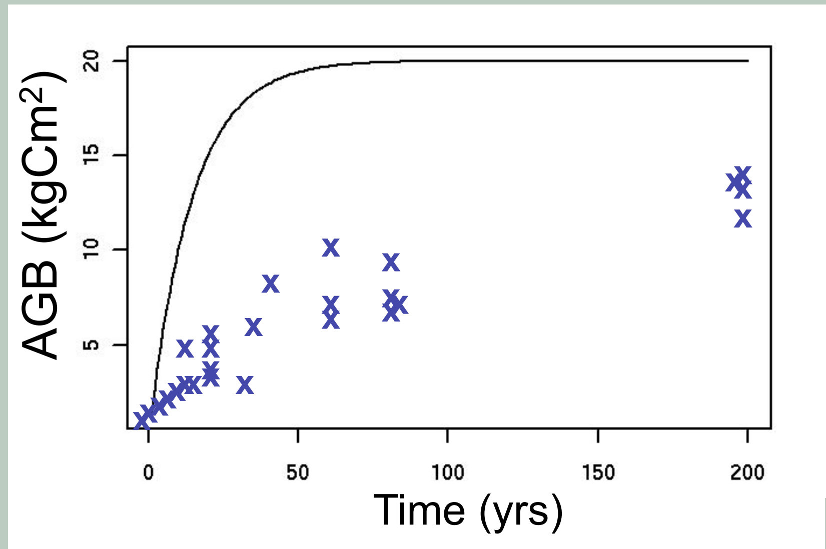
scale: $1^o \times 1^o$ ($\sim 10^4$ km^2)

Long-term ecosystem dynamics in big leaf terrestrial biosphere models

Above-ground biomass dynamics of evergreen tree spp. in IBiS



Comparison of above-ground biomass dynamics to observations at San Carlos (tropical forest) 2^{o}N,68^{o}W



- Unrealistic timescales of response

- Also the big-leaf assumption implies a single environmental niche within each grid cell. As a result, big-leaf models tend to predict homogeneous ecosystems (Gause competitive exclusion principle).

The long timescale at San Carlos is due to the ecological process of succession (changes in structure and composition as the ecosystem re-assembles following disturbance).

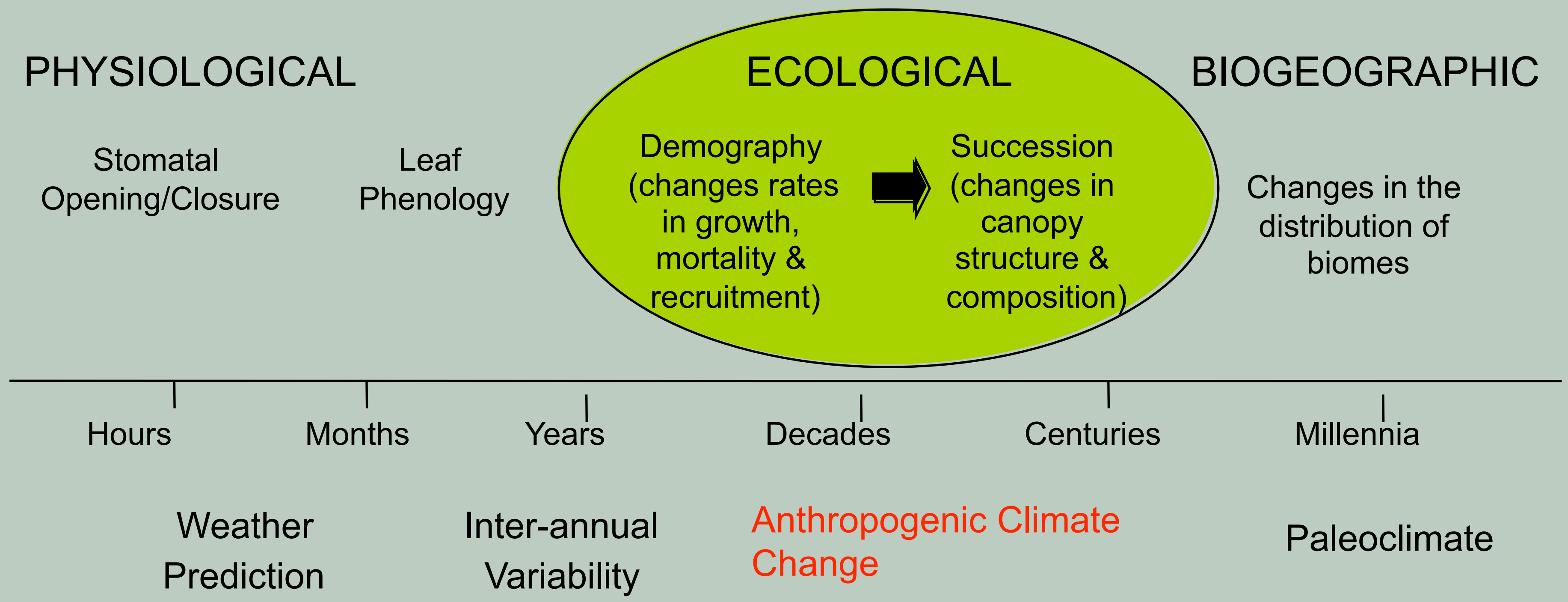
Successional heterogeneity at the San Carlos tropical forest 2°S,68°W

Stand Age (0-200 yrs) -->

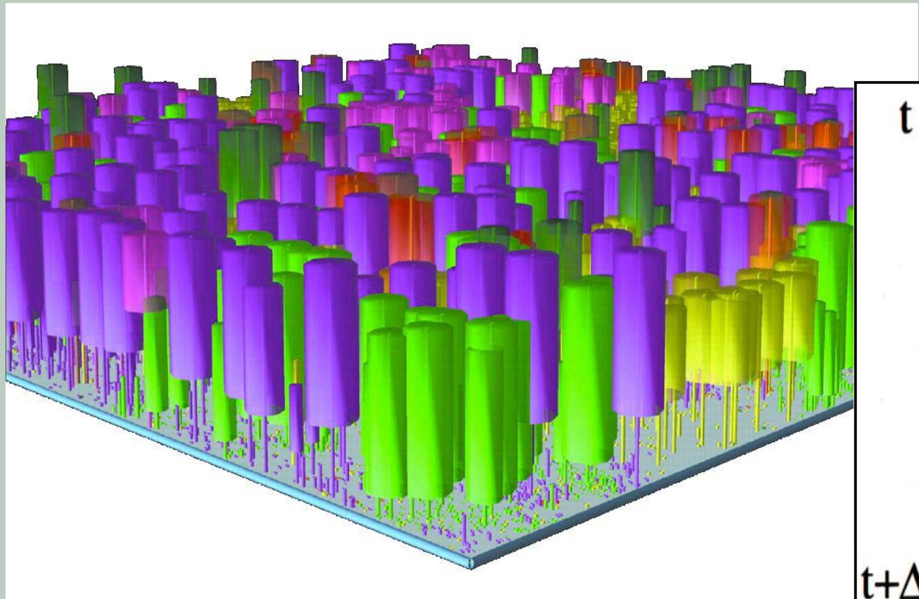
Species -->

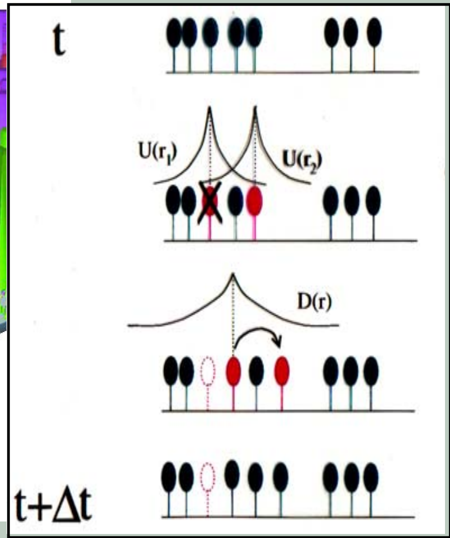
Species	Stand number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Vismia japurensis Reich	33	32		27		11																	
Cecropia sp.	26	15																					
Bellucia grossularioides (L.) Triana		21	21	33					16		18												
Ocotea opifera Martius			15					9															
Unidentified species (Bombacaeae)			13																				
Vochysia sp.					21												6		11				
Sclerolobium sp.					13			6										10					
Goupia glabra Aublet					11				20	12	12		18	14	15			14	7				
Vismia lauriformis cf. (Lam.) Choisy					8		13																
Inga sdp.						11		6											6				
Astrocaryum sp.						10	27			6								6					
Guatteria schomburgkiana Martius						6			10														
Alcornea sp.						5		7						5	15	8		6					
Myrcia bracteata (Rich.) D.C.							12																
Unidentified species								13															
Bellucia sp.								8			7							8					
Ormosia esmeraldana Moldenke ex Gleas.									8														
Eperua purpurea Bentham										24		13		5					23	22			
Humeria balsamifera (Aublet) St. Hil.										12	17	40	36						7				
Vochysia obscura Warming														9	7	12	15						
Jacaranda copaia (Aublet) D. Don														8									
Aspidosperma sp.														6			13						
Monopterix uaucu Spruce ex Bentham														5									
Conceveiba guianensis Aublet															7	13						5	
Ocotea sp.															5							6	
Unidentified species (Arecaceae)																12							
Protium sp.																8		6			18		10
Poraqueiba sericea Tul.																	13						
Unidentified species																				11			
Caryocar glabrum (Aublet) Pers.																				9			
Micrandra sprucei (Muell.-Ar.) Schultes																				8			
Mouriri uncitheca Morley Wurdack																				6			
Unidentified species																				5			
Virola surinamensis (Rolander) Warb.																				5			
Dialium guianensis (Aublet) Sandw.																				4			
Xilopia spruceana Bentham																				4			
Eschweilera sp.																					10		
Swartzia schomburgkii Bentham in Martius																						15	19
Jessenia bataua (Mart.) Burret																						9	
Unidentified species																						7	
Unidentified species (Sapotaceae)																						6	
Iryanthera sp.																						4	
Cedrelinga sp.																							15
Virola calophylla (Spruce) Warb.																							8

Timescales of Terrestrial Ecosystem Processes



Individual-based vegetation models (gap models)



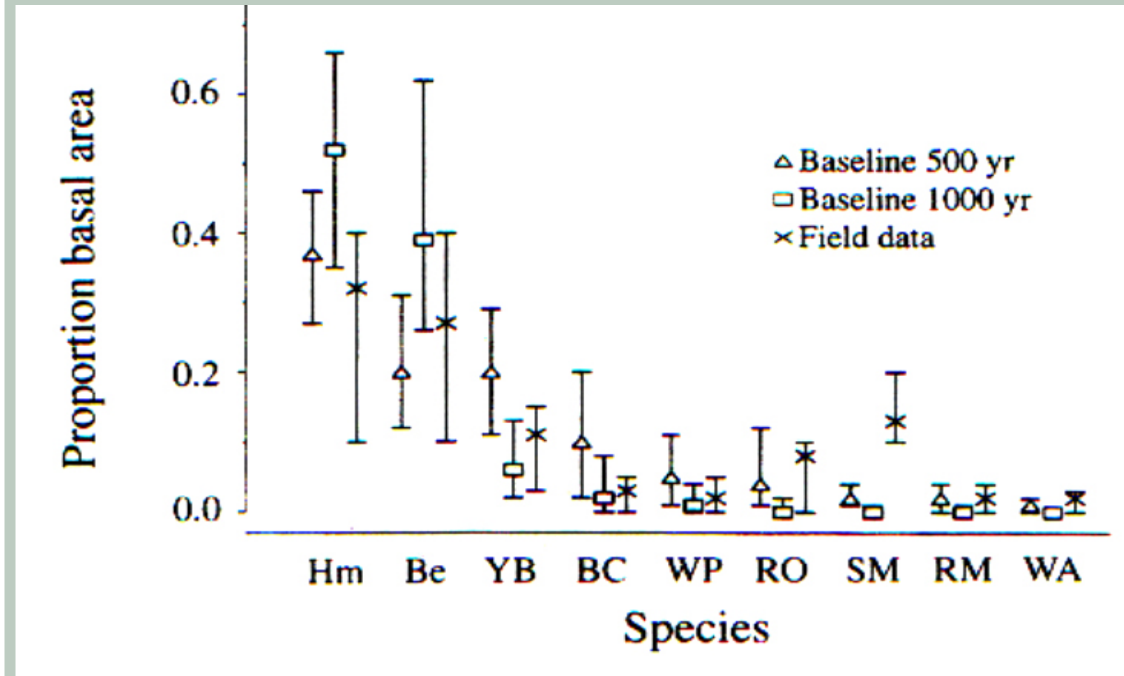


growth

height-structured competition

mortality

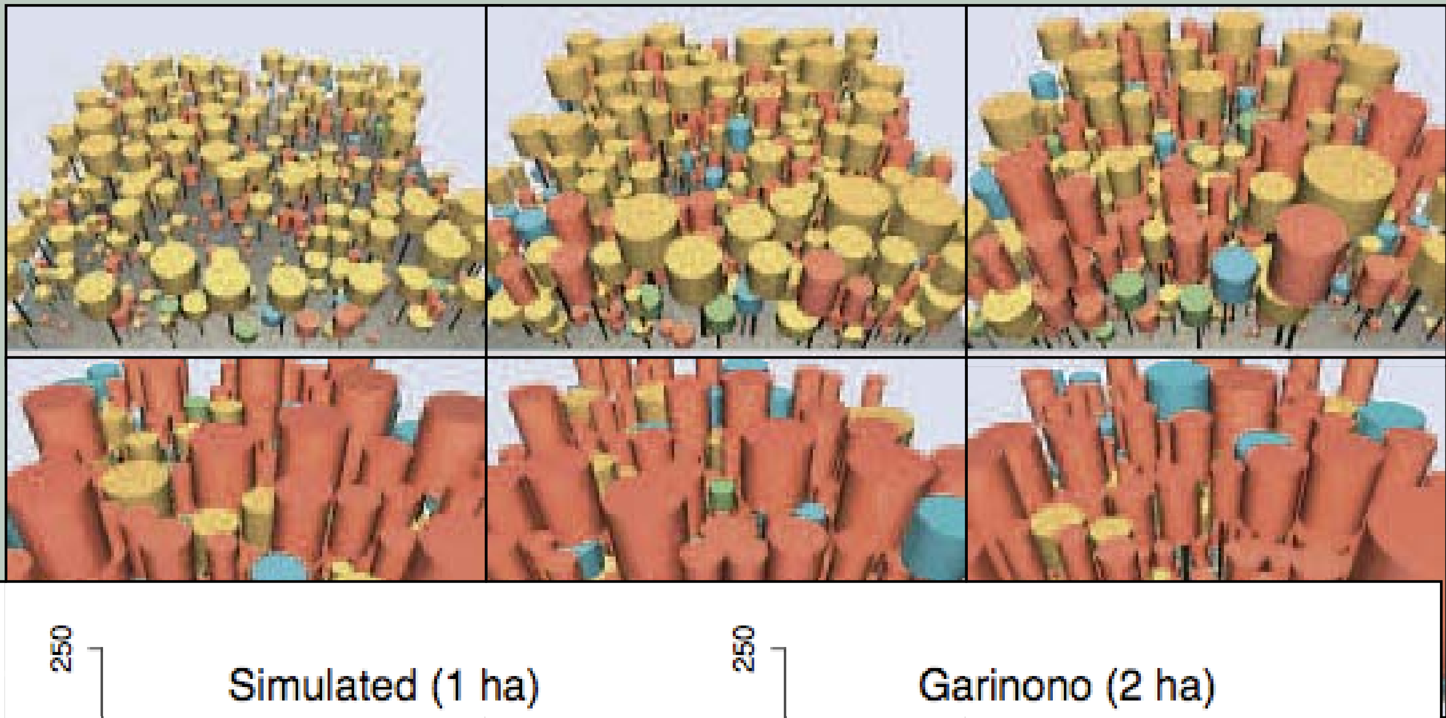
dispersal + recruitment

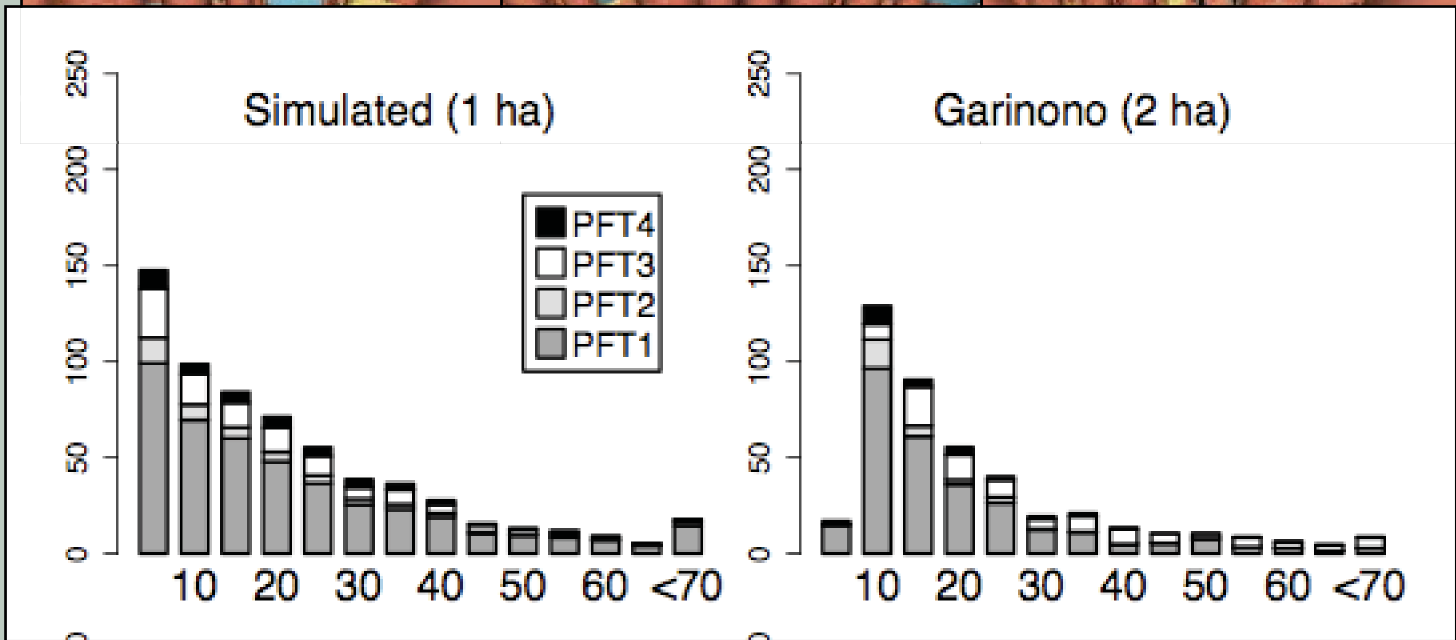


e.g.: SORTIE model of New England forests

(Pacala & Canham et al. 1996)

Individual-based vegetation models (gap models)



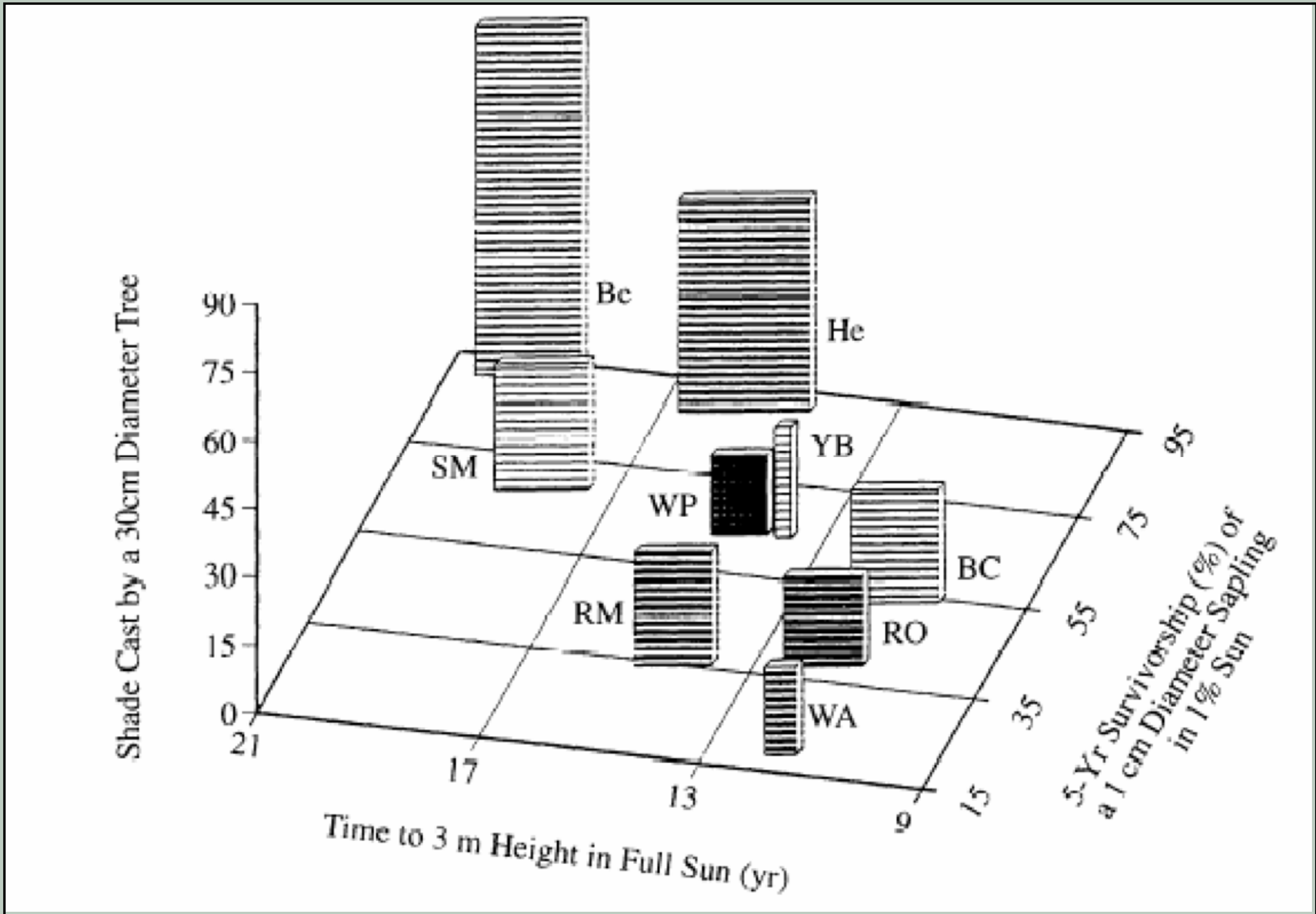


e.g.2: SEIB model of South-East Asian Tropical Forests

Sato et al. 2007

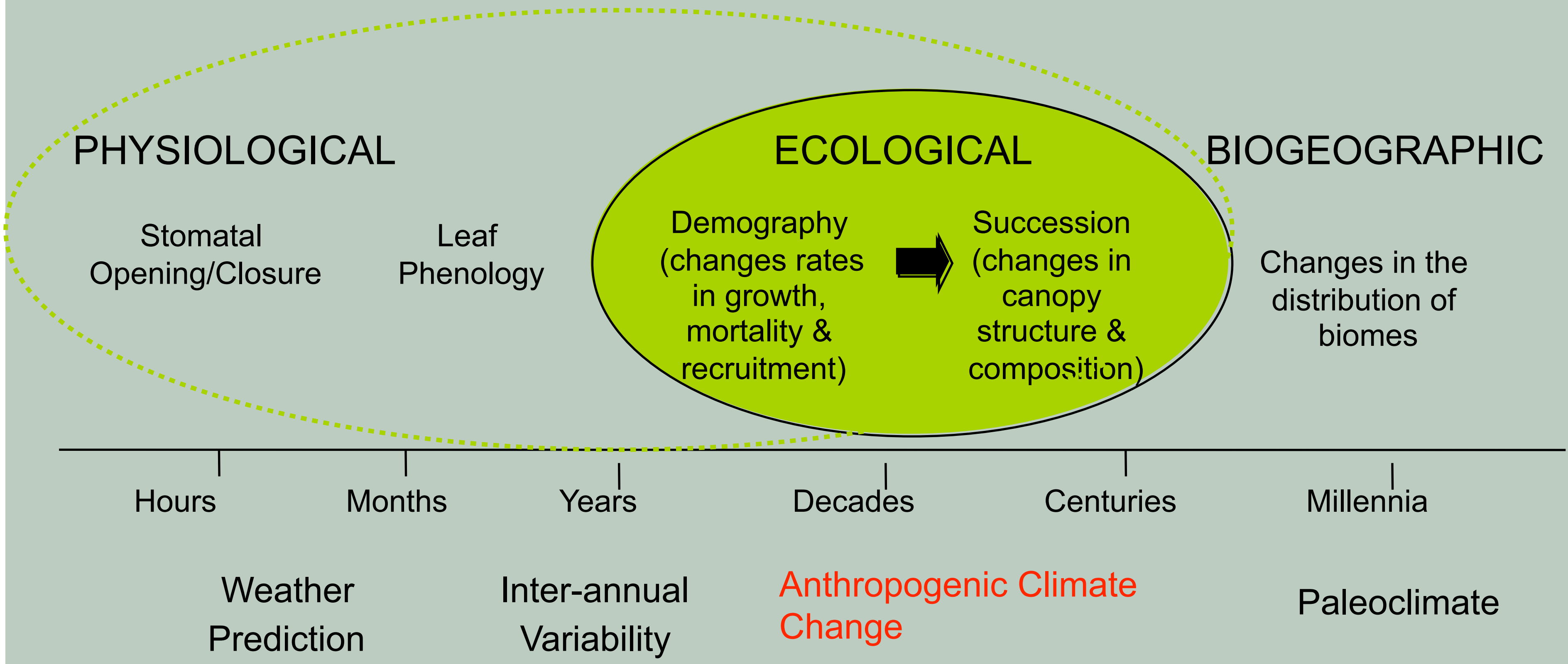
Traditionally gap-models were parameterized from field measurements of mortality, growth & recruitment in relation to resouce availability.

e.g. Variation in growth, mortality and recruitment among New England tree species

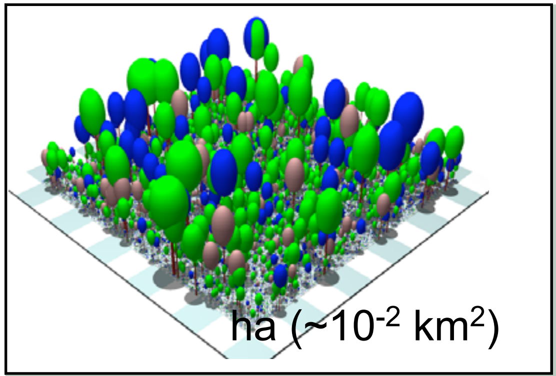


Pacala. Canham et al (1996)

Timescales of Terrestrial Ecosystem Processes



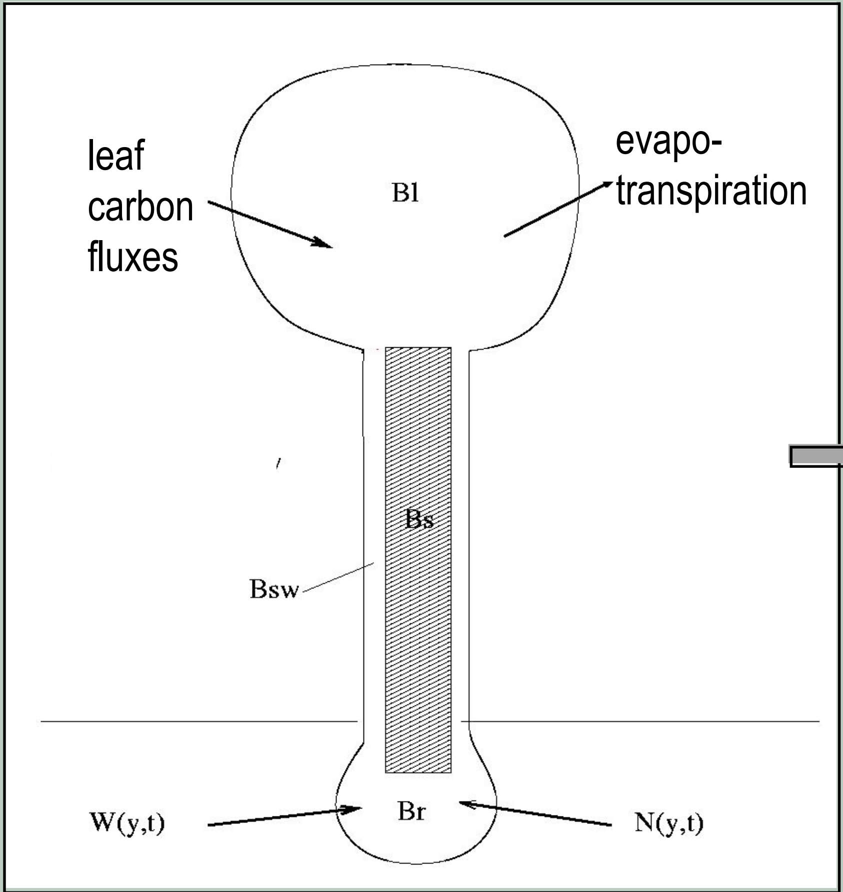
(*Moorcroft et al. 2001*)

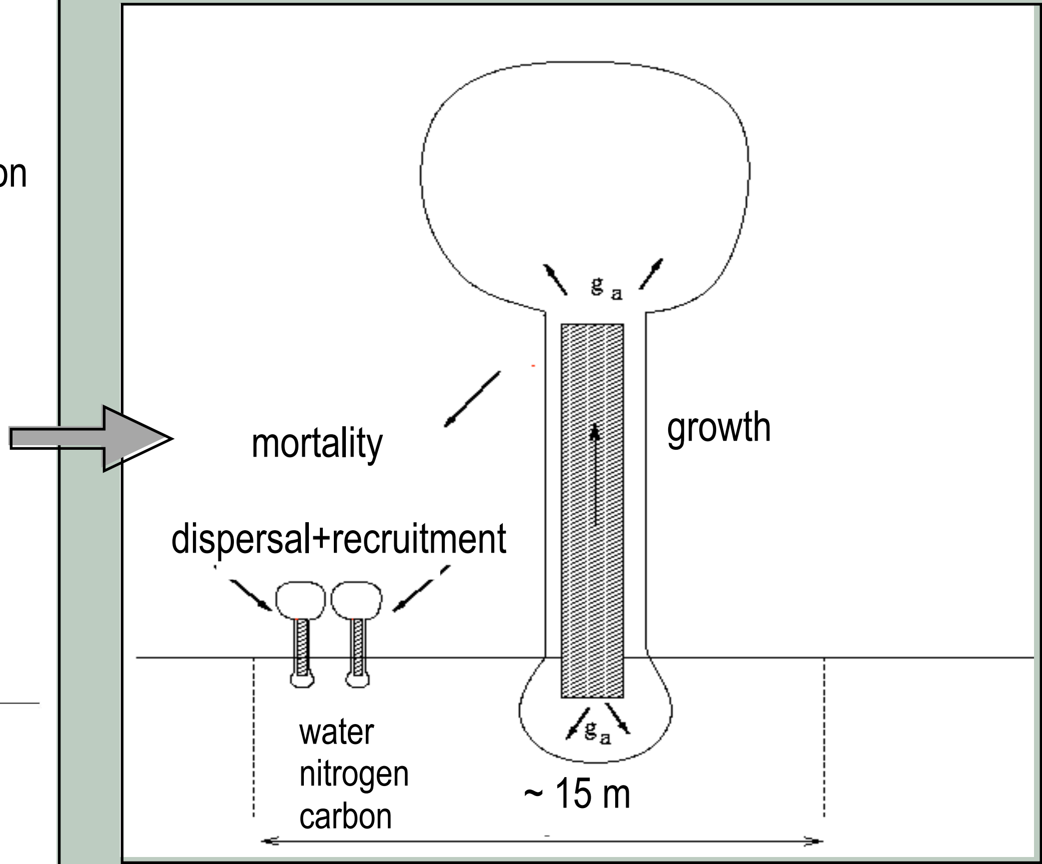


Physiologically-based gap models

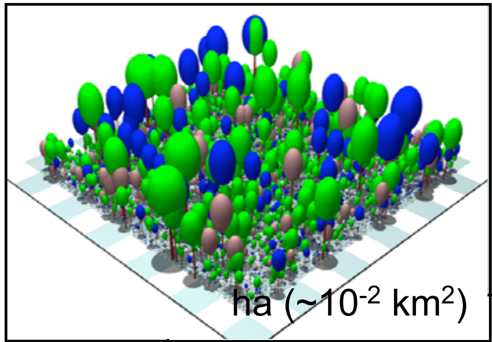
HYBRID (Friend et al. 1997)

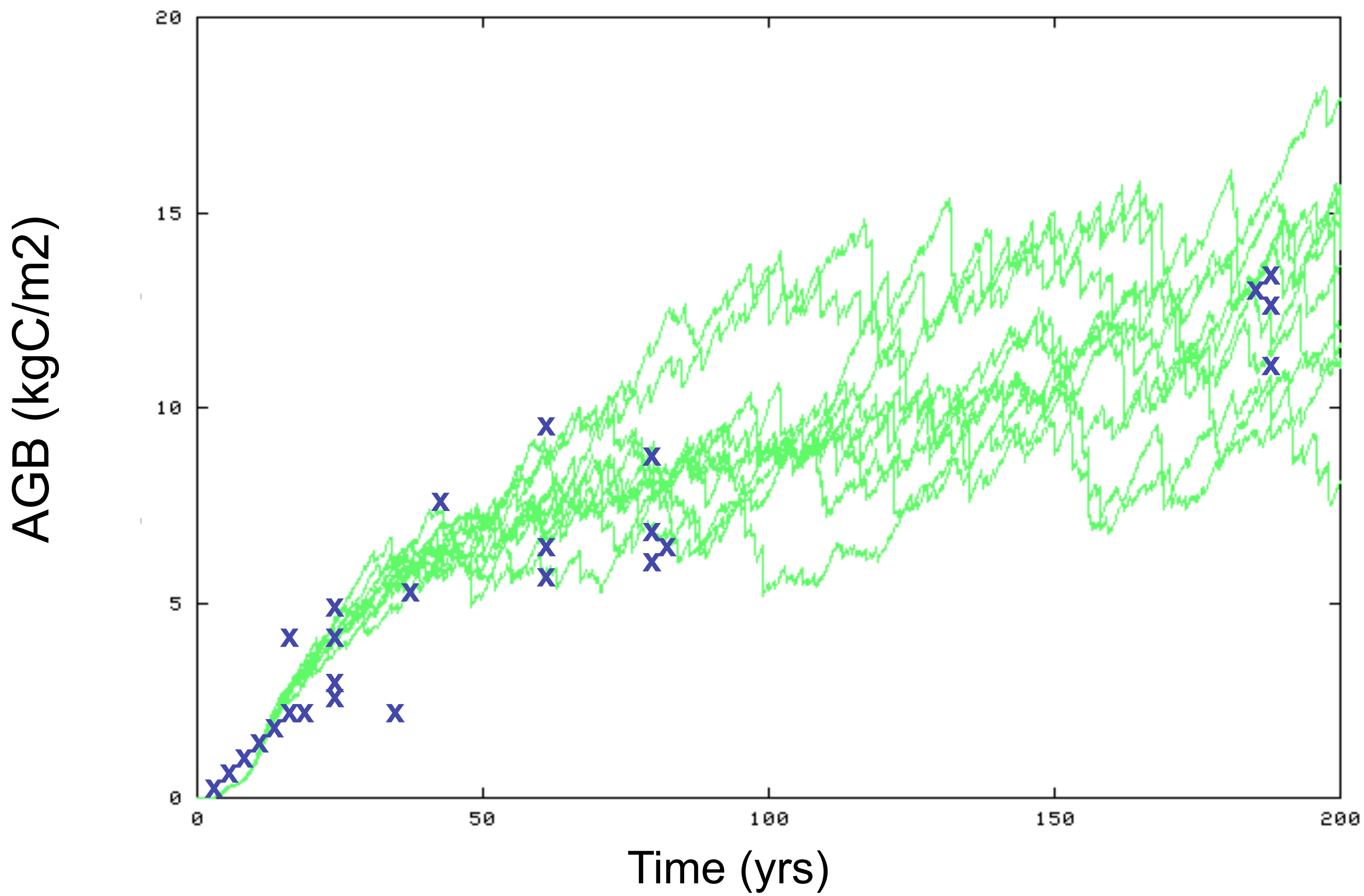
ED (Moorcroft et al. 2001)



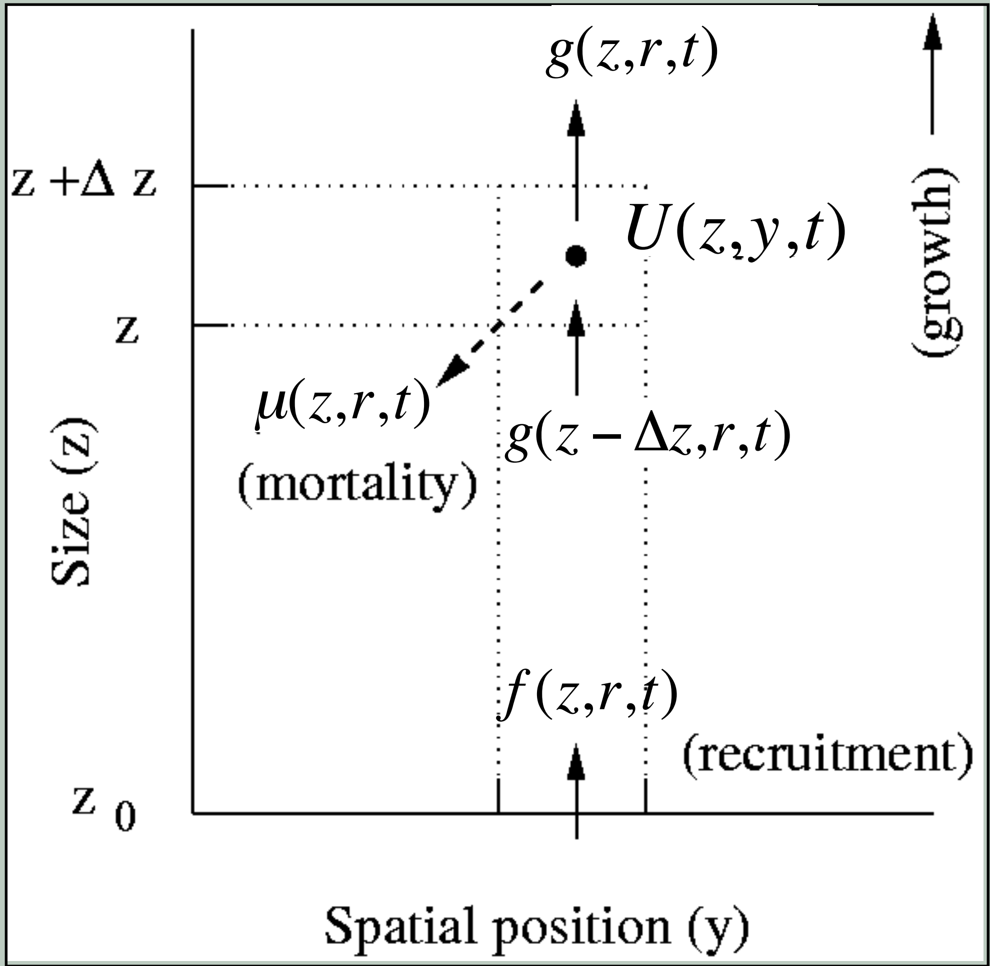


ED Model simulator dynamics at San Carlos (tropical forest) 2°N,68°W: trajectory of above-ground biomass





Size-structured approximation



$$u(z,t) = \langle U(z,y,t) \rangle$$

$$\Delta u(z,t) =$$

$$-\left\langle U(z,y,t)g(z,r,t)\frac{\Delta t}{\Delta z}\right\rangle$$

$$+\left\langle U(z-\Delta z,y,t)g(z,r,t)\frac{\Delta t}{\Delta z}\right\rangle$$

$$-\left\langle U(z,y,t)\mu(z,r,t)\frac{\Delta t}{\Delta z}\right\rangle$$

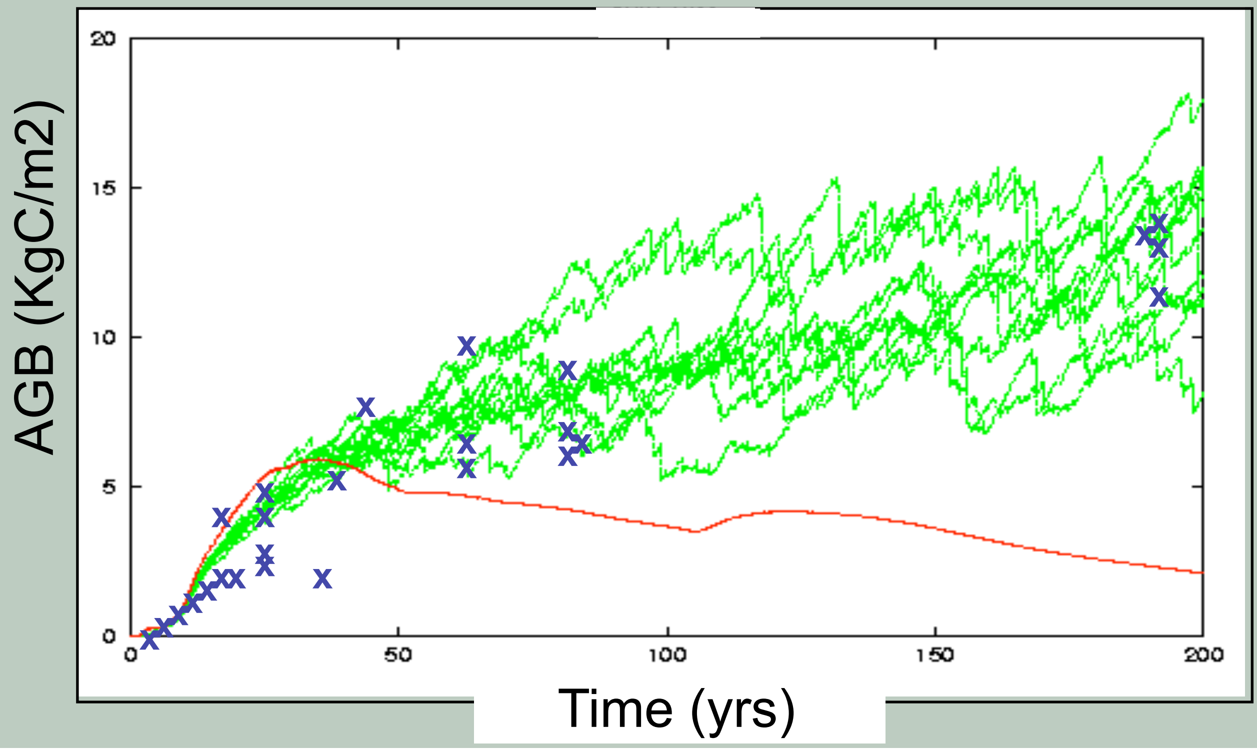
$r = r(z,y)$ = resource availability at location y,z

Size-structured approximation

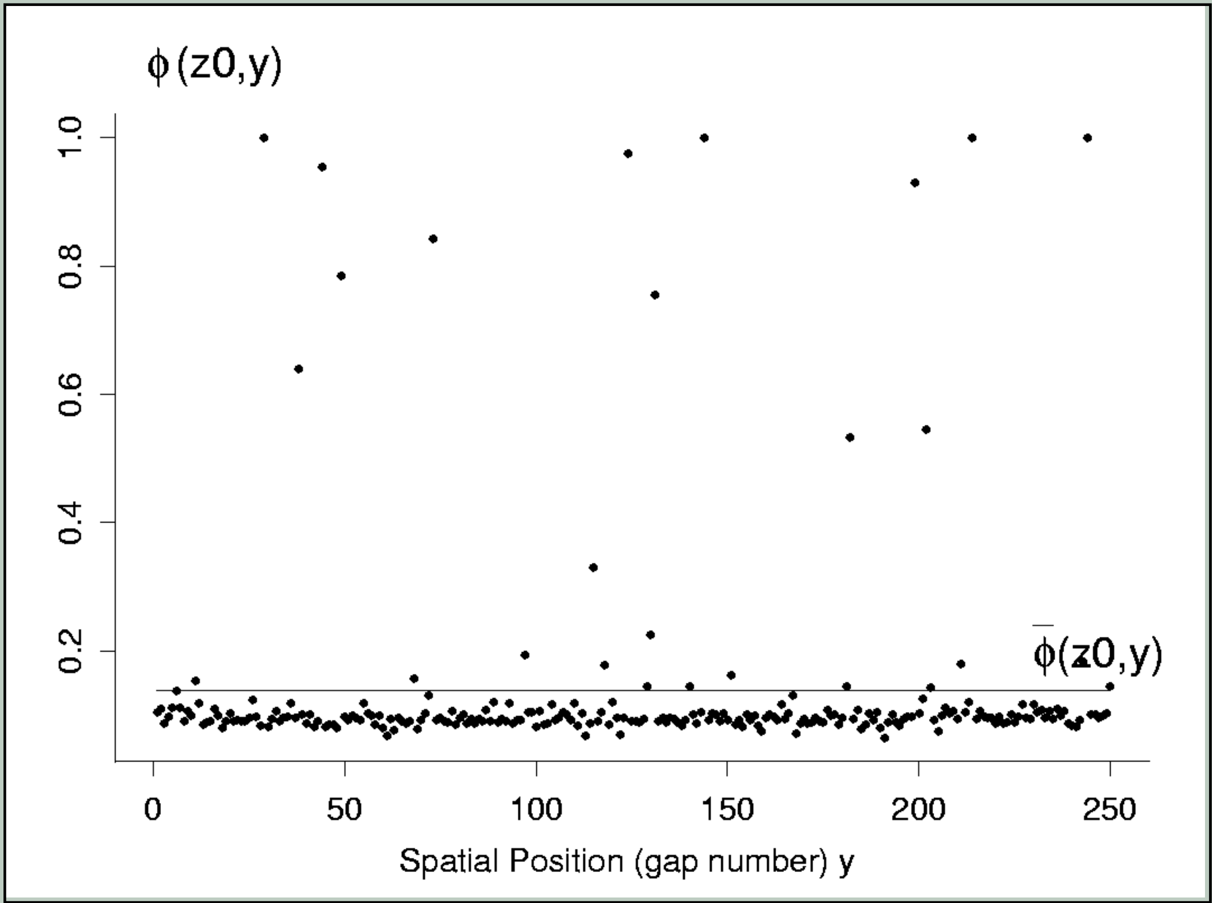
PDE: $$\underbrace{\frac{\partial n^{(i)}(z,t)}{\partial t}}_{\text{ch. in density of plant type } i} = \underbrace{-\frac{\partial}{\partial z}\left[g(z,t)^{(i)} n^{(i)}(z,t)\right]}_{\text{growth}} \underbrace{- \mu(z,t)^{(i)} n^{(i)}(z,t)}_{\text{mortality}}$$

BC: $$n^{(i)}(z_0,t) = \underbrace{\frac{1}{g^{(i)}(z_0,t)} \int_0^\infty f^{(i)}(z,t) n^{(i)}(z,t)\, dz}_{\text{reproduction}} \quad (i = 1 \ldots n_{plant\ types})$$

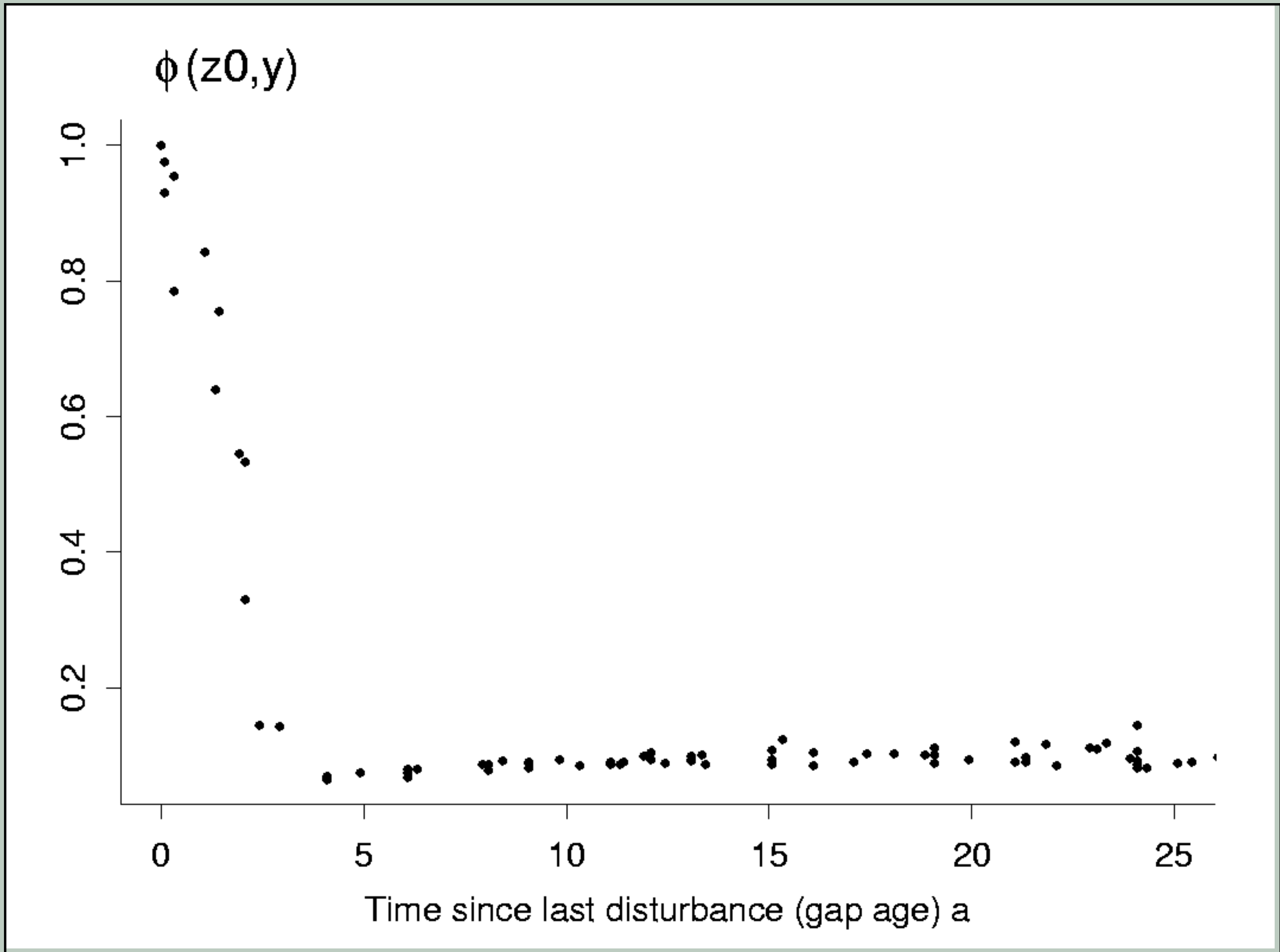
Size-structured approximation biomass dynamics at San Carlos:

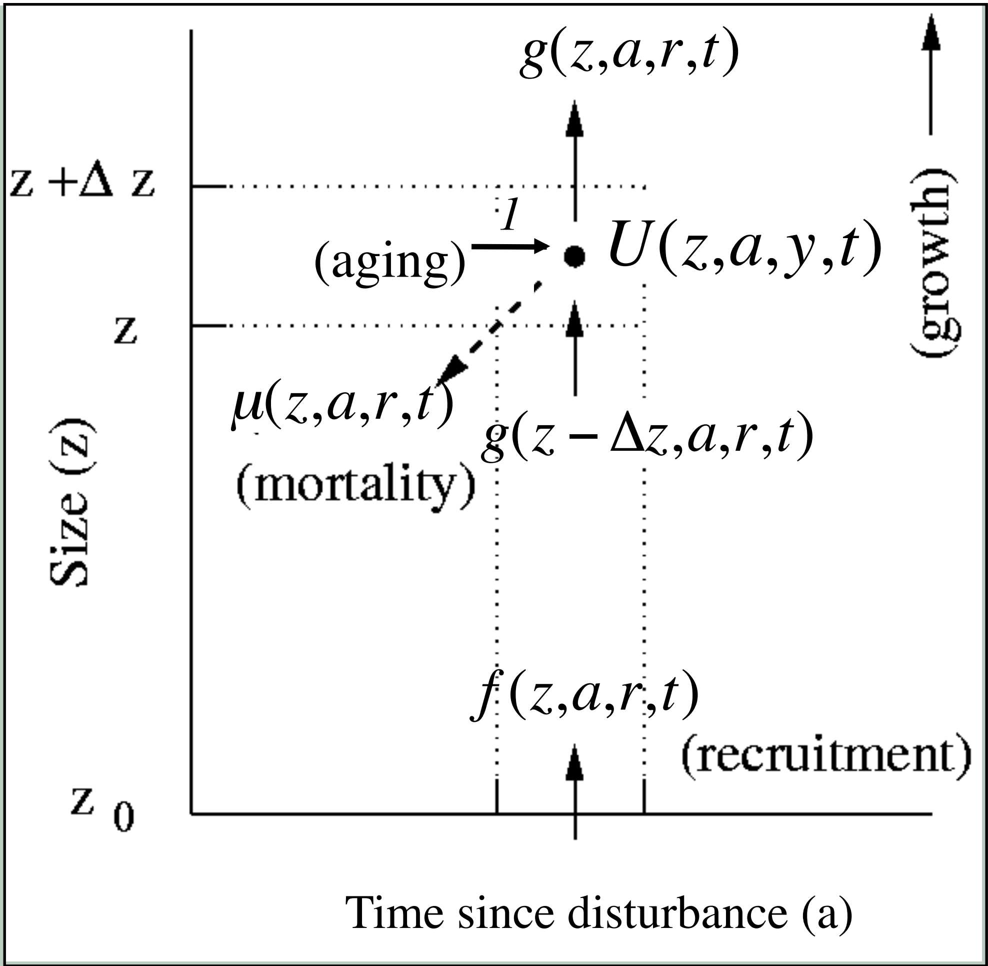


Light availability as a function of spatial position



Light availability as a function of time since disturbance





Size & age-structured approximation

$$u(z,a,t) = \langle U(z,a,y,t) \rangle$$

PDE:

$$\underbrace{\frac{\partial n^{(i)}(z,a,t)}{\partial t}}_{\text{ch. in density of plant type } i} = \underbrace{-\frac{\partial}{\partial z}\left[g(z,a,t)n^{(i)}(z,a,t)\right]}_{\text{growth}} \underbrace{-\frac{\partial}{\partial a}n^{(i)}(z,a,t)}_{\text{ageing}} \underbrace{-\mu(z,a,t)n^{(i)}(z,a,t)}_{\text{mortality}}$$

Landscape age structure

Levin & Paine (1974)

Disturbance dynamics

McKendrick Von-Forester Equation:

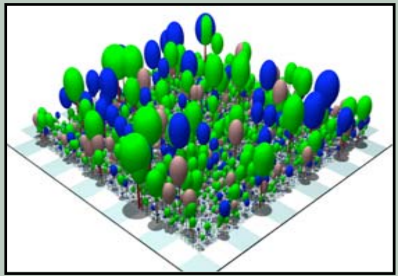
$$\frac{\partial p(a,t)}{\partial t} = -\frac{\partial}{\partial a} p(a,t) - \lambda(a,t)\,p(a,t) \qquad p(0,t) = \int_0^\infty \lambda(a,t)\,p(a,t)\,da$$

Where:

$p(a)da$ = proportion of the grid-cell disturbed between a and $a + da$ years ago

$\lambda(a,t)$ = rate of disturbance

(Moorcroft et al. 2001)



A size & age-structured terrestrial biosphere model

PDE:
$$\underbrace{\frac{\partial n^{(i)}(z,a,t)}{\partial t}}_{\text{ch. in density of plant type } i} = \underbrace{-\frac{\partial}{\partial z}\left[g(z,a,t)\,n^{(i)}(z,a,t)\right]}_{\text{growth}} \underbrace{-\frac{\partial}{\partial a}n^{(i)}(z,a,t)}_{\text{ageing}} \underbrace{-\,\mu(z,a,t)\,n^{(i)}(z,a,t)}_{\text{mortality}}$$

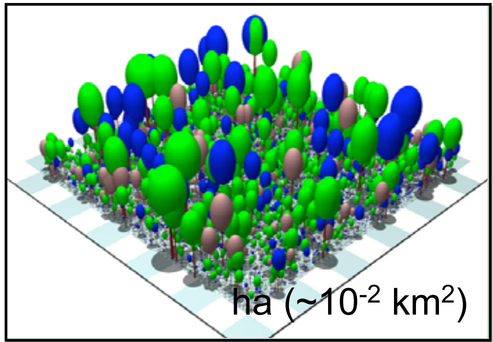
PDE:
$$\underbrace{\frac{\partial p(a,t)}{\partial t}}_{\text{ch. landscape age distribution}} = \underbrace{-\frac{\partial}{\partial a}p(a,t)}_{\text{ageing}} \underbrace{-\,\lambda(a,t)\,p(a,t)}_{\text{disturbance}}$$

BC: $$n(z_0,t) = \frac{1}{g(z_0,t)}\int_0^\infty f(z,t)\,n(z,t)\,dz$$

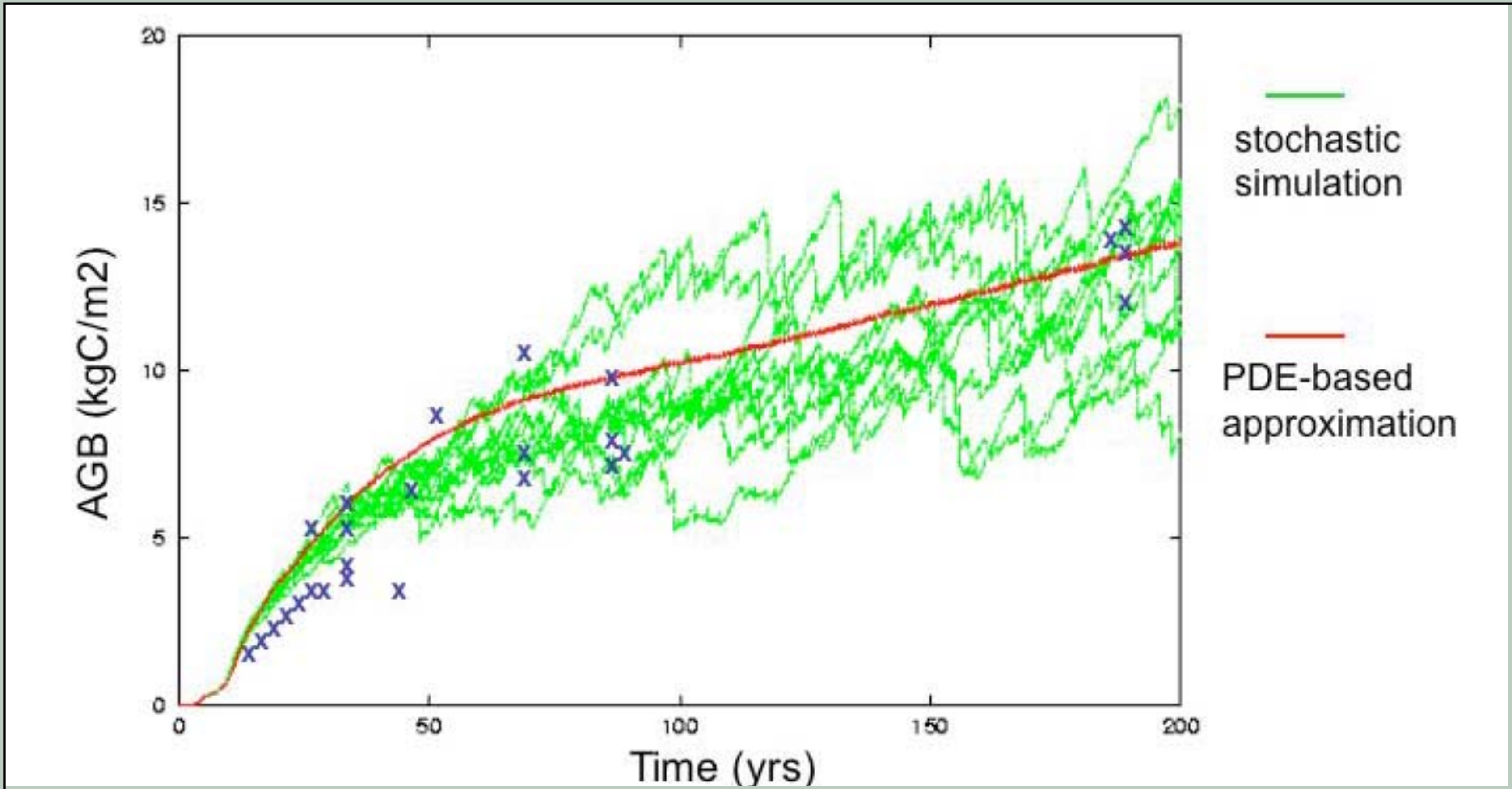
BC: $$p(0,t) = \int_0^\infty \lambda(a,t)\,n(a,t)\,da$$

BC: $$n^{(i)}(z,0,t) = s(z,a,t)\int_0^\infty s(z,a,t)\,n^{(i)}(z,a,t)\,da$$

(Moorcroft et al. 2001)

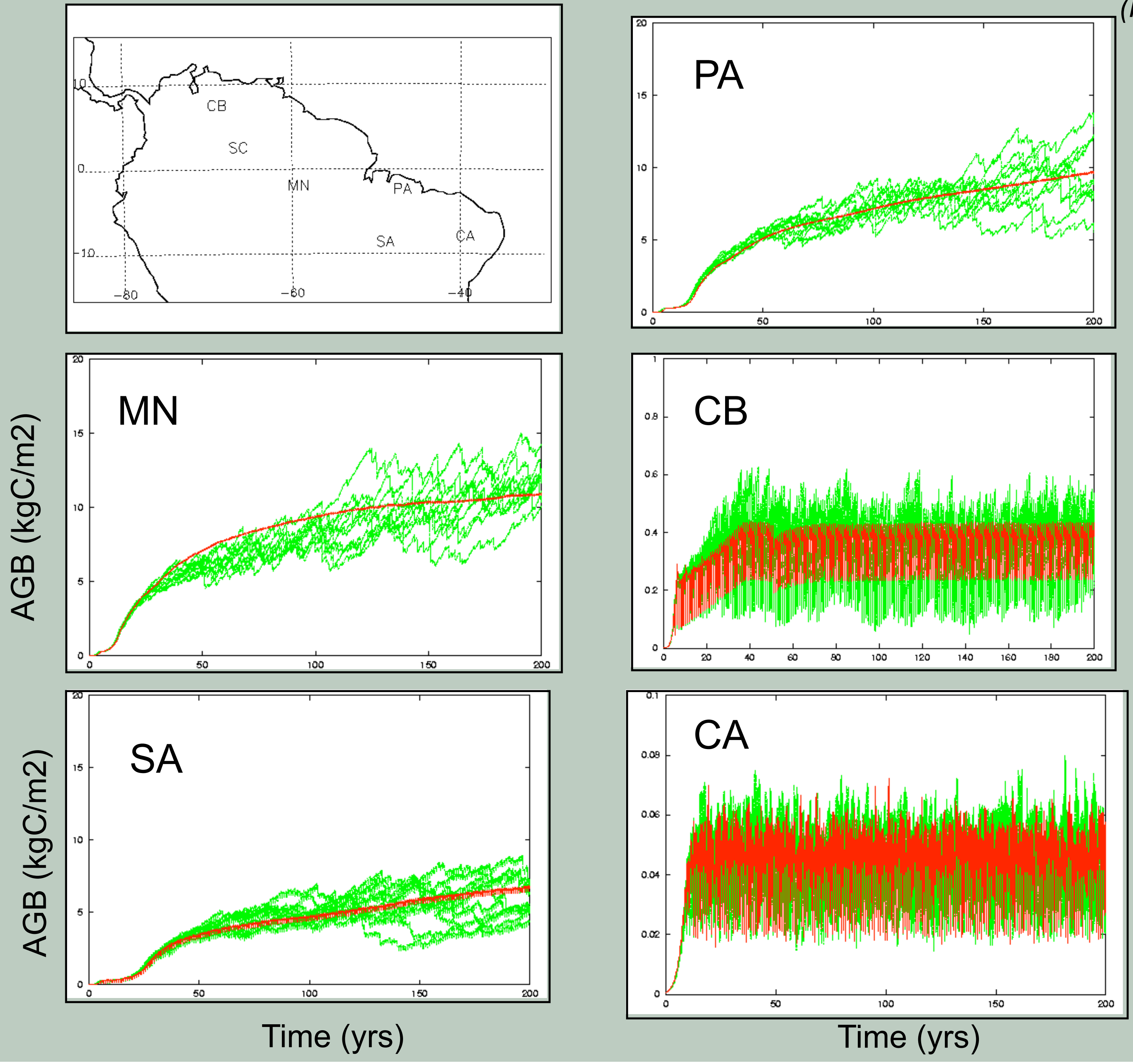


ED dynamics at San Carlos Tropical forest (2°N,68°W): trajectory of above-ground biomass:



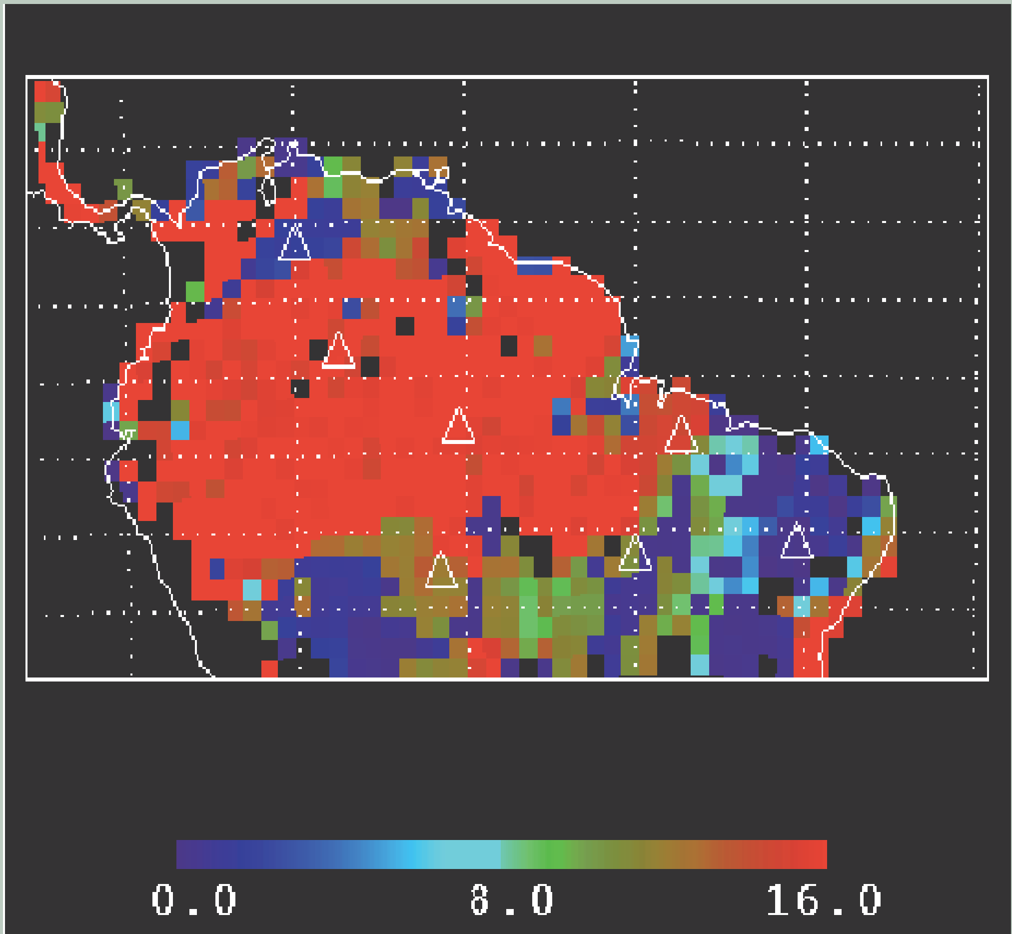
- accurately captures the behavior of corresponding individual-based model by tracking the dynamic horizontal & vertical sub-grid scale heterogeneity in canopy structure.

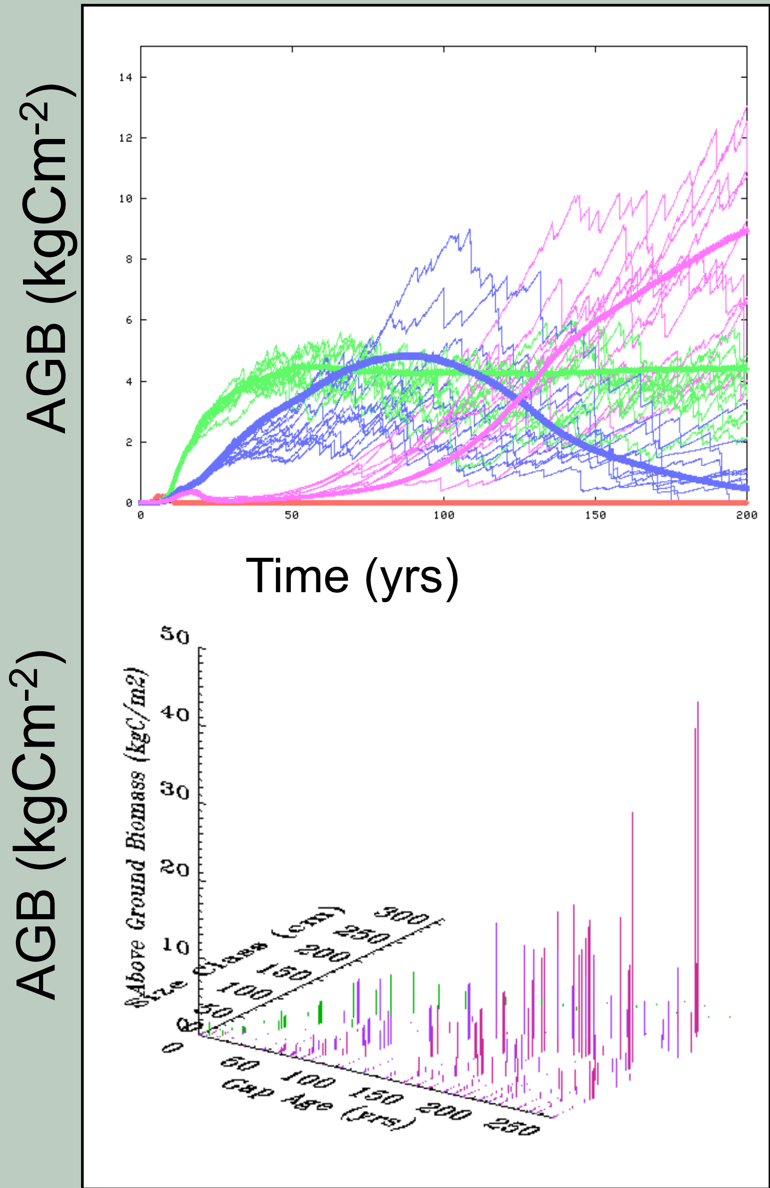
(Moorcroft et al 2001)



(*Moorcroft et al. 2001*)

ED Model: Regional pattern of above-ground biomass (AGB) after 200 year simulation ($kgCm^{-2}$)





Forms of disturbance

Treefall Gap Malaysia

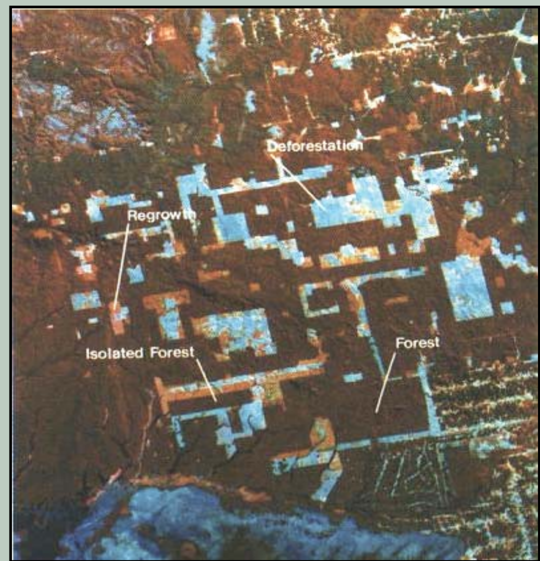
Land-slip Malaysia

Fires in Amazonia

Forest Pathogens Alaska

Shifting Agriculture Venezuela

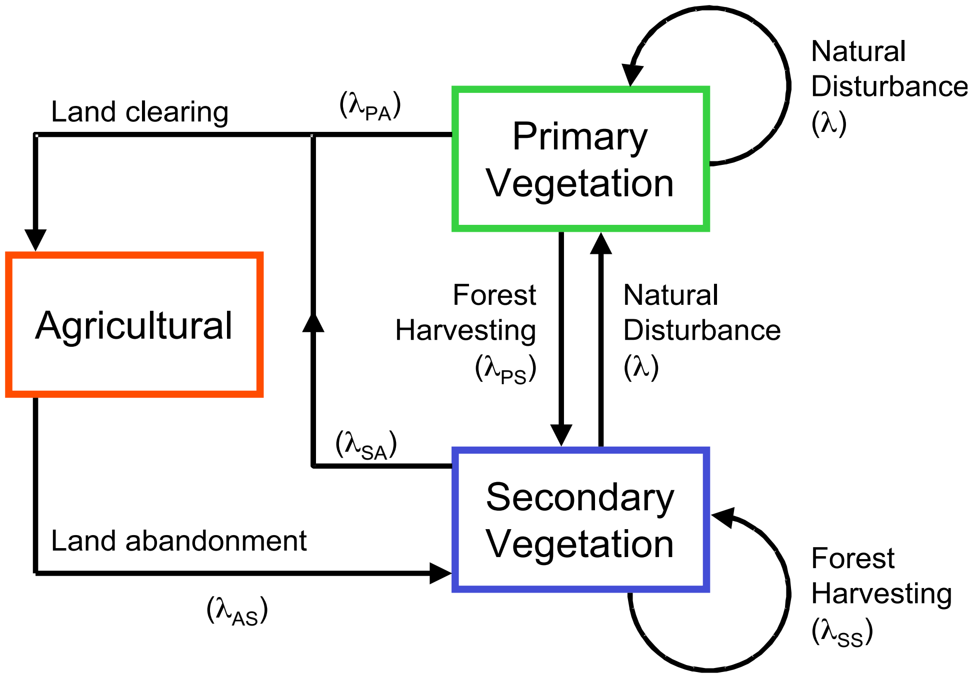
Land-Use Change Rondonia



Albani et al. 2006

Incorporating land-use change

$$\underbrace{\frac{\partial}{\partial t}\underline{p}(a,t)}_{\text{ch. in land class \& age distribution}} = \underbrace{-\frac{\partial}{\partial a}\underline{p}(a,t)}_{\text{aging}} - \underbrace{\mathbf{\Lambda}(a,t)\underline{p}(a,t)}_{\text{disturbance}},$$



$$\underline{p}(a,t) = [p_1(a), p_j(a), \ldots p_m \;]$$

$$\mathbf{\Lambda}(a,t) = \begin{pmatrix} \lambda & \lambda & 0 \\ \lambda_{PS} & \lambda_{SS} & \lambda_{AS} \\ \lambda_{PA} & \lambda_{SA} & 0 \end{pmatrix}$$

$$\underbrace{\underline{p}(0,t) = \sum_{j=1}^{n_{dist}} \int_0^\infty \lambda(a,t) p_j(a,t)\, da.}_{\text{formation of newly disturbed areas}}$$

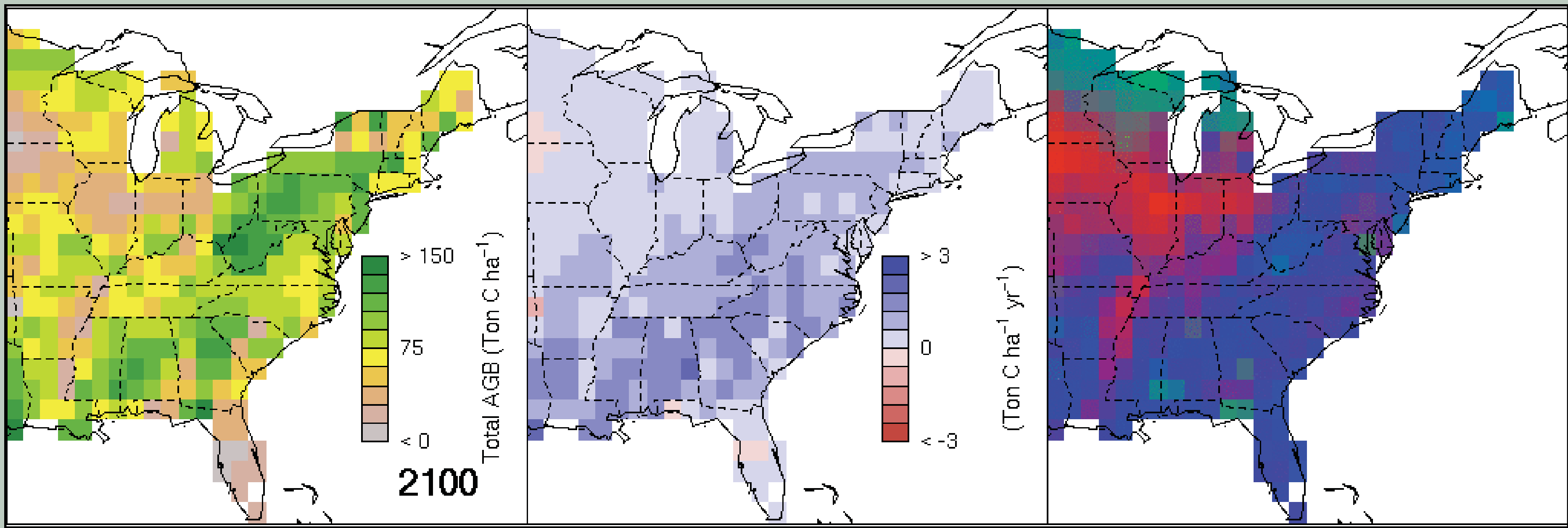
historical fraction of agricultural land in each county 1800-2100

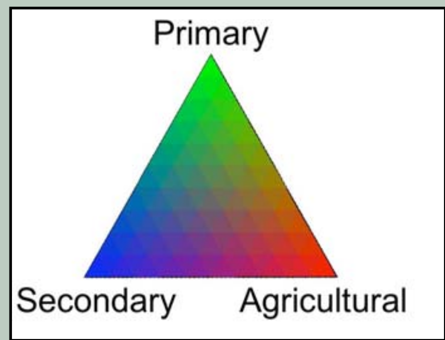
regional historical patterns of forest harvesting (USFS)

Albani et al. 2006

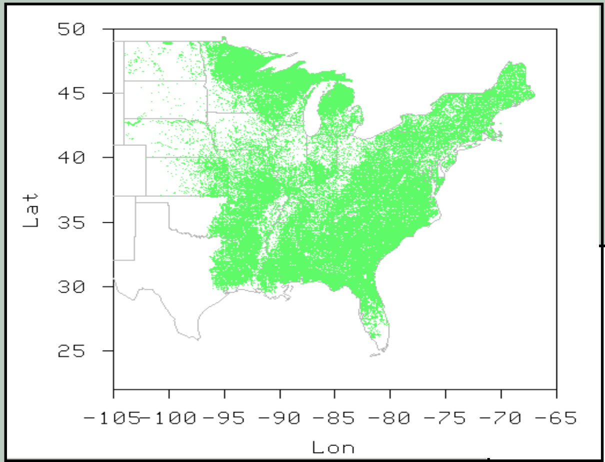
ED model: predicted impacts of land-use history on the carbon dynamics of the Eastern US

above gnd. biomass (tC ha^{-1})   carbon uptake (NEP, tC ha^{-1} y^{-1})   land use

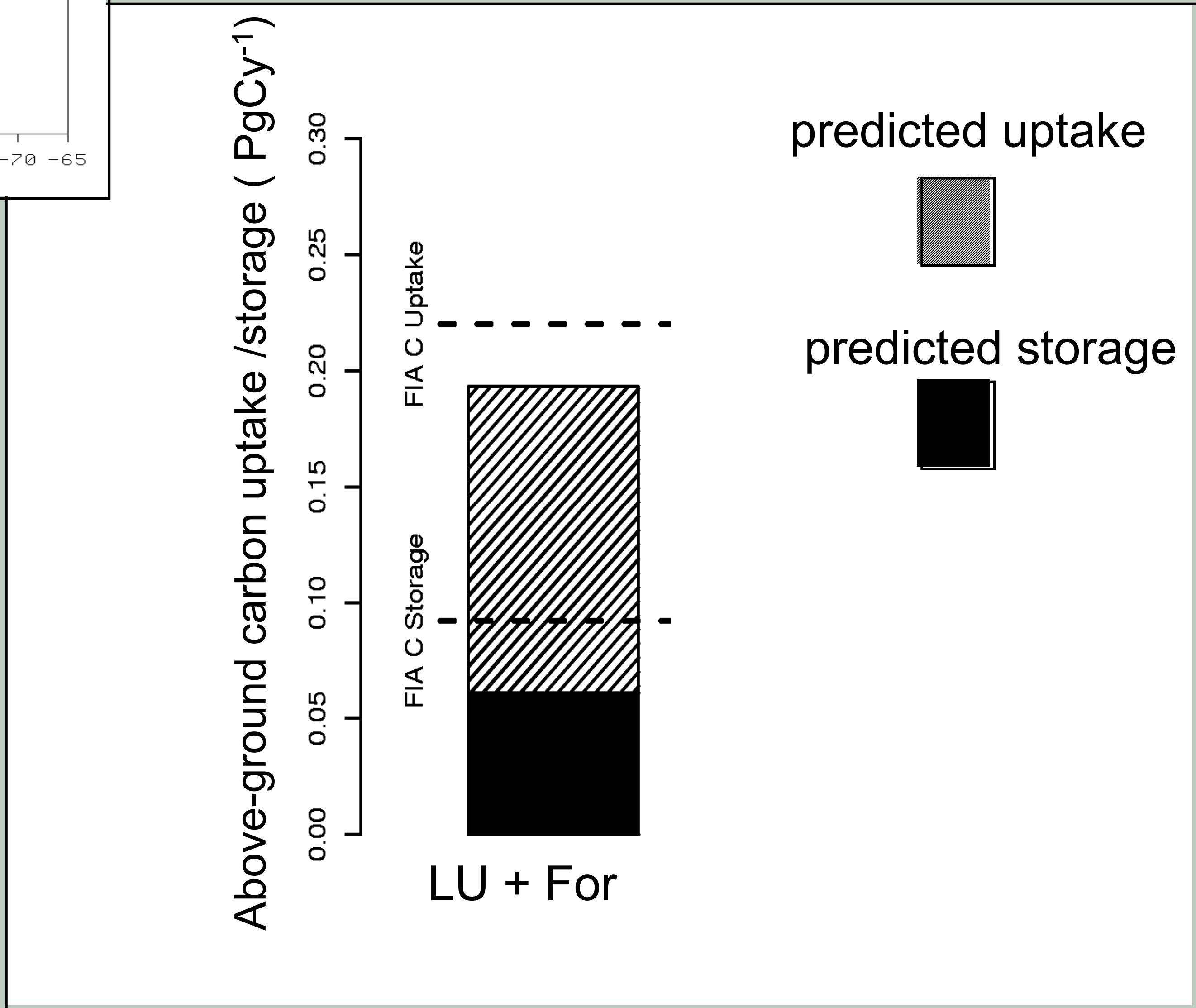




Albani et al. 2006



<- USFS FIA forest inventory measurements of current above-ground C uptake and storage



Results imply that:

- significant carbon uptake occurring as a result of land-use dynamics

- ~ 2/3 of the uptake is forest re-growth following harvesting, not carbon storage in forests.

(Moorcroft et al. 2001, Moorcroft 2006)

Conclusions

In contrast to traditional 'big-leaf' biosphere models, structured biosphere models such as ED scale formally between fast timescale plant-level physiological responses to climate, and long-term large-scale ecosystem dynamics.

Enables them to:

- have both realistic short-term and long-term vegetation dynamics.

- incorporate the effects of natural and anthropogenic disturbances (wind-throw fire, land clearing, land abandonment, forest harvesting etc.) on ecosystem composition, structure & function.

- ability to connect to measurements