Multiples States of Equilibrium in Climate-Vegetation Interactions: an Application to South American Tropical Forests

Carlos A Nobre,
Instituto Nacional de Pesquisas Espaciais (CPTEC-INPE)
carlos.nobre@inpe.br

Marcos Oyama, Manoel Cardoso, Gilvan Sampaio, Luis Salazar, Marina Hirota,David Lapola, Guillermo Obregon

II Simpósio Internacional de Climatologia da SBMET

São Paulo, 03 November 2007

Slide courtesy: IPAM

Does vegetation matter for the Earth System ?

Is vegetation distribution a fingerprint of climate ?

or

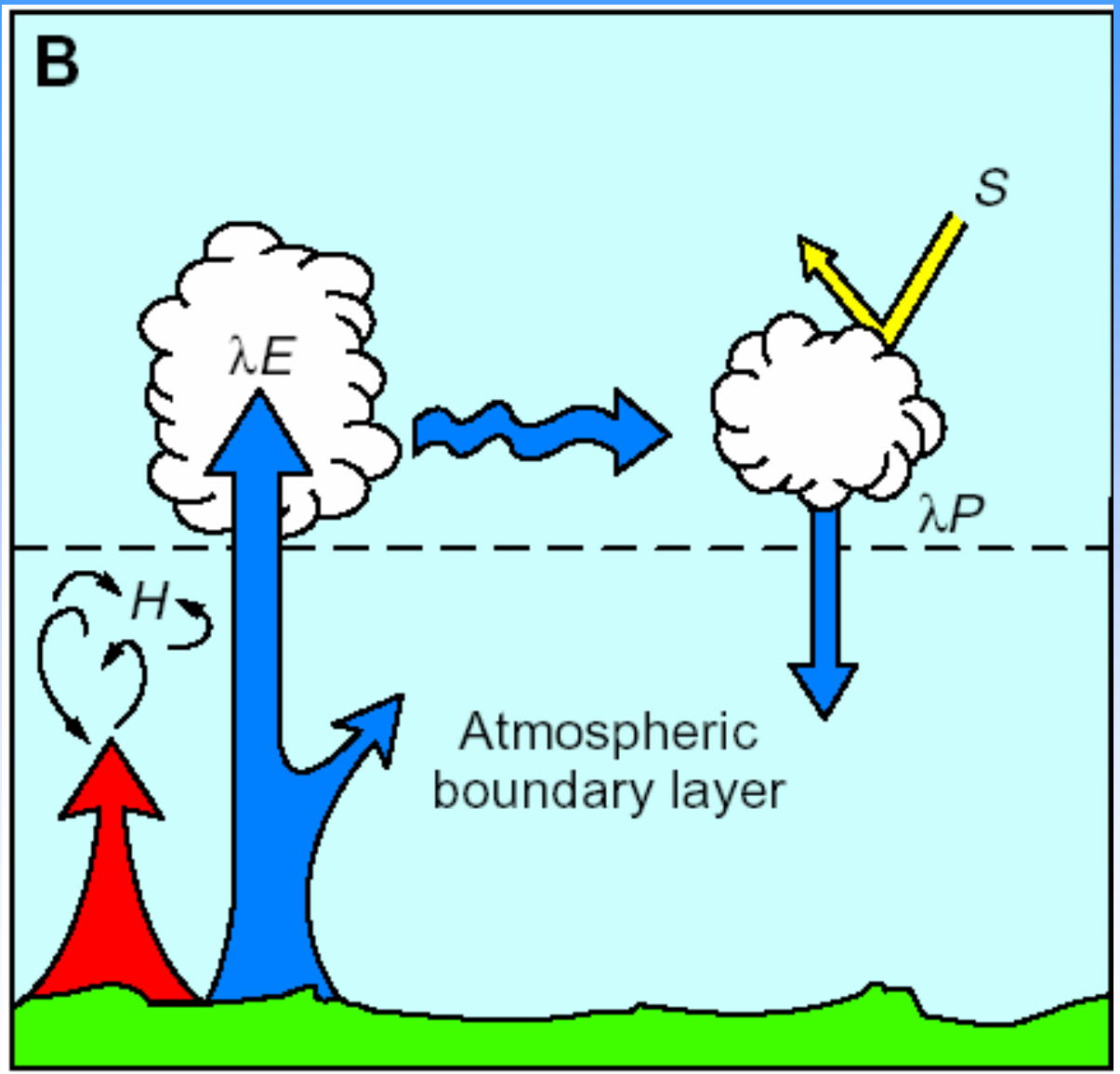
Does vegetation distribution influence
and participate to climate (state and changes) ?

Does vegetation matter for the Earth System ?

• The impacts of human activity on the Amazon rainforest could result in the collapse of large portions of the rainforest and significant loss of biodiversity within 30 to 50 years.

• A comparison is made with similar events in the Saharan ecosystem, which was once a region of richer vegetation, before its abrupt collapse about 6000 years ago

Vegetation partitions net radiation into more latent and less sensible heat



(figure taken from Kabat et al.: Vegetation, Water, Humans, and the Climate, IGBP BAHC)

Remove vegetation from the continents

➔ large changes will happen in the water cycle

Remove vegetation from the continents

➔ large changes will happen in the water cycle

Land=desert

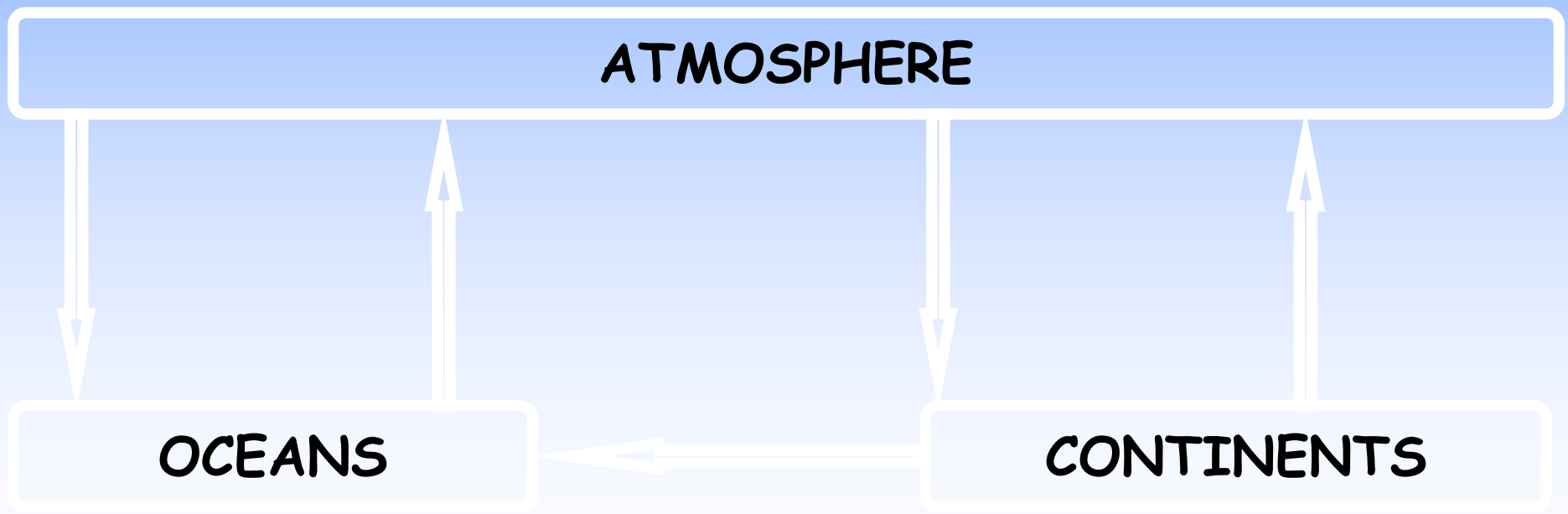
Land=forest

Remove vegetation from the continents

➔ large changes will happen in the water cycle

Land=desert

Land=forest



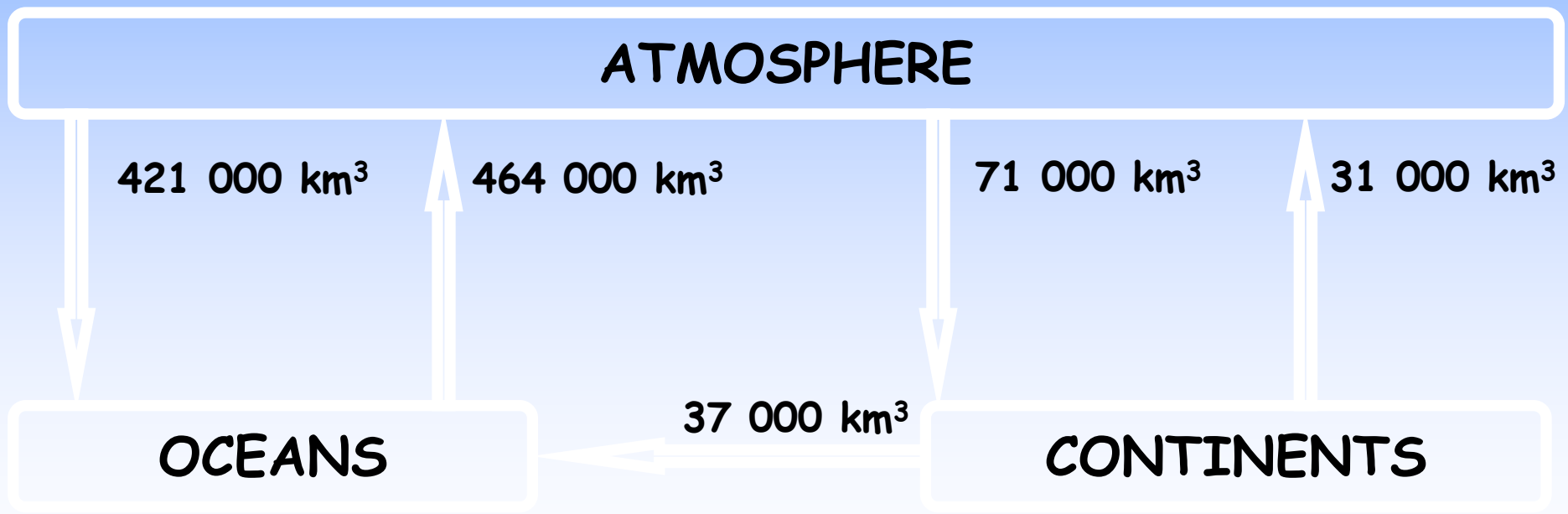
Kleidon et al. (2000)

Remove vegetation from the continents

➔ large changes will happen in the water cycle

Land=desert

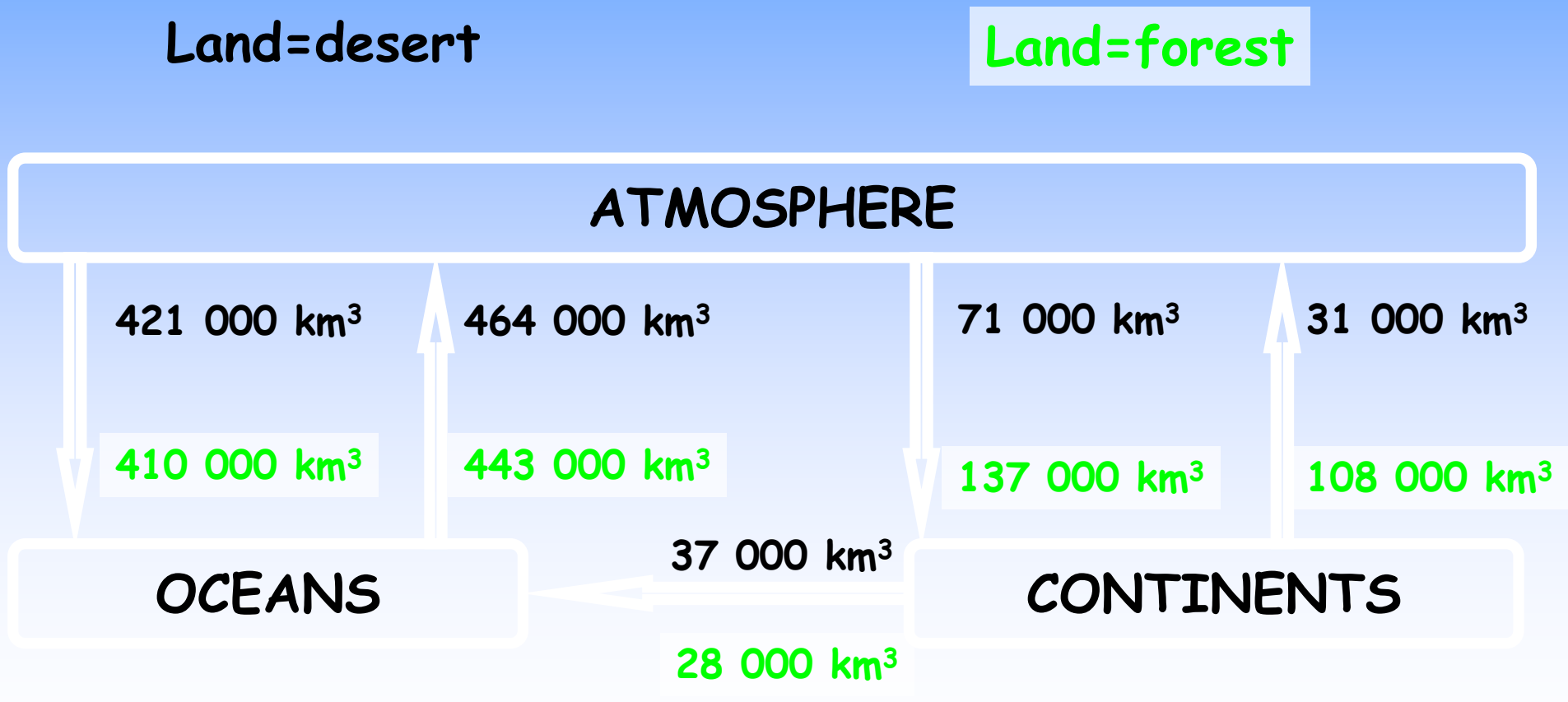
Land=forest



Kleidon et al. (2000)

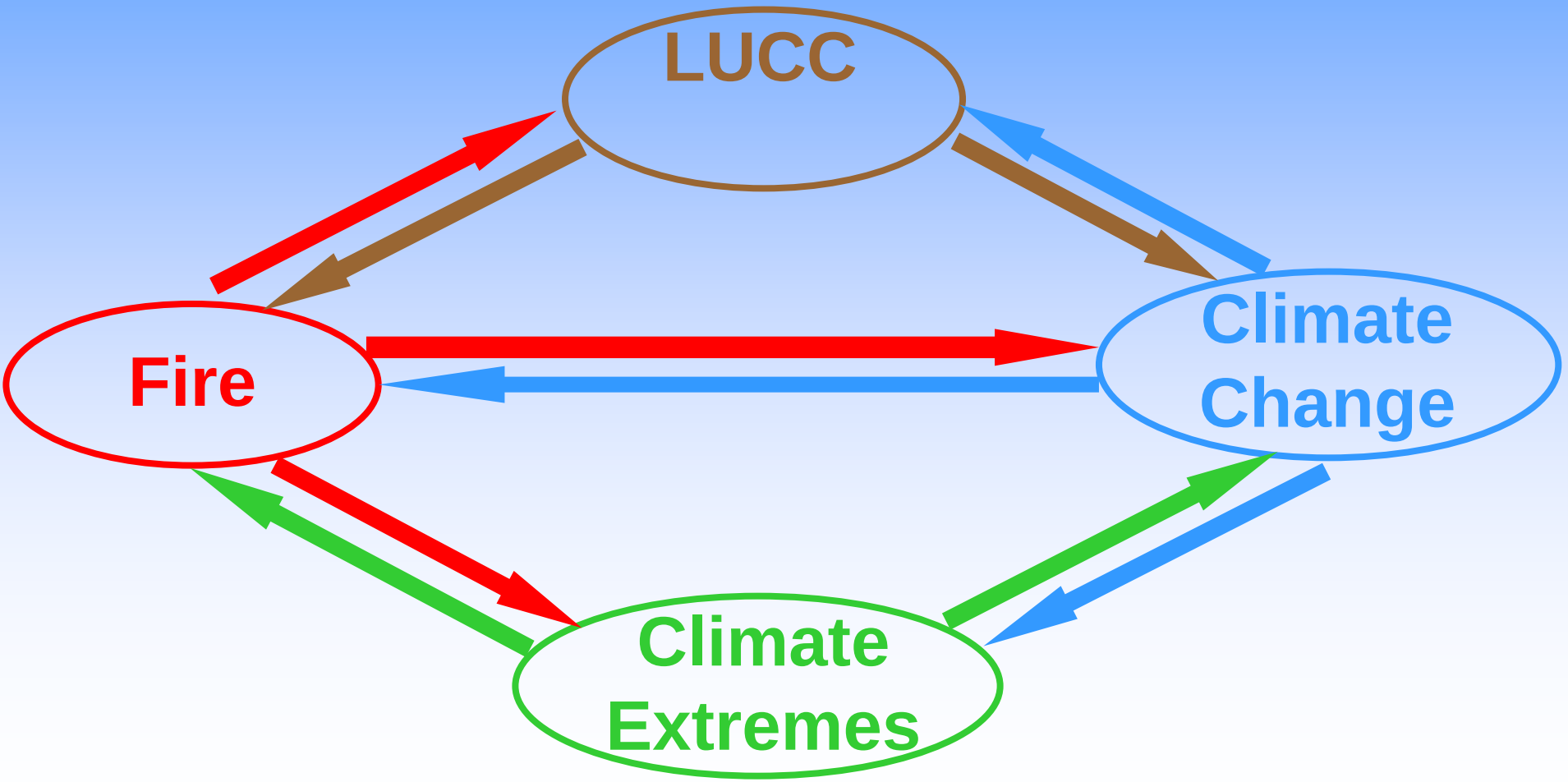
Remove vegetation from the continents

➔ large changes will happen in the water cycle



Kleidon et al. (2000)

The ecosystems of Amazonia are subjected to a suite of environmental drivers of change



The Hypothesis of Amazonian '*Savannization*'

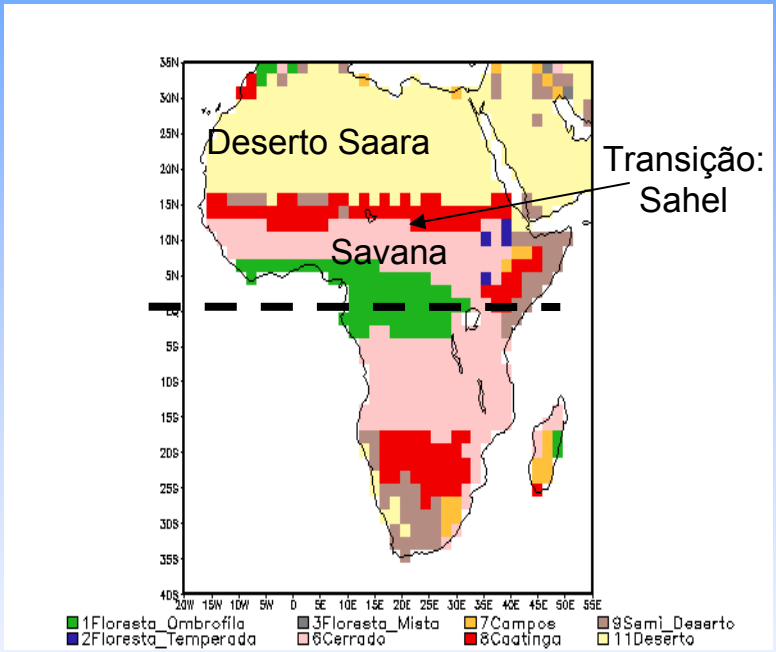
- Nobre et al. (1991) proposed that a post-deforestation climate in Southern Amazonia would be warmer, drier and with longer dry season, typical of the climate envelope of the tropical savanna (Cerrado) domain of Central South America.

- '*Savannization*' in this context is a statement on regional climate change and not intended to describe complex ecological processes of vegetation replacement.

Por exemplo, no planeta Terra...

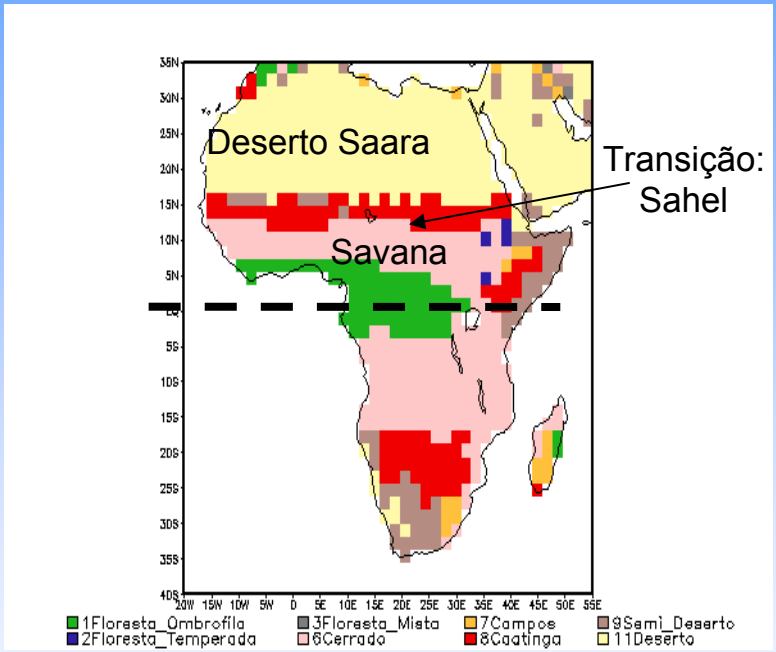
Por exemplo, no planeta Terra...

Região Saara/Sahel

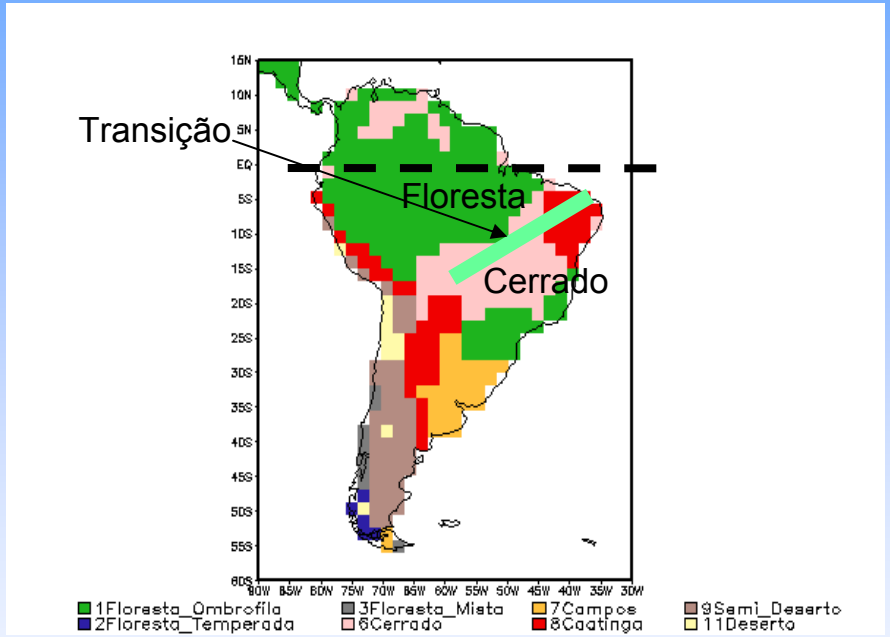


Por exemplo, no planeta Terra...

Região Saara/Sahel

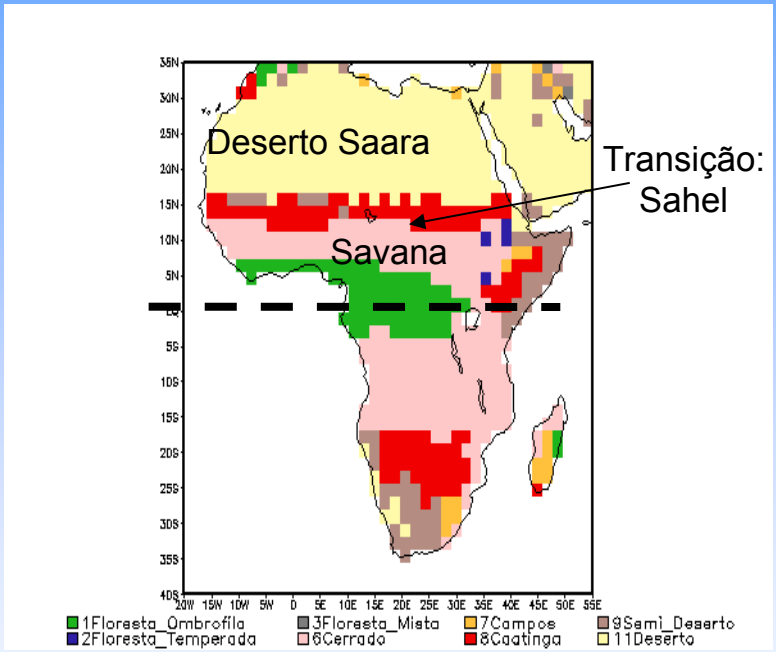


América do Sul tropical

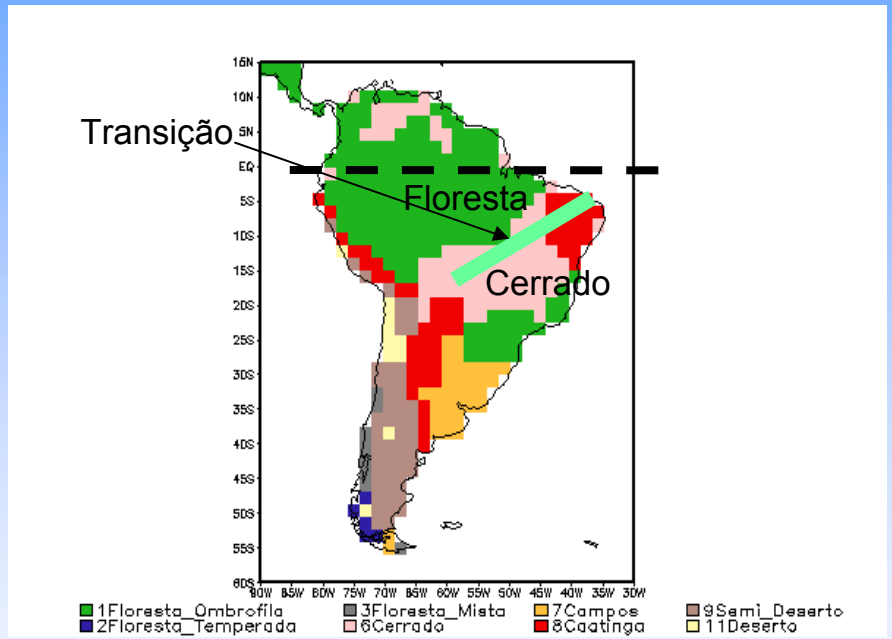


Por exemplo, no planeta Terra...

Região Saara/Sahel



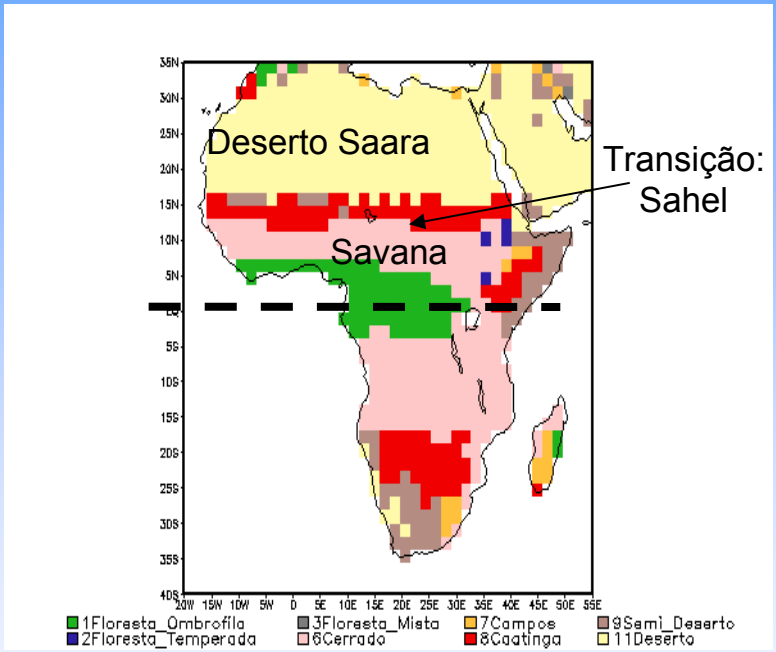
América do Sul tropical



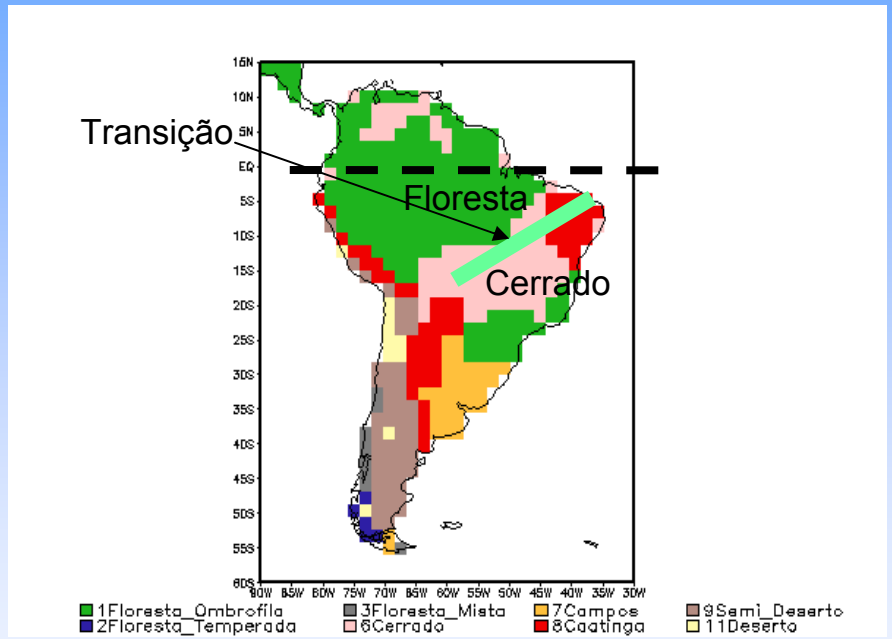
Transições: regiões mais sensíveis a distúrbios naturais e antrópicos!

Por exemplo, no planeta Terra...

Região Saara/Sahel



América do Sul tropical



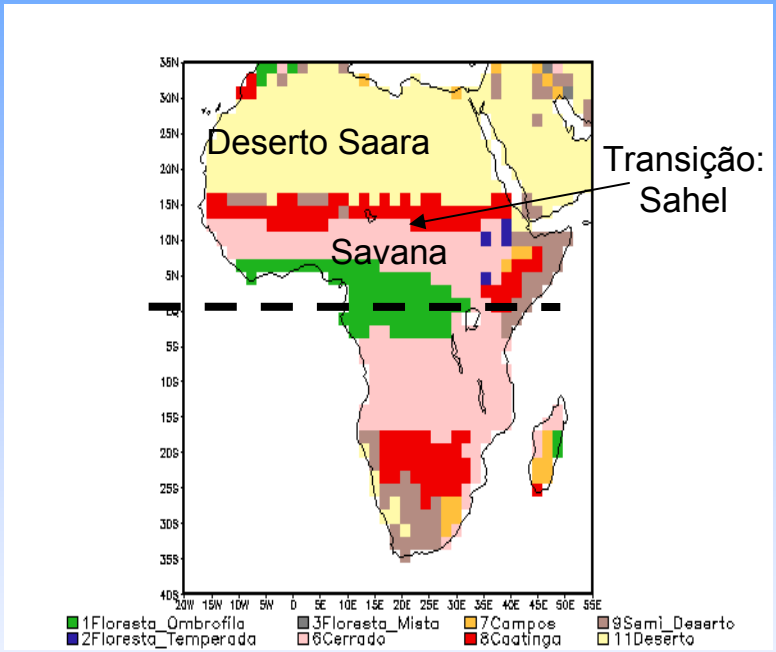
Transições: regiões mais sensíveis a distúrbios naturais e antrópicos!

→

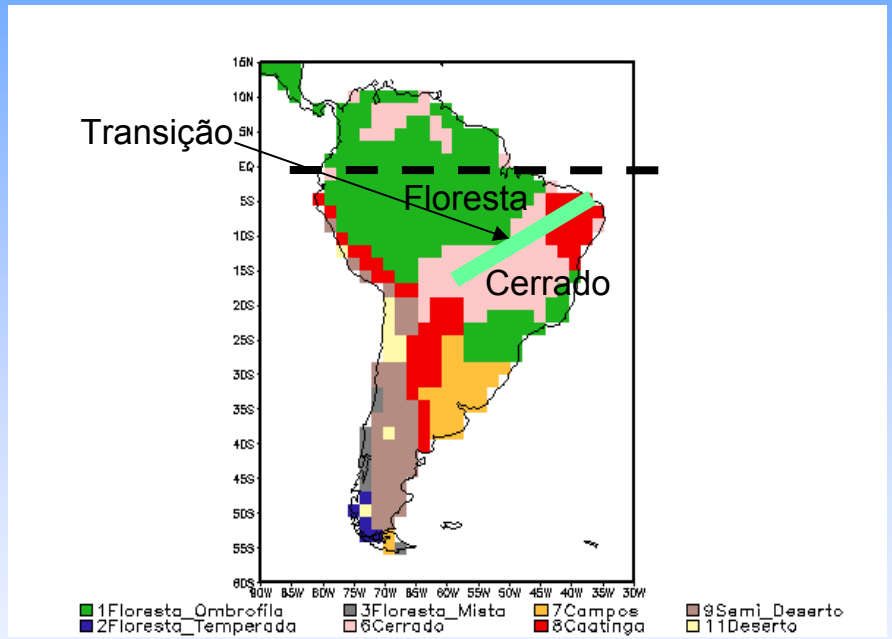
Possibilidade de múltiplos estados de equilíbrio entre a vegetação e o clima

Por exemplo, no planeta Terra...

Região Saara/Sahel



América do Sul tropical



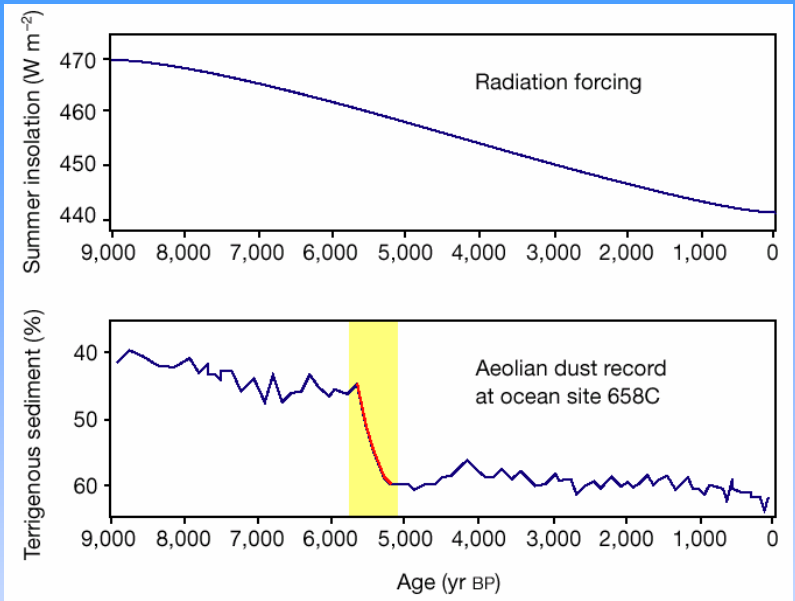
Transições: regiões mais sensíveis a distúrbios naturais e antrópicos!

→

Possibilidade de múltiplos estados de equilíbrio entre a vegetação e o clima

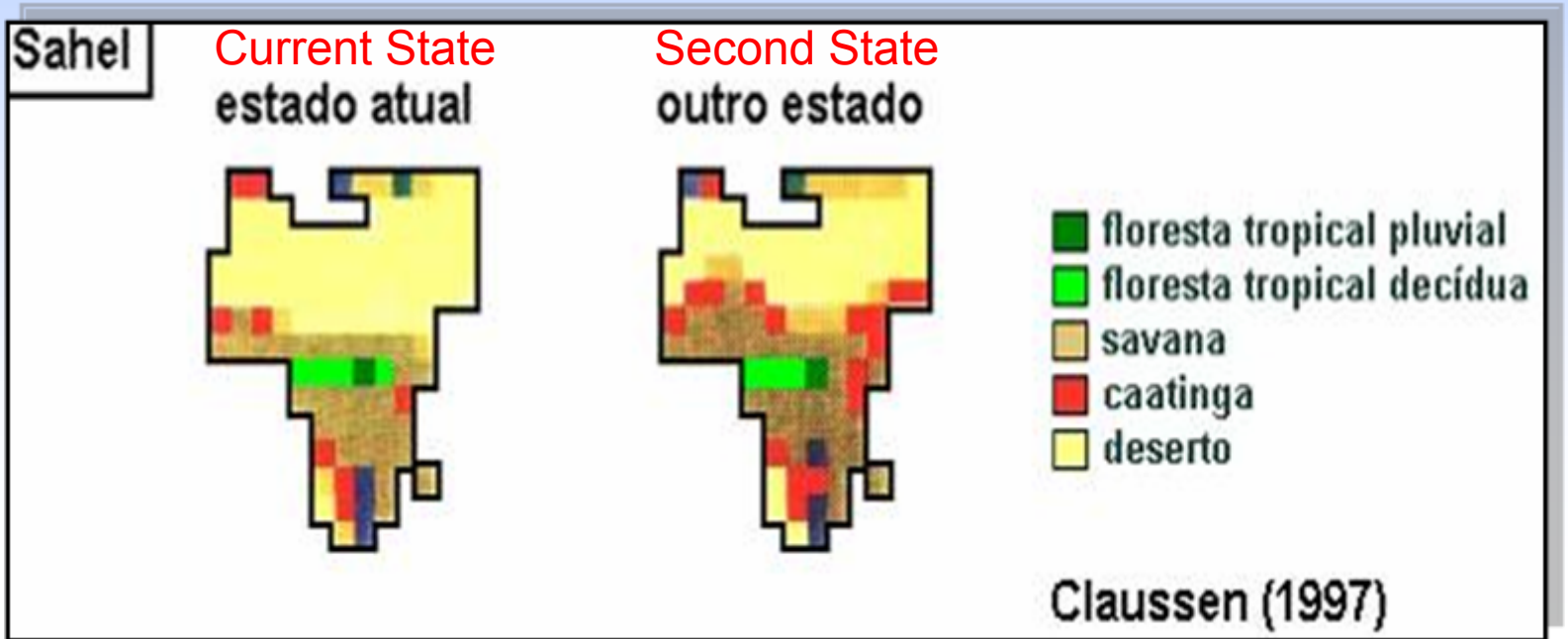
Como aplicar a teoria de sistemas dinâmicos para esses casos?

Biome-Climate Bi-Stability for the Sahel



The second equilibriun state depend mostly on vegetation (albedo) feedback and secondarily on ocean feedbacks

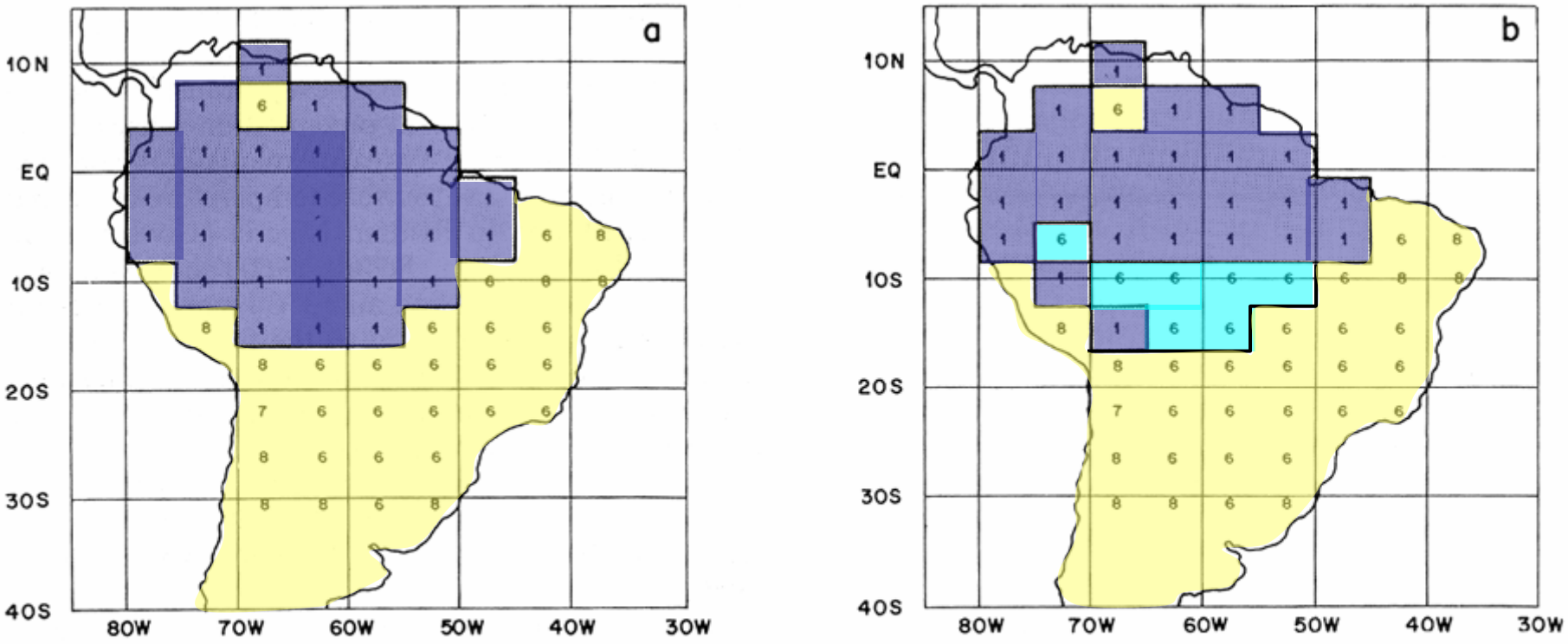
SCHEFFER EL AL., NATURE | VOL 413 | 11 OCTOBER 2001



Modeling Deforestation and Biogeography in Amazonia

Current Biomes

Post-deforestation



Bioclimatology for the control case (a, current bioclimatology) associated with deforestation (b, revised bioclimatology after deforestation such as the analysis of the vegetation stress index fields shows). The shaded area with "1" is tropical forest, "6" refers to cerrado. The forest boundary is depicted by the heavy solid line.

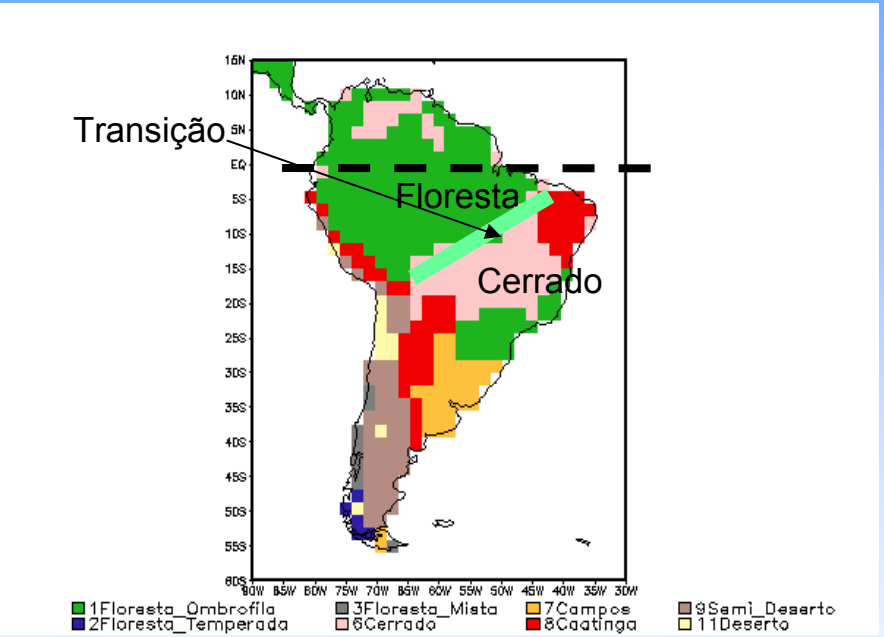
Nobre et al. 1991, J. Climate

"1" Tropical Forest
"6" Savanna

E se o sistema tiver uma escala maior???

Por exemplo:

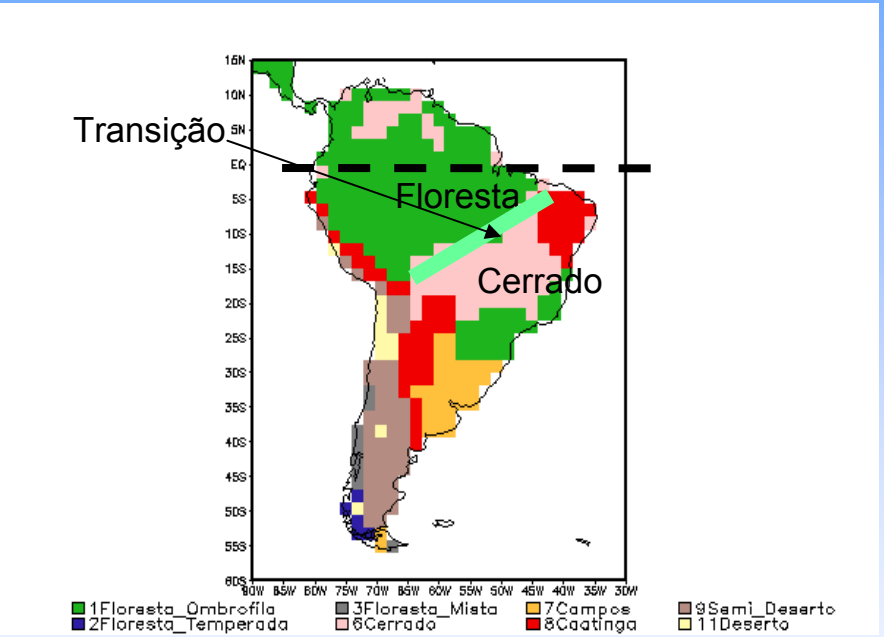
América do Sul Tropical



E se o sistema tiver uma escala maior???

Por exemplo:

América do Sul Tropical

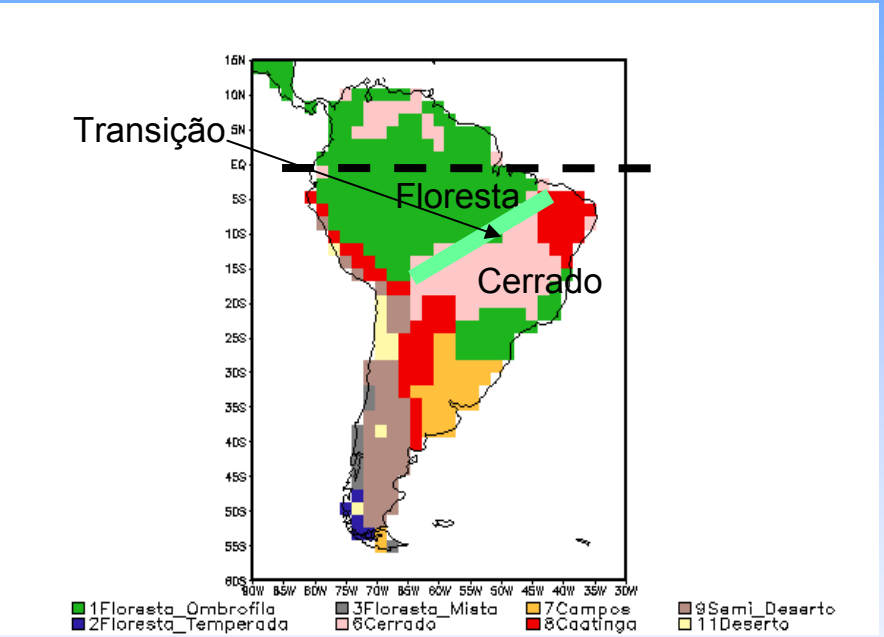


Caso haja um colapso para um novo estado de equilíbrio MAIS SECO, como propõem alguns estudos...

E se o sistema tiver uma escala maior???

Por exemplo:

América do Sul Tropical



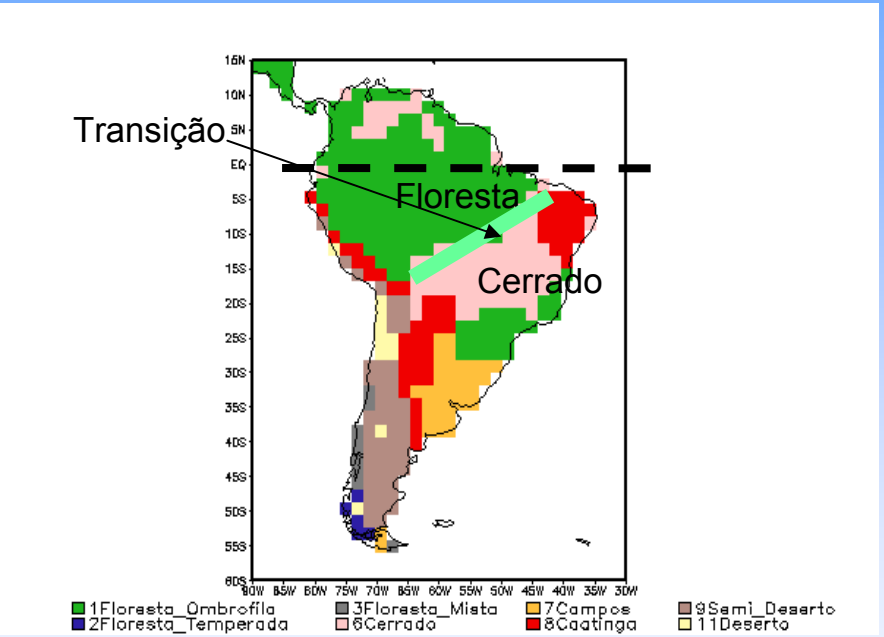
Caso haja um colapso para um novo estado de equilíbrio MAIS SECO, como propõem alguns estudos...

Há volta????

E se o sistema tiver uma escala maior???

Por exemplo:

América do Sul Tropical



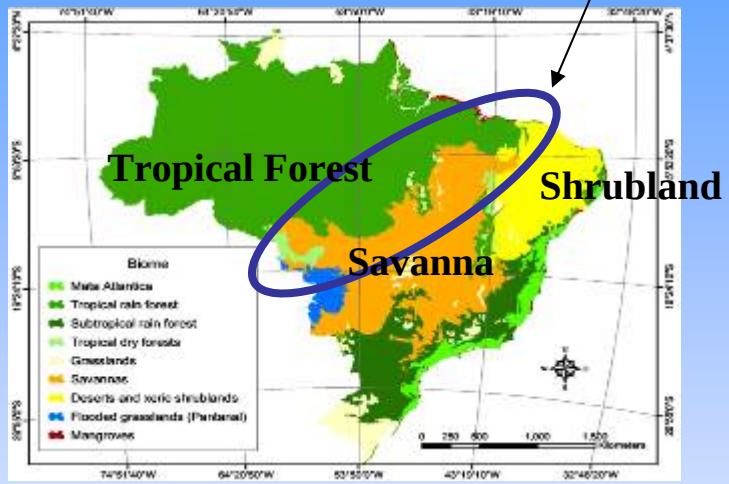
Caso haja um colapso para um novo estado de equilíbrio MAIS SECO, como propõem alguns estudos...

Há volta????

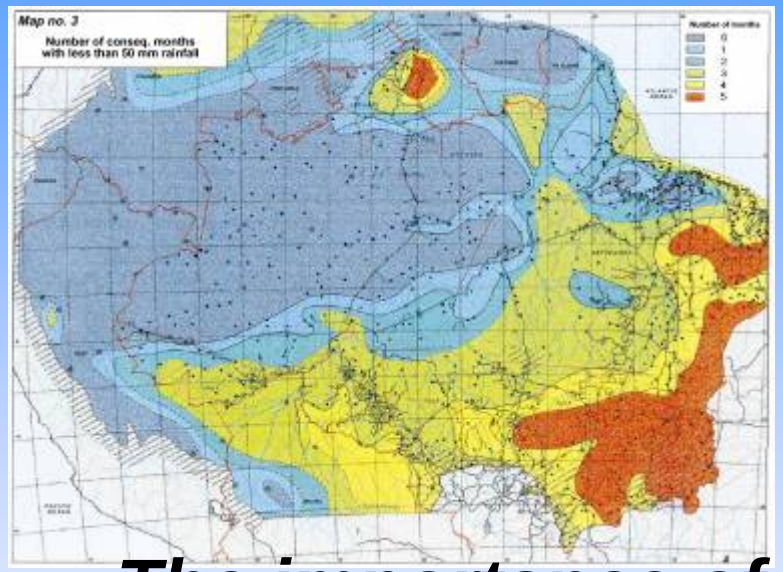
Conseqüências econômicas e sociais...

Biomes of tropical south America and precipitation seasonality

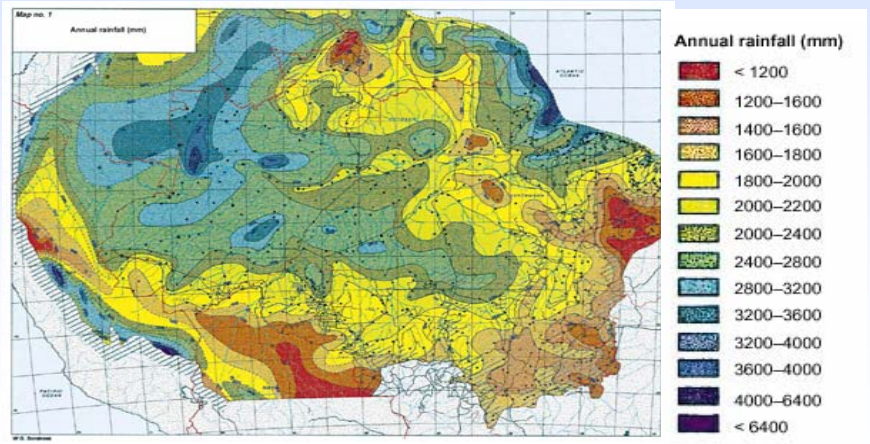
Biomes of Brazil



Number of consecutive months with less than 50 mm rainfall



Annual Rainfall

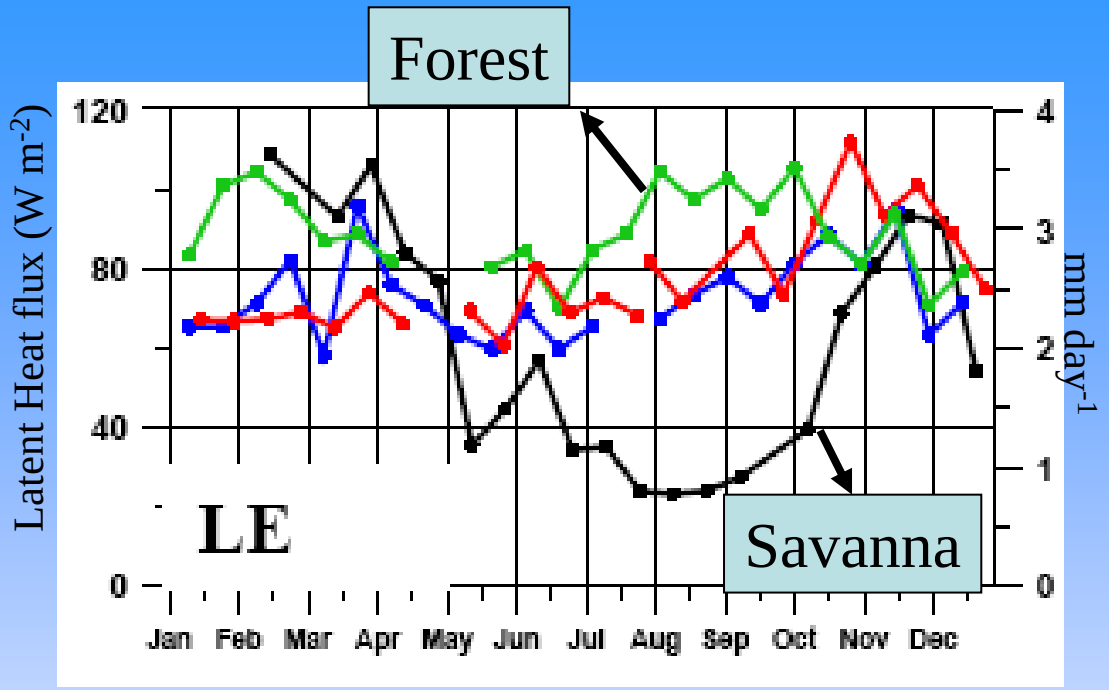


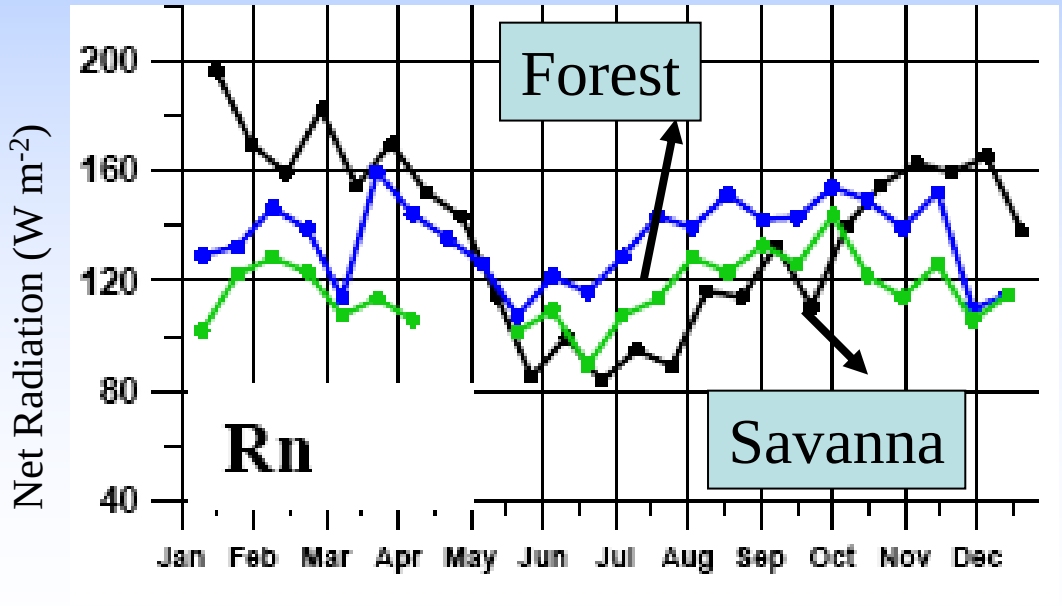
The importance of rainfall seasonality (short dry season) for maintaining tropical forests all over Amazonia

Sombroek 2001, Ambio

Evapotranspiration seasonality in the Amazon tropical forest and savanna

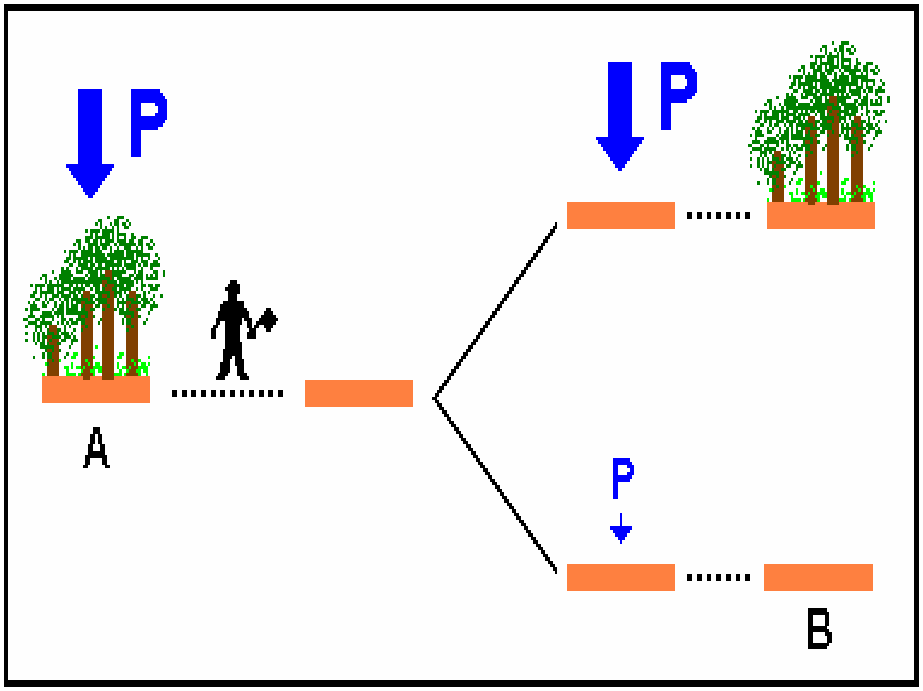
Source: Rocha (2004)

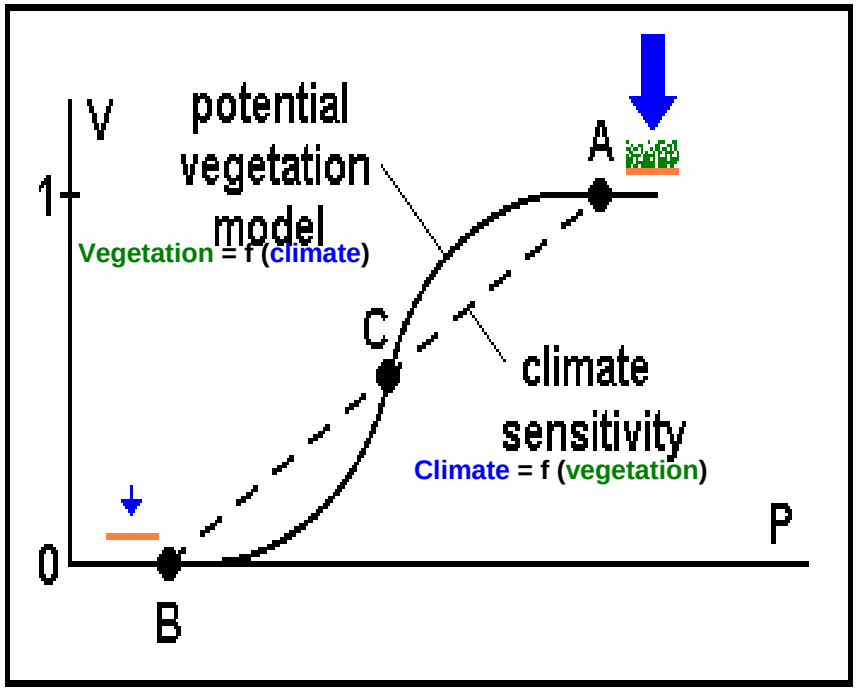




Is the current Climate-Biome equilibrium in Amazonia the only stable equilibrium possible?

Climate Equilibrium States



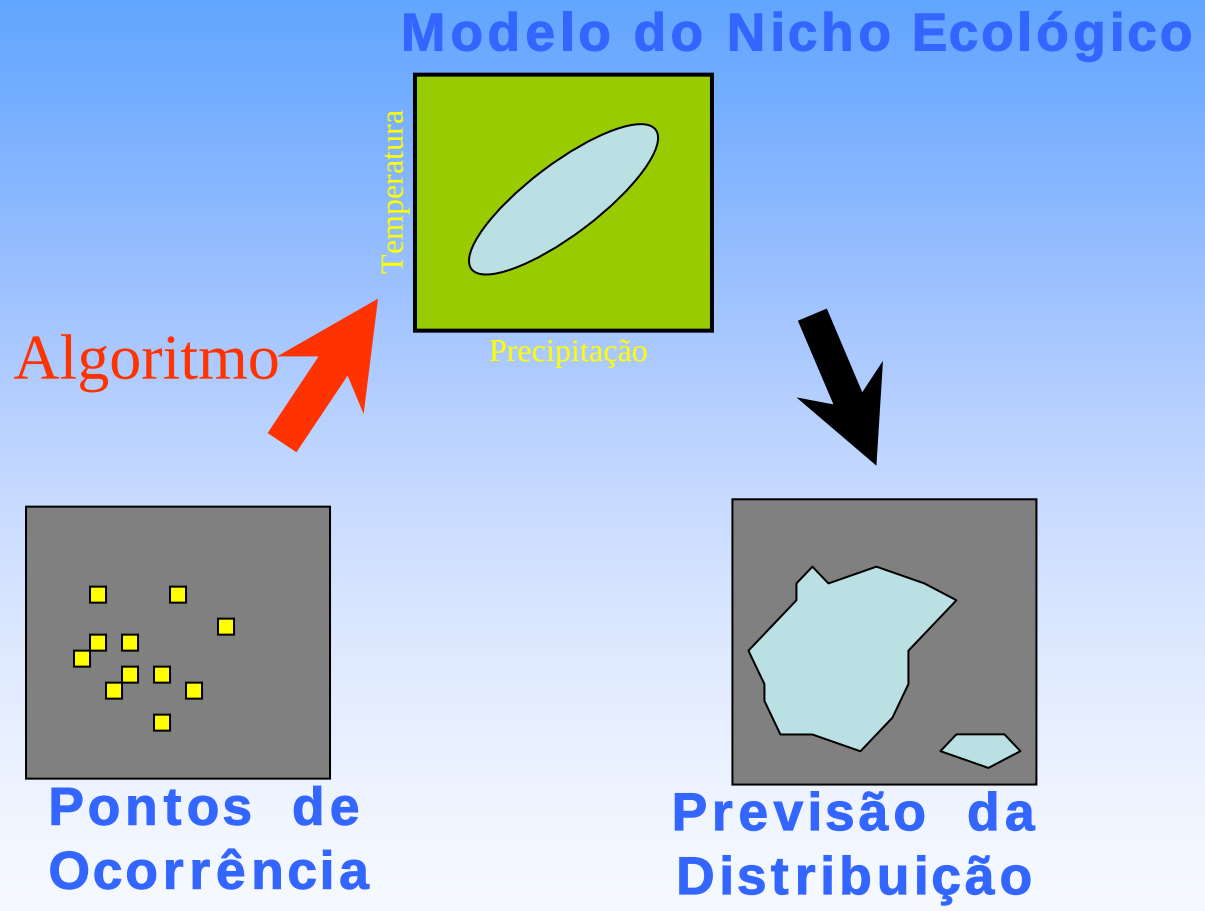


Oyama, 2002

Modelagem de Distribuição Geográfica de Espécies

Ecologia

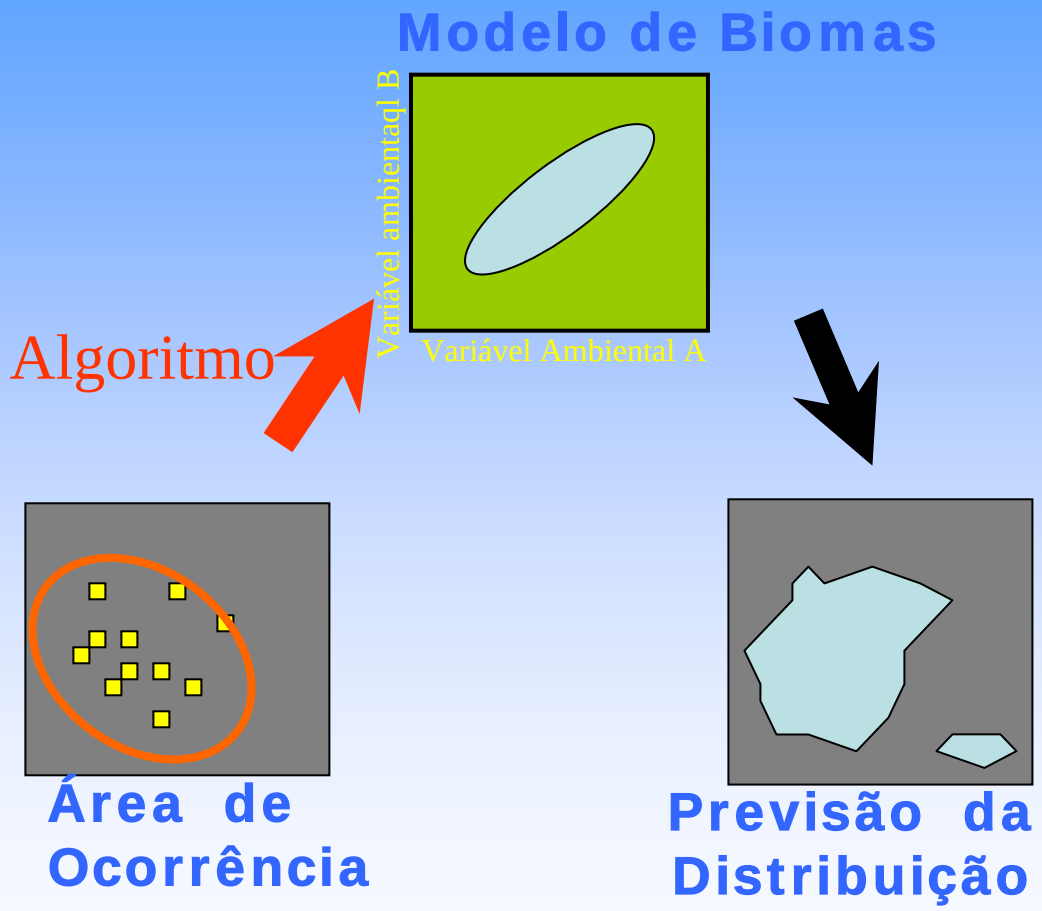
Geografia



Modelagem de Distribuição Geográfica de Biomas

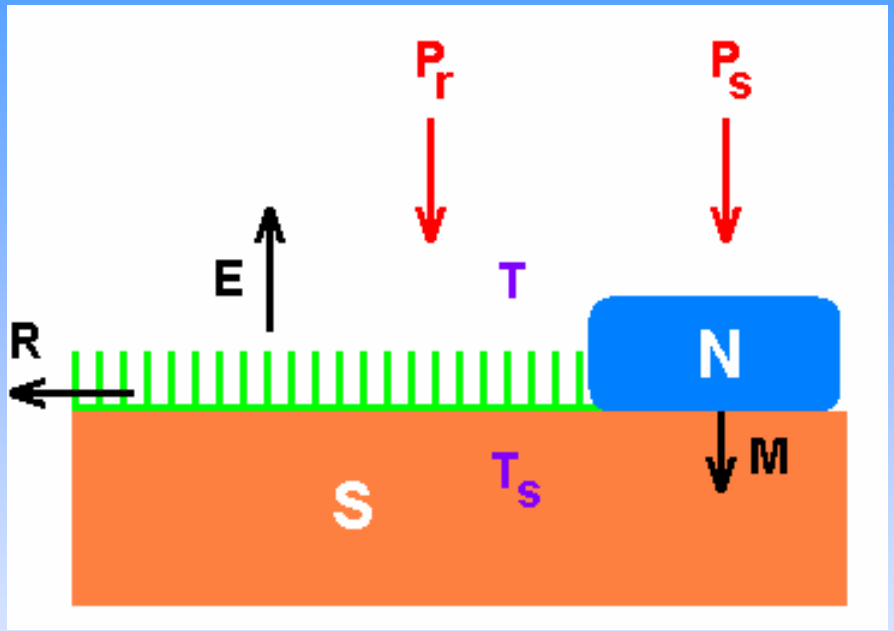
Ecologia

Geografia



- A Potential Vegetation Model that uses 5 or 6 climate parameters to represent the (SiB) biome classification was developed (CPTEC-PVM).
- CPTEC-PVM is able to represent quite well the world's biome distribution. A dynamical vegetation model was constructed by coupling CPTEC-PVM to the CPTEC Atmospheric GCM (CPTEC-DVM)).

Simple Land Surface Model



Pr: rain

Ps: snow

T: sfc air temperature

Ts: soil temperature

S: soil water storage

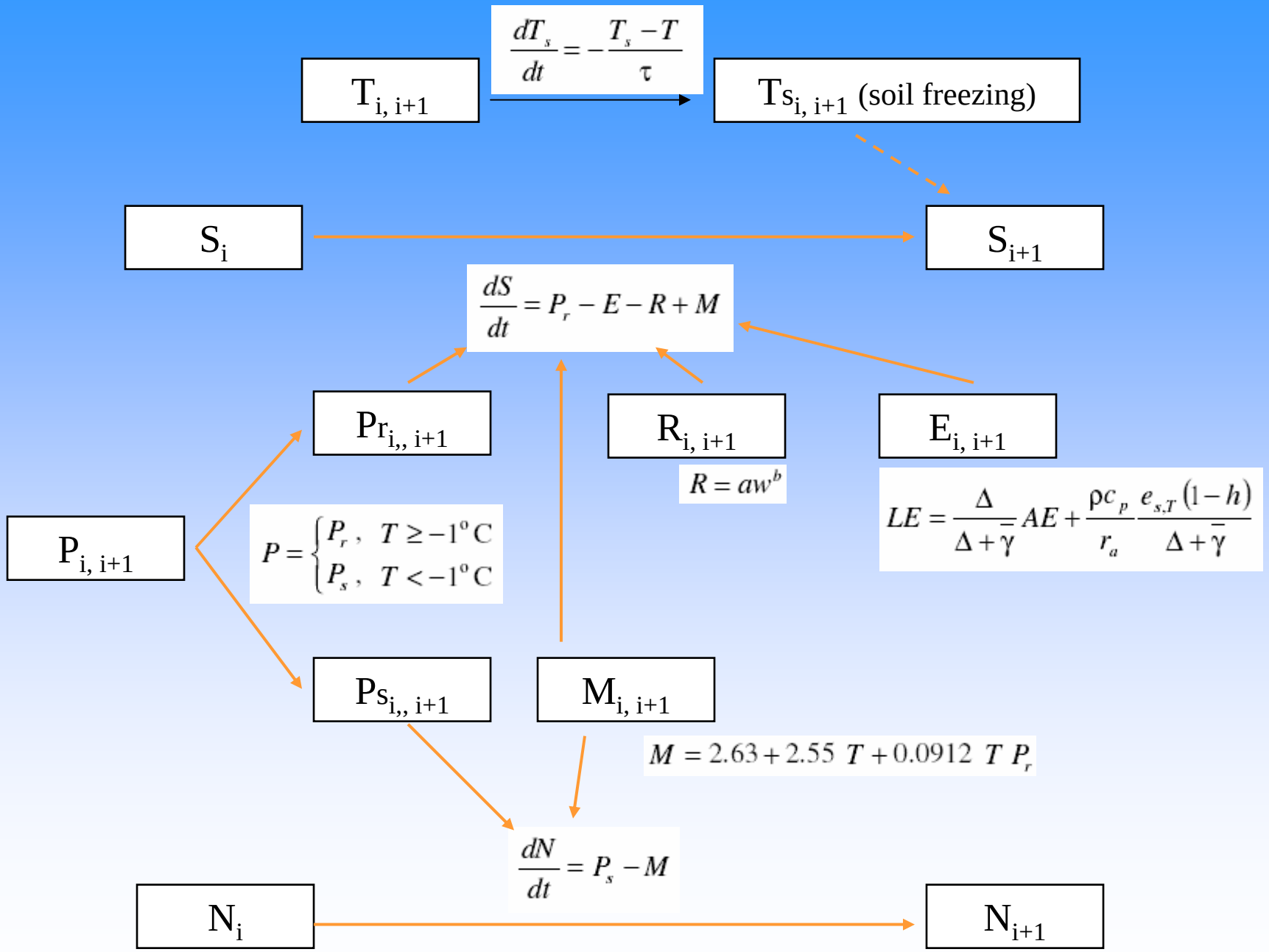
N: overland snow storage

E: evapotranspiration

R: runoff

M: snowmelt

Oyama and Nobre, 2004


$\frac{dT_s}{dt} = -\frac{T_s - T}{\tau}$
$T_{i,\,i+1}$
$Ts_{i,\,i+1}$ (soil freezing)
S_i
S_{i+1}
$\frac{dS}{dt} = P_r - E - R + M$
$Pr_{i,,\,i+1}$
$R_{i,\,i+1}$
$E_{i,\,i+1}$
$R = aw^b$
$LE = \frac{\Delta}{\Delta+\bar{\gamma}} AE + \frac{\rho c_p}{r_a} \frac{e_{s,T}(1-h)}{\Delta+\bar{\gamma}}$
$P_{i,\,i+1}$
$P = \begin{cases} P_r, & T \geq -1^{\circ}\mathrm{C} \\ P_s, & T < -1^{\circ}\mathrm{C} \end{cases}$
$Ps_{i,,\,i+1}$
$M_{i,\,i+1}$
$M = 2.63 + 2.55\ T + 0.0912\ T\ P_r$
$\frac{dN}{dt} = P_s - M$
N_i
N_{i+1}

Five climate parameters drive the potential vegetation model

Monthly values of precipitation and temperature

P_i , T_i , i = 1...12

Water Balance Model

MODELO DE BALANÇO HÍDRICO

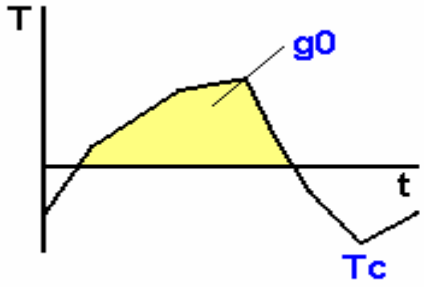
g5 , g0 , Tc , s , h

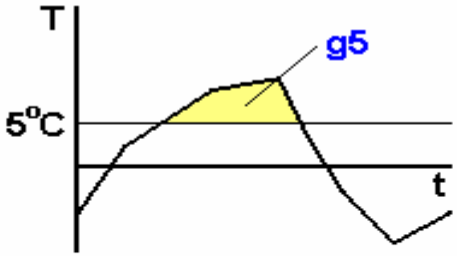
Potential Vegetation Model

MODELO DE VEGETAÇÃO POTENCIAL

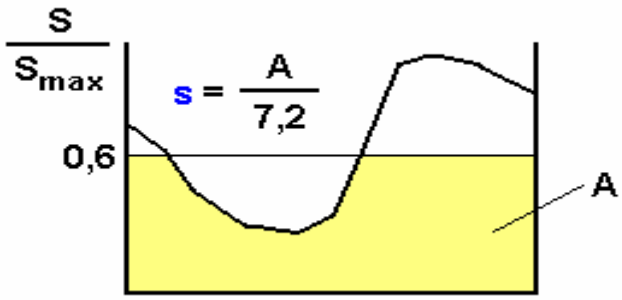
bioma do SSiB

SSiB Biomes

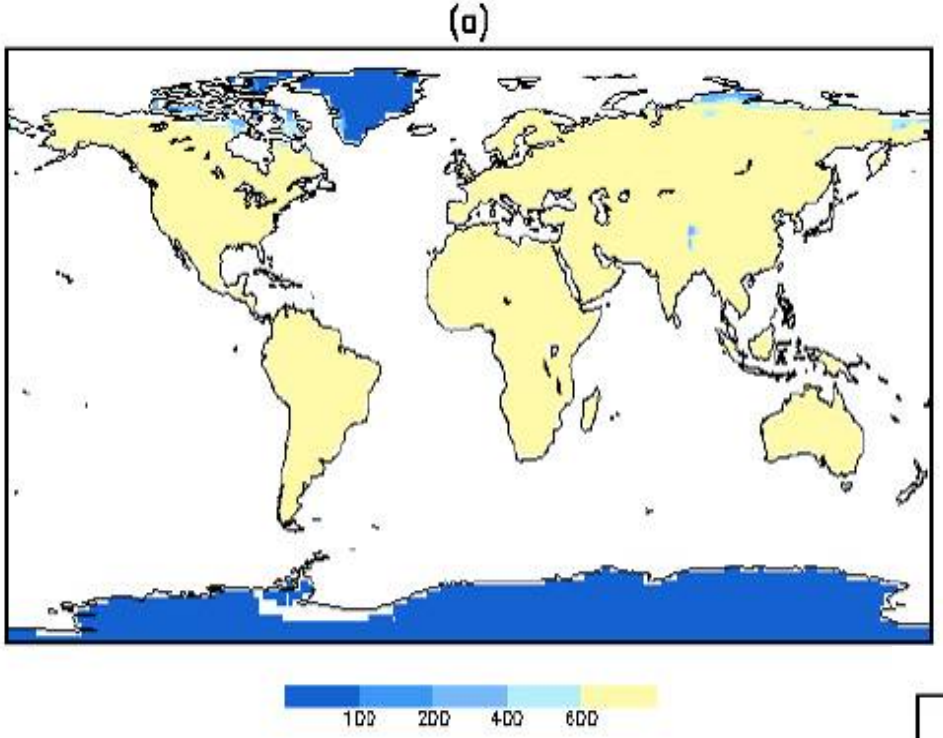




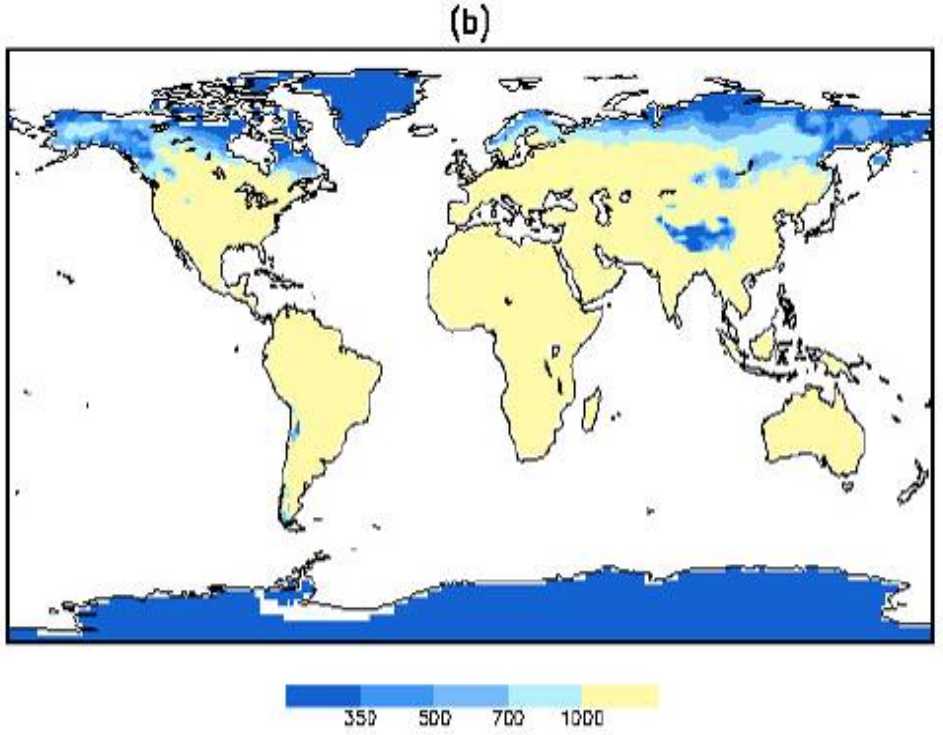
$$h = \frac{ET}{ET_{max}}$$



Oyama and Nobre, 2004



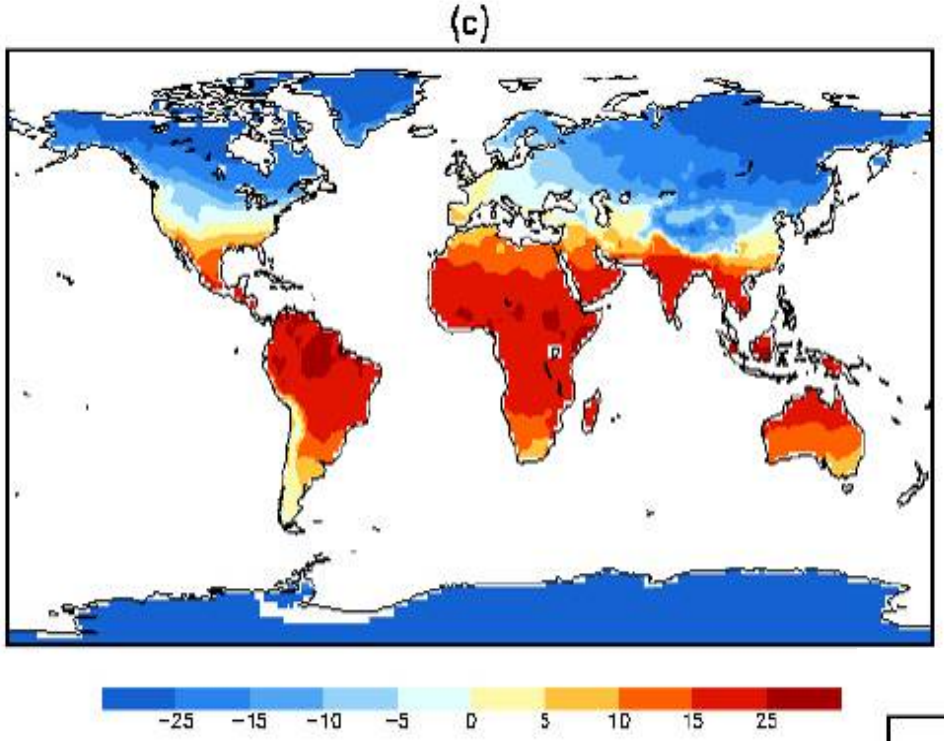
growing degree-days on 0ºC base



growing degree-days on 5ºC base

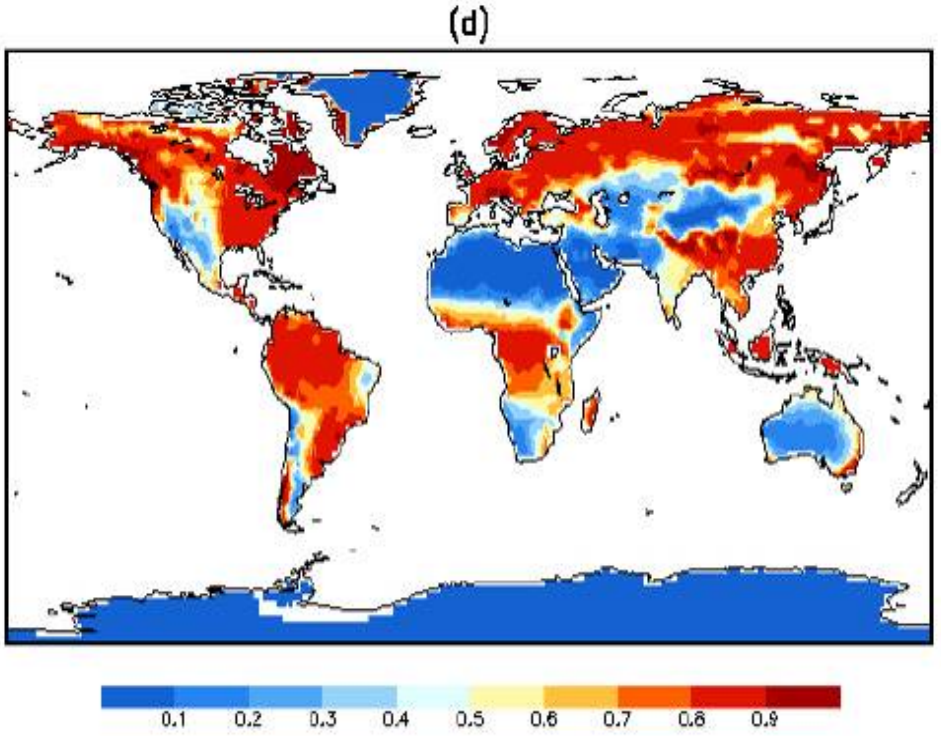
Figure 6. Environmental variables used in CPTEC PVM: growing degree-days on 0ºC base (a), growing degree-days on 5ºC base (b), mean temperature of the coldest month (c), wetness index (d), seasonality index (e). Growing degree-days in oC day month^{-1}, and temperature in ºC.

Oyama and Nobre, 2002

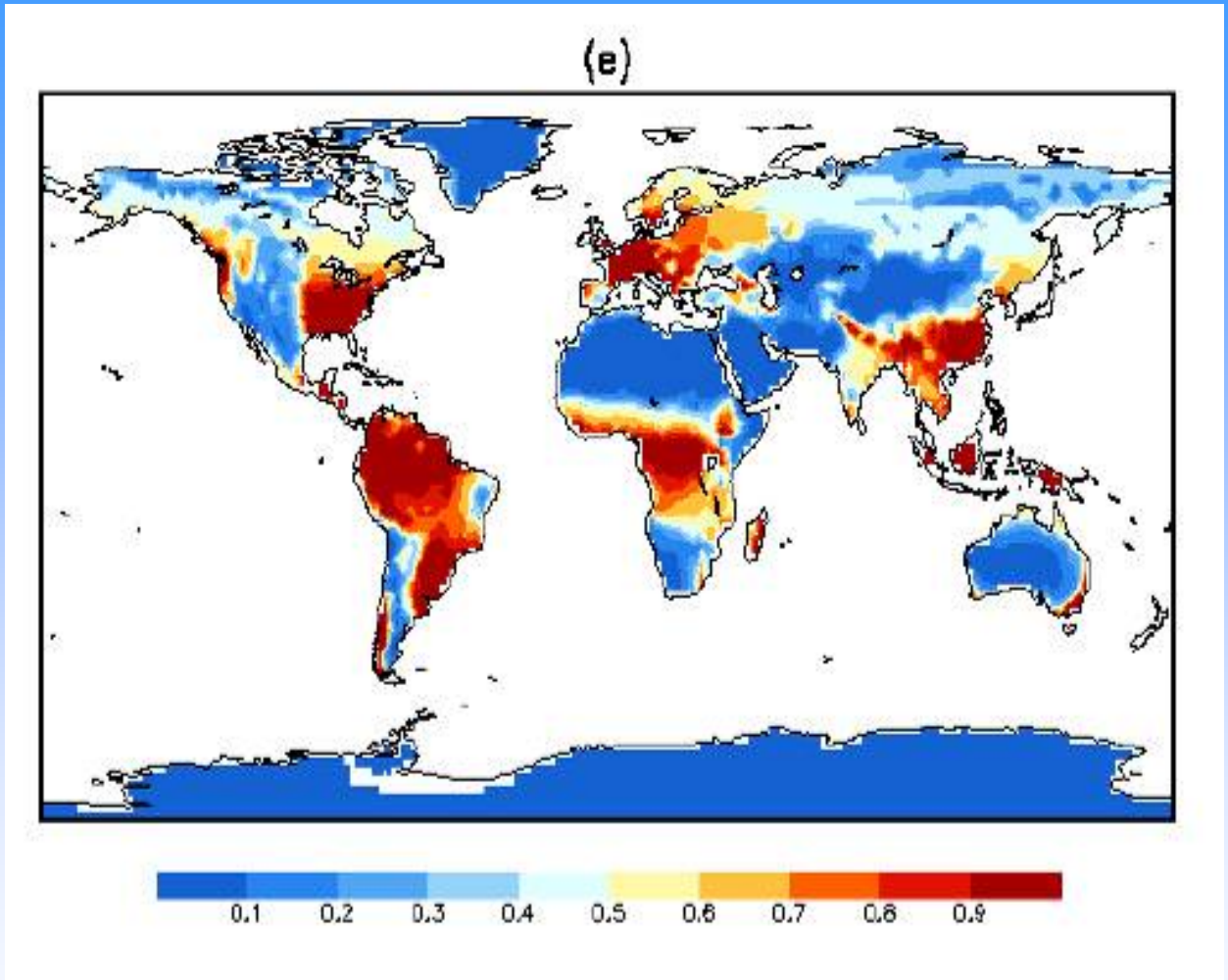


mean temperature of the coldest month

Wetness index

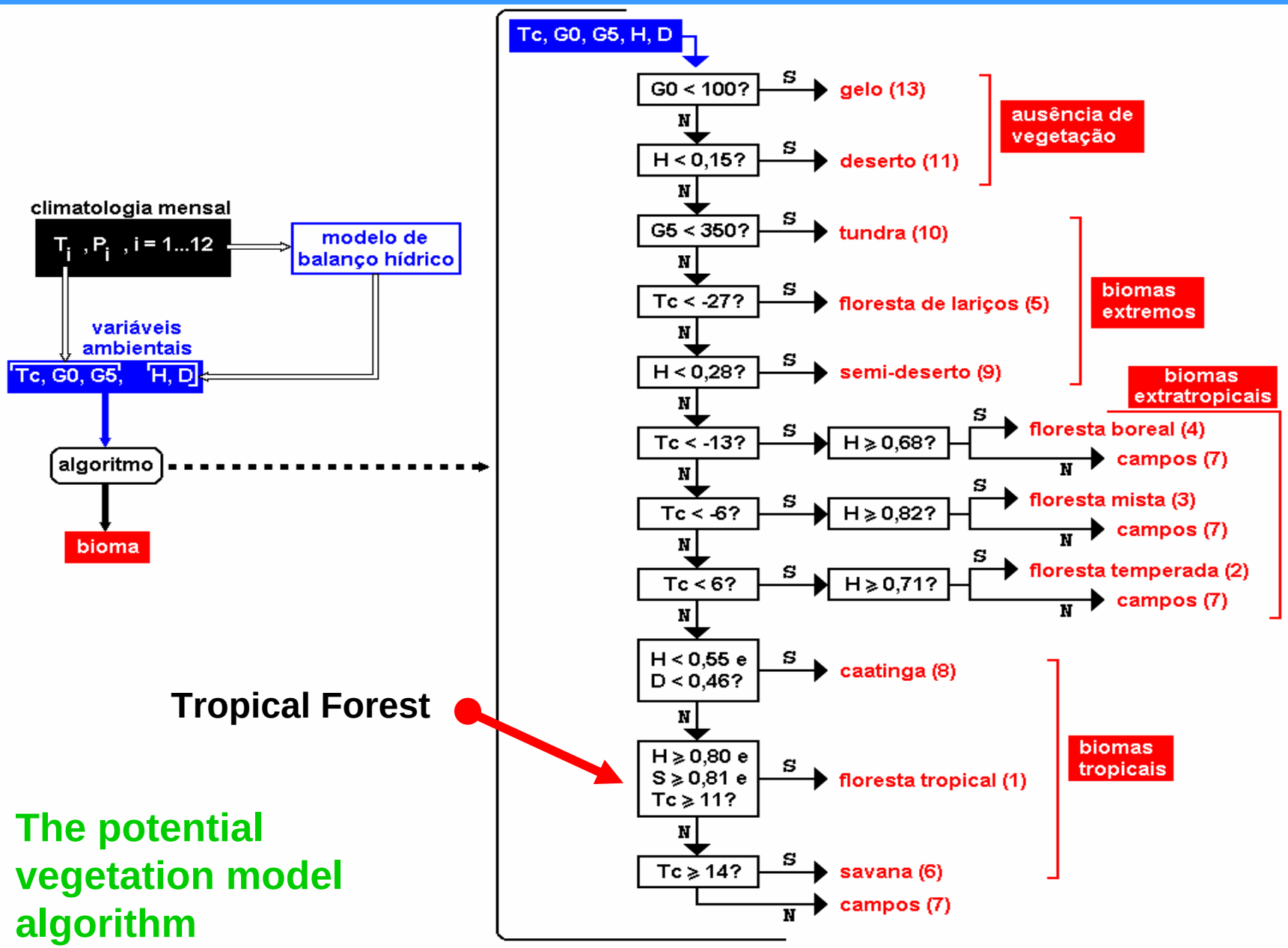


Oyama and Nobre, 2002



seasonality index

Oyama and Nobre, 2002

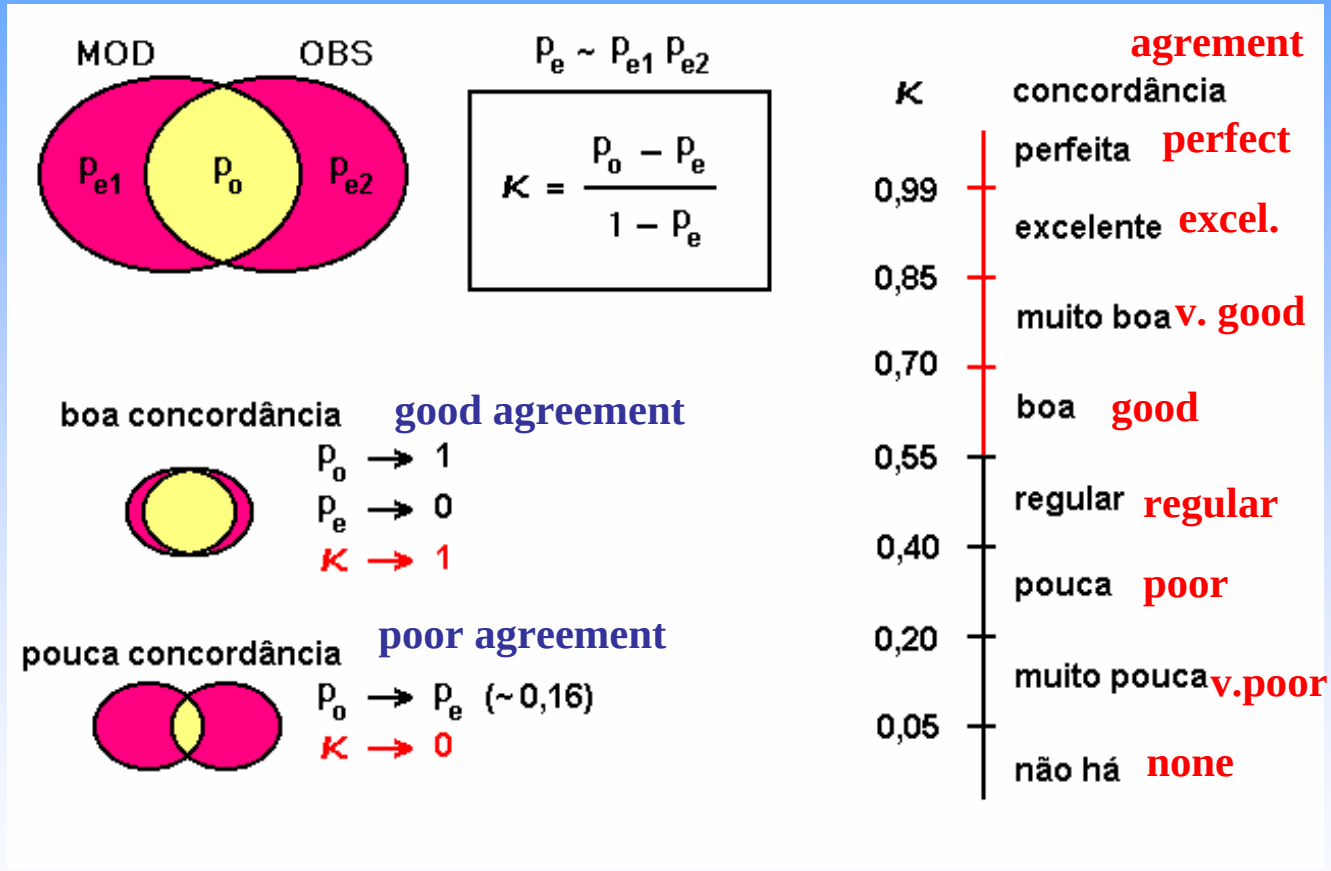


Tropical Forest

The potential vegetation model algorithm

Oyama and Nobre, 2002

Statistic κ
(Monserud e Leemans 1992)



Oyama and Nobre, 2004

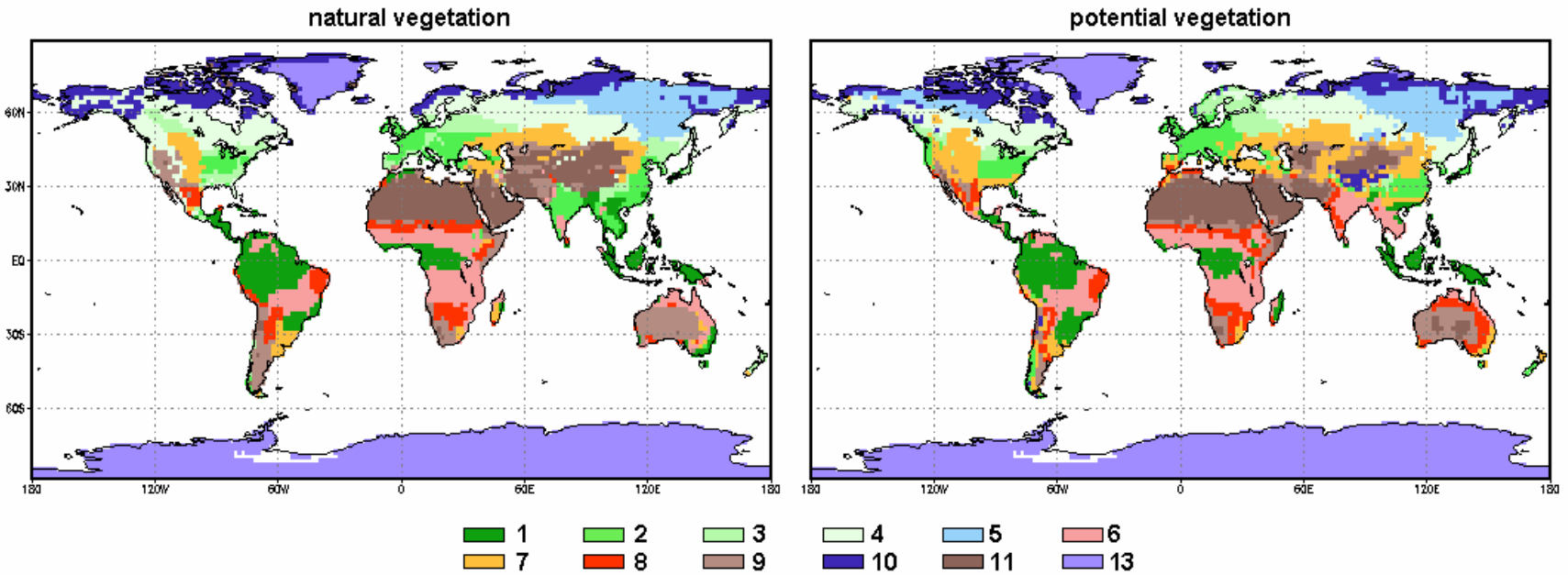
Objective verification of CPTEC-PBM

bioma	nome	p_0 (%)	κ	concordância	agreement
1	floresta tropical	71	0,73	muito boa	Very Good
2	floresta temperada Temperate Forest	52	0,49	regula	Regular
3	floresta mista Mixed Forest	26	0,26	pouca	Poor
4	floresta de coníferas	55	0,56	boa	Good
5	lariços	70	0,65	boa	Good
6	savana	56	0,60	boa	Good
7	campos extratropicais Grasslands	76	0,50	regular	Regular
8	caatinga Dry shrubland	50	0,40	regular	Regular
9	semi-deserto	57	0,55	boa	Good
10	tundra	62	0,67	boa	Good
11	deserto	70	0,74	muito boa	Very Good
Global Mean	**média global**	**62**	**0,58**	**boa**	**Good**
Literatu	**literatura**	**~ 40**	**0,40 - 0,50**	**regular**	

Oyama and Nobre, 2004

Visual Comparison of CPTEC-PBM versus Natural Vegetation Map

CPTEC-PBM



SiB Biome Classification

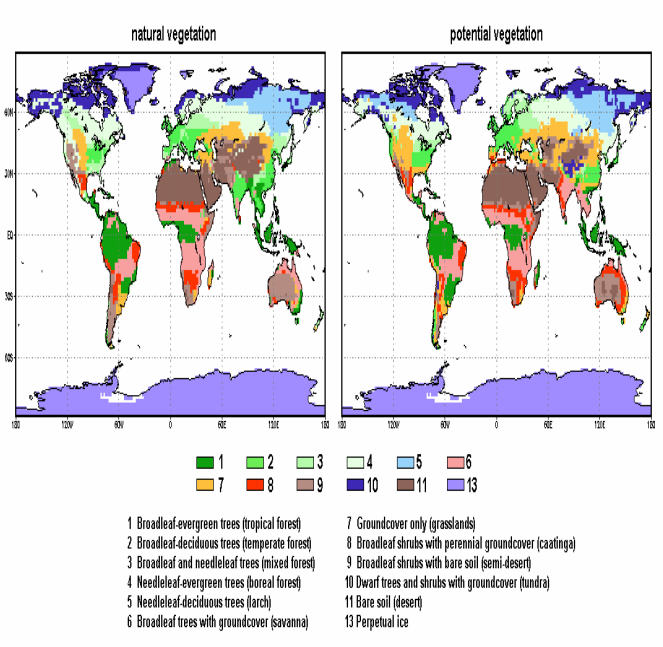
1 Broadleaf-evergreen trees (tropical forest)
2 Broadleaf-deciduous trees (temperate forest)
3 Broadleaf and needleleaf trees (mixed forest)
4 Needleleaf-evergreen trees (boreal forest)
5 Needleleaf-deciduous trees (larch)
6 Broadleaf trees with groundcover (savanna)
7 Groundcover only (grasslands)
8 Broadleaf shrubs with perennial groundcover (caatinga)
9 Broadleaf shrubs with bare soil (semi-desert)
10 Dwarf trees and shrubs with groundcover (tundra)
11 Bare soil (desert)
13 Perpetual ice

62% agreement on a global 2 deg x 2 deg grid

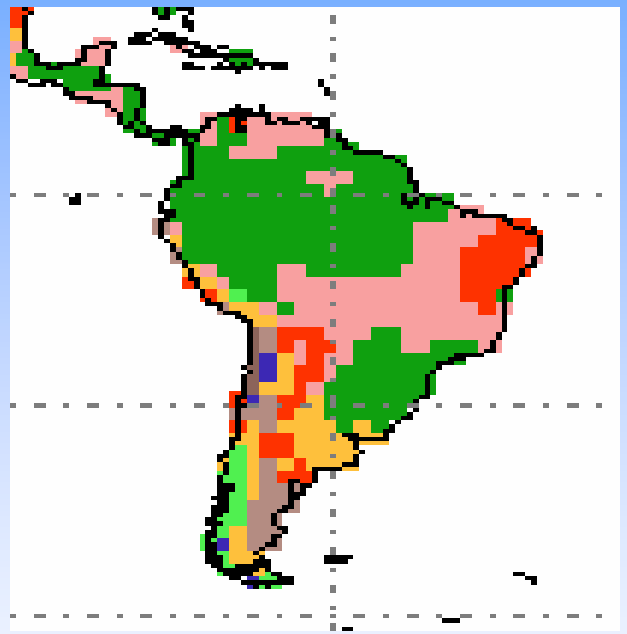
Oyama and Nobre, 2004

Visual Comparison of CPTEC-PBM versus Natural Vegetation Map

NATURAL VEGETATION



POTENTIAL VEGETATION



SiB Biome Classification

1 2 3 4 5 6
7 8 9 10 11 13

1 Broadleaf-evergreen trees (tropical forest)
2 Broadleaf-deciduous trees (temperate forest)
3 Broadleaf and needleleaf trees (mixed forest)
4 Needleleaf-evergreen trees (boreal forest)
5 Needleleaf-deciduous trees (larch)
6 Broadleaf trees with groundcover (savanna)
7 Groundcover only (grasslands)
8 Broadleaf shrubs with perennial groundcover (caatinga)
9 Broadleaf shrubs with bare soil (semi-desert)
10 Dwarf trees and shrubs with groundcover (tundra)
11 Bare soil (desert)
13 Perpetual ice

Oyama and Nobre, 2004

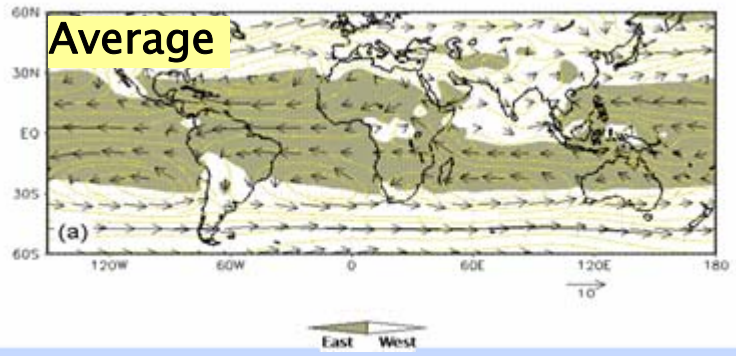

What about the effect of natural fires?

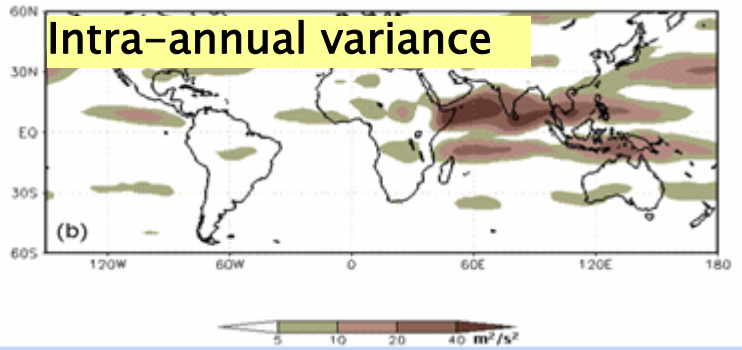
At long term, fires have also important effects on biomes distribution:

To account for fires when estimating the distribution of the natural biomes, we developed a new long-term fire parameterization based on the potential for lightning during dry-wet season transitions

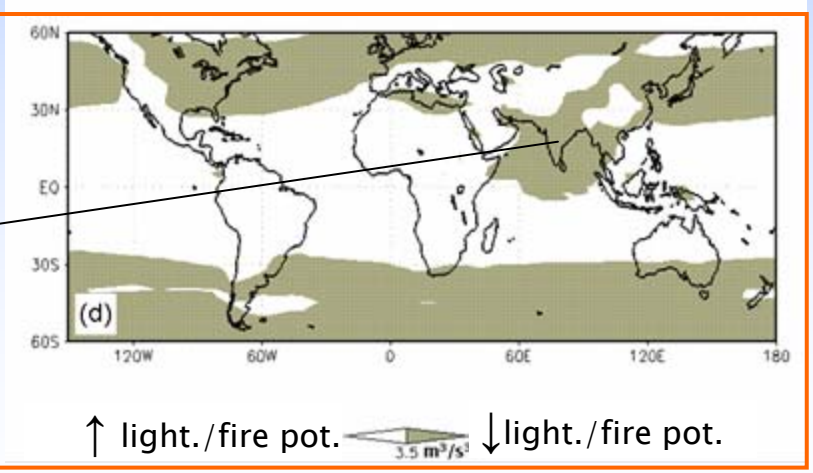
The new long-term natural fires parameterization is based on major circulation patterns:

Long-term characteristics of the zonal wind





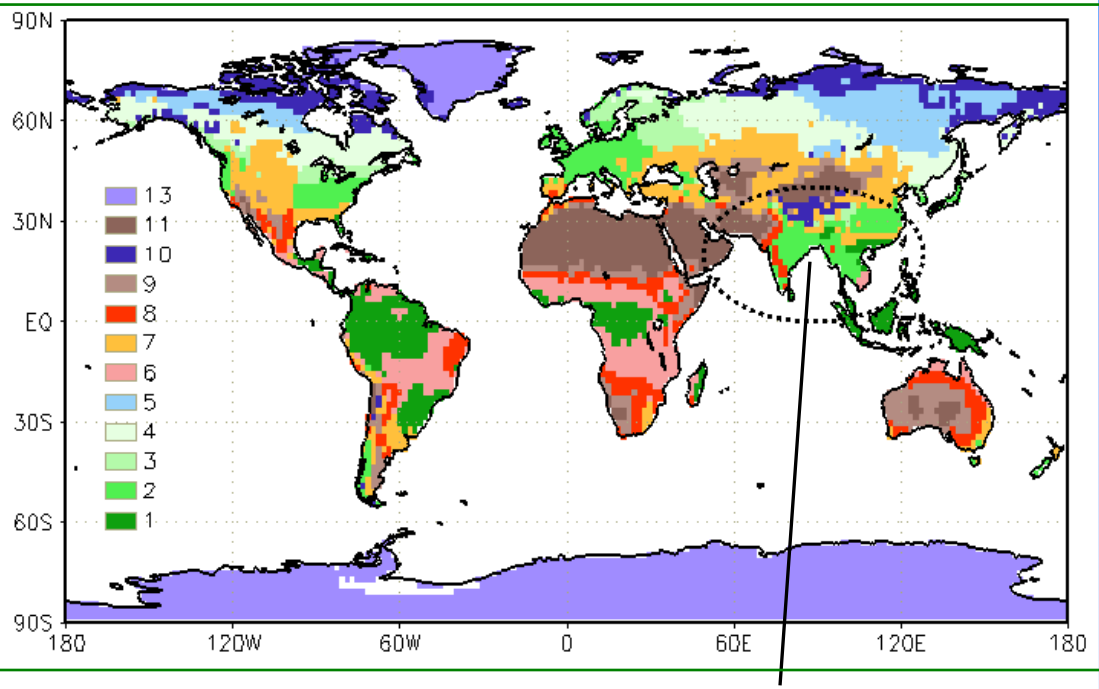
The potential for lightning/fires in the tropics is higher were combined long-term average and intra-annual variance of the zonal wind is lower than 3.5 m^3/s^3 (in grey):



Cardoso et al. (2007), in review

Impact of using the new fire parameterization in the biome estimates of the CPTEC Potential Vegetation Model:

Major vegetation types:
(1) broadleaf-evergreen trees (tropical forest),
(2) broadleaf-deciduous trees (temperate forest)
(3) broadleaf and needleleaf trees (mixed forest)
(4) needleleaf-evergreen trees (boreal forest)
(5) needleleaf-deciduous trees (larch),
(6) broadleaf trees with groundcover (savanna)
(7) groundcover only (prairie, steppes)
(8) broadleaf shrubs with perennial groundcover (caatinga)
(9) broadleaf shrubs with bare soil (semi-desert)
(10) dwarf trees and shrubs with groundcover (tundra)
(11) bare soil (desert)
(13) ice.



Accounting for fires corrected important differences between previous model estimates and reference data for the position of natural savannas in the tropics. In specific, large areas in India and SE Asia that were initially estimated as savannas are now corrected to dry forests.

Cardoso et al. (2007), in review

How to find numerically multiple stables states of climate-vegetation equilibrium?

Vegetation = f_1 (climate variables)

= f_1 (g_0, g_5, Tc, h, s)

g_0 = degree-days above 0 C

g_5 = degree-days above 5 C

Tc = mean temperature of the coldest month

h = aridity index

s = sesonality index

f_1 is a highly nonlinear function

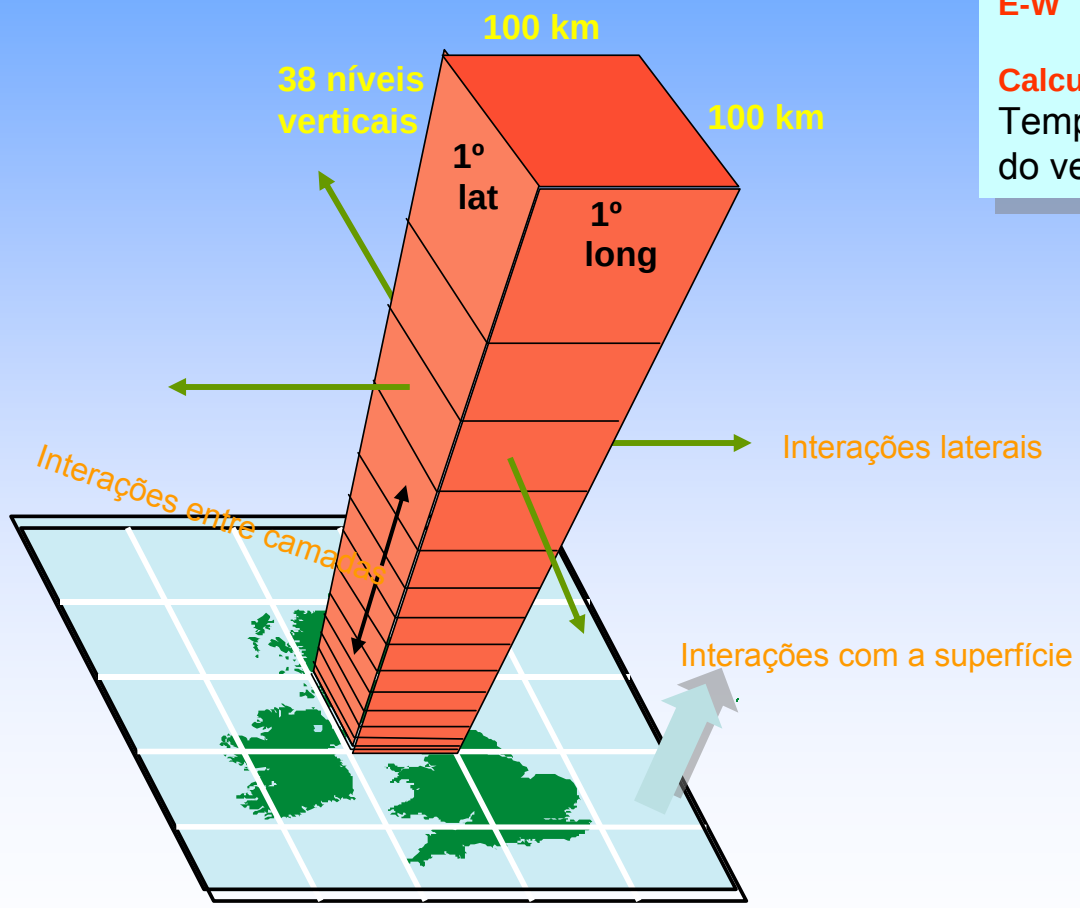
Climate = f_2 (vegetation)

= f_2 (AGCM coupled to vegetated land surface scheme)

f_2 is also a nonlinear function

Modelo Atmosférico Global para Previsão de Tempo:

Código computacional (centenas de milhares de linhas de código) que representa aproximações numéricas de equações matemáticas, equações estas representativas das Leis Físicas que regem os movimentos da atmosfera e as interações com a superfície; o cálculo é feito para até 10 dias de previsão.



Número de elementos:

400 x 200 x 28= 2,24 milhões

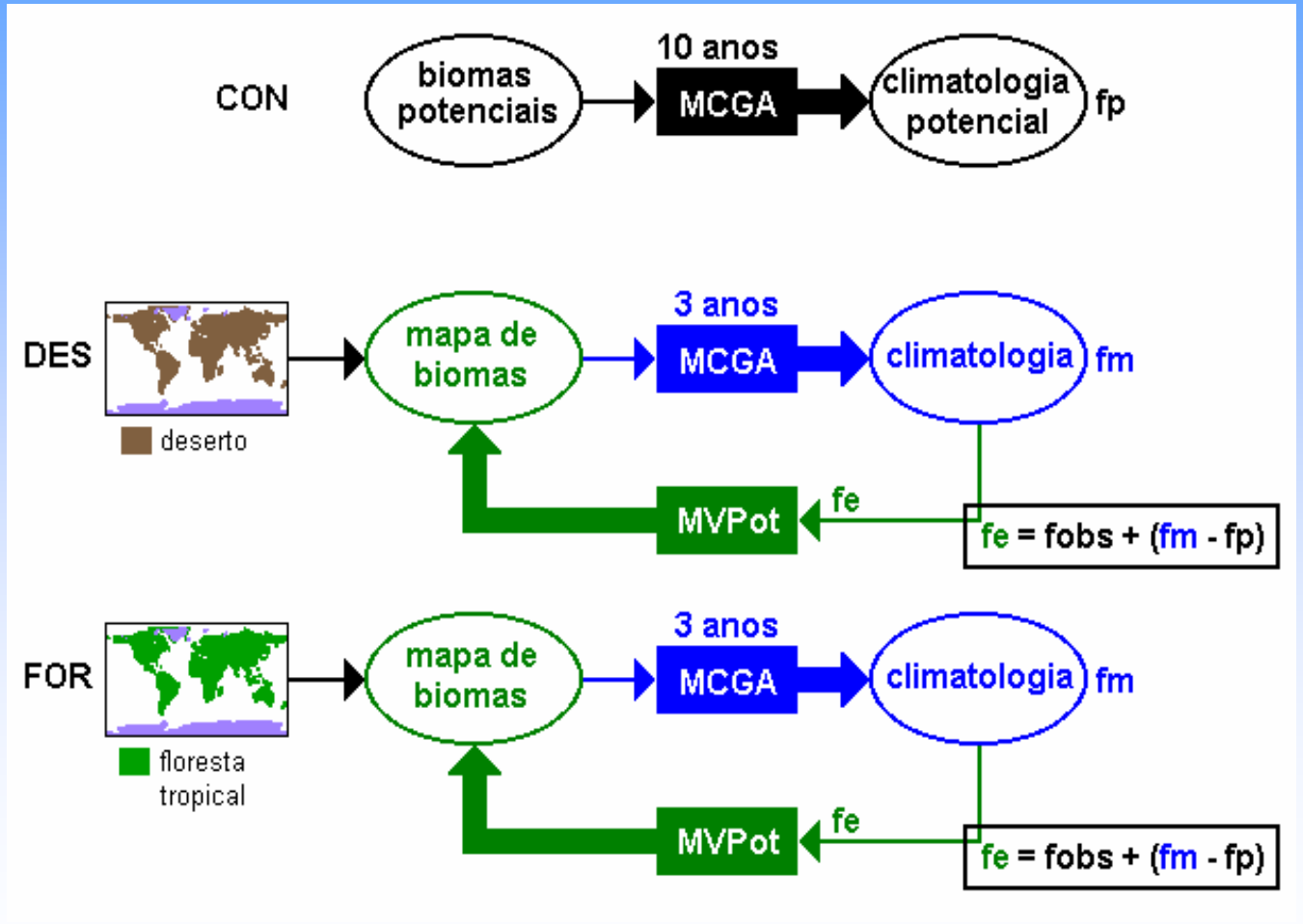
E-W N-S Vertical

Calcula-se para cada um destes volumes:

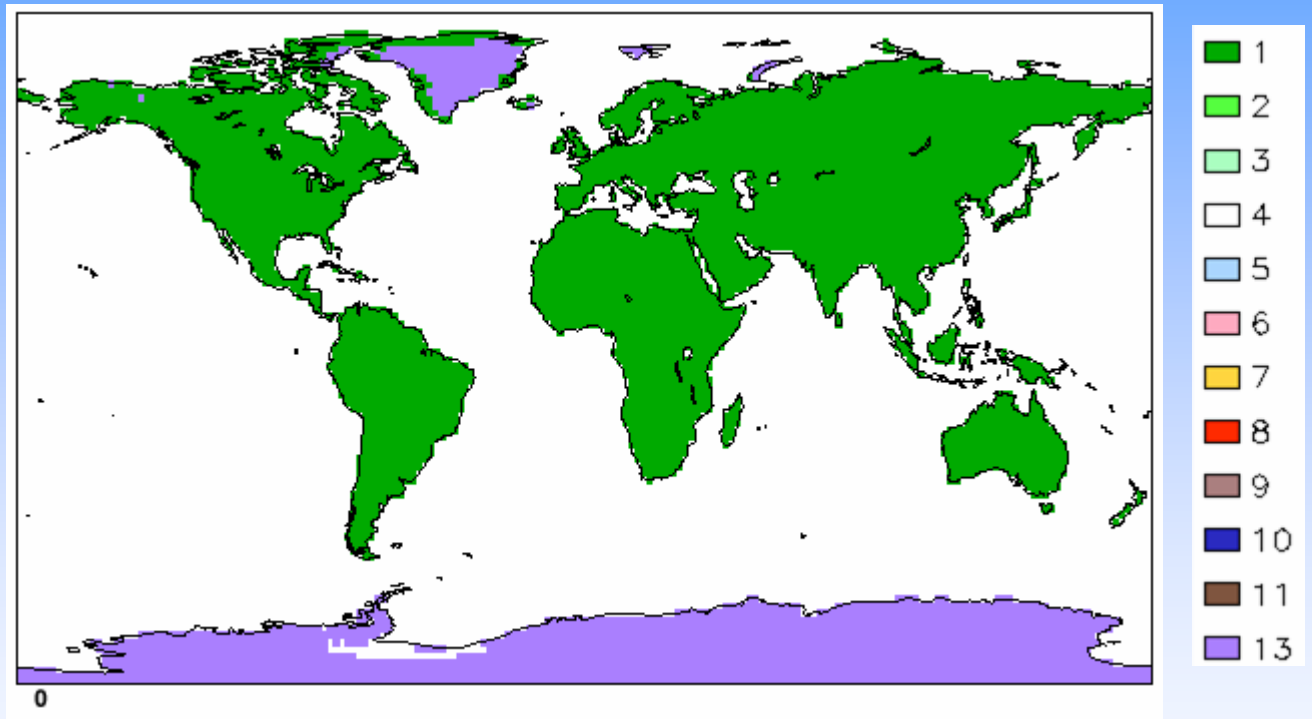
Temperatura, umidade, direção e velocidade do vento, altura geopotencial.

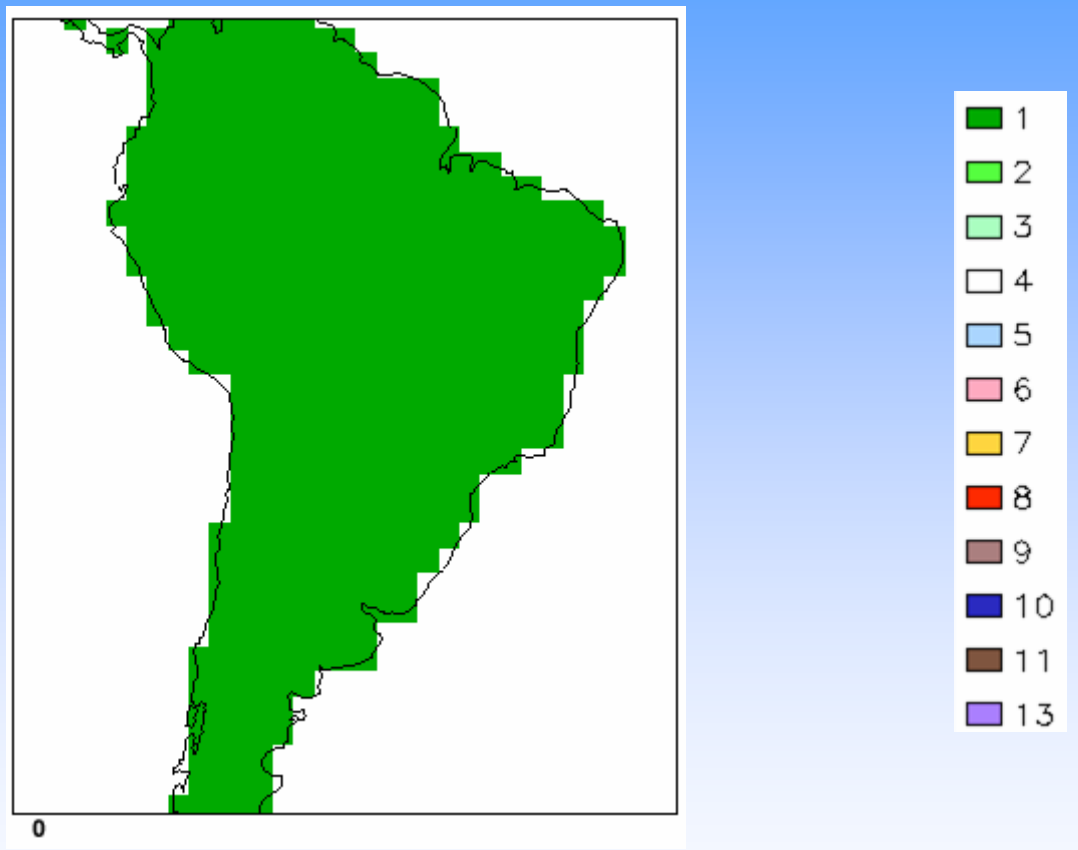
Domínio Geográfico

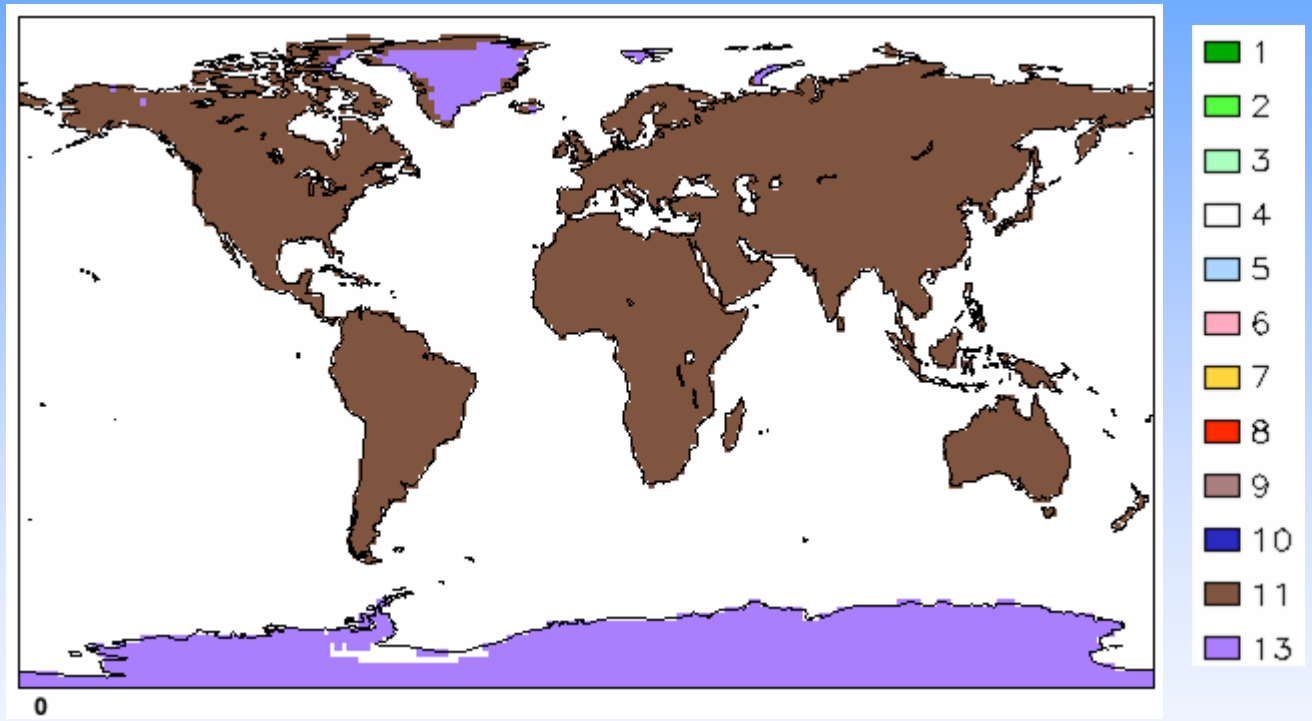
How to find numerically Multiple Vegetation-Climate Equilibrium States?

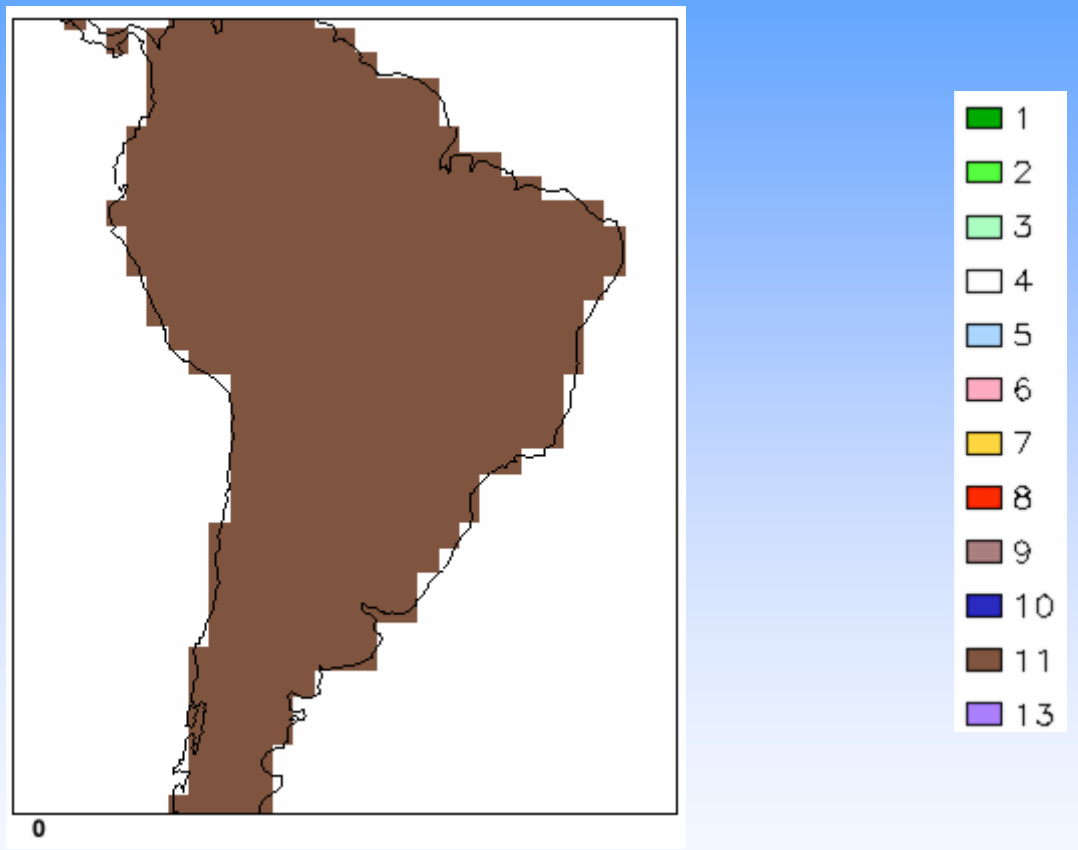


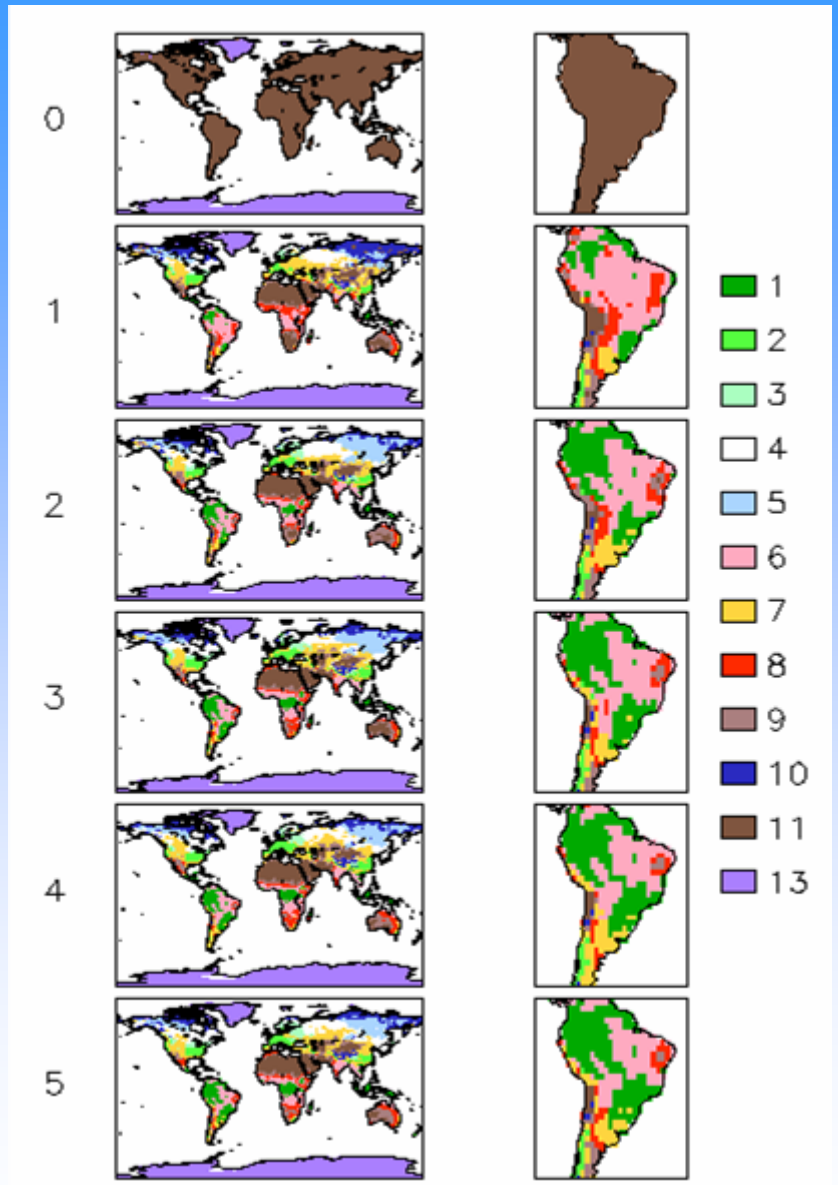
Oyama, 2002

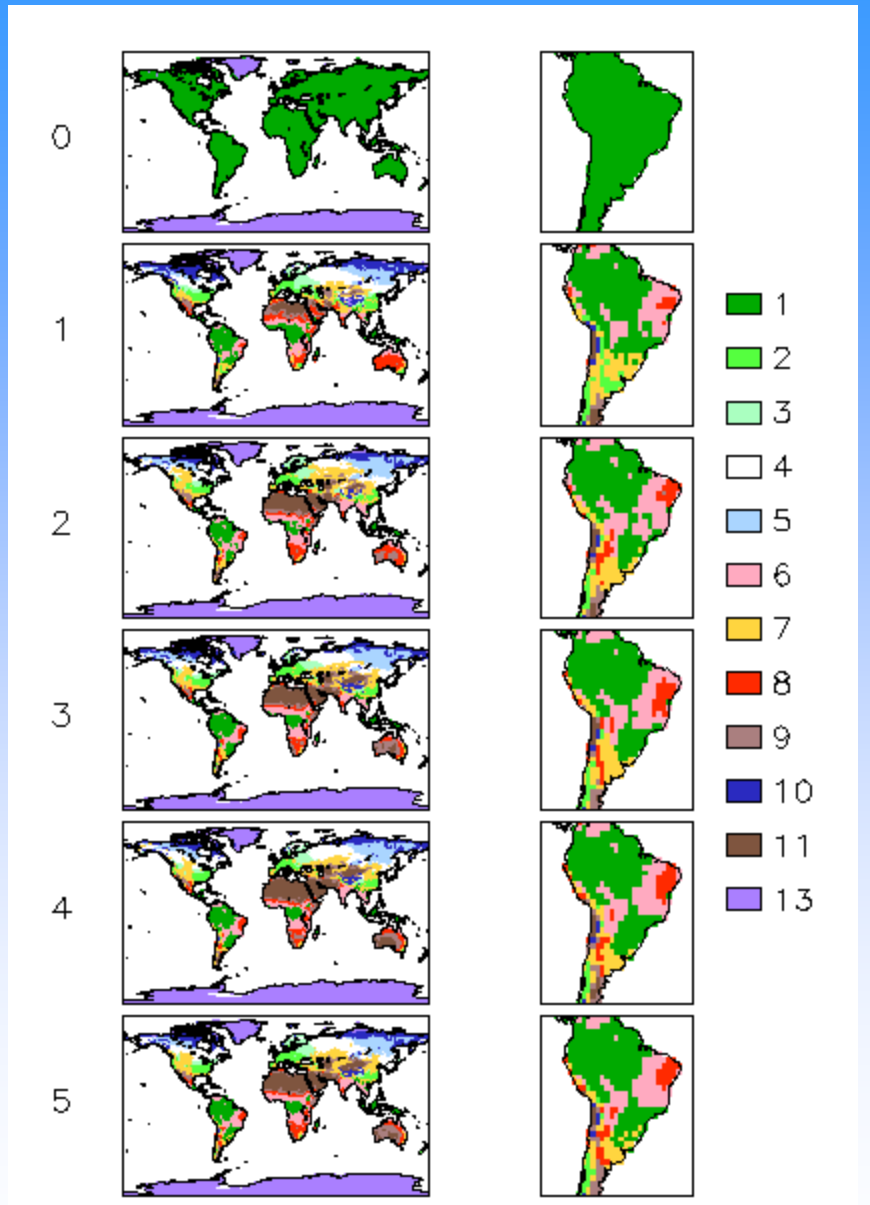

1
2
3
4
5
6
7
8
9
10
11
13
0


1
2
3
4
5
6
7
8
9
10
11
13
0

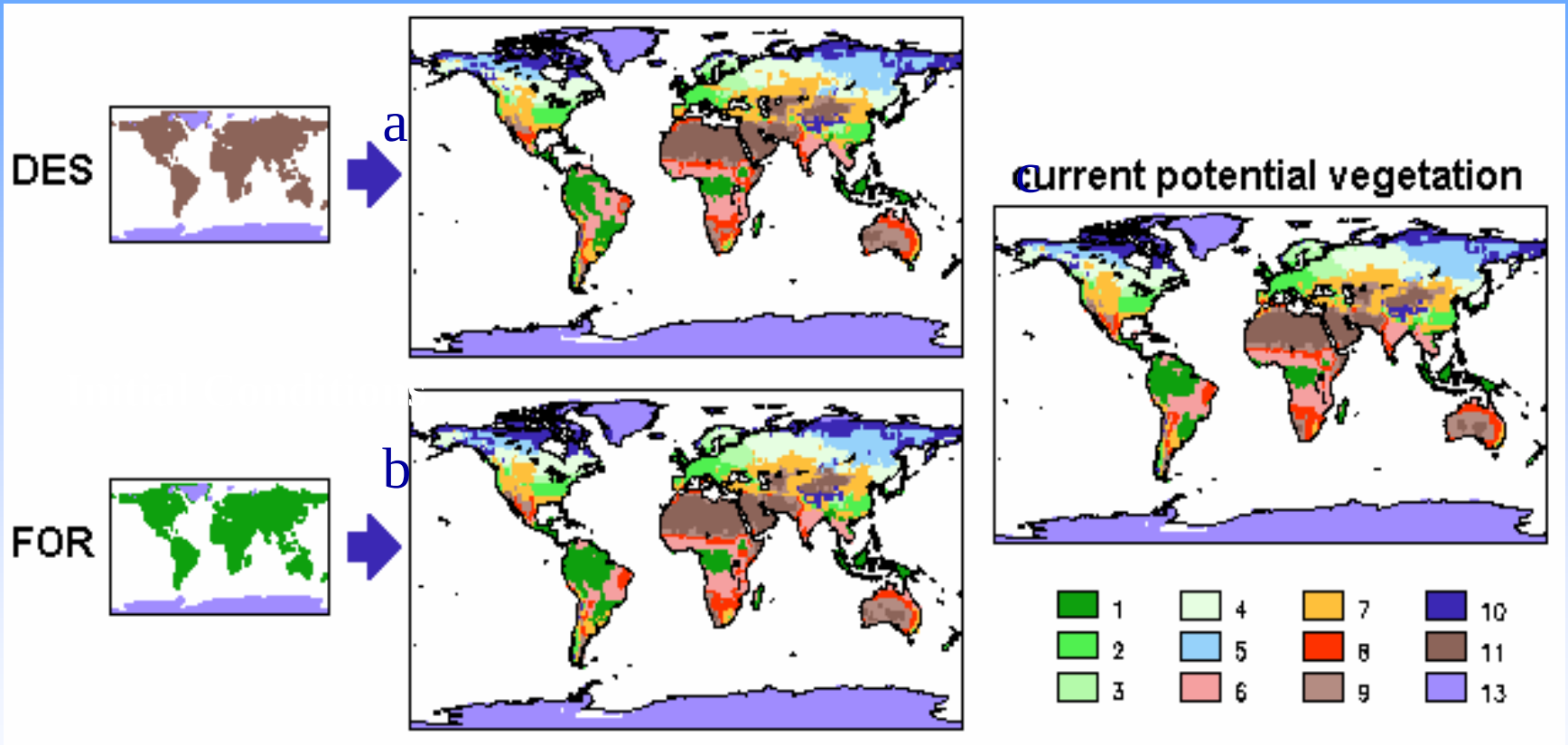

1
2
3
4
5
6
7
8
9
10
11
13
0


1
2
3
4
5
6
7
8
9
10
11
13
0


0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
13


0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
13

Results of CPTEC-DBM for two different Initial Conditons: all land areas covered by desert (a) and forest (b)

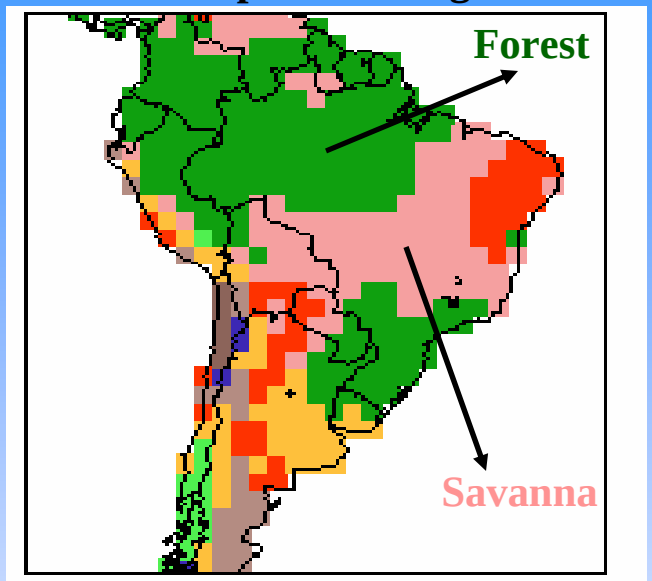


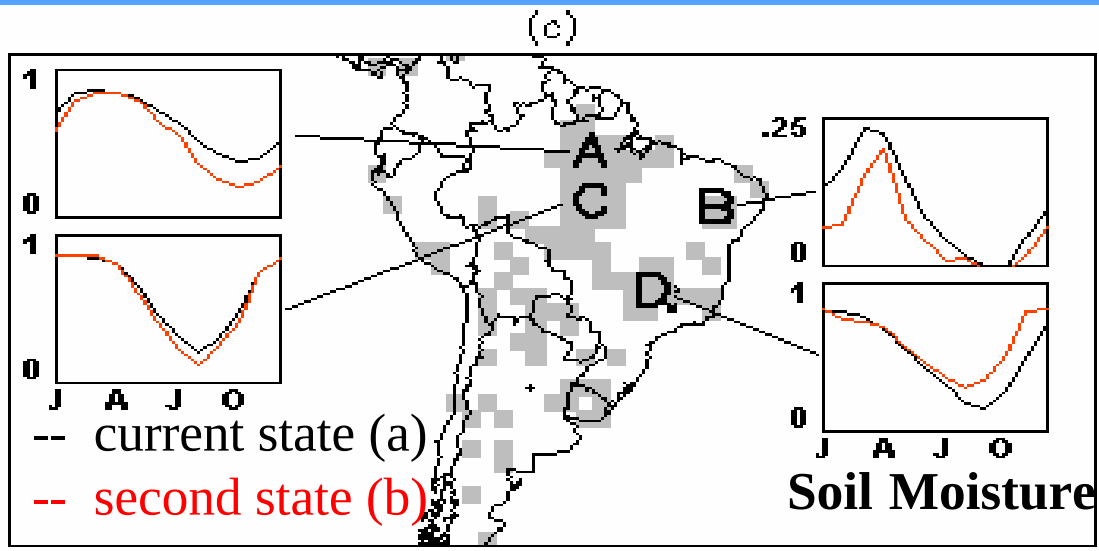
Biome-climate equilibrium solution with IC as forest (a) is similar to current natural vegetation (c); when the IC is desert (b), the final equilibrium solution is different for Tropical South America

Oyama, 2002

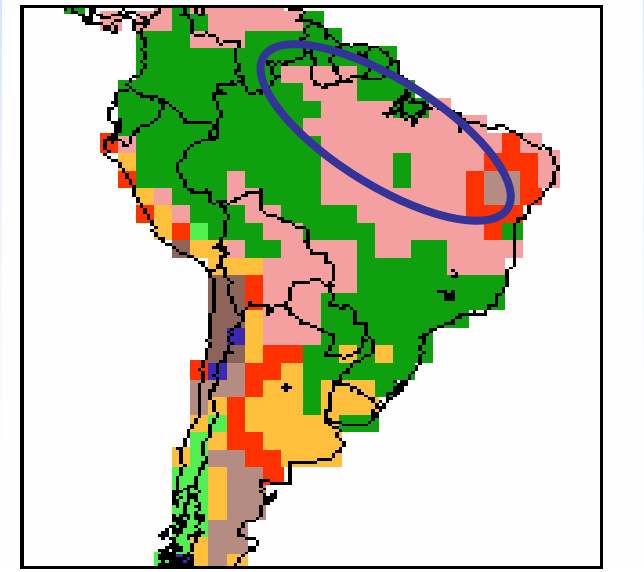
Two Biome-Climate Equilibrium States found for South America

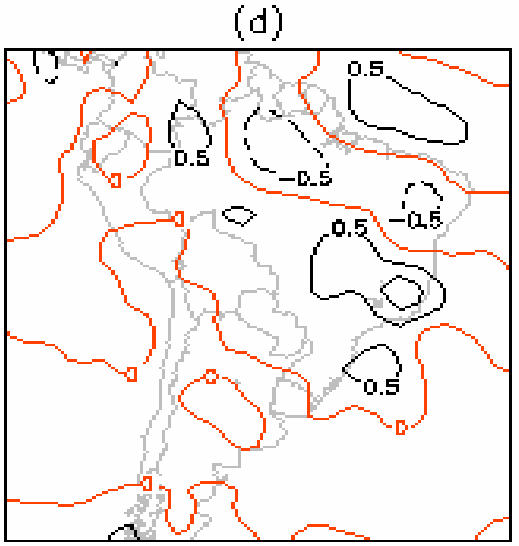
Current potential vegetation





Second State
Results of CPTEC-DBM Initial Conditions : desert





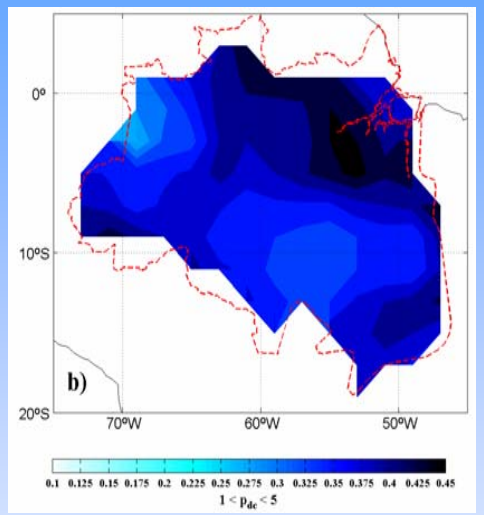
Rainfall anomalies

Source: Oyama and Nobre, 2003

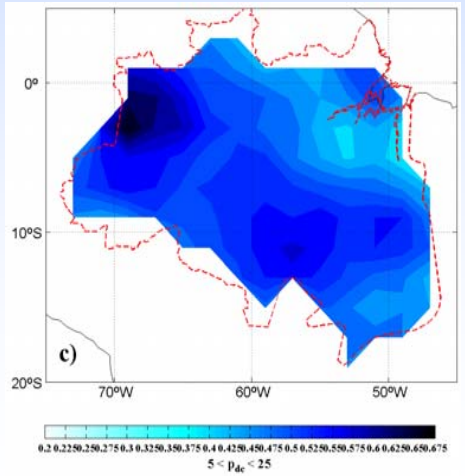
Precipitation mechanism in the Amazon

Unconditional probability of a wet day.
The daily data spans 1979 to 1993

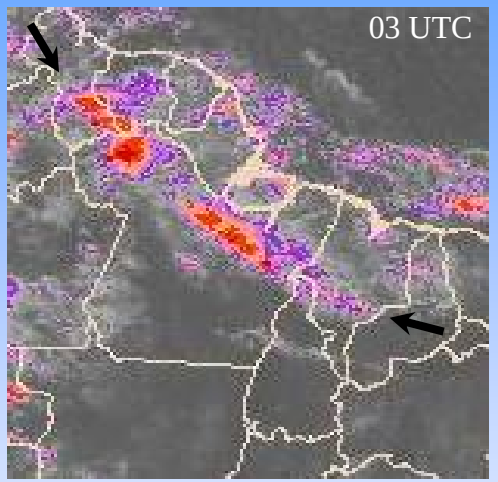
1 mm < P < 5 mm

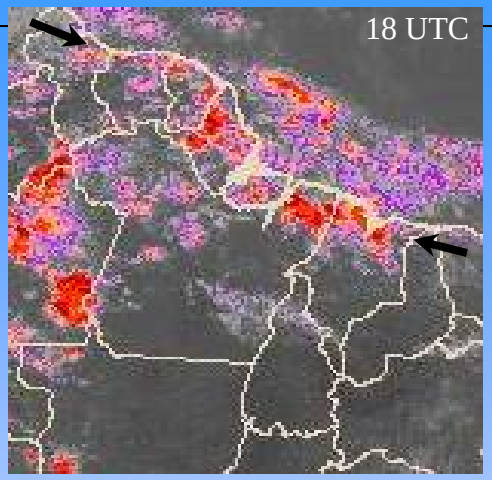


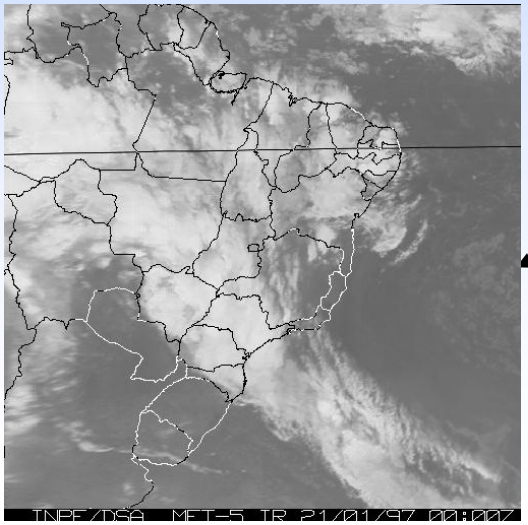
5 mm < P < 25 mm



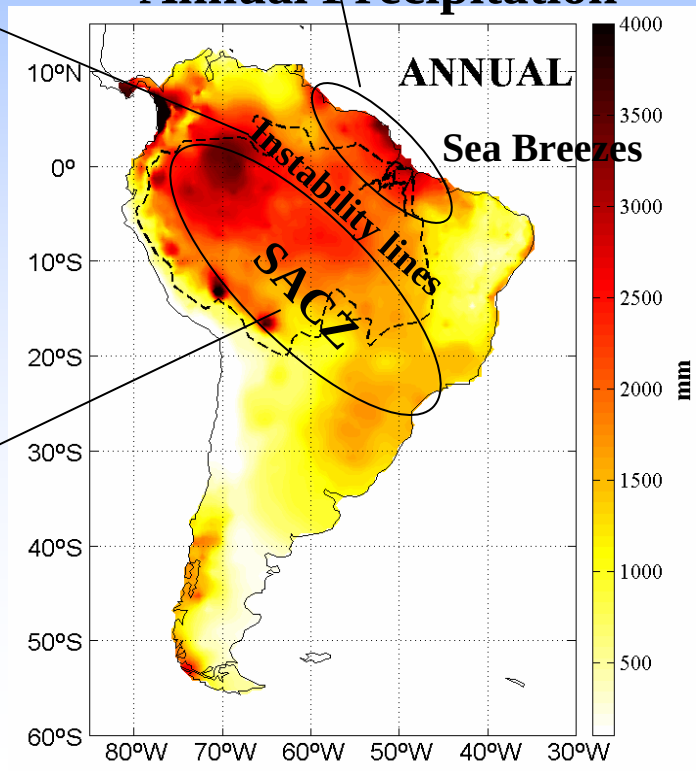
Source: Obregon, 2001



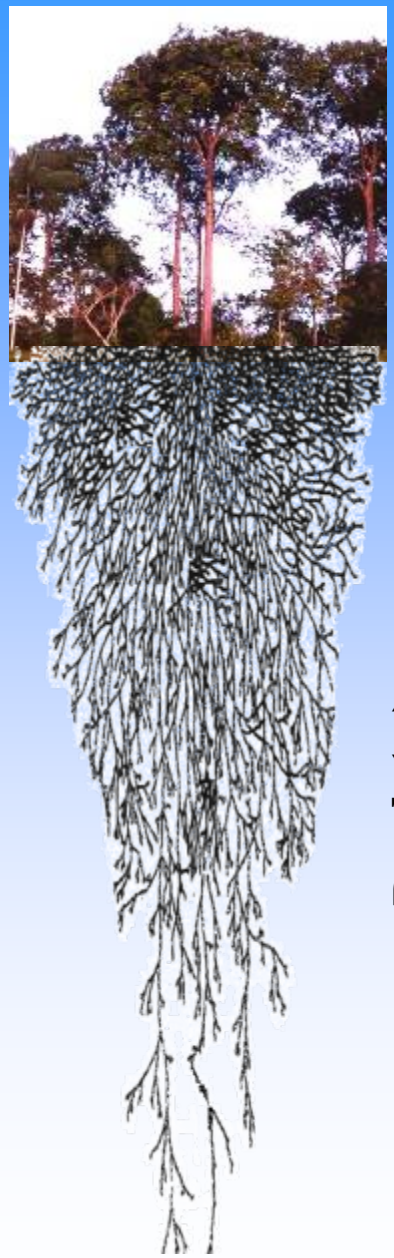


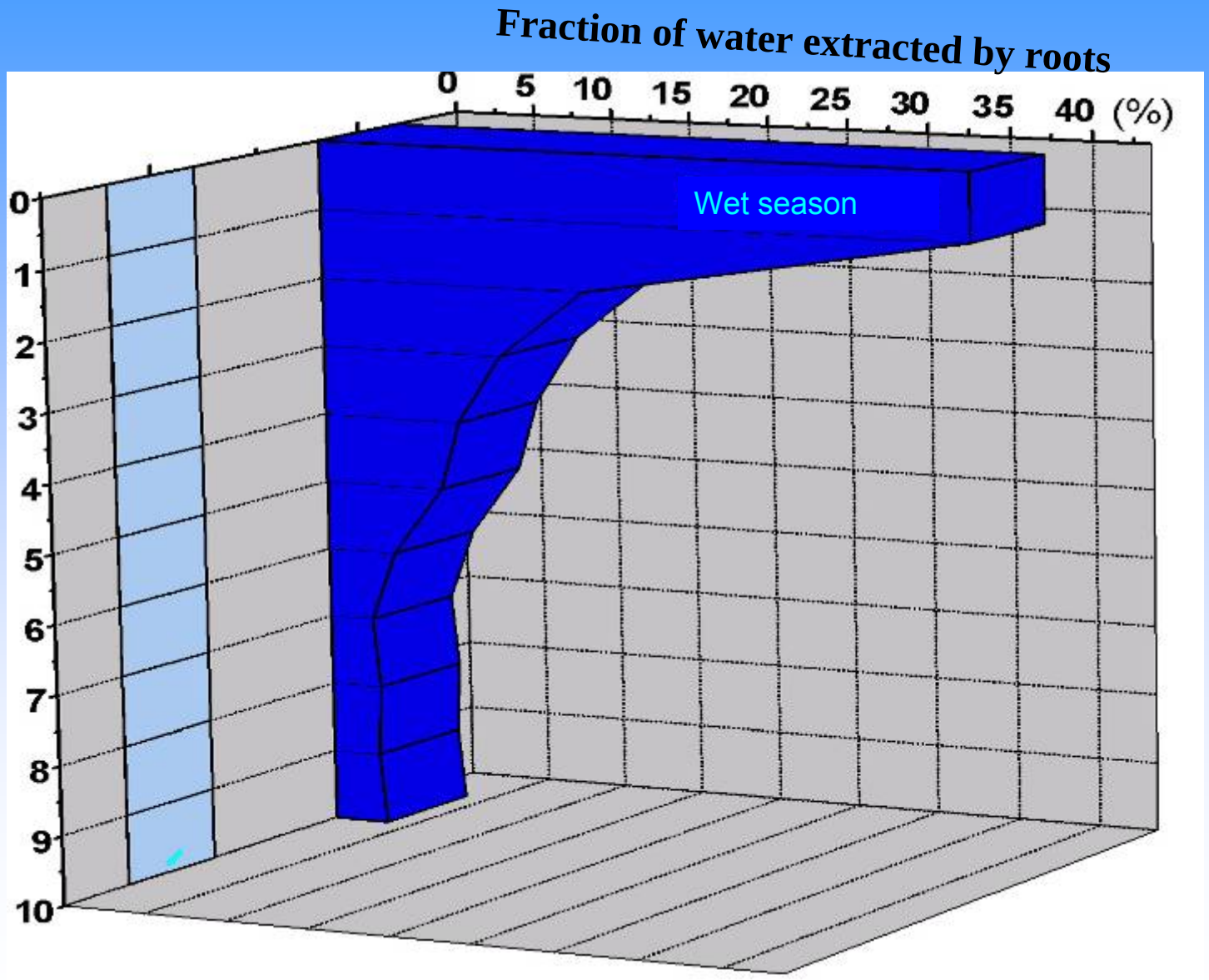


Annual Precipitation



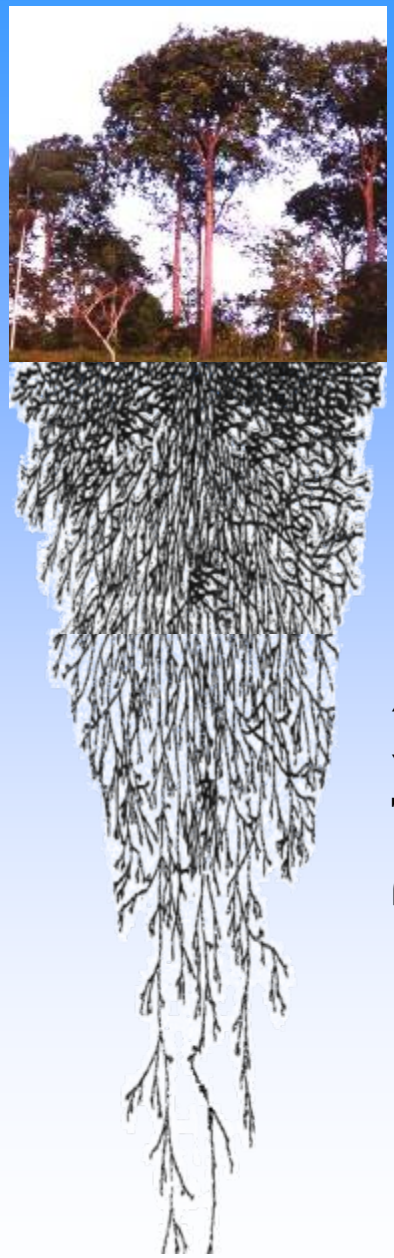
Ecological adaptation I: Deep rooting

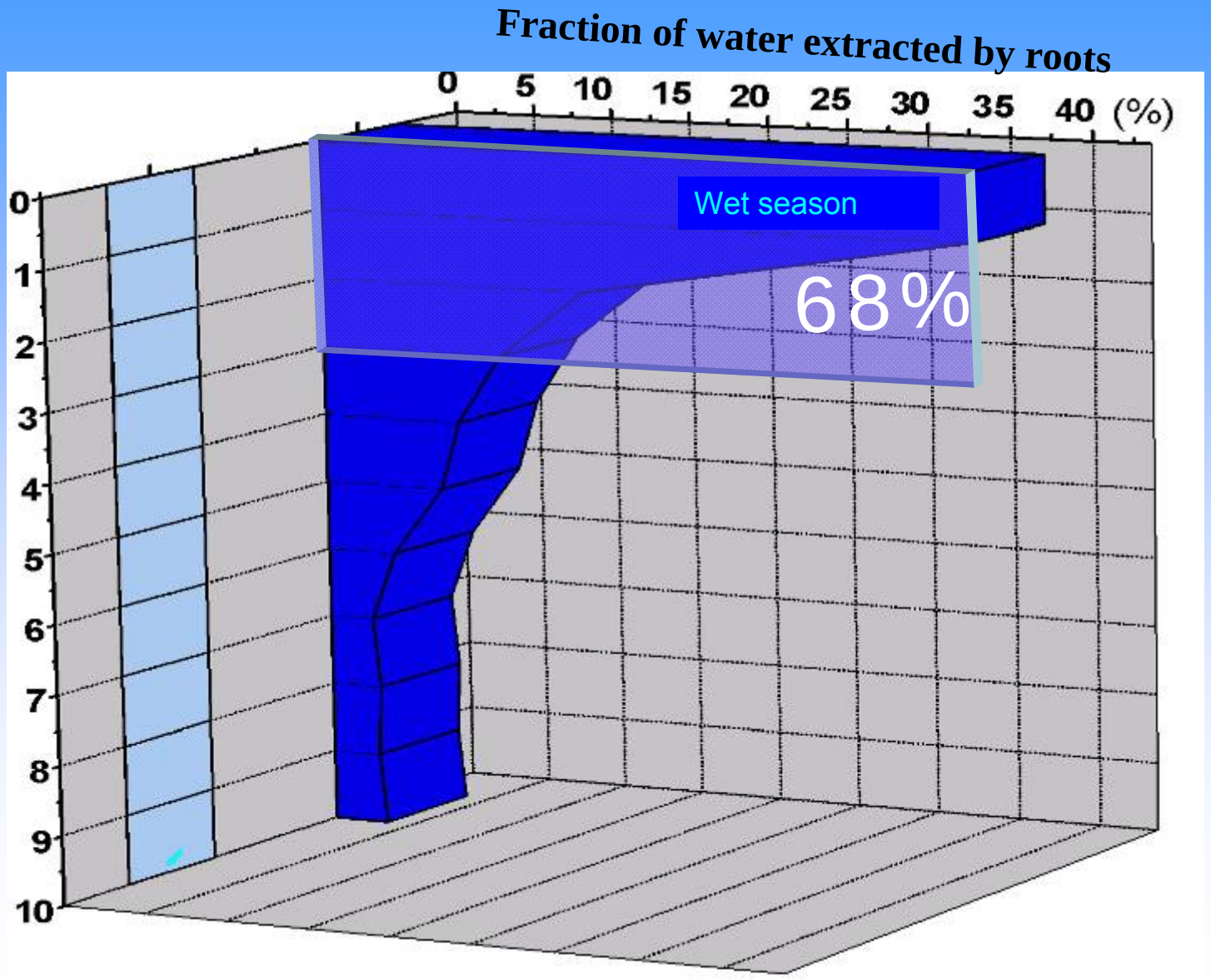




Source: Bruno et al., 2005 – Tropical forest data in Santarem km83

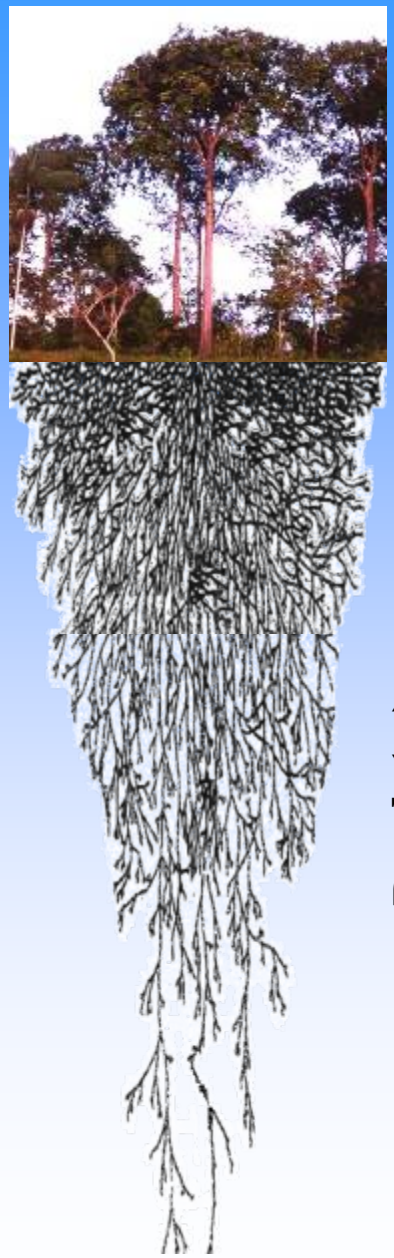
Ecological adaptation I: Deep rooting

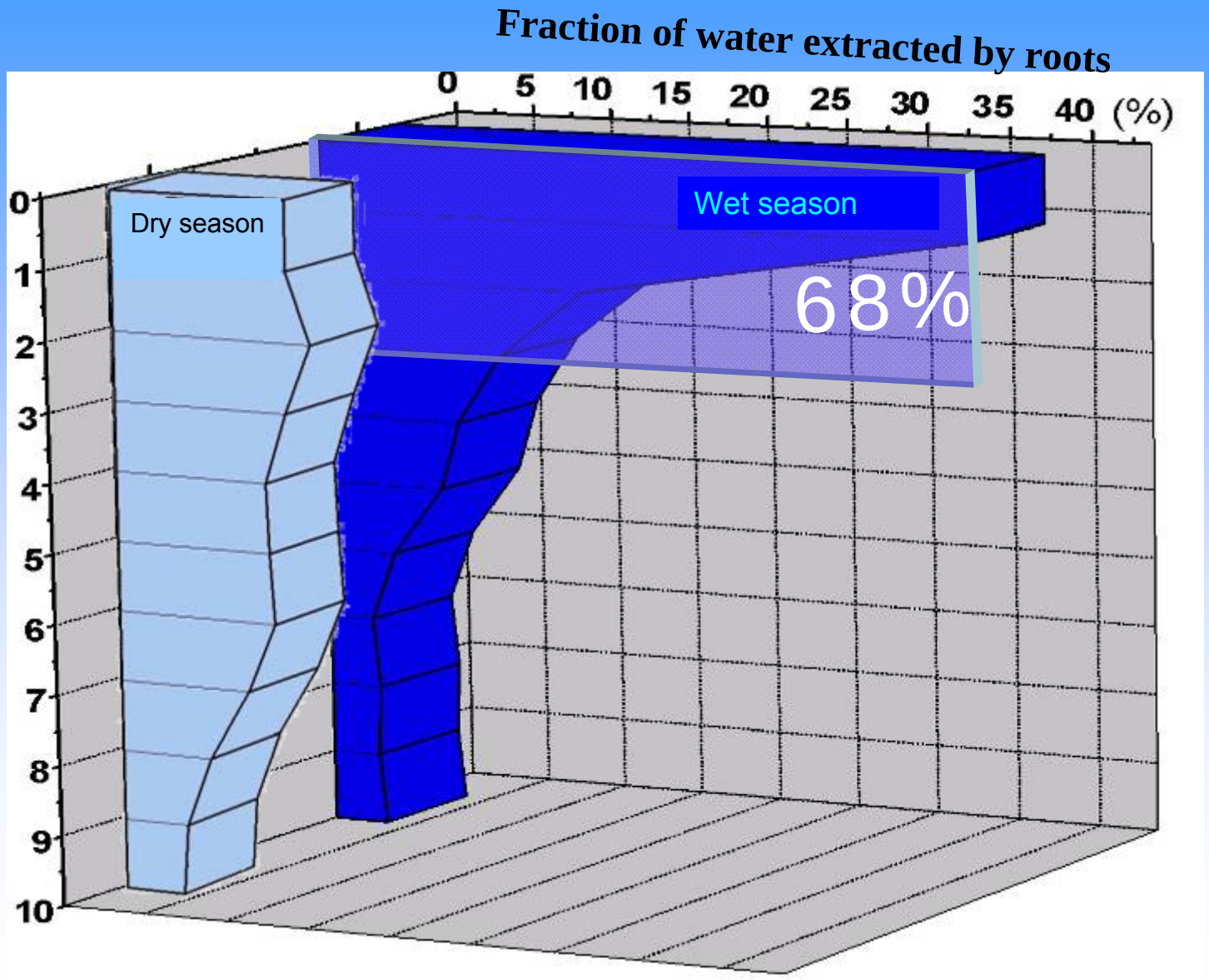




Source: Bruno et al., 2005 – Tropical forest data in Santarem km83

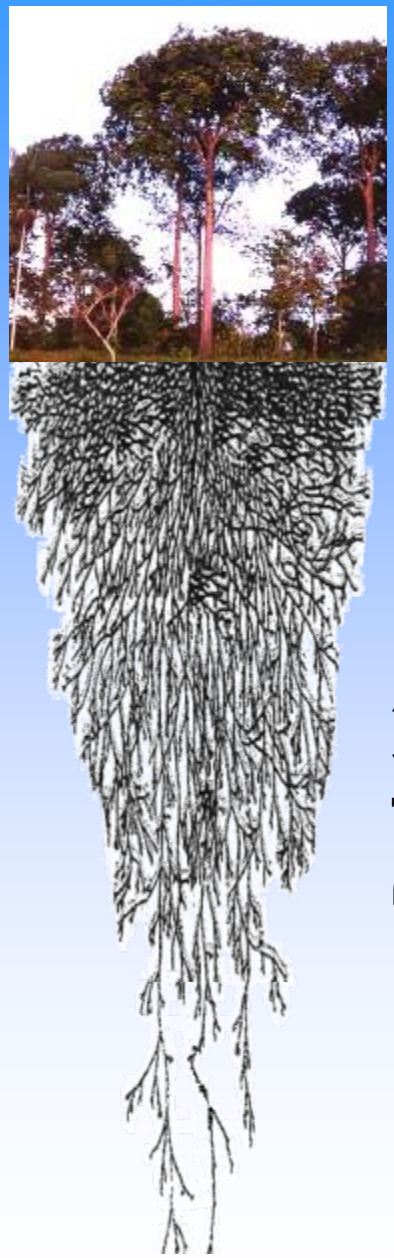
Ecological adaptation I: Deep rooting

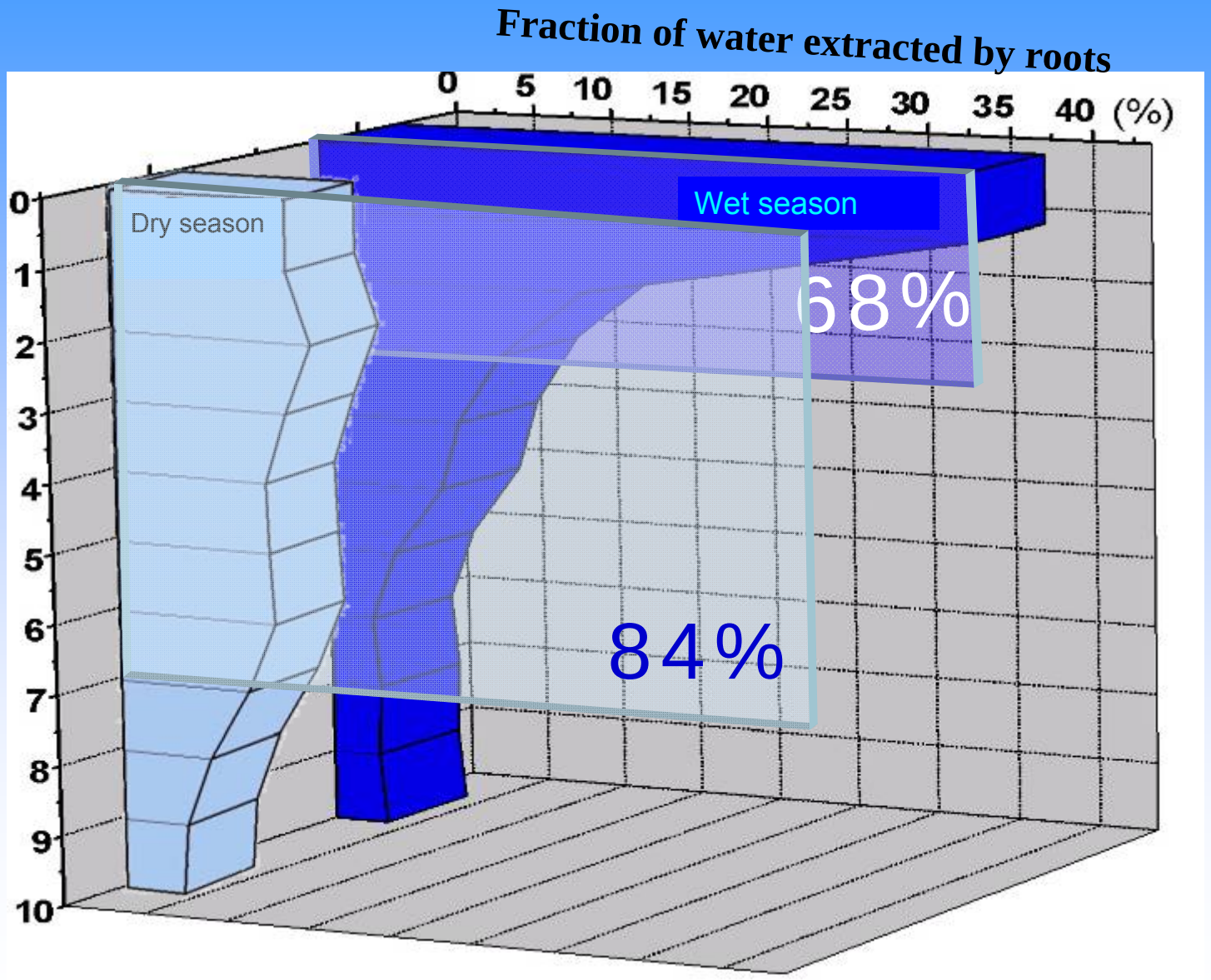




Source: Bruno et al., 2005 – Tropical forest data in Santarem km83

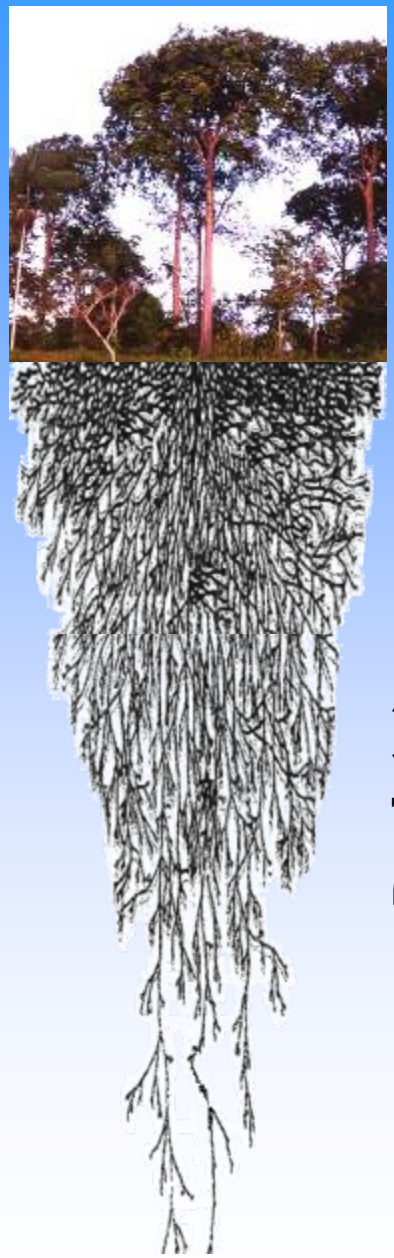
Ecological adaptation I: Deep rooting

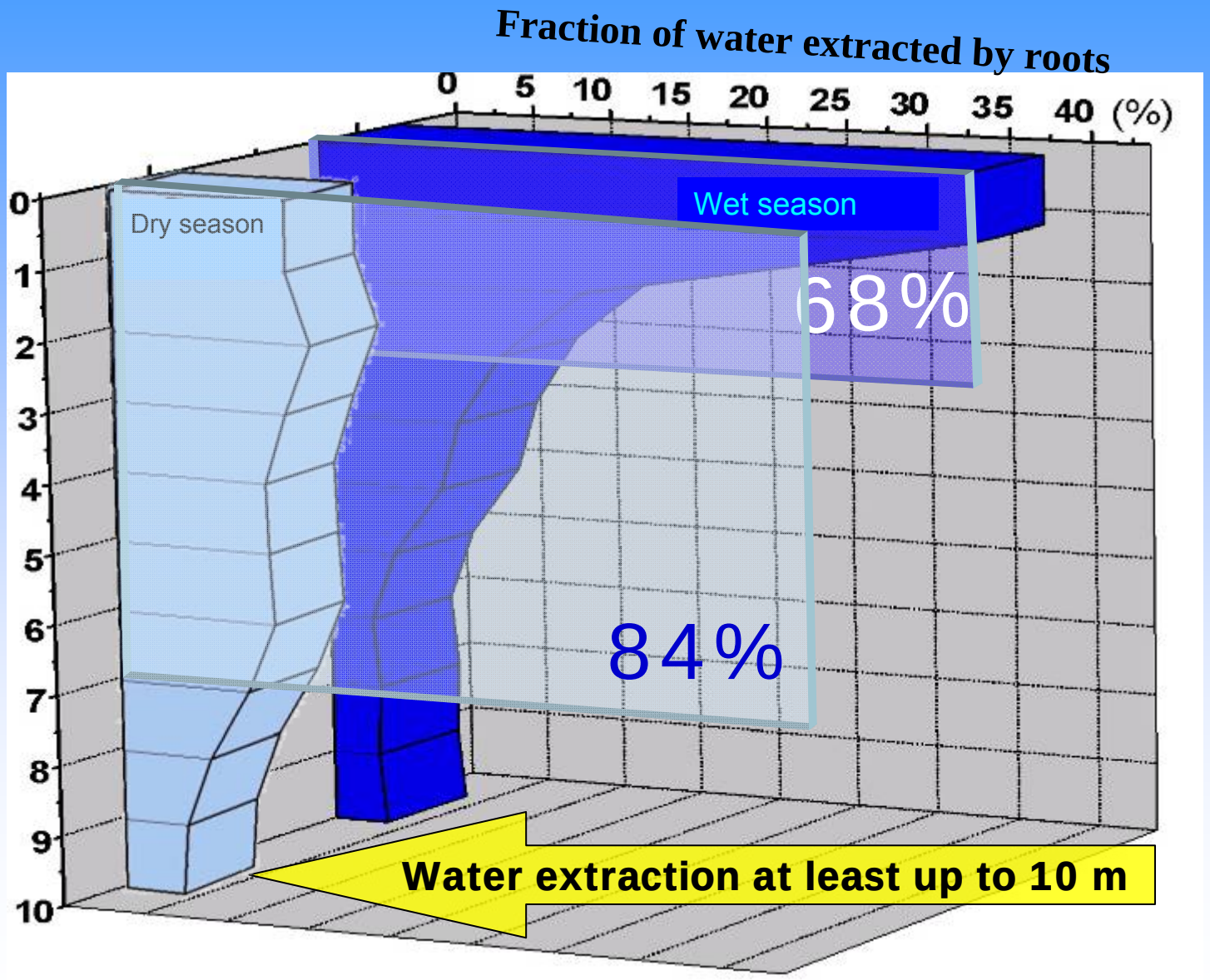




Source: Bruno et al., 2005 – Tropical forest data in Santarem km83

Ecological adaptation I: Deep rooting

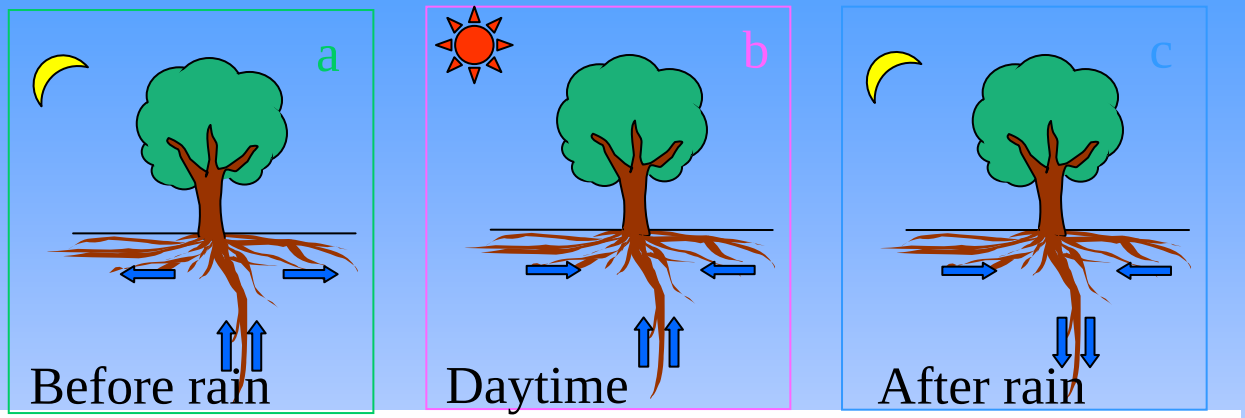


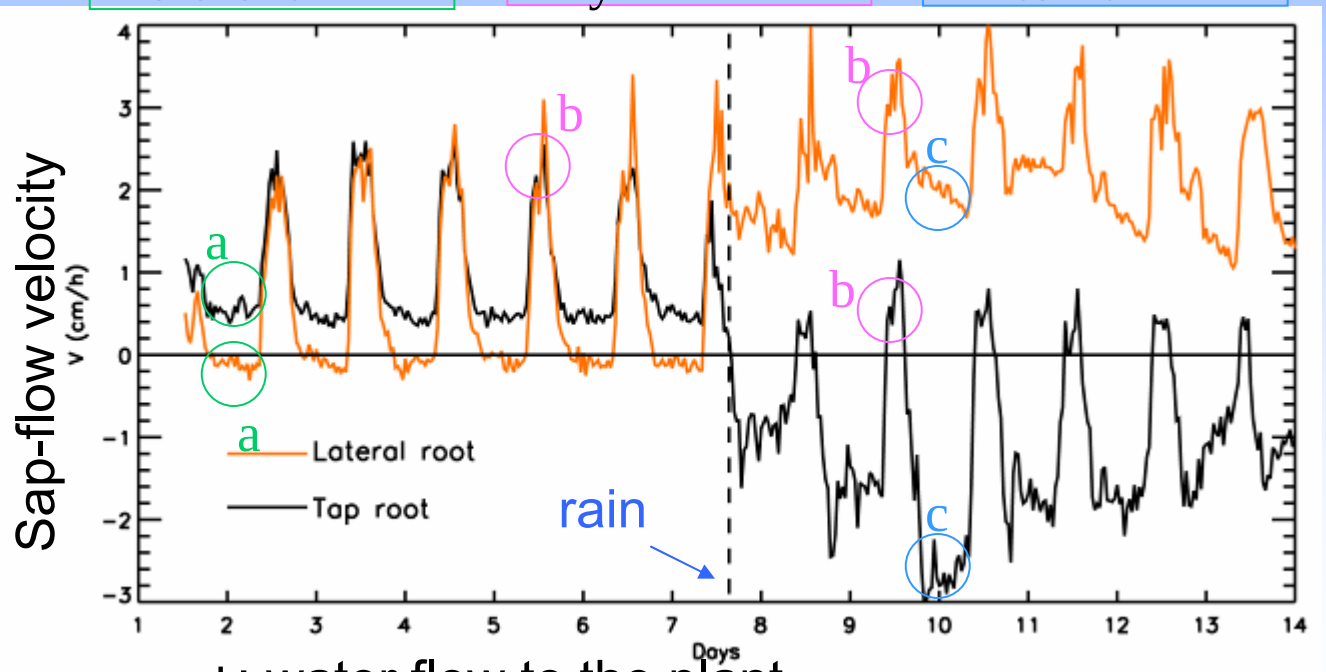


Source: Bruno et al., 2005 – Tropical forest data in Santarem km83

Ecological adaptation II: Hydraulic redistribution

Source: R. Oliveira

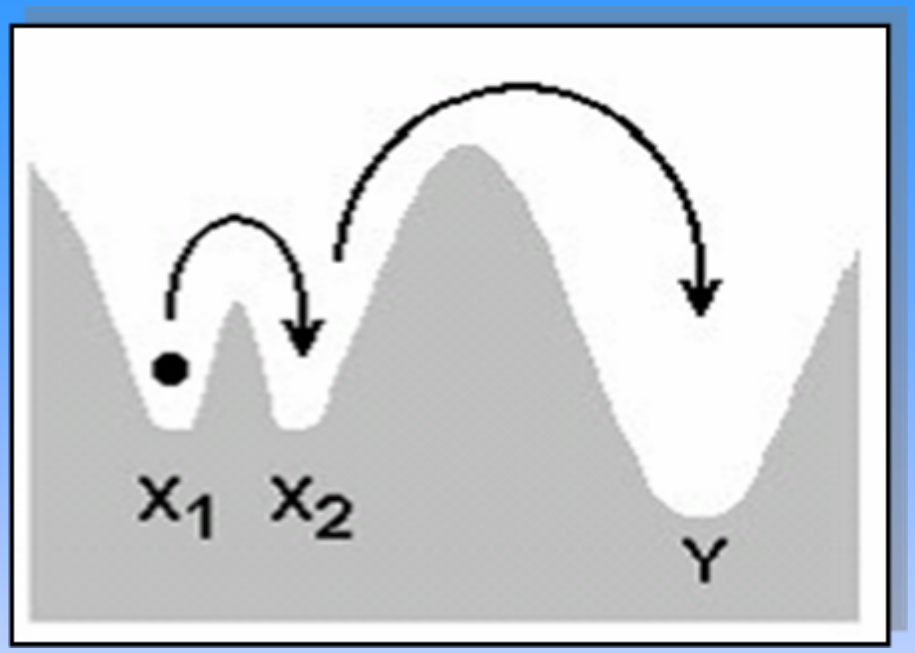


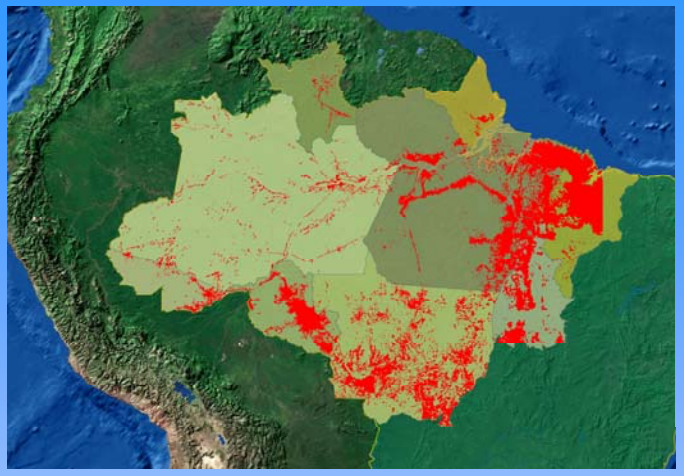


+: water flow to the plant

-: water flow away from the plant

Source: Oliveira et al., 2005





In 2007, total deforested area (clear-cutting) is 700,000 km^2 in Brazilian Amazonia (18%)

Resilience **Stochastic Perturbations**

Gradual Perturbations affect Resilience (e.g., deforestation, fire, Fragmentation, global warming, etc.)

Source: Greenpeace/Daniel Beltra

Does *climate variability (severe droughts)* play the key role linking together climate change, edaphic factors, and human use factors?

Conclusions
The future of biome distribution in Amazonia in face of land cover and climate changes

- Natural ecosystems in Amazonia have been under increasing land use change pressure.

- Tropical deforestation, global warming, increased forest fires and intense/more frequent droughts all act to reduce the resilience of the tropical forest.

- The synergistic combination of regional climate changes caused by both global warming and land cover change over the next several decades, exacerbated by increased drought and forest fire frequency, could tip the biome-climate state to a new stable equilibrium with '*savannization*' of parts of Amazonia and catastrophic species losses.


THANK YOU!