The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

2066-14

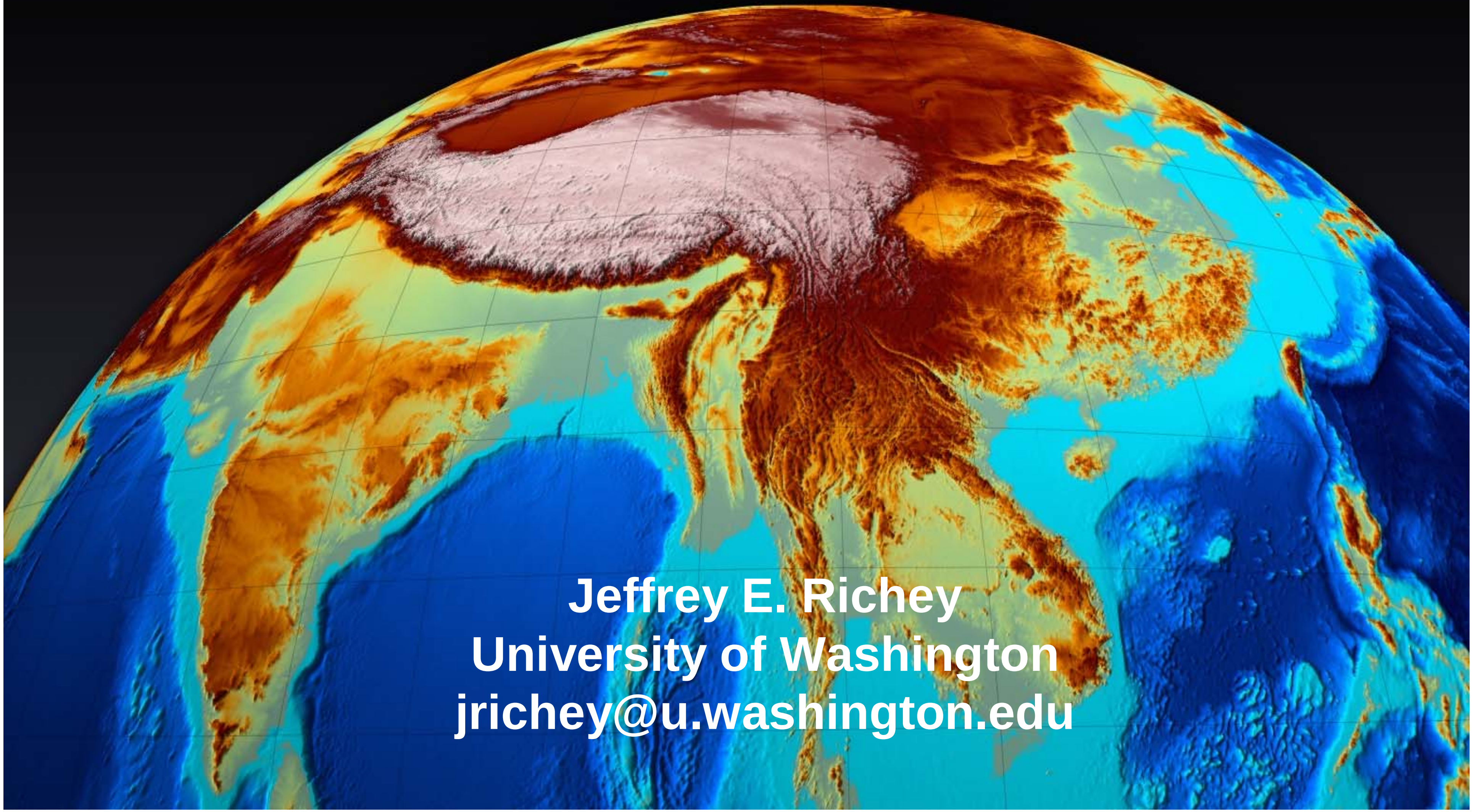
Workshop and Conference on Biogeochemical Impacts of Climate and Land-Use Changes on Marine Ecosystems

2 - 10 November 2009

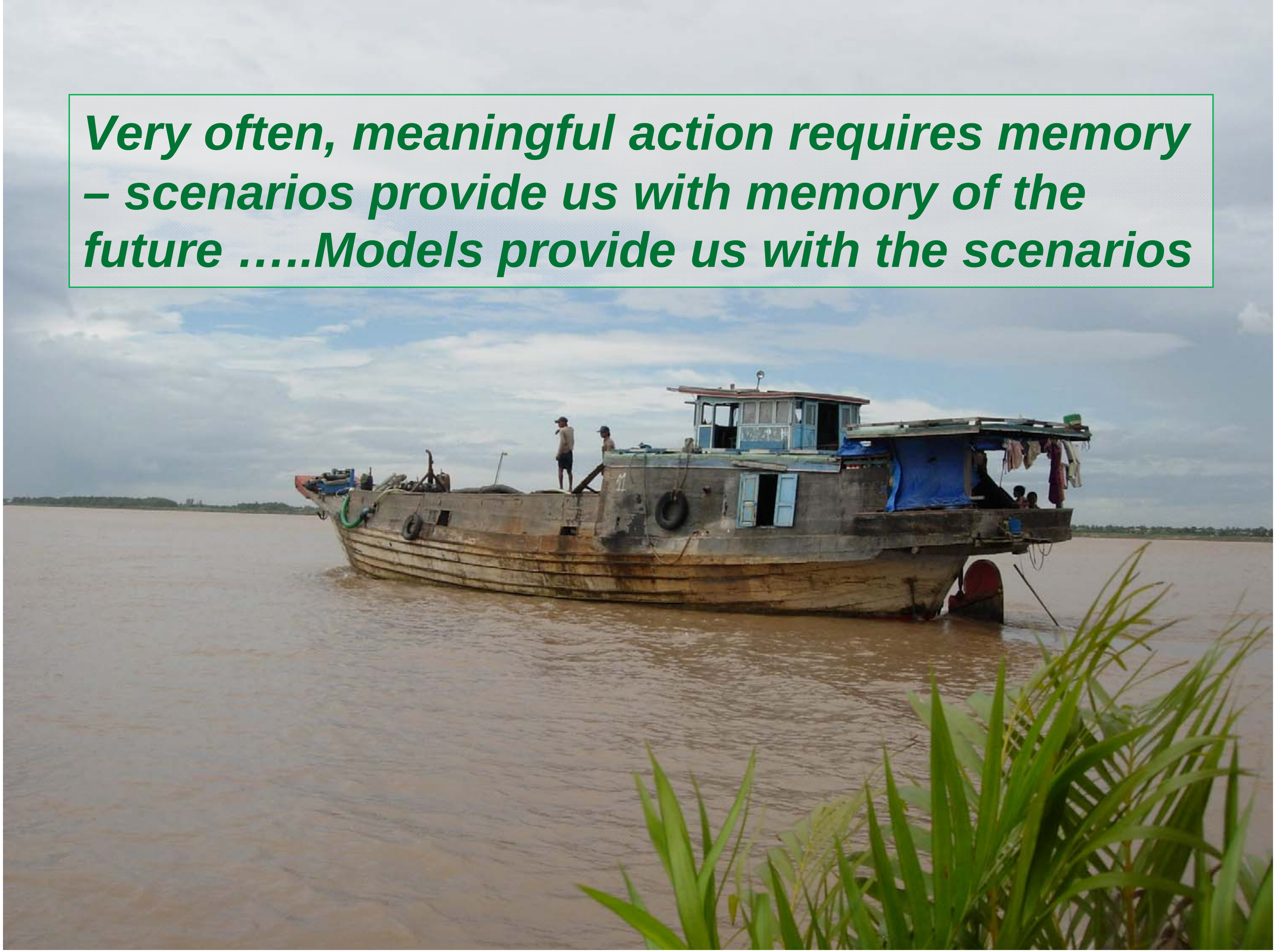
Drainage Basin Structure and Dynamics - How does a River Get its Water and Chemistry that it Delivers to the Sea?

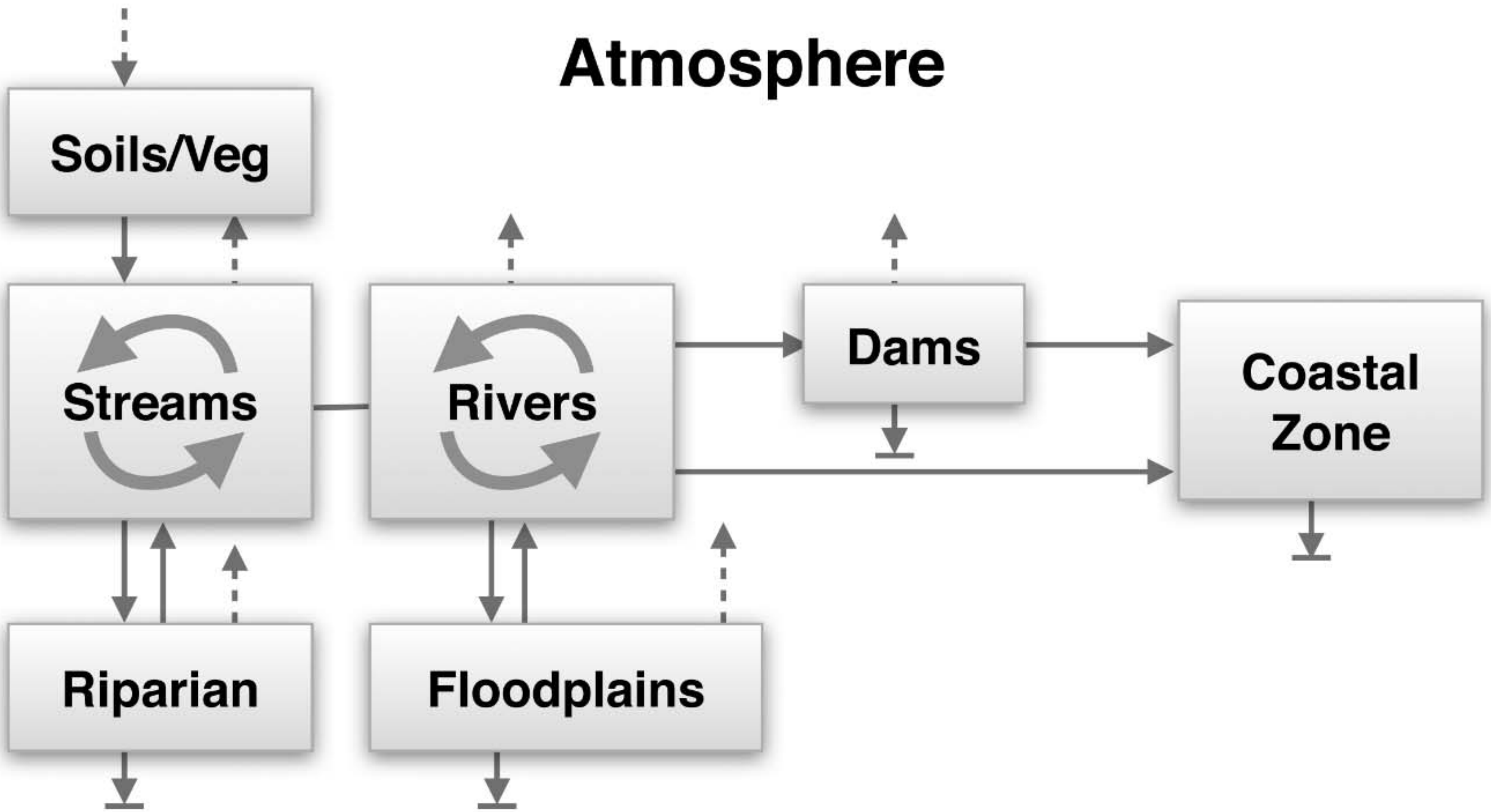
J. Richey
University of Washington
U.S.A

Part 1. Drainage Basin Structure and Dynamics - How does a River Get its Water and Chemistry that it Delivers to the Sea?



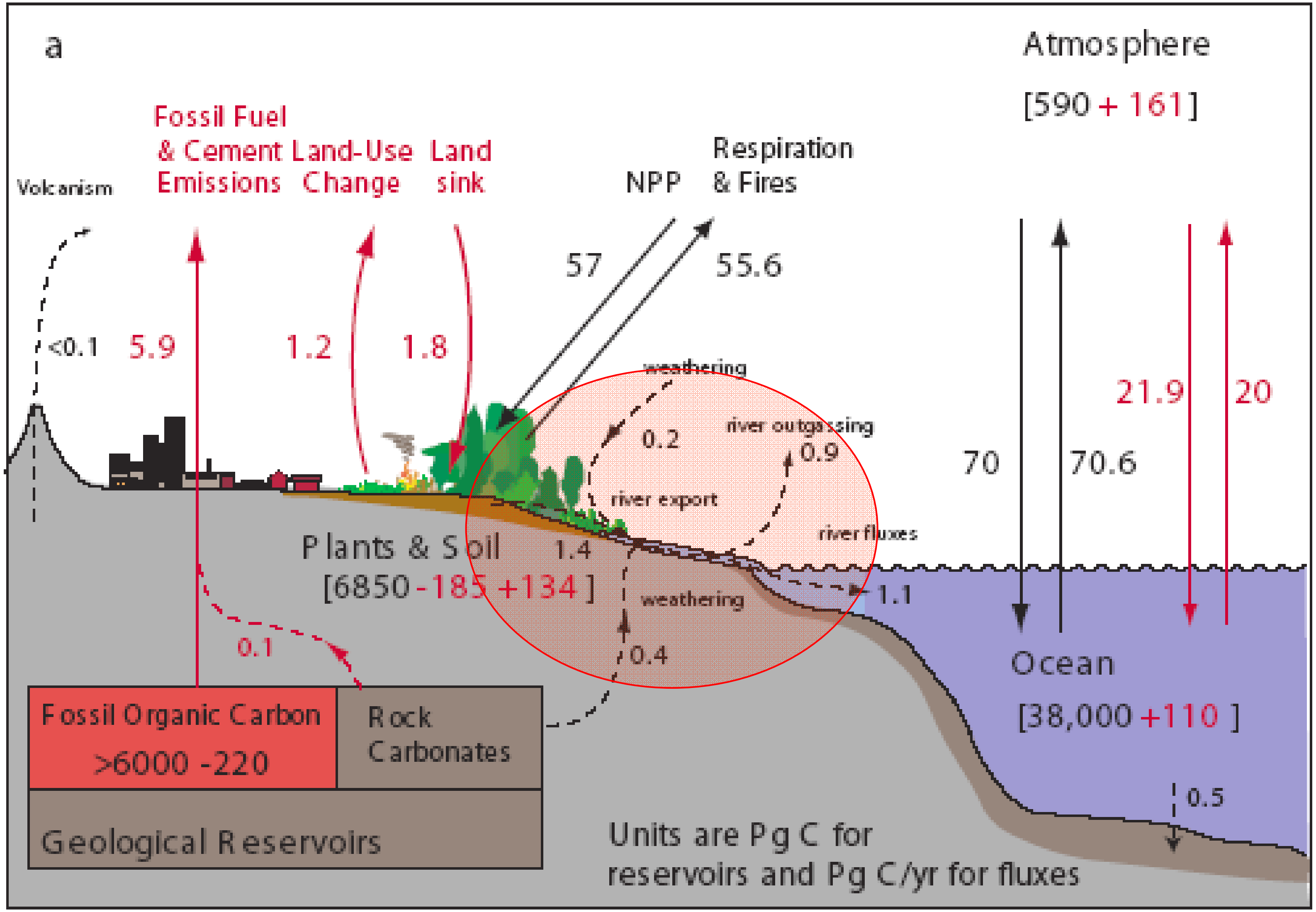
Jeffrey E. Richey
University of Washington
jrichey@u.washington.edu


Very often, meaningful action requires memory – scenarios provide us with memory of the future …..Models provide us with the scenarios



Atmosphere
Soils/Veg
Streams
Rivers
Dams
Coastal Zone
Riparian
Floodplains

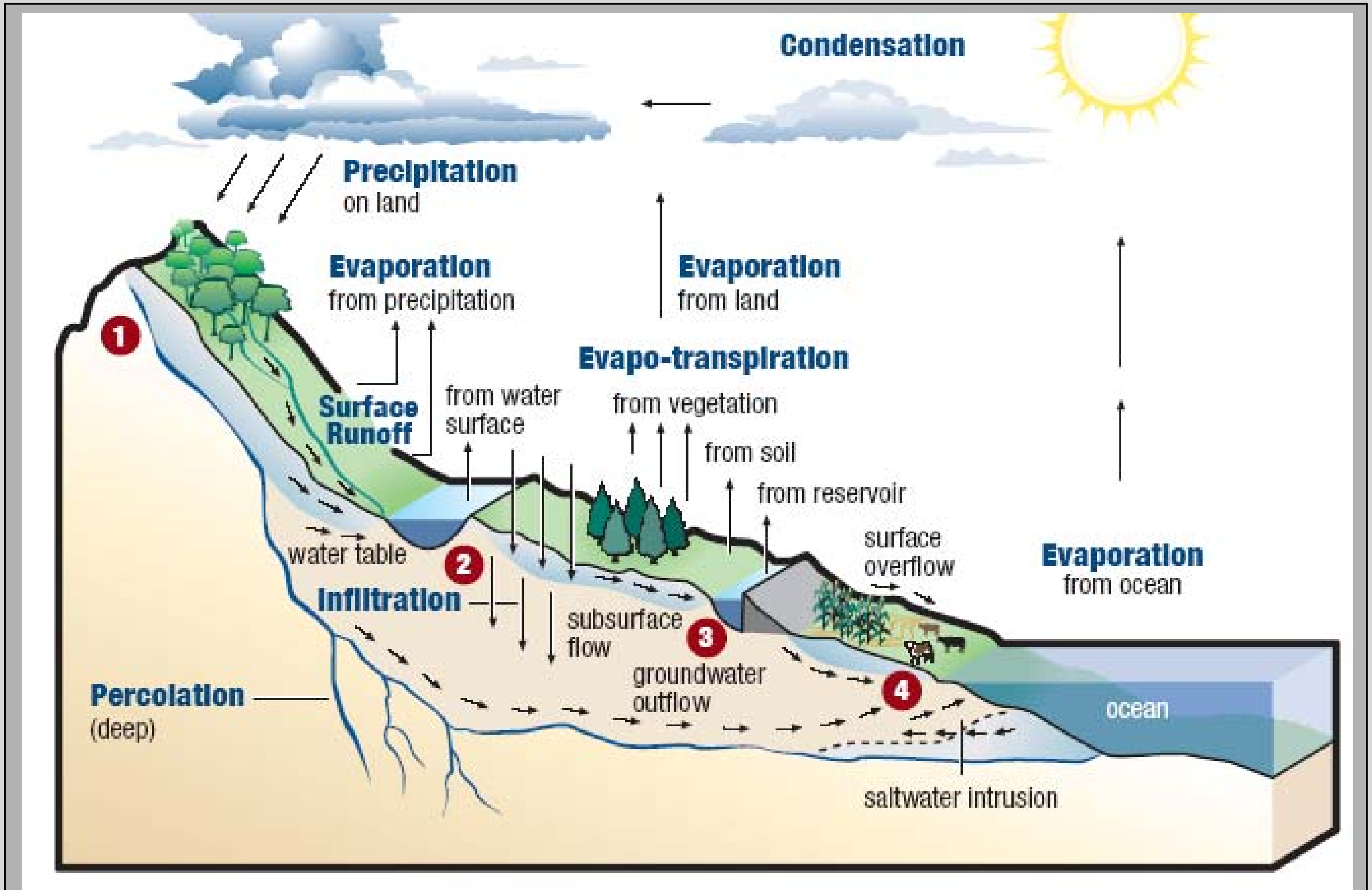
THE GLOBAL C CYCLE

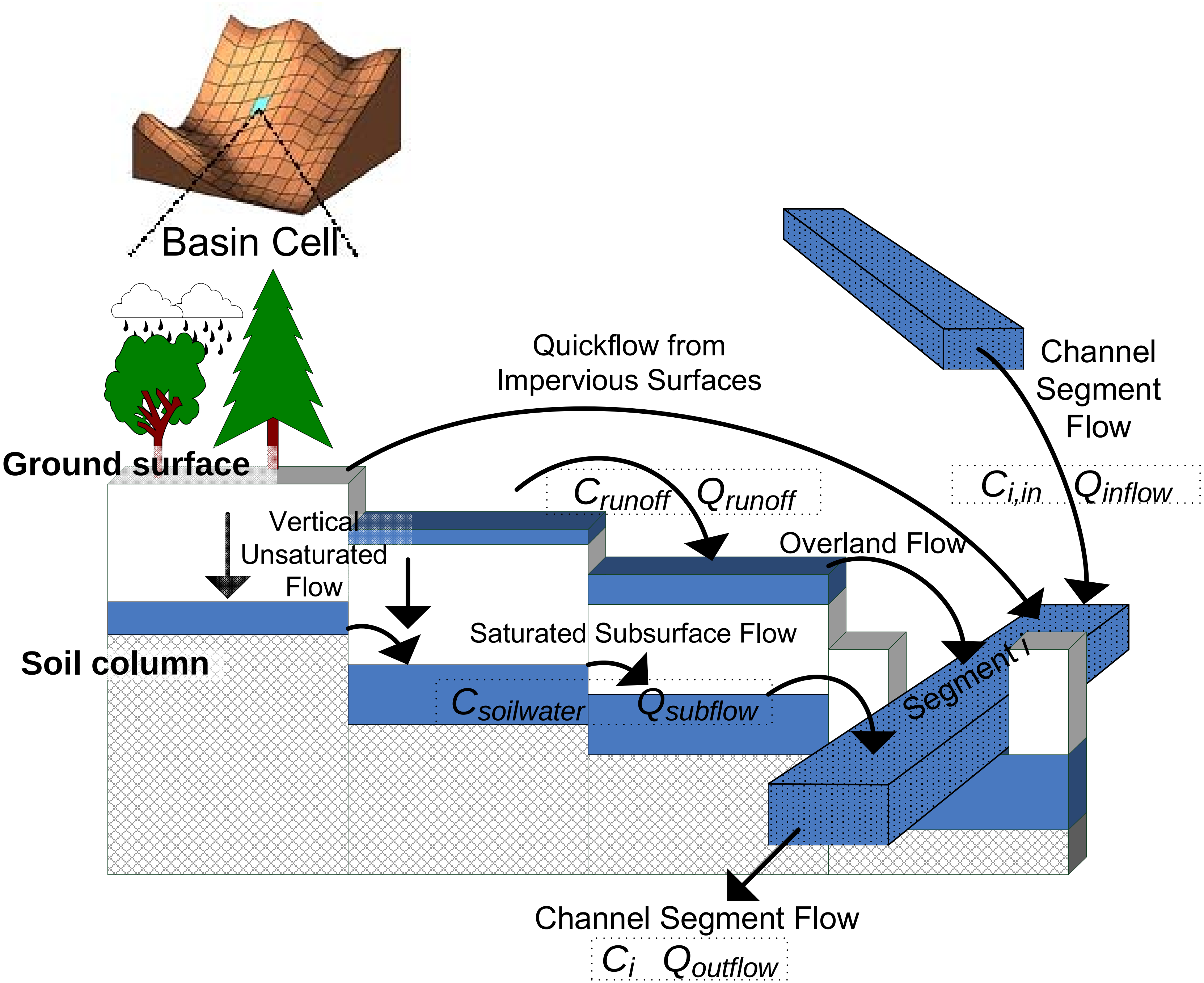


SCOPE RAPID ASSESSMENT

Climate-Land Surface-Water: The Hydrologic Cycle as Defining Framework

Q (runoff) = P (precipitation) - ET (evapotranspiration) + ΔSM (soil moisture/GW)

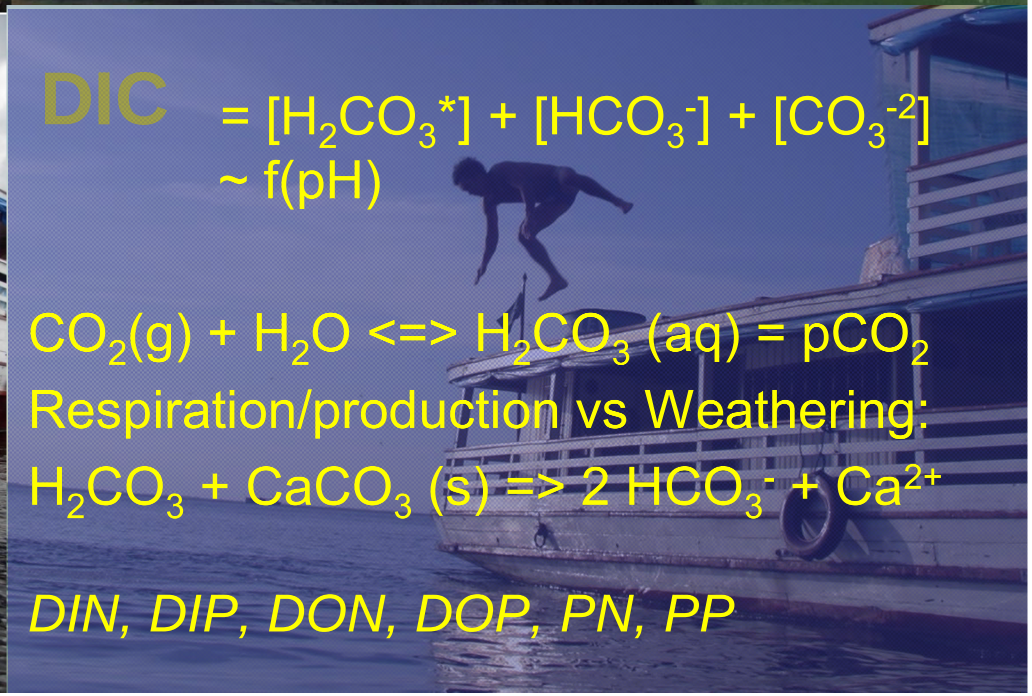



Basin Cell
Quickflow from
Impervious Surfaces
Channel
Segment
Flow
$C_{i,in}$ Q_{inflow}
Ground surface
C_{runoff} Q_{runoff}
Vertical
Unsaturated
Flow
Overland Flow
Saturated Subsurface Flow
Soil column
$C_{soilwater}$
$Q_{subflow}$
Segment i
Channel Segment Flow
C_i $Q_{outflow}$

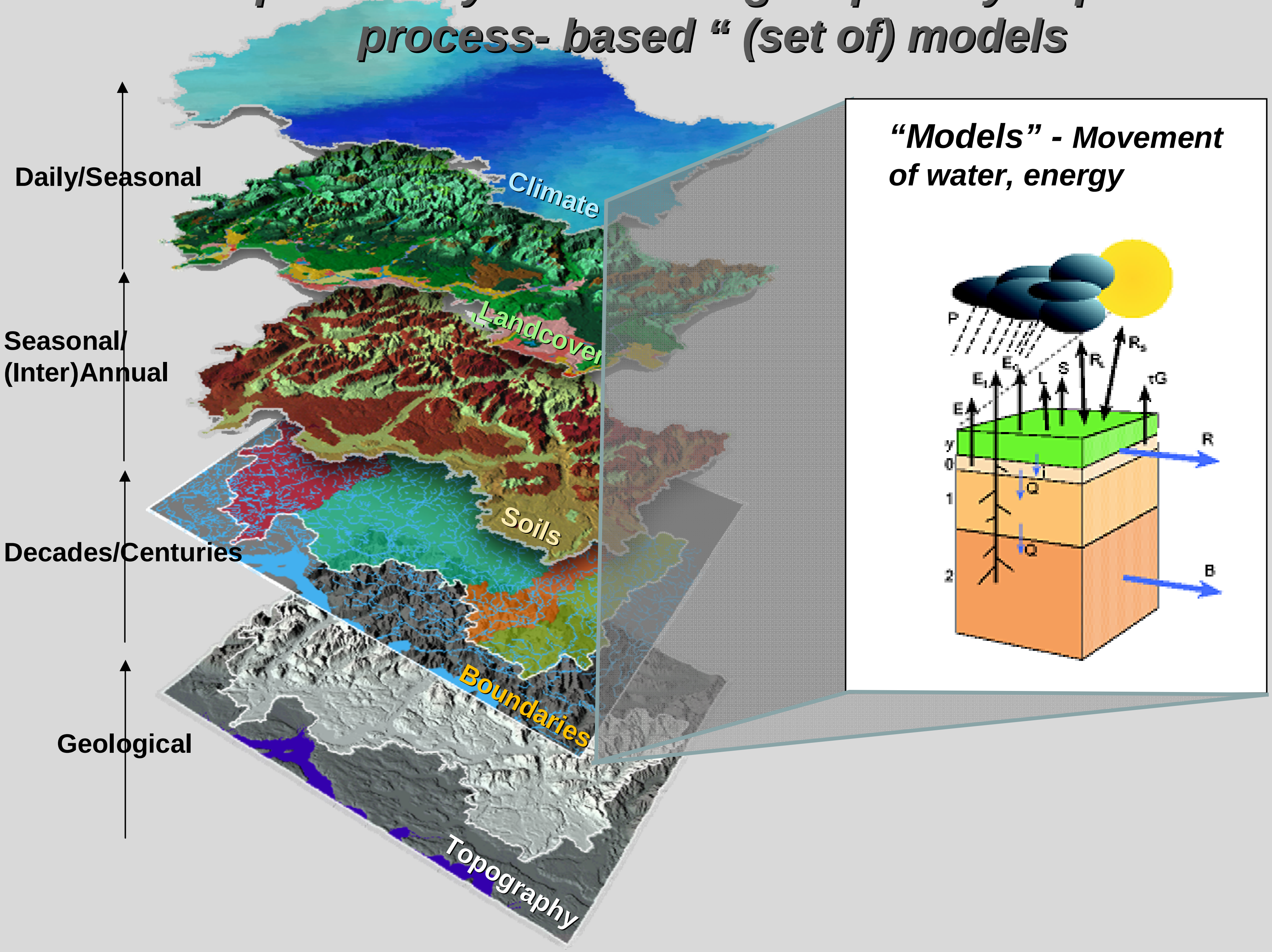

CPOM
(>63um)


FPOM
(<63um)
E2L AMANAÍ


ATIDI
DOM
(<.1-.7um)
11.10.2004 10:32


DIC $= [H_2CO_3^*] + [HCO_3^-] + [CO_3^{-2}]$
$\sim f(pH)$
$CO_2(g) + H_2O <=> H_2CO_3\ (aq) = pCO_2$
Respiration/production vs Weathering:
$H_2CO_3 + CaCO_3\ (s) => 2\ HCO_3^- + Ca^{2+}$
DIN, DIP, DON, DOP, PN, PP

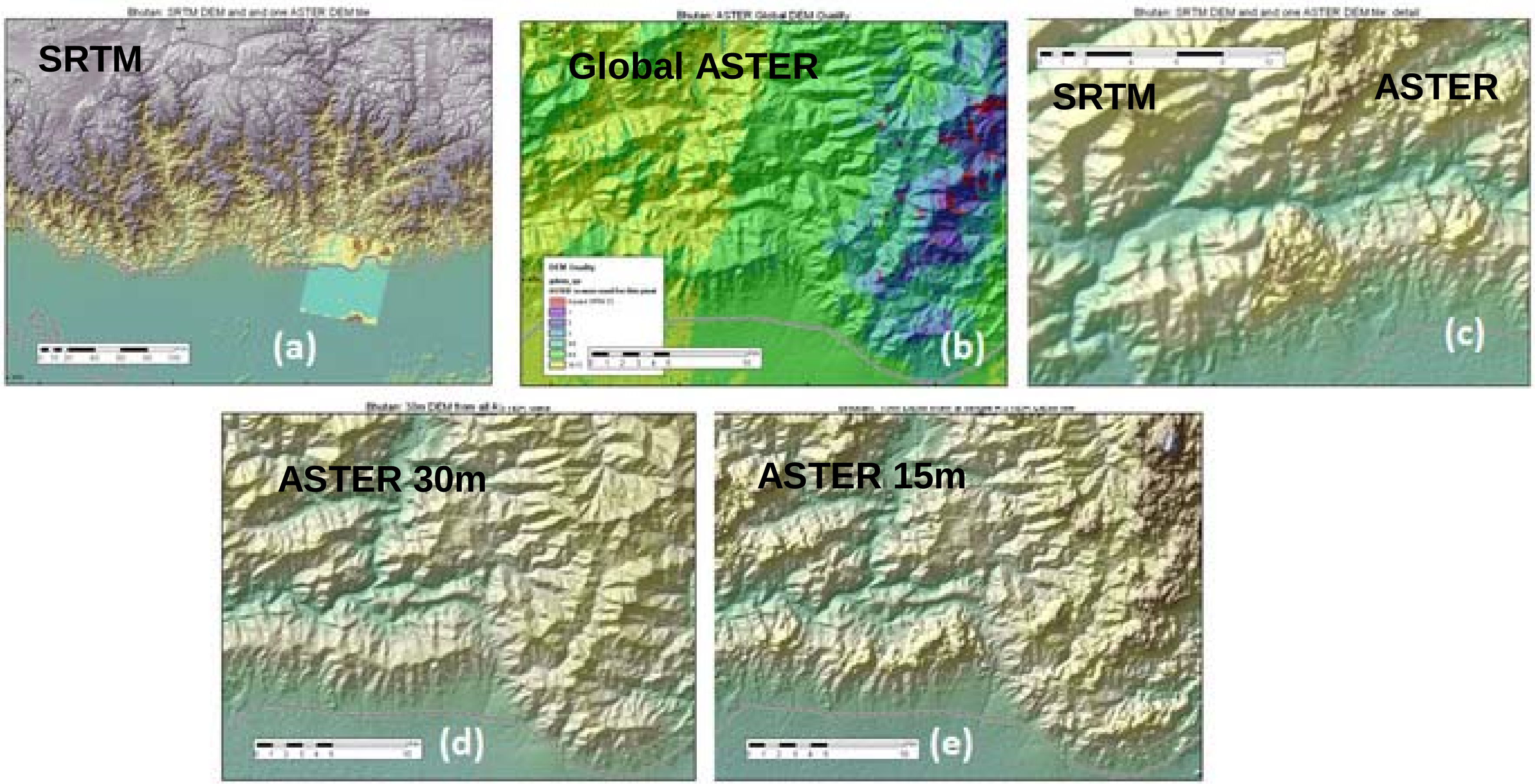
Represent dynamics as "geospatially-explicit & process- based " (set of) models



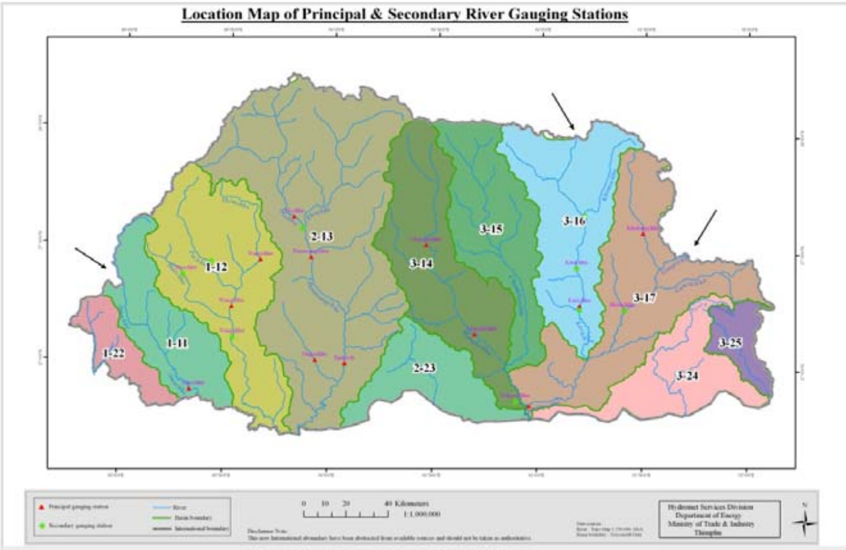
Topography

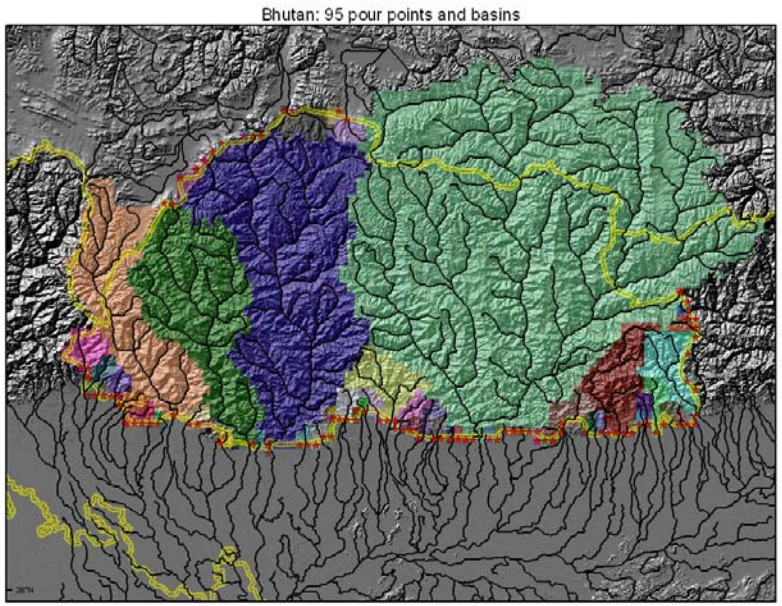
Bhutan

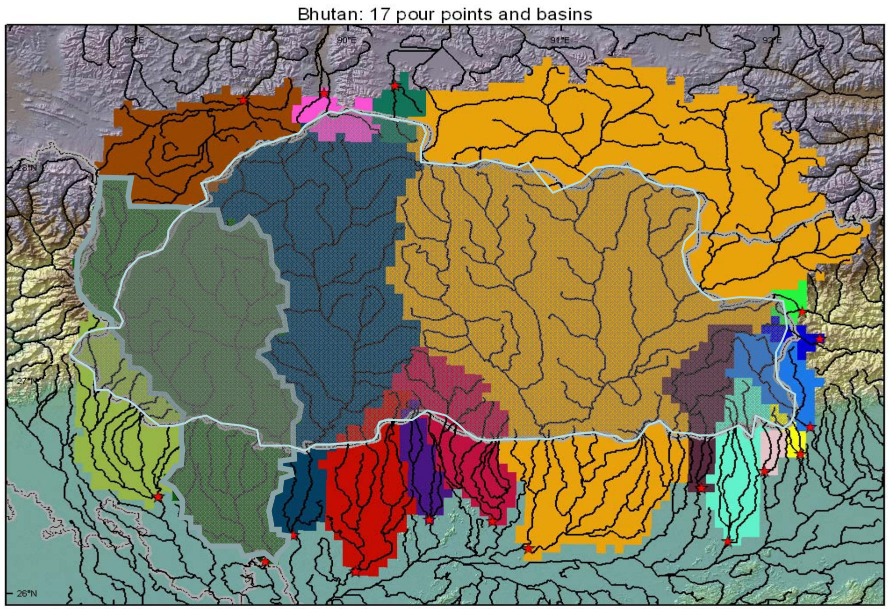
FROM DEMs to TOPOGRAPHY, SLOPE, AND RIVER NETWORKS



DEFINE THE BASINS AND RIVER NETWORKS

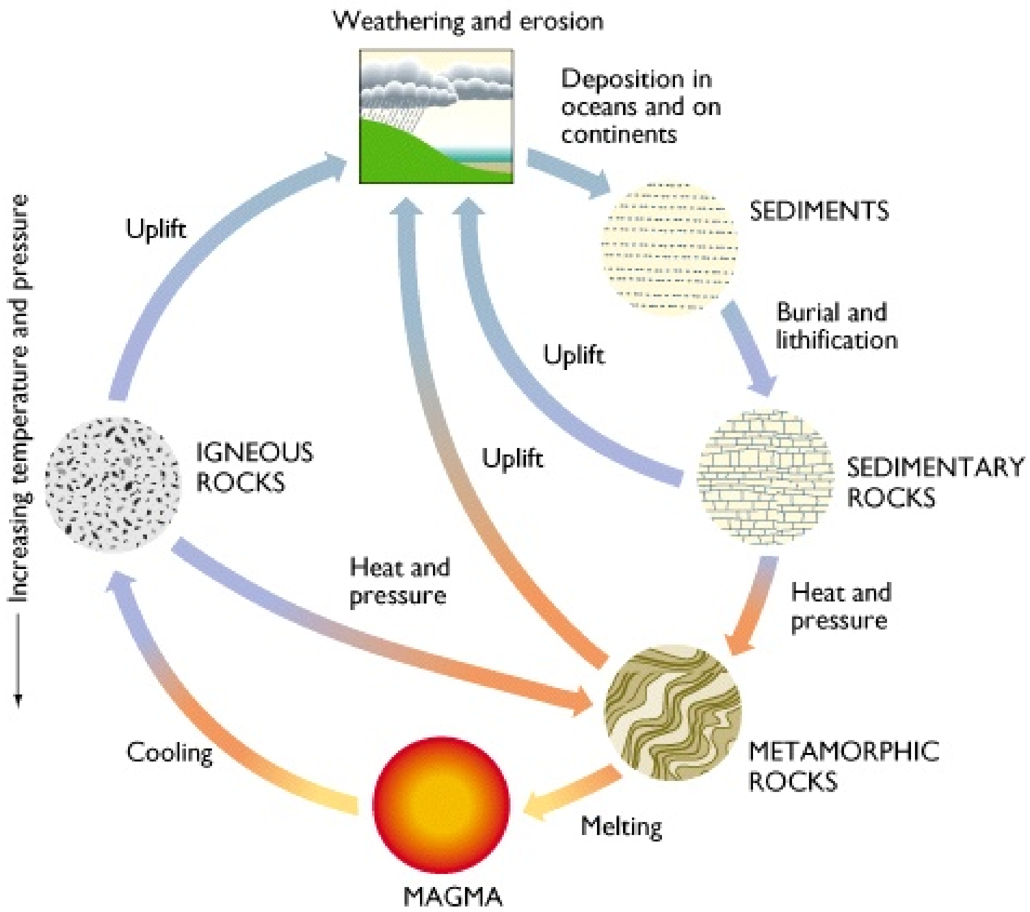


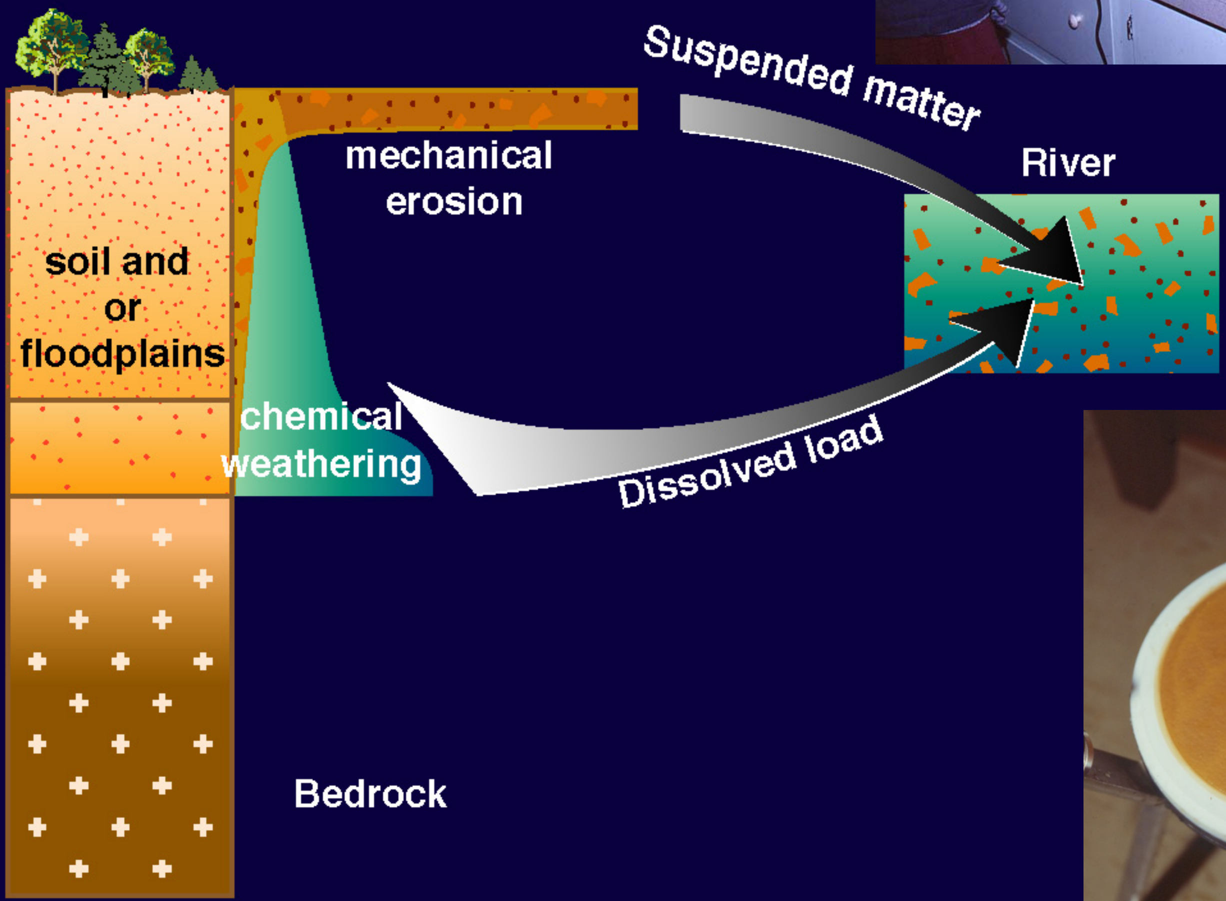




Weathering and Sedimentation in the Rock Cycle

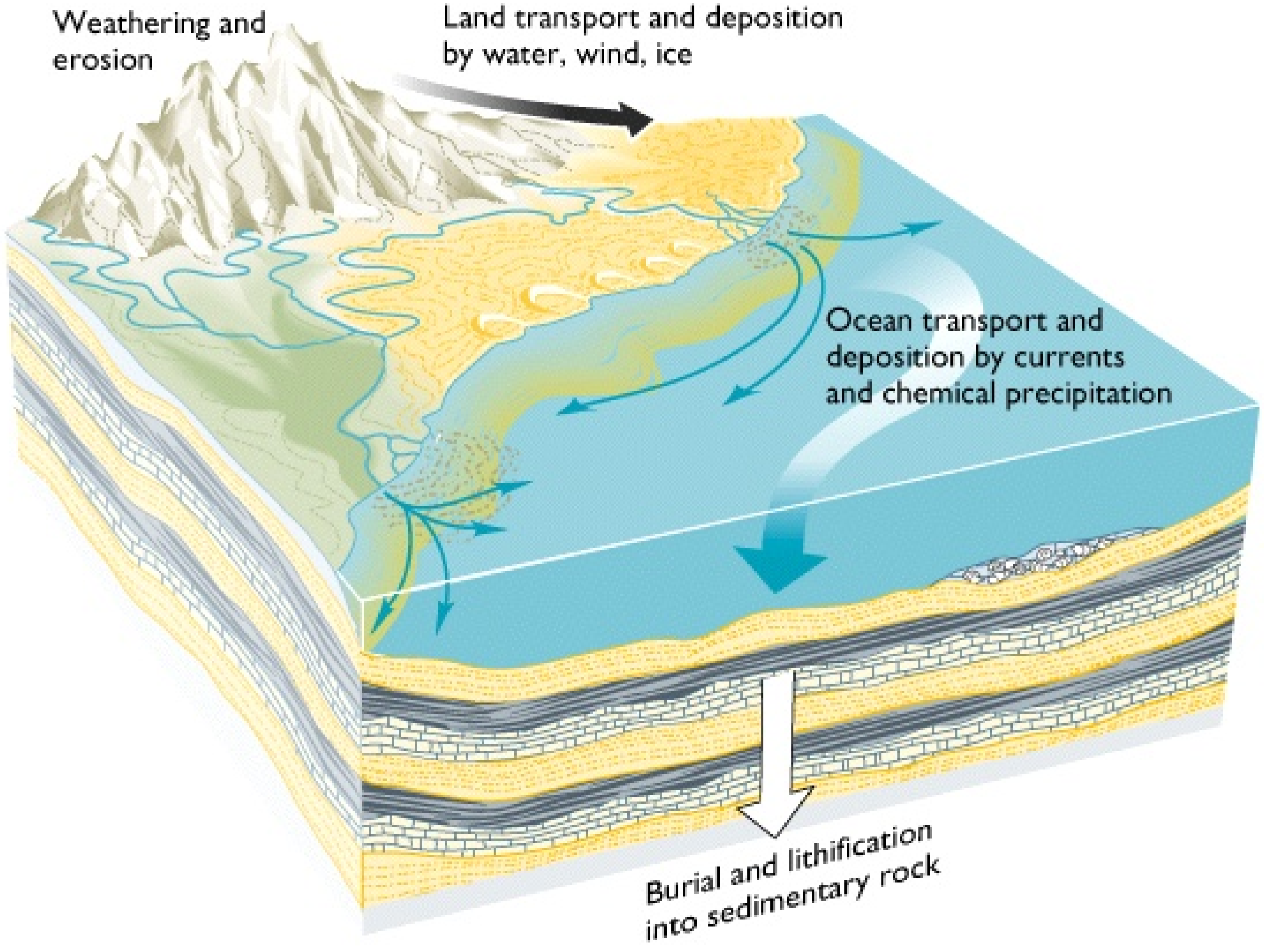
- Weathering and erosion are the processes that break down rocks and make particles and dissolved ions available to form sediment.
- Sedimentation, burial and lithification are the processes that transform weathering products into sedimentary rocks.





Suspended matter
mechanical erosion
River
soil and or floodplains
chemical weathering
Dissolved load
Bedrock

Weathering: decomposition of rocks



Weathering: Chemical and Physical

The destruction of rocks at the Earth's surface by weathering has two fundamental modes of operation:

- Physical weathering is fragmentation into progressively smaller particles, from intact outcrop to boulders and on down to mineral fragments and sand grains.
  - Physical weathering makes loose pieces of rock available for downslope movement by mass wasting or transport in flowing water as suspended or bed load.

Table 6.2 Stability of Common Minerals Under Weathering

Stability of Minerals	Rate of Weathering
Most stable	**Slowest**
Iron oxides (hematite)	↓
Aluminum hydroxides (gibbsite)	
Quartz	
Clay minerals	
Muscovite mica	
Potassium feldspar (orthoclase)	
Biotite mica	
Sodium-rich feldspar (albite)	
Amphiboles	
Pyroxene	
Calcium-rich feldspar (anorthite)	
Olivine	
Calcite	
Halite	
Least stable	**Fastest**

Chemical Weathering

Chemical weathering is driven by thermodynamic energy minimization, just like chemical reactions at high temperature.

- The system seeks the most stable assemblage of phases.
- The differences are that

(1) kinetics are slow and metastable phases can persist indefinitely under the right circumstances;

(2) the stable minerals under wet, ambient conditions are very different from those at high *T* and *P*;

(3) aqueous solutions are major players in the stability relations, so that solubility in water and the dependence of solubility on water chemistry (notably pH) are major determinants in the stability of minerals in weathering.

Chemical Weathering

TABLE 2.2 Principal processes of chemical weathering

Name of process	Nature of process	Examples	Principal types of rock materials affected
Hydrolysis	Reaction between H^+ and OH^- ions of water and the ions of silicate minerals, yielding soluble cations, silicic acid and clay minerals (if Al present)	$Mg_2SiO_4 + 4H_2O \rightarrow 2Mg^{+2} + 4OH^- + H_4SiO_4$ (fosterite) (silicic acid) $2KAlSi_3O_8 + 2H^+ + 9H_2O \rightarrow H_4Al_2Si_2O_9 + 4H_4SiO_4 + 2K^+$ (orthoclase) aq (kaolinite) (silicic acid) aq $2NaAlSi_3O_8 + 2H^+ + 9H_2O \rightarrow H_4Al_2Si_2O_9 + 4H_4SiO_4 + 2Na^+$ (albite) aq (kaolinite) (silicic acid)	Silicate minerals
Hydration/ dehydration	ain or loss of water molecules from a mineral, resulting in formation of a new mineral	$CaSO_4 \cdot 2H_2O \rightleftarrows CaSO_4 + 2H_2O$ (gypsum) (anhydrite) $Fe_2O_3 + H_2O \rightleftarrows 2FeOOH$ (hematite) (goethite)	Evaporites Ferric oxides
Oxidation	Loss of an electron from an element (commonly Fe or Mn) in a mineral, resulting in the formation of oxides or, if water is present, hydroxides	$4FeSiO_3 + O_2 \rightarrow 2Fe_2O_3 + 4SiO_2$ (pyroxene) (hematite) (quartz) $MnSiO_3 + \frac{1}{2}O_2 + 2H_2O \rightarrow MnO_2 + H_4SiO_4$ (rhodonite) $2FeS_2 + 15/2\ O_2 + 4H_2O \rightarrow Fe_2O_3 + 4SO_4^{2-} + 8H^+$ (pyrite) (hematite)	Iron and manganese-bearing silicate minerals, sulfur
Solution	Dissolution of soluble minerals, commonly in the presence of CO_2, to yield cations and anions in solution	$H_2O + CO_2 + CaCO_3 \rightleftarrows Ca^{2+} + 2HCO_3^-$ [carbonation] (calcite) (bicarbonate) $CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O$ [direct solution] (gypsum)	Carbonate rocks Evaporites
Ion Exchange	hange of ions, principally ations, between solutions and minerals	$Na\text{-clay} + H^+ \rightarrow H\text{-clay} + Na^+$	Clay minerals
Chelation	Bonding of metal ions to organic molecules having ring structures	Metal ions (cations) + chelating agent [excreted by lichens] $\rightarrow H^+$ ions + chelate [in solution]	Silicate minerals

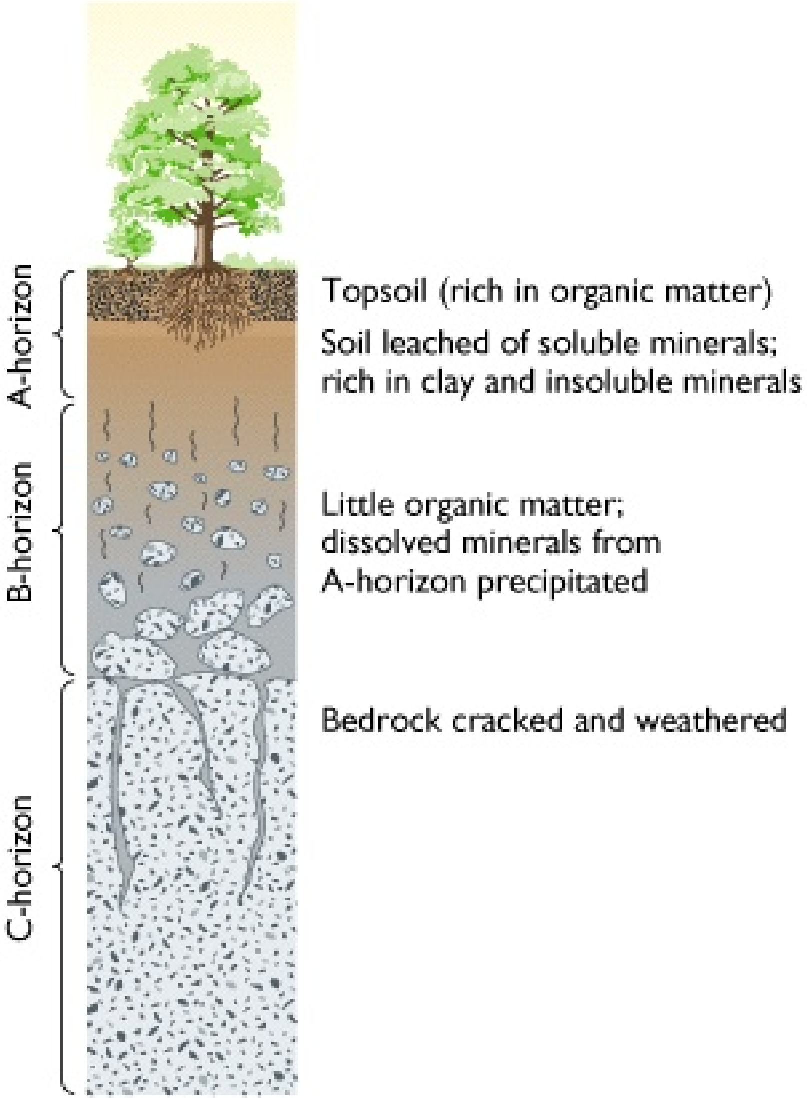
Physical Weathering

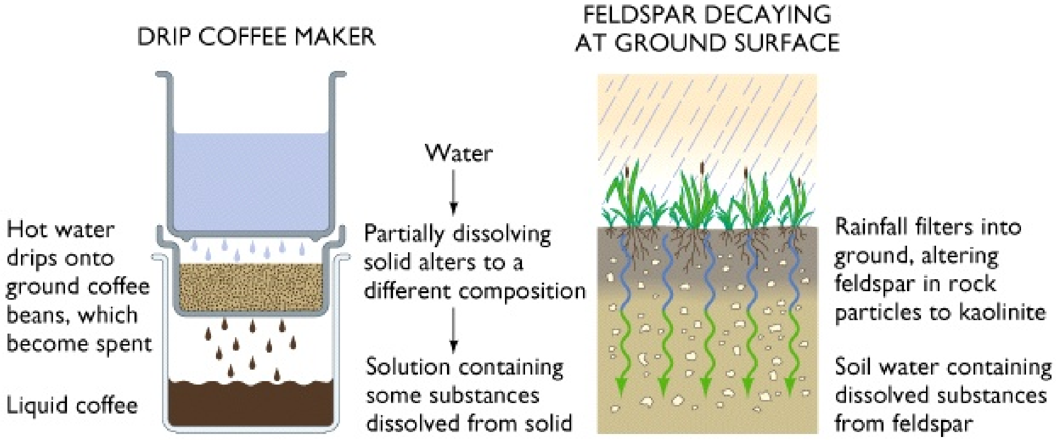
- Anything that promotes disaggregration of a rock so that pieces can form soil or be eroded away by wind, water, or gravity transport is physical weathering.
  - The distinction between physical weathering and erosion is subtle, but think of physical weathering as fragmenting the rock and erosion as carrying the fragments away; at times these may be the same event, of course.
- Rocks that are jointed or faulted or have pre-existing weak zones are most easily weathered.
  - Few of the stresses associated with physical weathering are significant compared to the tensile strength of intact rocks; something, has to start the process, either initial cracks and weaknesses or chemical attack on mineral cohesion.
- Organisms, especially plants (think tree roots), are fond of breaking up rocks.
- Freeze-thaw, frost wedging, frost heave…the volume change between ice and water is effective in widening cracks in rock in suitable climates.
- Physical abrasion by flowing air or water, or more often by rock particles already mobilized by water or wind (think Fossil Falls).
- Tectonics…rocks caught in a fault zone are definitely undergoing physical weathering.
- Etc.

Soils
Lower Zambezi

Soil Formation

Chemically and physically weathered rock that is not eroded or transported but remains in place becomes *soil*.

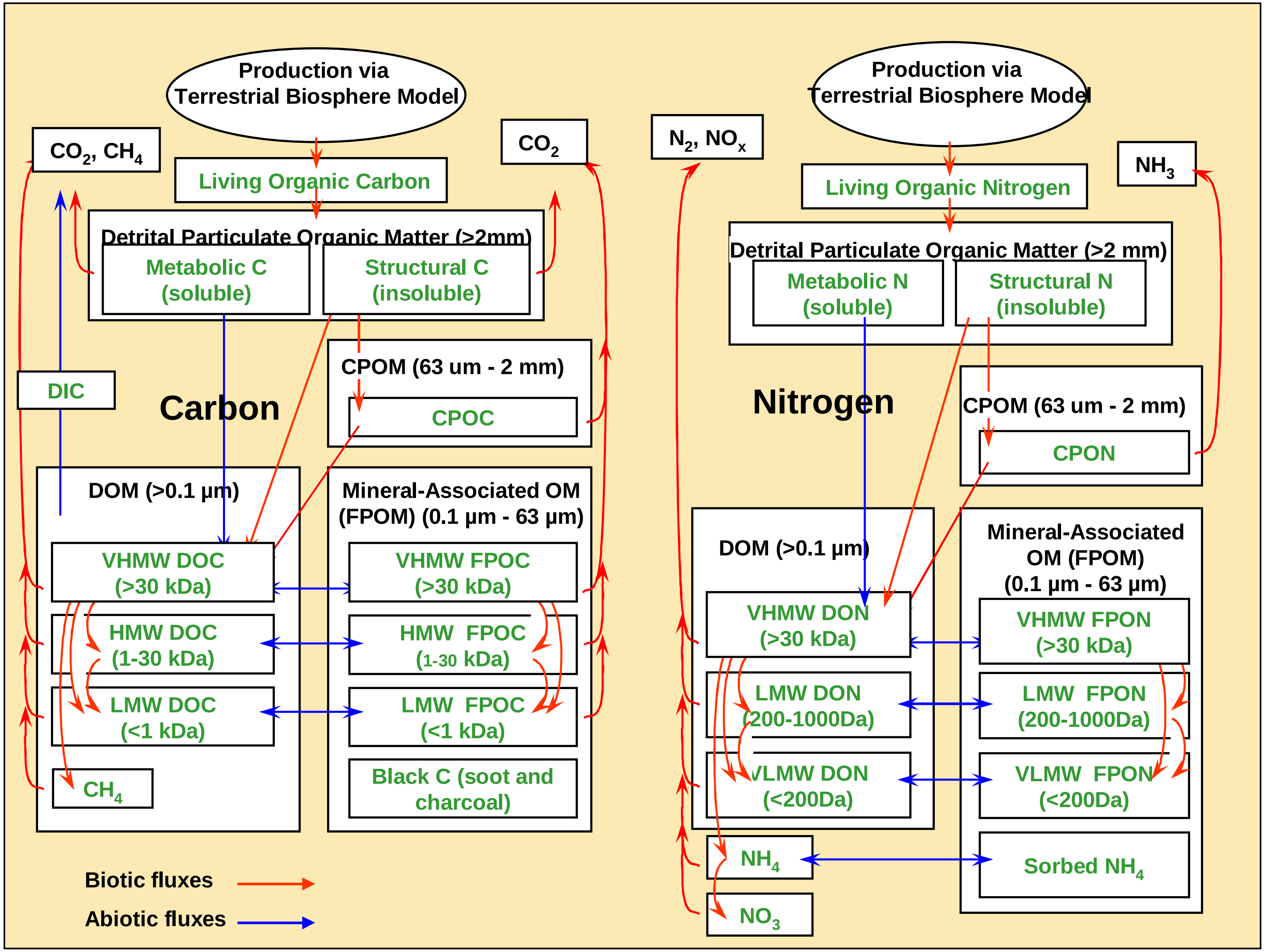




- A weathered surface develops a stratified structure, with intact rock at the bottom (or inside) and maximum weathering at the top .
- Leachable ions are transported downwards by groundwater flow, possibly redeposited as water chemistry adjusts towards equilibrium with the developing soil profile.

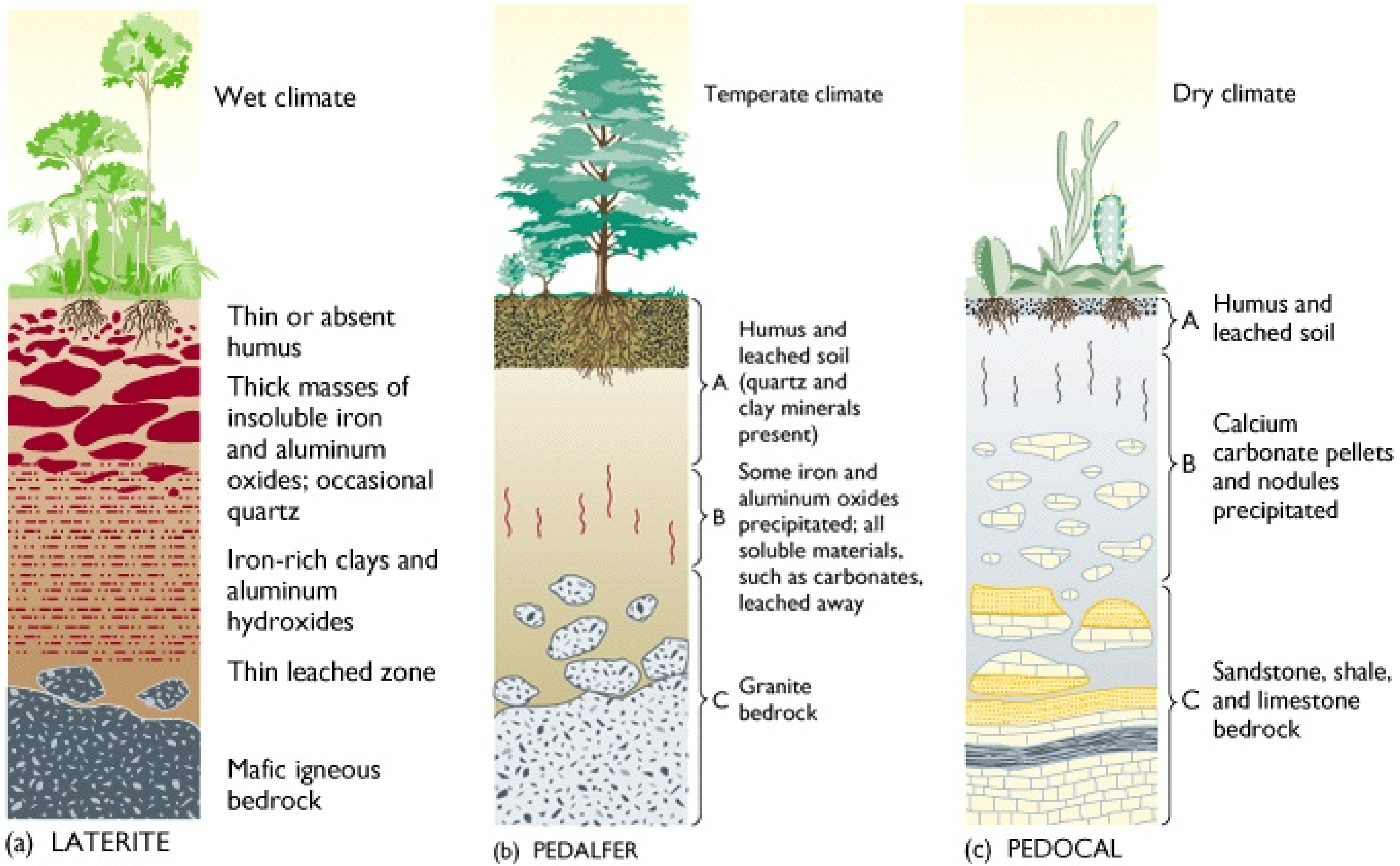
Rock Particles <-> OM

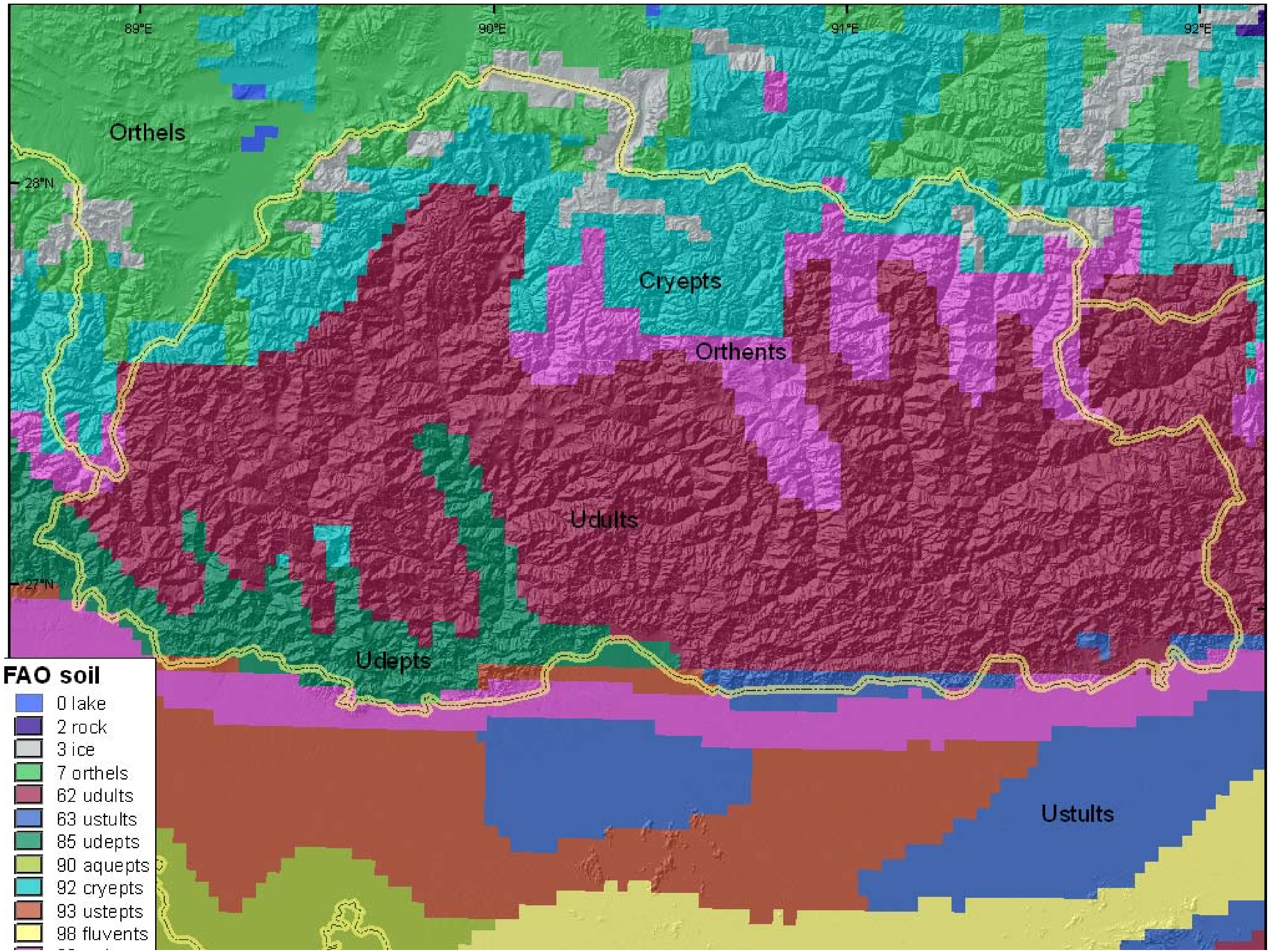
(River basin Organic Matter and Biogeochemistry Synthesis Model)



Soil Formation

- The mineralogy and thickness of soil layers depends on source rock, climate (temperature and rainfall), and age.
- Which of these soil types would you rather farm?





89°E
90°E
91°E
92°E
28°N
27°N
Orthels
Cryepts
Orthents
Udults
Udepts
Ustults
FAO soil
0 lake
2 rock
3 ice
7 orthels
62 udults
63 ustults
85 udepts
90 aquepts
92 cryepts
93 ustepts
98 fluvents

Soil Data Preparation

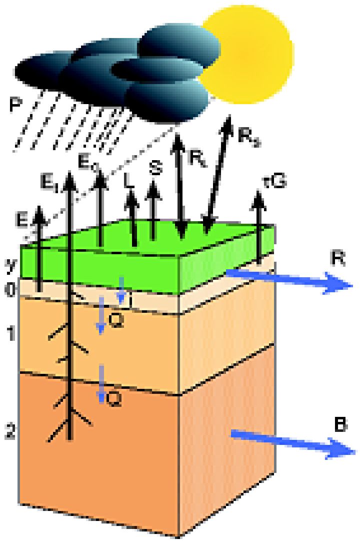
Soil Physical Properties were obtained from the FAO Soil Program

- Bulk Density
- Sand/Clay content. From sand and clay content, each 1/12 degree pixel grid cell is assigned to one of the twelve FAO soil textural classes
- Soil hydrologic parameters estimated from the USDA soil texture class, following *Schaake (2000).*
  - Porosity
  - Saturated Hydraulic Conductivity
  - Field Capacity
  - Wilting Point
  - Soil depths are taken as 10, 20 and 120 cm as initial guess for the layers one to three respectively. It is to be changed after calibration of simulated to observed flows.

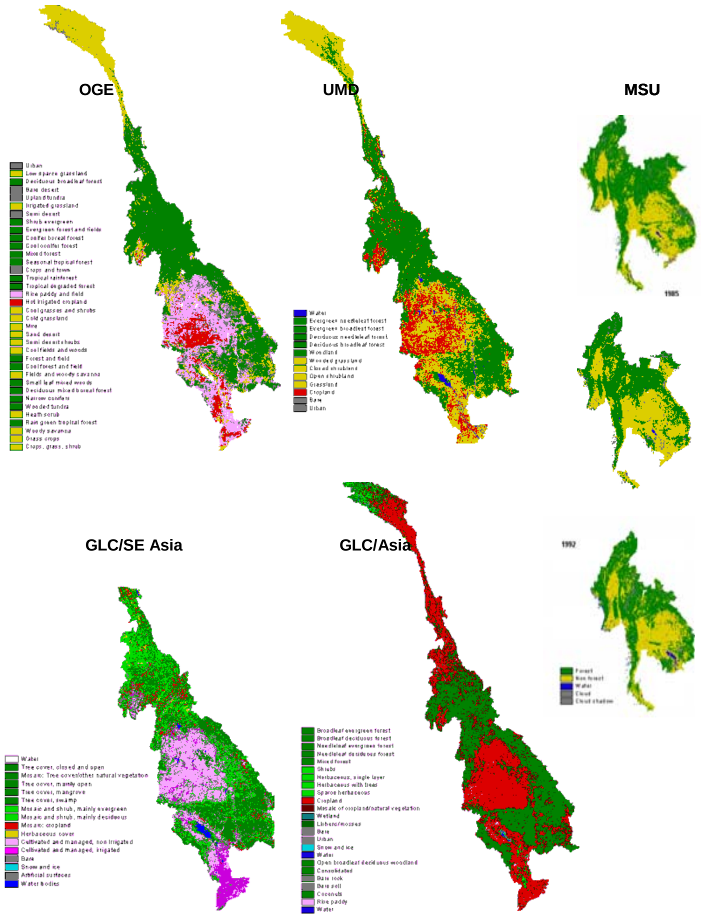
Other soil parameters are either computed from those already obtained ; for instance , particle density computed from Bulk density and porosity or recommended values from previous studies are used

Landcover

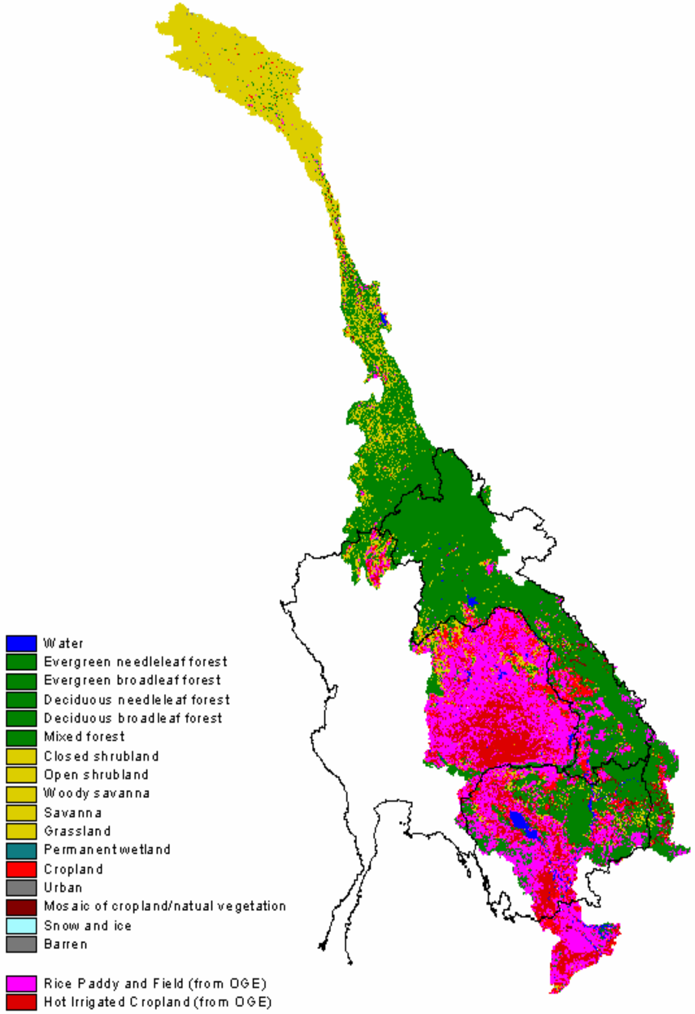
Specific to each class, information on the biophysical attributes (rooting depth, height, etc) is required, which can come from multiple sources.



VEGETATION – *GETTING IT RIGHT*

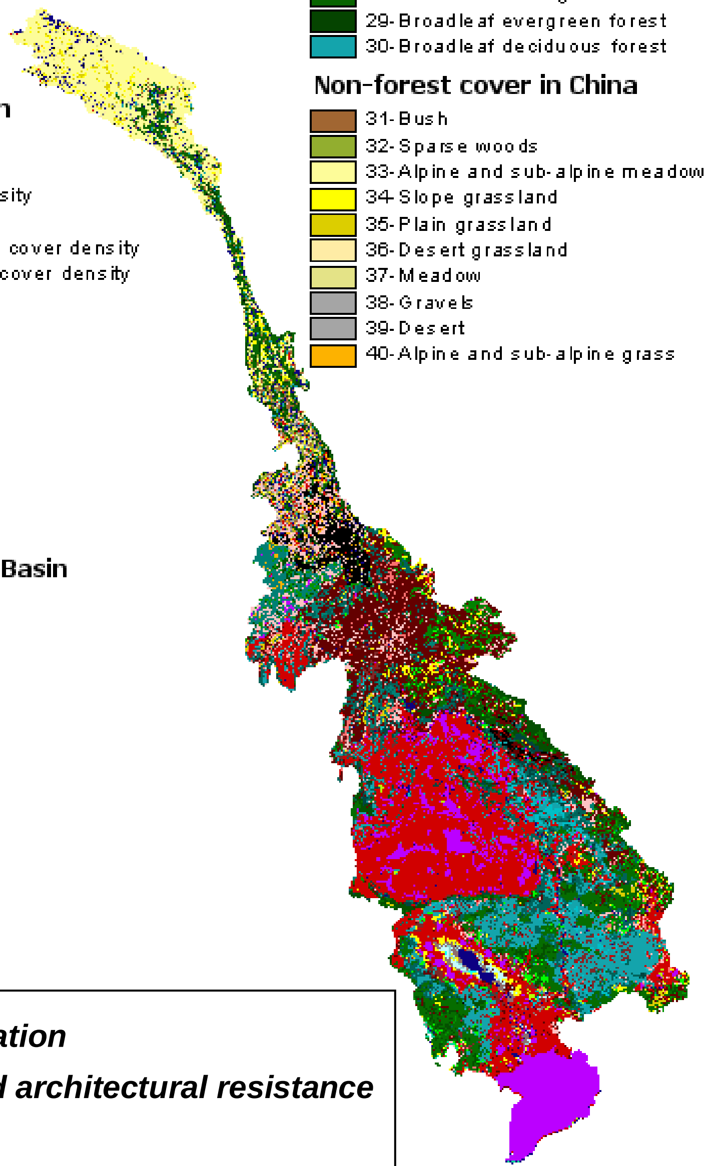


MODIS/ OGE Rice



VEGETATION "CLASSES"

….of interest to many, for multiple purposes…



Forest cover in China

- 27-Needleleaf deciduous forest
- 28-Needleleaf evergreen forest
- 29-Broadleaf evergreen forest
- 30-Broadleaf deciduous forest

Non-forest cover in China

- 31-Bush
- 32-Sparse woods
- 33-Alpine and sub-alpine meadow
- 34-Slope grassland
- 35-Plain grassland
- 36-Desert grassland
- 37-Meadow
- 38-Gravels
- 39-Desert
- 40-Alpine and sub-alpine grass

Forest cover in Lower Mekong Basin and Burma

- 1-Evergreen, high cover density
- 2-Evergreen, medium to low cover density
- 3-Evergreen mosaic
- 4-Mixed (evergreen & deciduous), high cover density
- 5-Mixed (evergreen & deciduous), low cover density
- 6-Mixed mosaic
- 7-Deciduous
- 8-Deciduous mosaic
- 9-Regrowth
- 10-Regrowth, inundated
- 11-Inundated
- 12-Mangrove
- 13-Plantations
- 14-Other forest cover
- 15-Inundated mosaic

Non-forest cover in Lower Mekong Basin and Burma

- 16-Woodland & shrubland, evergreen
- 17-Grassland
- 18-Bamboo
- 19-Woodland & shrubland, dry
- 20-Woodland & shrubland, inundated
- 21-Cropping mosaic (crop<30%)
- 22-Cropping mosaic (crop>30%)
- 23-Agricultural land
- 24-Baren land
- 25-Rocks
- 26-Urban or built up
- 41-Irrigated lands
- 42-Water

Minimum stomatal resistance, RGL, and solar radiation attenuation

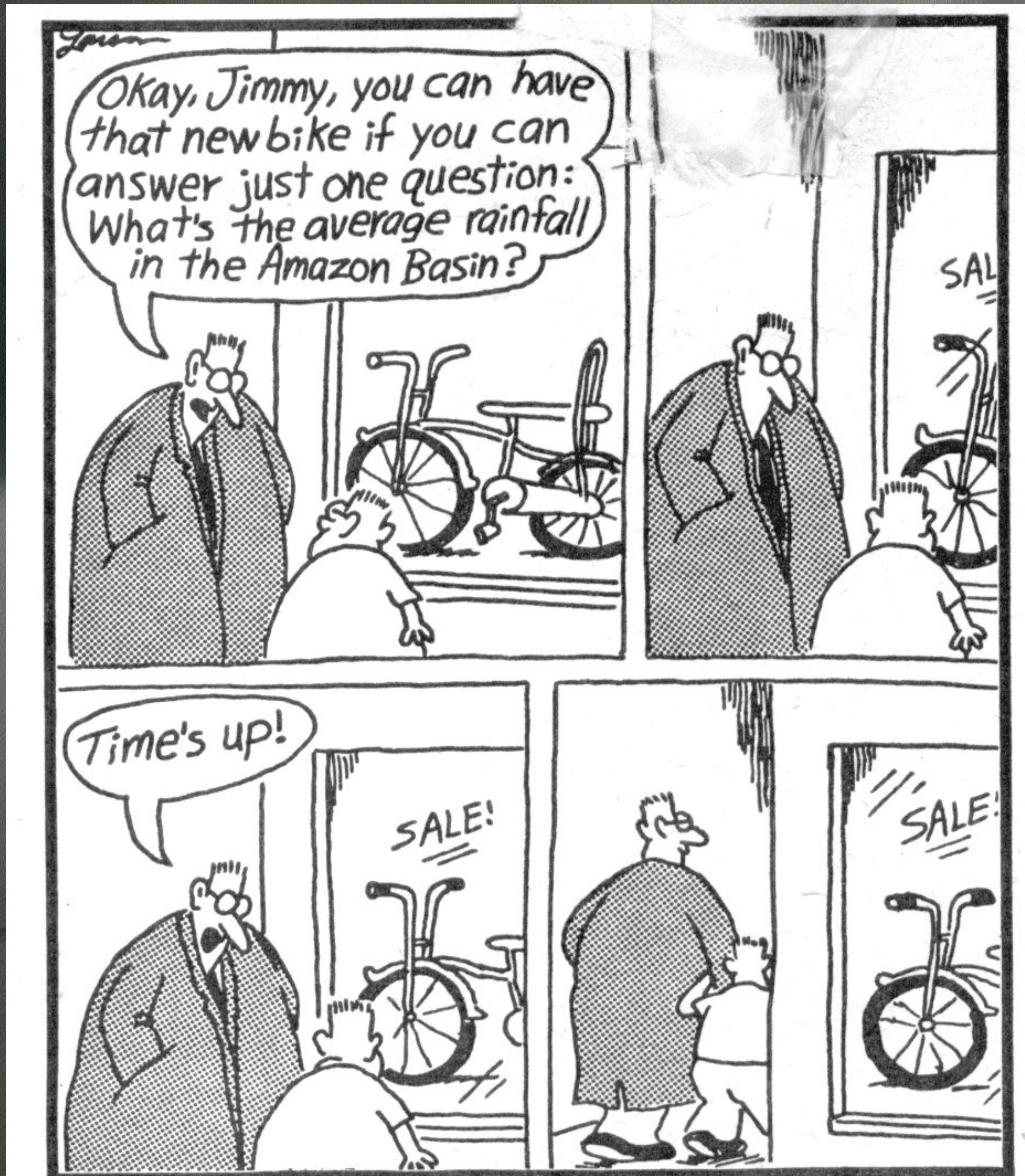
Vegetation height, displacement height, roughness length, and architectural resistance

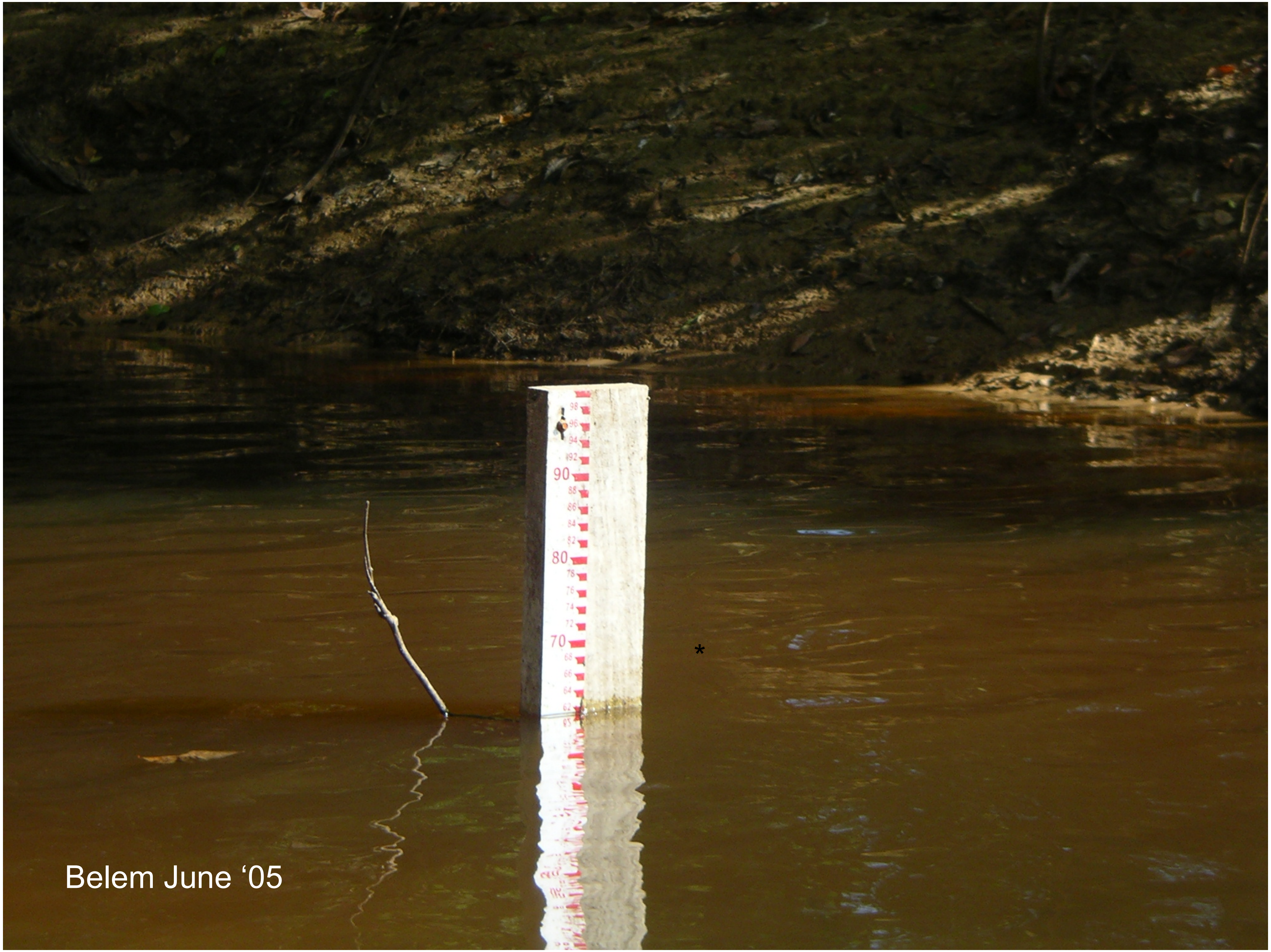
Leaf Area Index, albedo

Maximum rooting depth, and distribution of root mass with depth

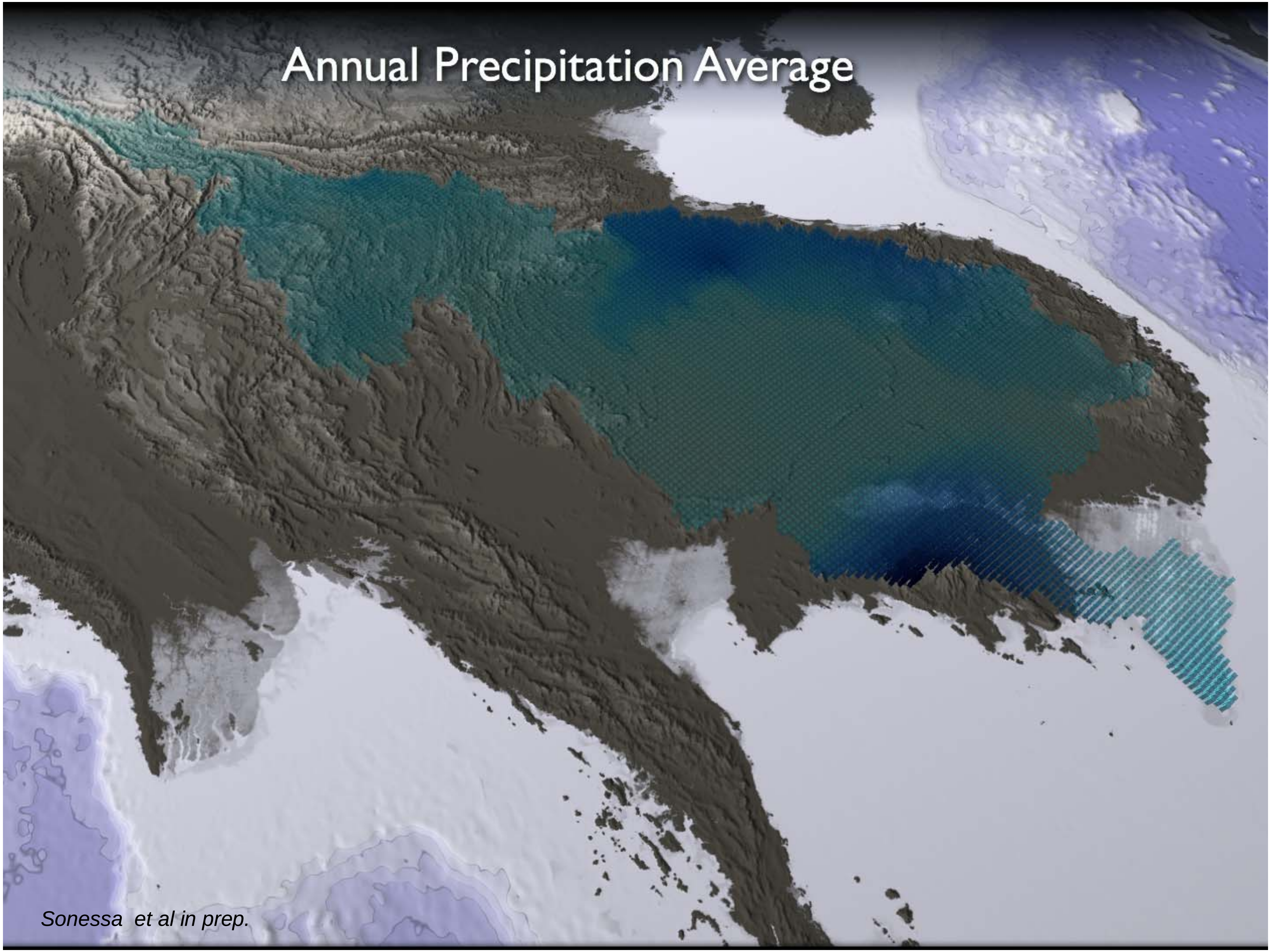
Wind height and wind attenuation

Climate


Okay, Jimmy, you can have that new bike if you can answer just one question: What's the average rainfall in the Amazon Basin?
SAL
Time's up!
SALE!
SALE!


90
80
70
*
Belem June ‘05

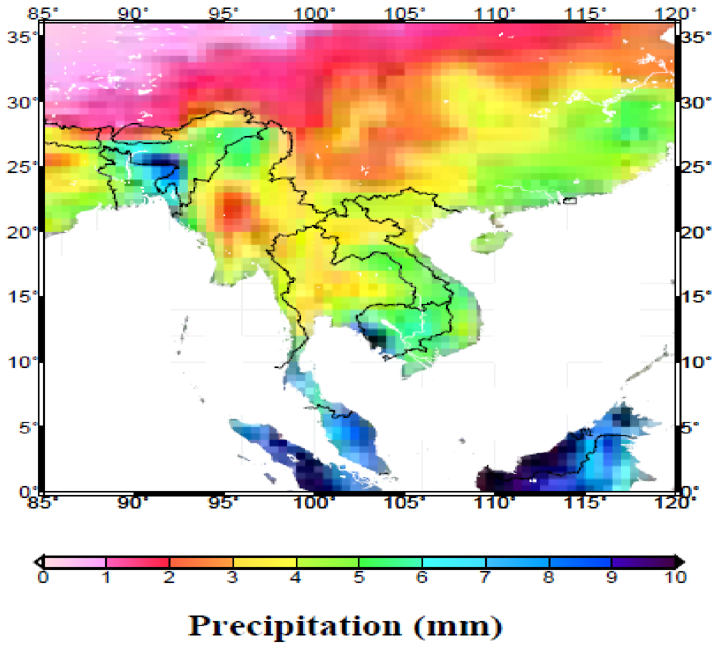
Annual Precipitation Average



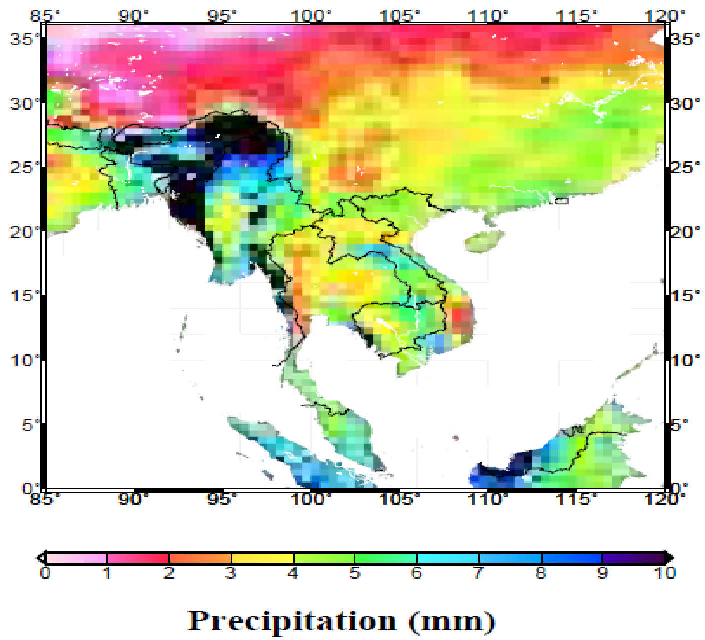
Sonessa et al in prep.

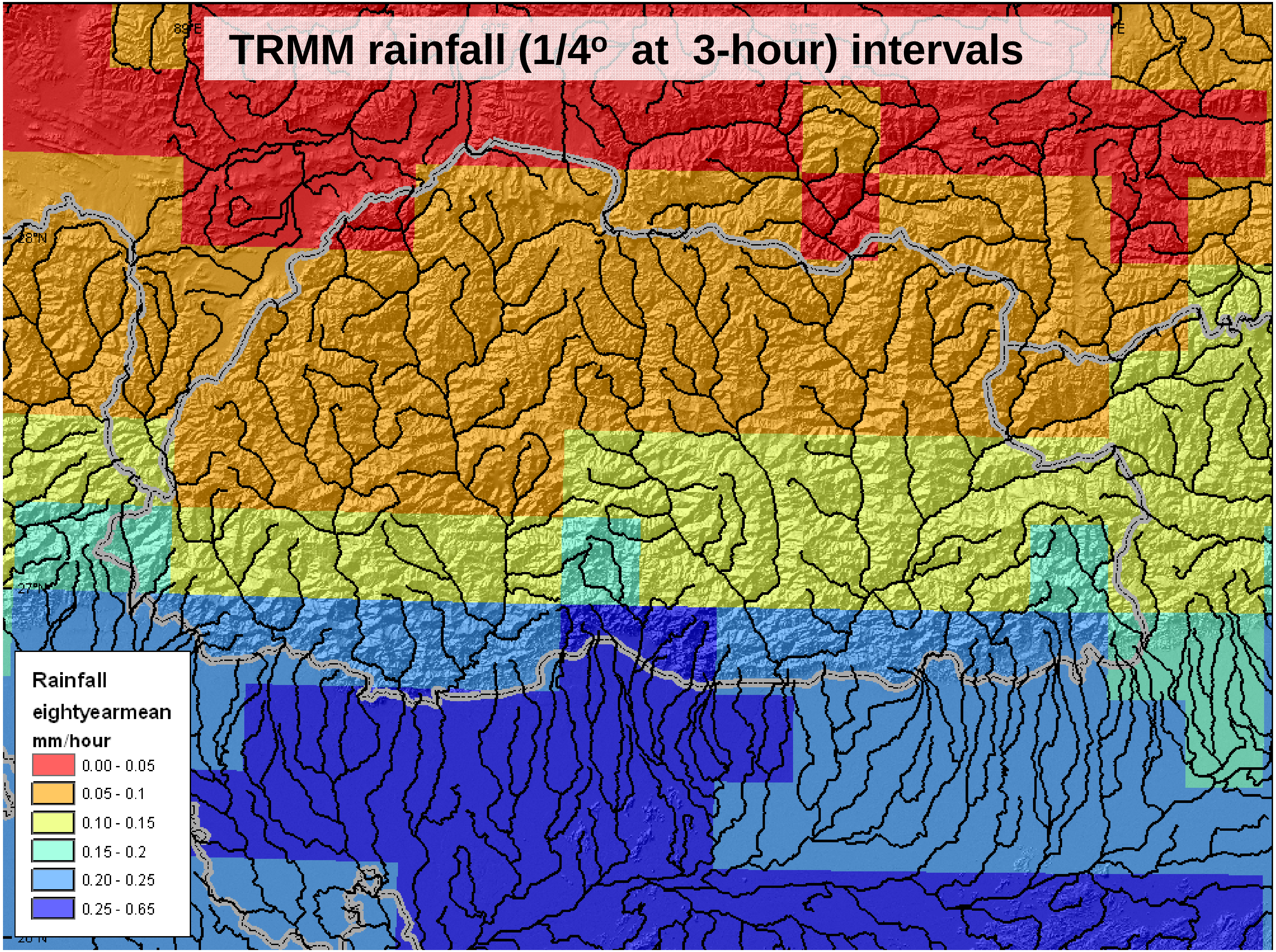
Mean Daily Precipitation

TRMM (1998-2008)



NCEP/NCAR (1948-2007)

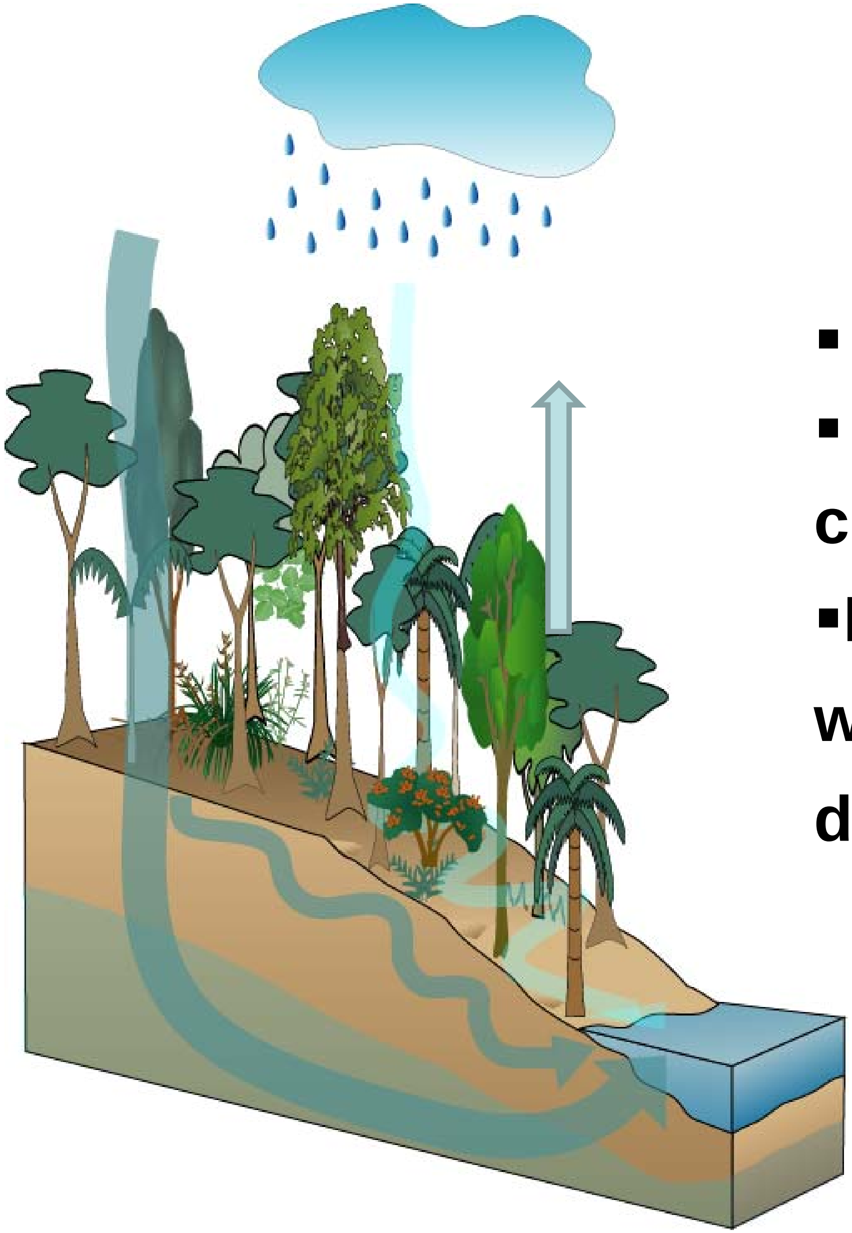



TRMM rainfall (1/4° at 3-hour) intervals
28°N
27°N
Rainfall
eightyearmean
mm/hour
0.00 - 0.05
0.05 - 0.1
0.10 - 0.15
0.15 - 0.2
0.20 - 0.25
0.25 - 0.65

- The daily variability of NCEP/NCAR is used to create daily P and T data using monthly CRU (for T) and Udel (for P) as a control.
  - So, for a given month the daily precipitation varies like the NCEP/NCAR data while the amount is controlled by (add up to) that month's U-Delaware precipitation.

- The data prepared using the above mentioned steps are of 0.5 degree resolution. Those data were interpolated to 1/24 grid cells using the SYMAP algorithm (Shepard, 1984) to obtain daily time series of precipitation and maximum and minimum temperature for each grid cell.

- Temperature data were interpolated using a lapse rate of -6.5 °C per km to adjust temperature from the 0.5 degree grid cell to each elevation of the 1/24 grid cell.



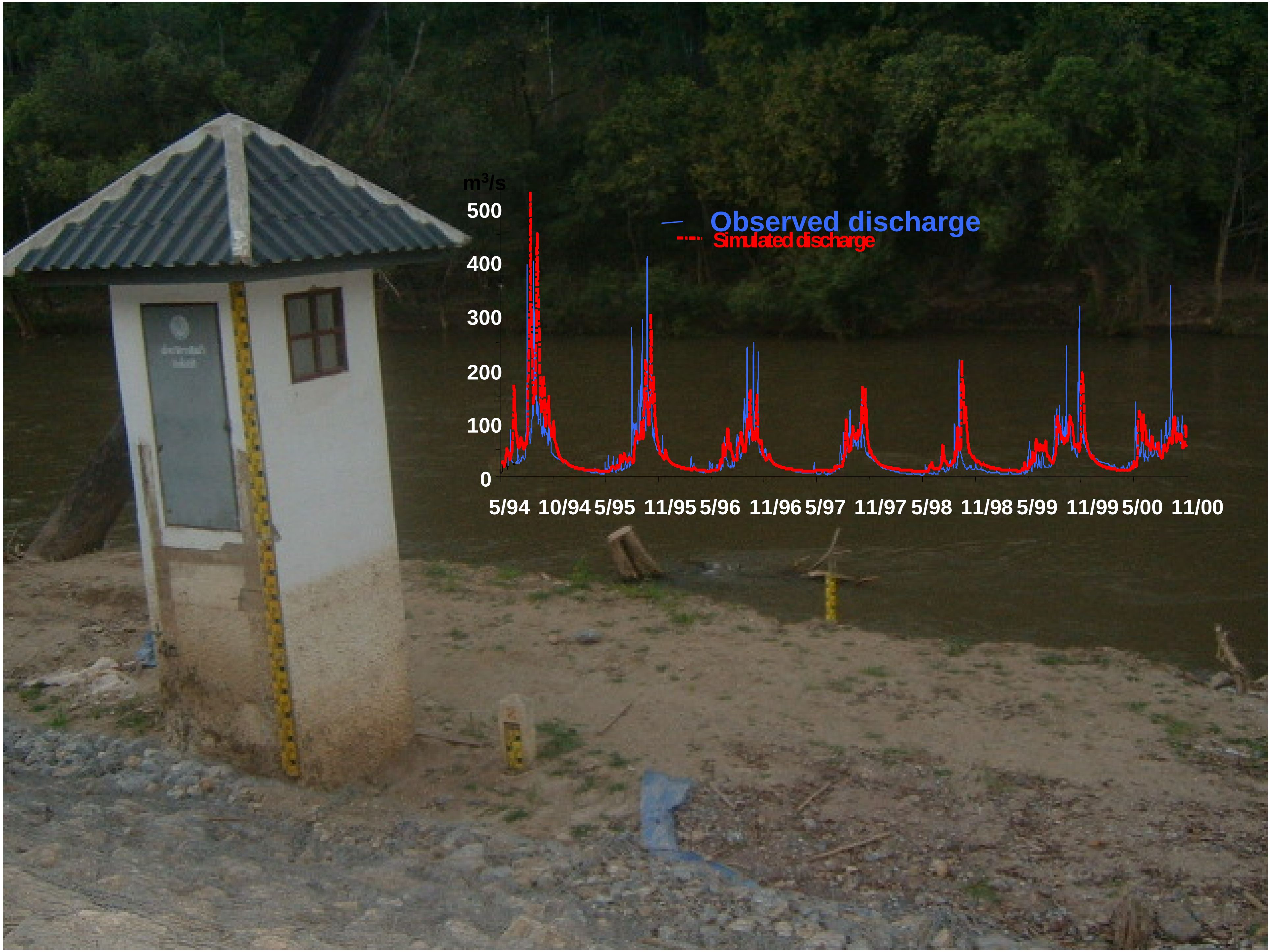
- What are “flowpaths?”
- How do flowpaths change with soil type?
- How do flowpaths change with landuse? deforestation?

INFILTRATION RATE

Saturated Hydrologic Conductivity (K_s)

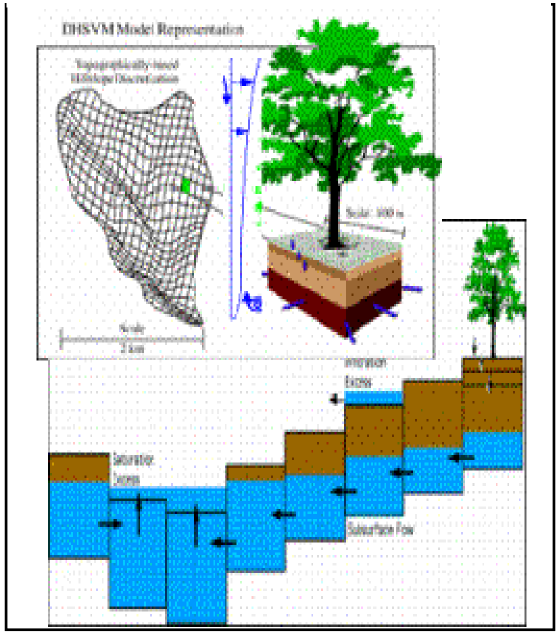
- K_s high for undisturbed forest soils
- Deforestation lowers K_s because of:

  Compaction by humans, animals, vehicles
  Soil crust formation from direct impact of raindrops
  Breakdown of soil structure - less extensive root systems

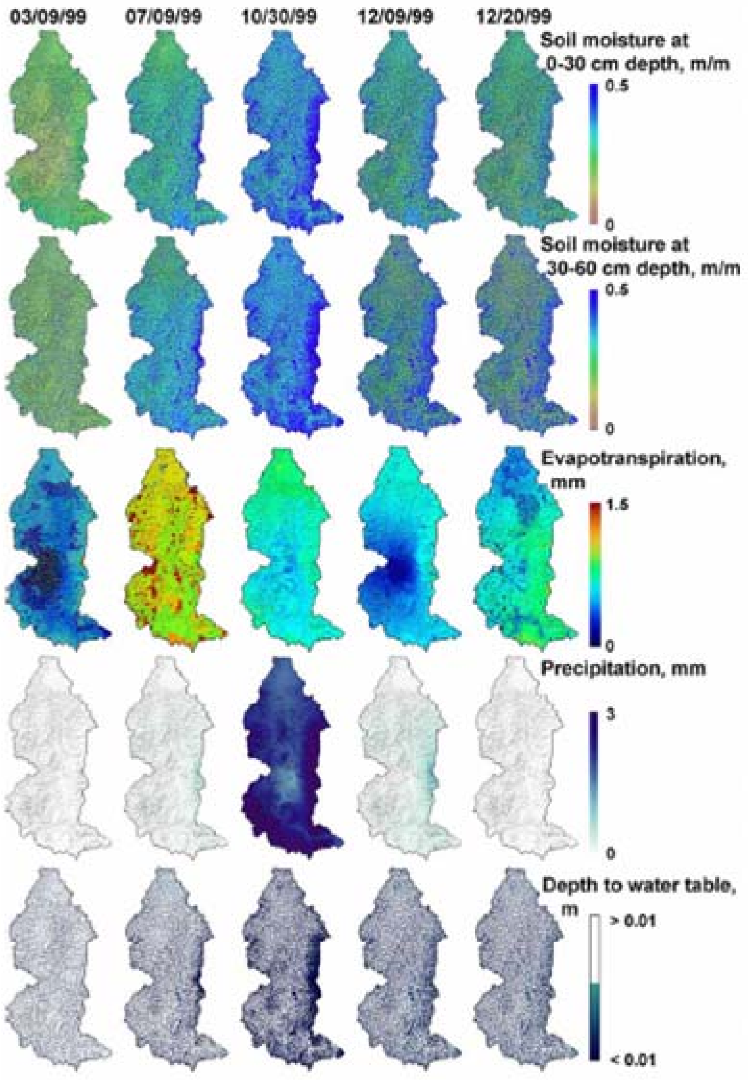


m3/s
500
400
300
200
100
0
Observed discharge
Simulated discharge
5/94
10/94
5/95
11/95
5/96
11/96
5/97
11/97
5/98
11/98
5/99
11/99
5/00
11/00

DHSVM (Distributed Hydrology Soil Vegetation Model) (150m)



Underlying Dynamic Changes



WHAT HAPPENS WITH LANDUSE CHANGE?

reducing poverty and improving conservation at the tropical forest margins

ASB

Alternatives to Slash-and-Burn

Debunking Myths about Forests and Water: A Policy Briefing Road Show

Land Use and Water Resources Research

Forests and Hydrological Services: Reconciling public and science perceptions*

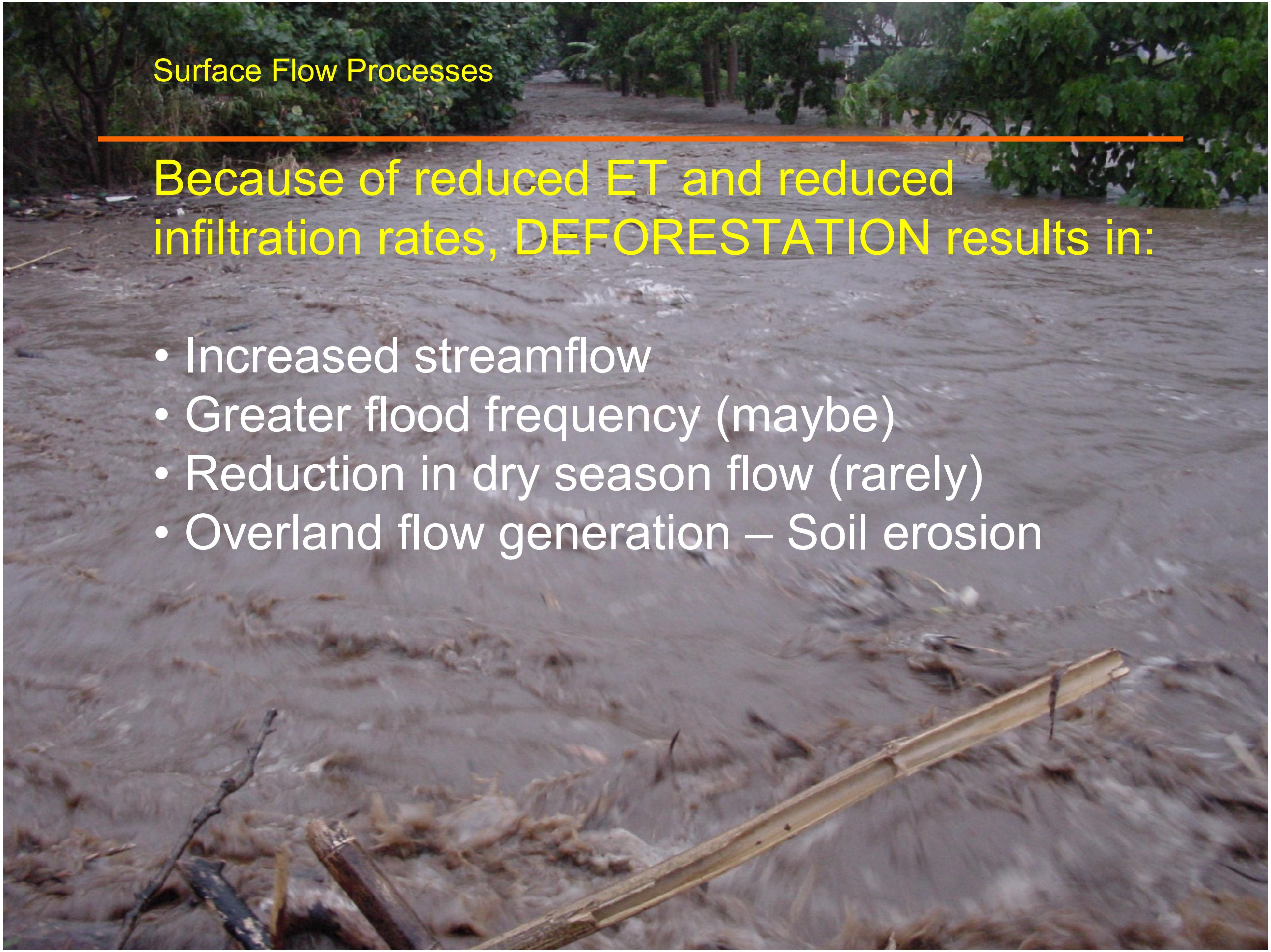
EDITORIAL

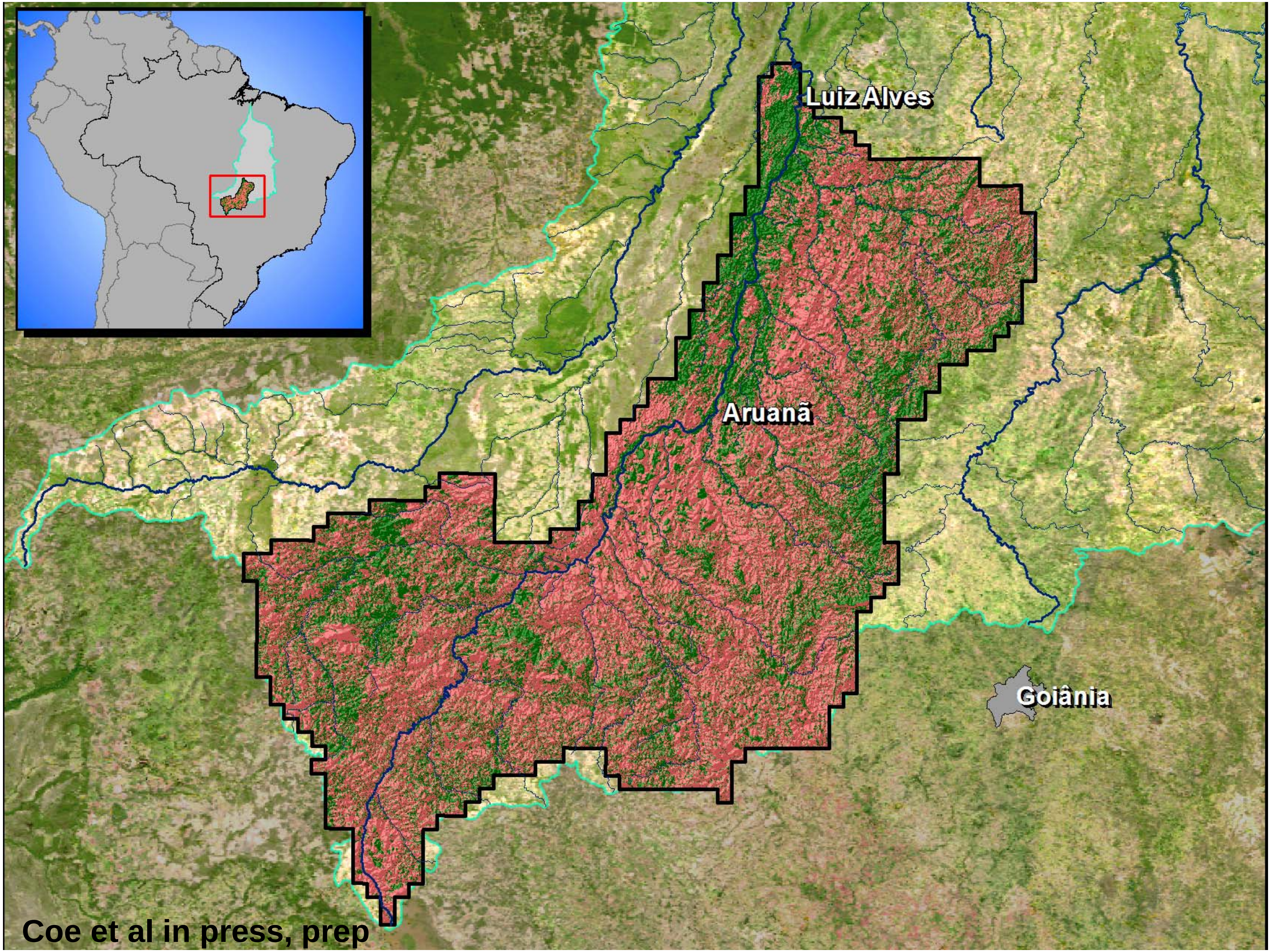
FOREST, WATER AND LIVELIHOODS

European Tropical Forest Research Ne

ETFRN NEWS 45/46: Forests, Water and Livelihoods

UNCERTAINTIES IN THE HYDROLOGY OF TROPICAL REFORESTATION: BEYOND "FROM THE MOUNTAIN TO THE TAP"[1]


Surface Flow Processes
Because of reduced ET and reduced infiltration rates, DEFORESTATION results in:
• Increased streamflow
• Greater flood frequency (maybe)
• Reduction in dry season flow (rarely)
• Overland flow generation – Soil erosion


Luiz Alves
Aruanã
Goiânia
Coe et al in press, prep

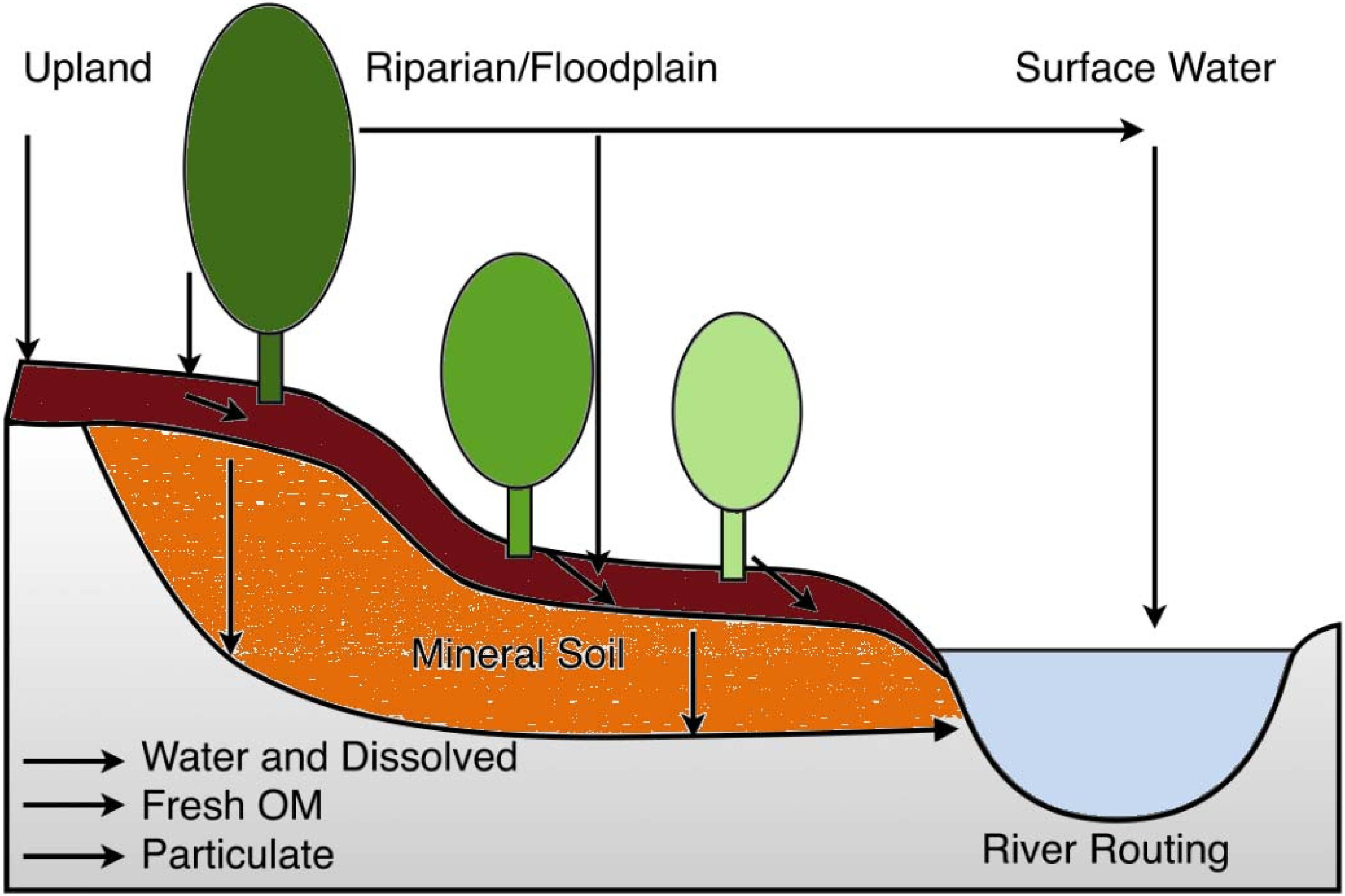
- By 2006, 62% of the land in the Araguaia River basin has been converted to agriculture.

- Sediment flux within the Araguaia River increased by 28% from 1965 to 1998.

- The river is re-organizing its physical structure to accommodate the increased sediment; with a central channel being carved from what was once a multi-branching river.

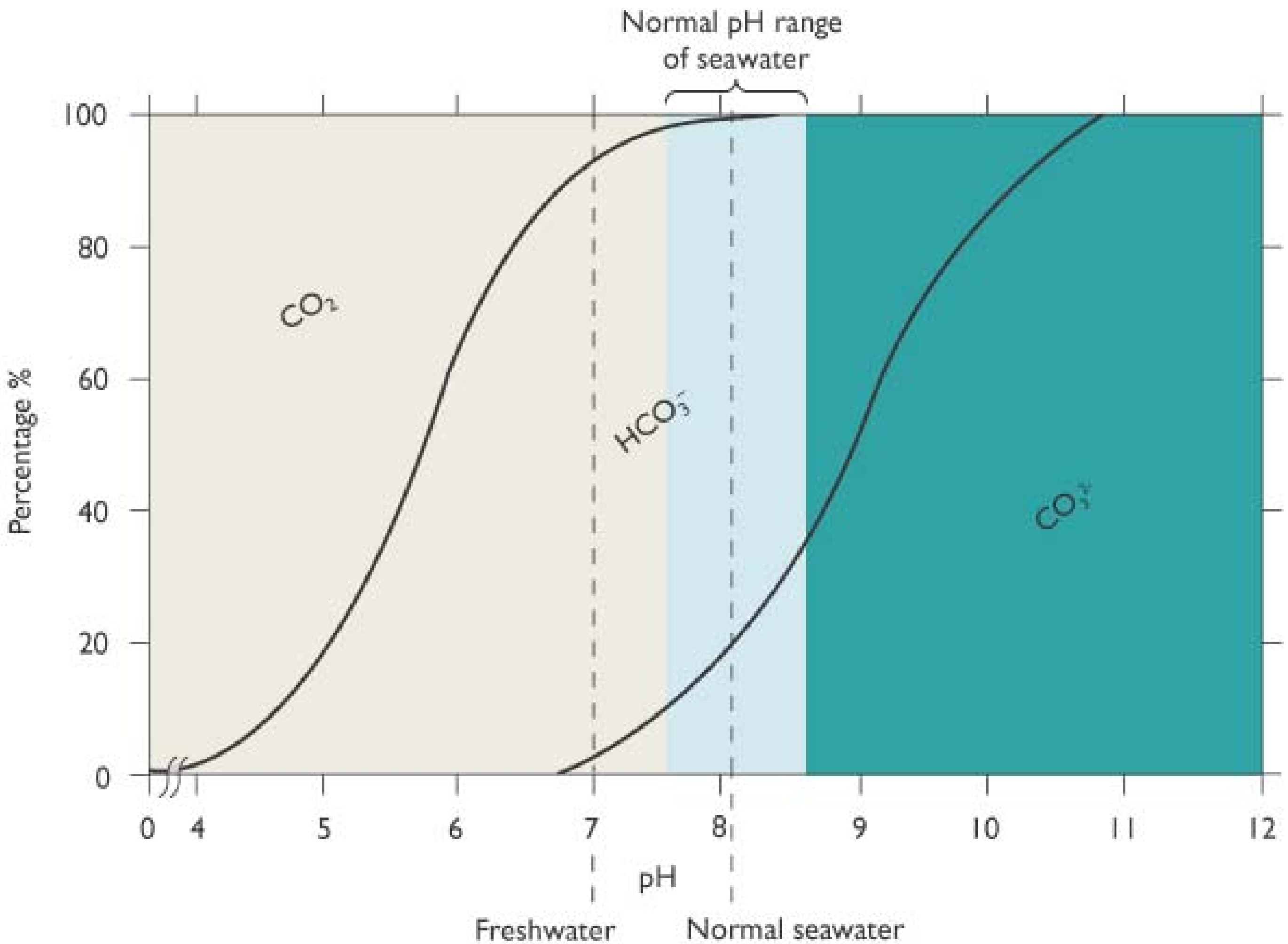
- Discharge has increased by 25% since the 1970s.

- Simulations indicate that about 2/3 of the change in discharge is attributable to changes in land cover.



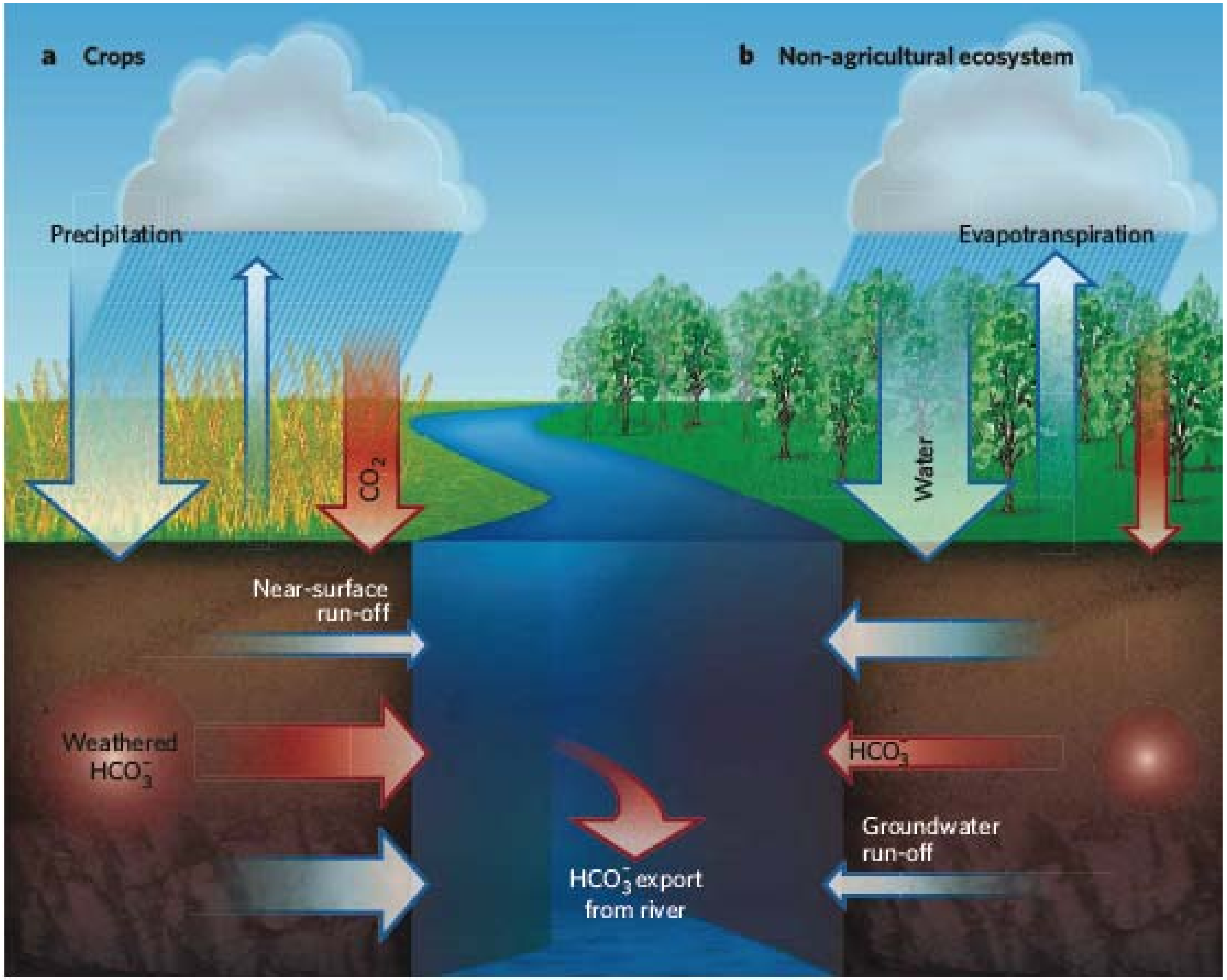
Upland
Riparian/Floodplain
Surface Water
Mineral Soil
Water and Dissolved
Fresh OM
Particulate
River Routing

Distribution of Carbon species in water

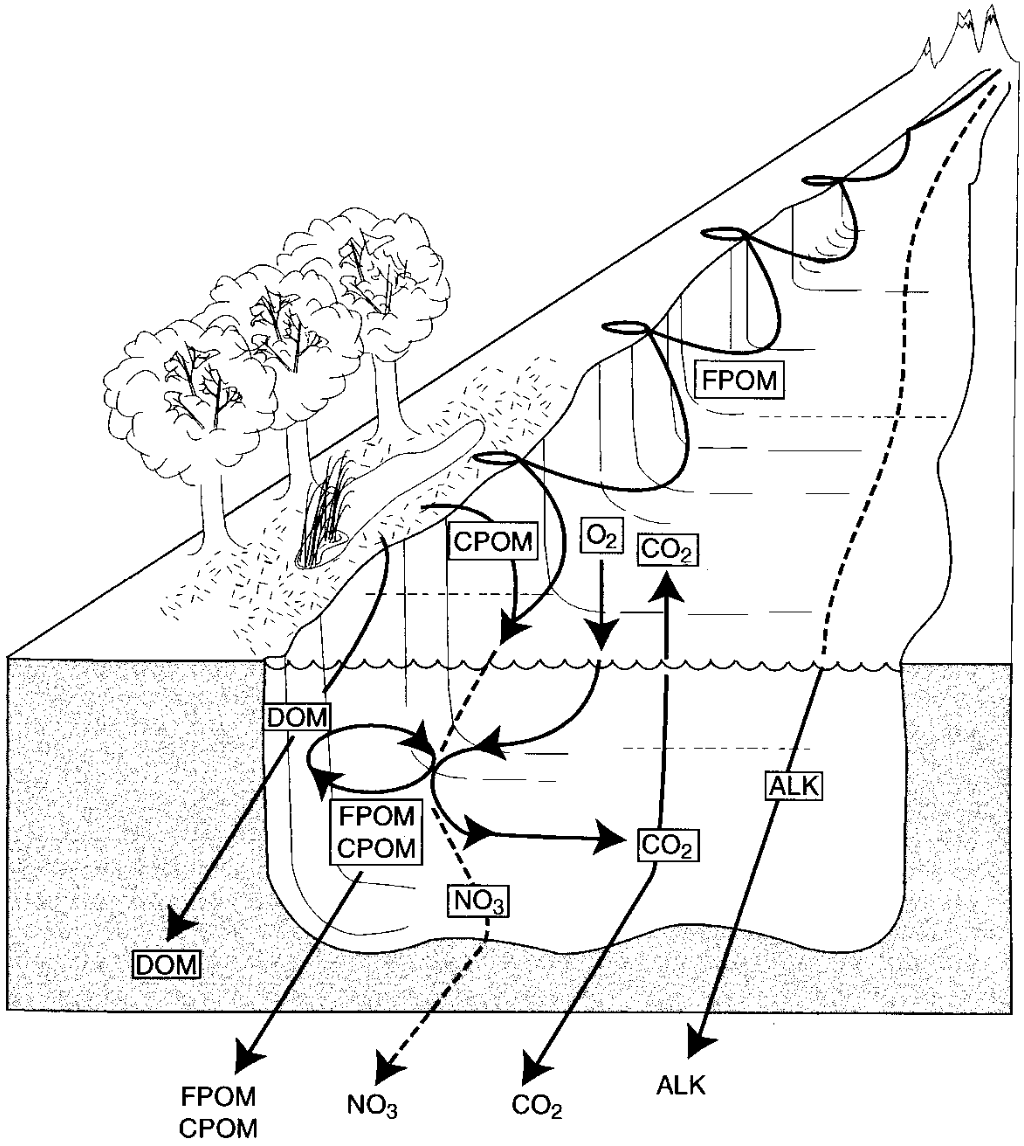


$+ \quad \frac{[HCO_3^-]}{[CO_3^{2-}]} \longleftrightarrow - \quad \frac{[HCO_3^-]}{[CO_3^{2-}]}$

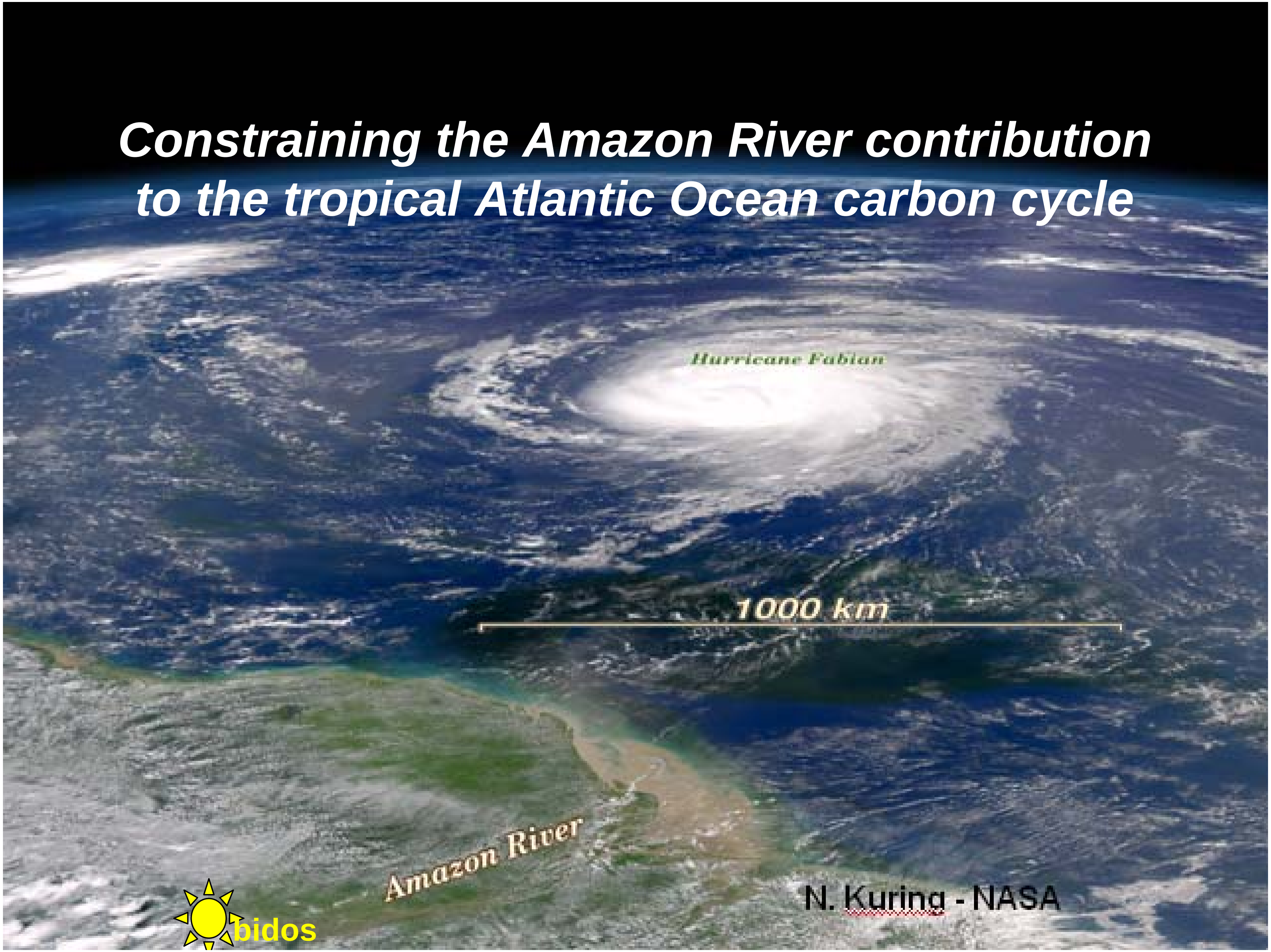
Landuse Change - Carbon exchange and Nutrient Release



Mayorga 2008


FPOM
CPOM
O2
CO2
DOM
FPOM
CPOM
CO2
ALK
NO3
DOM
FPOM
CPOM
NO3
CO2
ALK

Constraining the Amazon River contribution to the tropical Atlantic Ocean carbon cycle





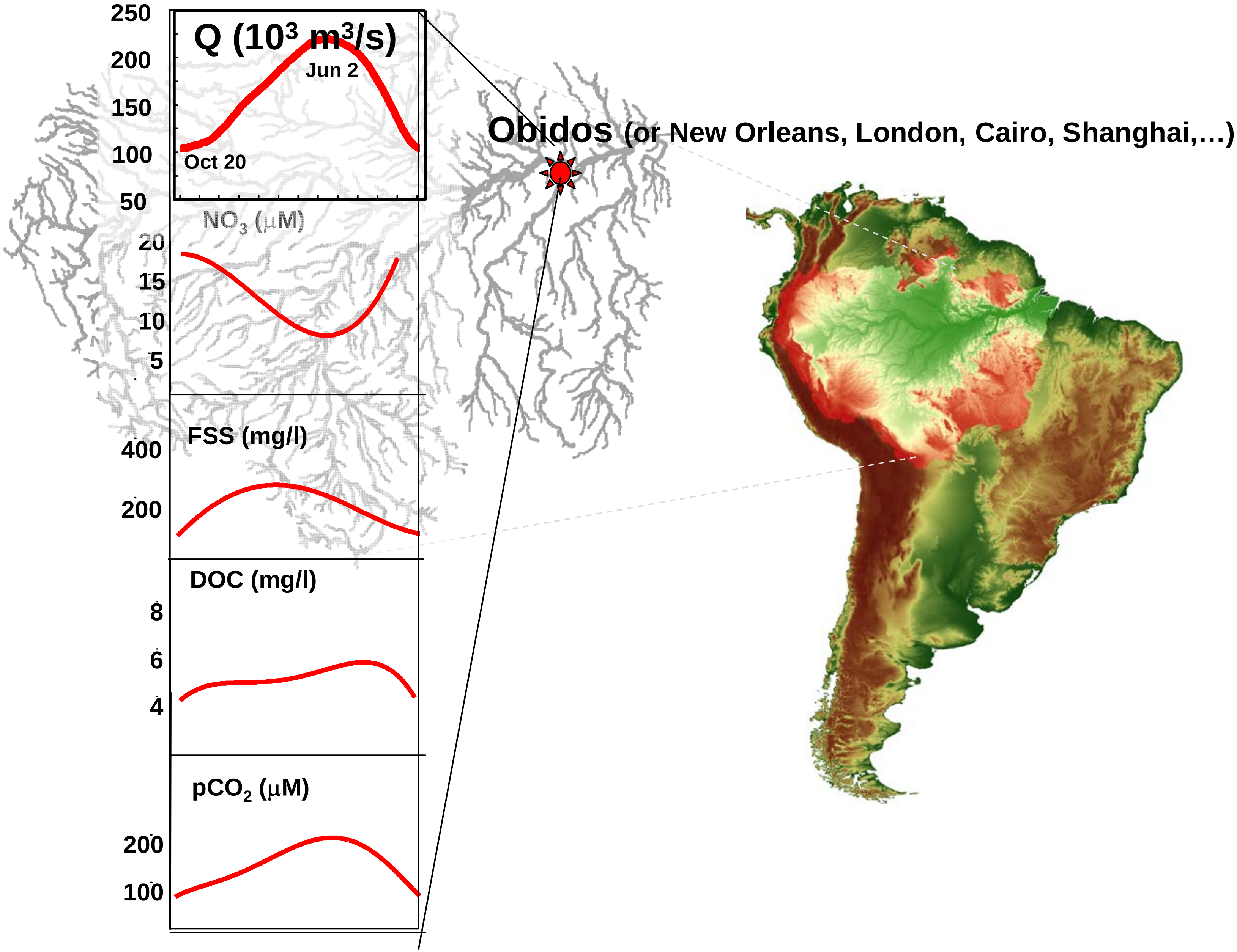
How do composite processes of land-water interactions scale up to generate regional patterns?

What is the size and character of the riverine carbon pool and the timing of its mobilization compared to net atmosphere-land carbon uptake? (and what are the factors controlling the partitioning of carbon between evasion and fluvial export?).

What do these regional patterns in carbon transport and transformation indicate about the overall relation among water movement, landscape structure (topography, soils), and vegetation structure and productivity across the Amazon basin?

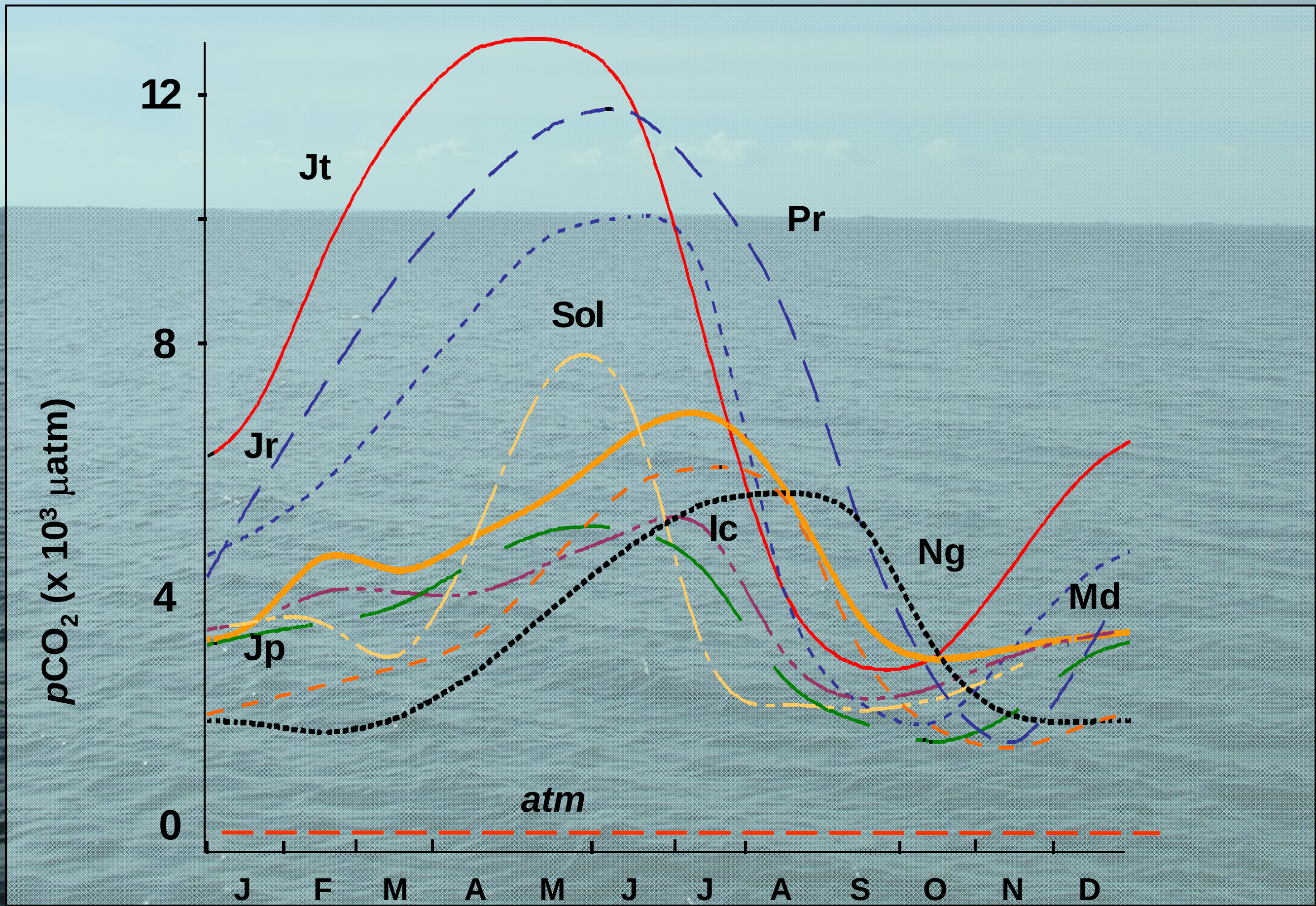
What are the effects of climate variability and human forcing on water and fluvial carbon mobilization?

Alter do Chao

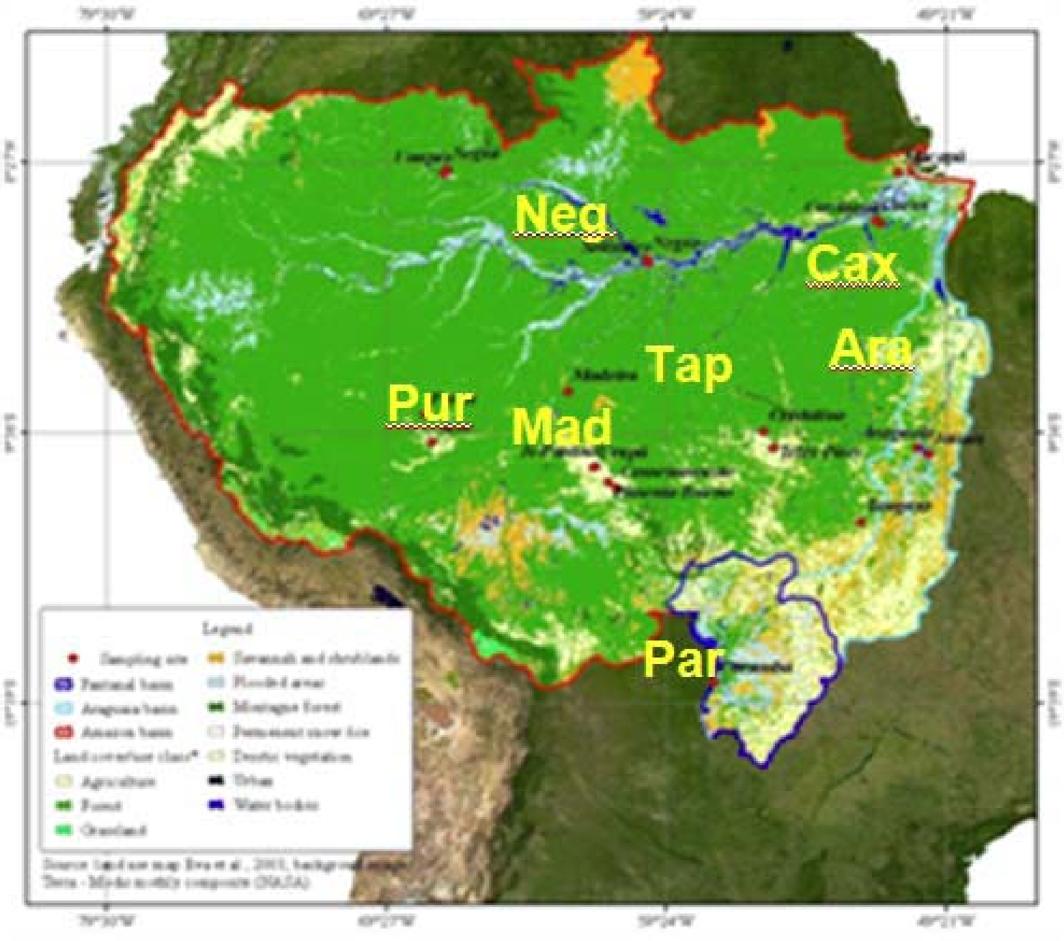


Q (10^3 m^3/s)
250
200
150
100
50
Jun 2
Oct 20
Obidos (or New Orleans, London, Cairo, Shanghai,…)
NO$_3$ (μM)
20
15
10
5
FSS (mg/l)
400
200
DOC (mg/l)
8
6
4
pCO$_2$ (μM)
200
100

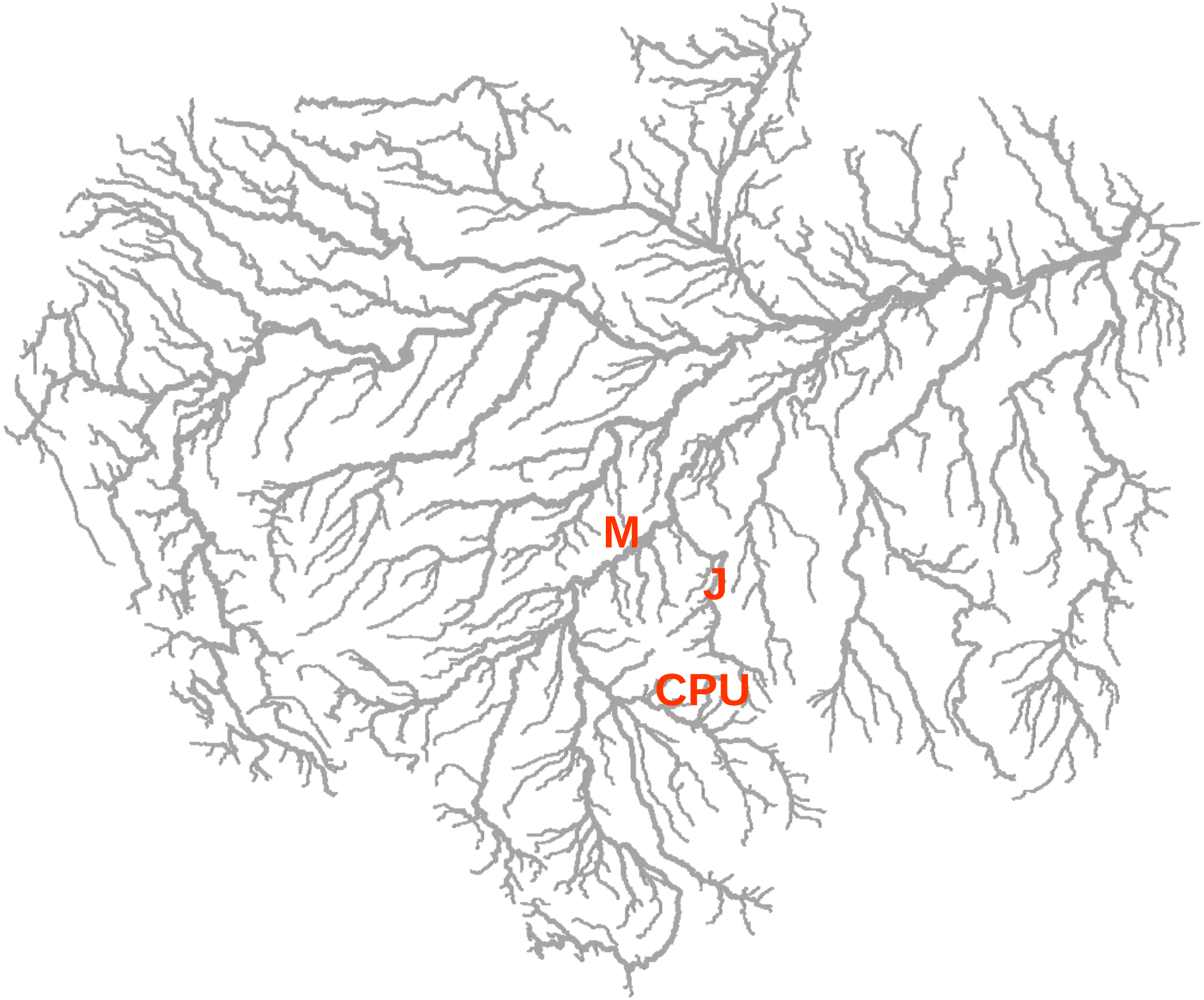
Composites from Mouths of Major Tributaries – what are seasonal and interannual patterns? Downscaling? Relations of parameters?



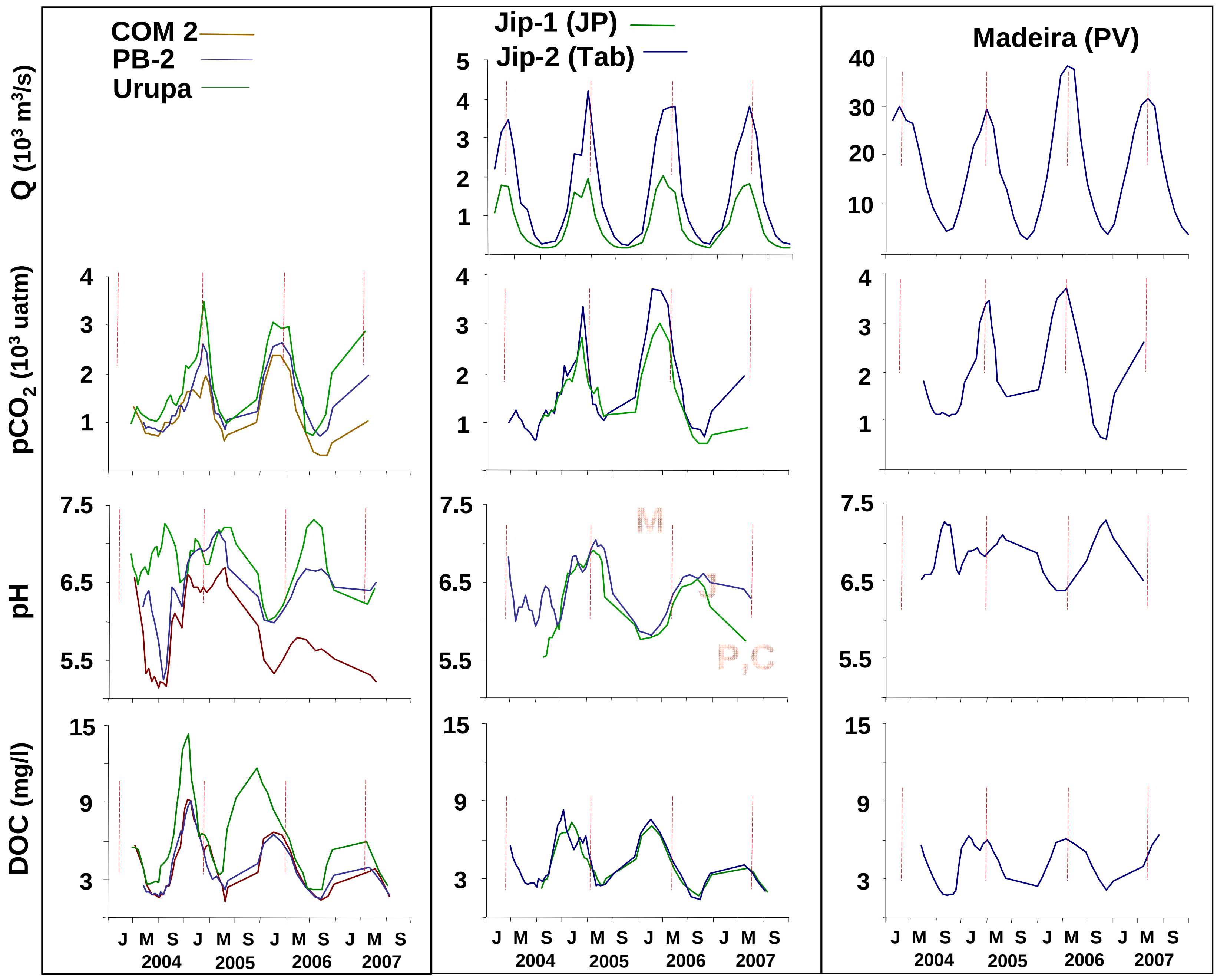
"Rede Beija Rio"
Education, Training, & Distributed Sampling



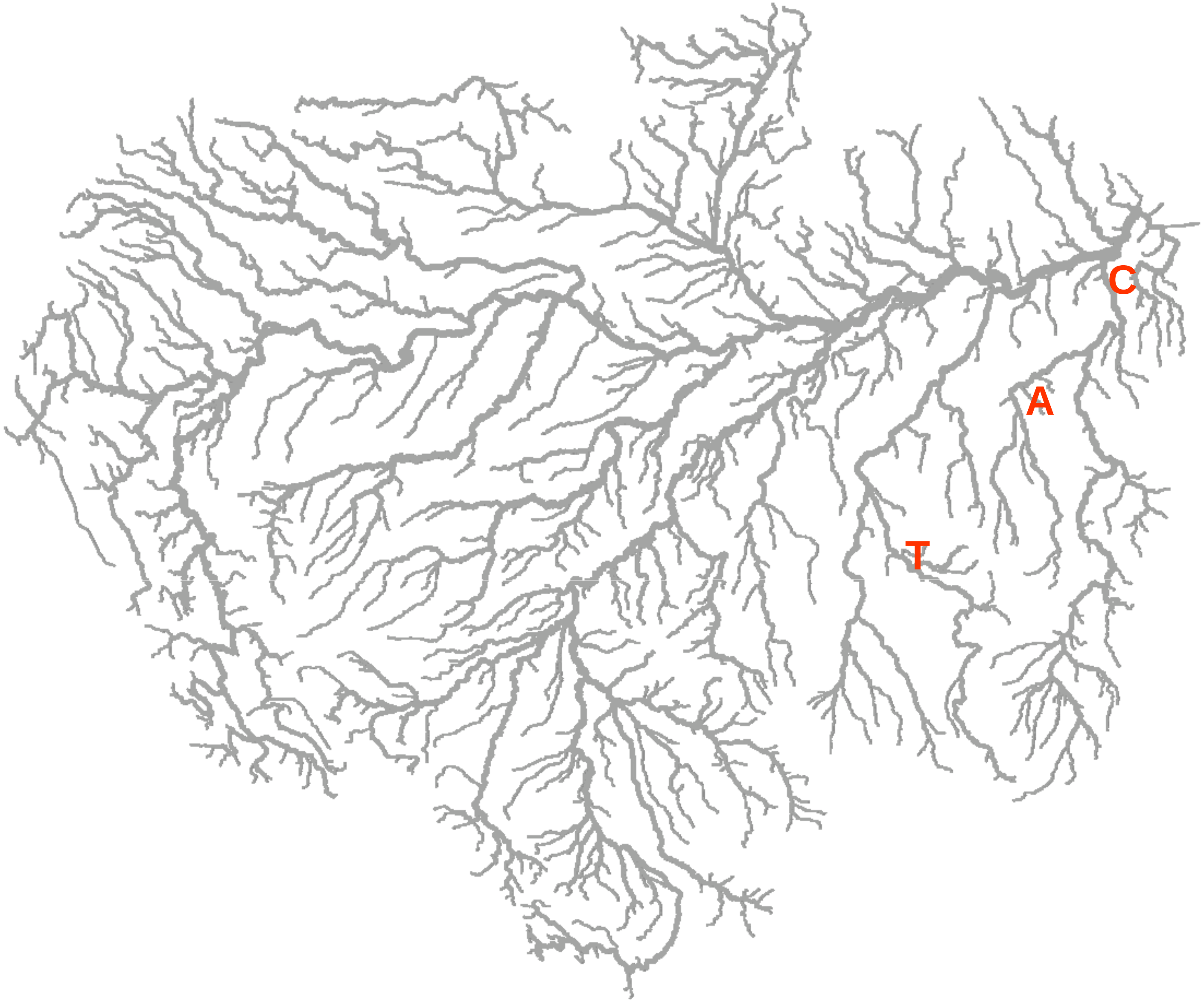
Space-Time Variance in pCO2 (relative to Q, pH, DOC)



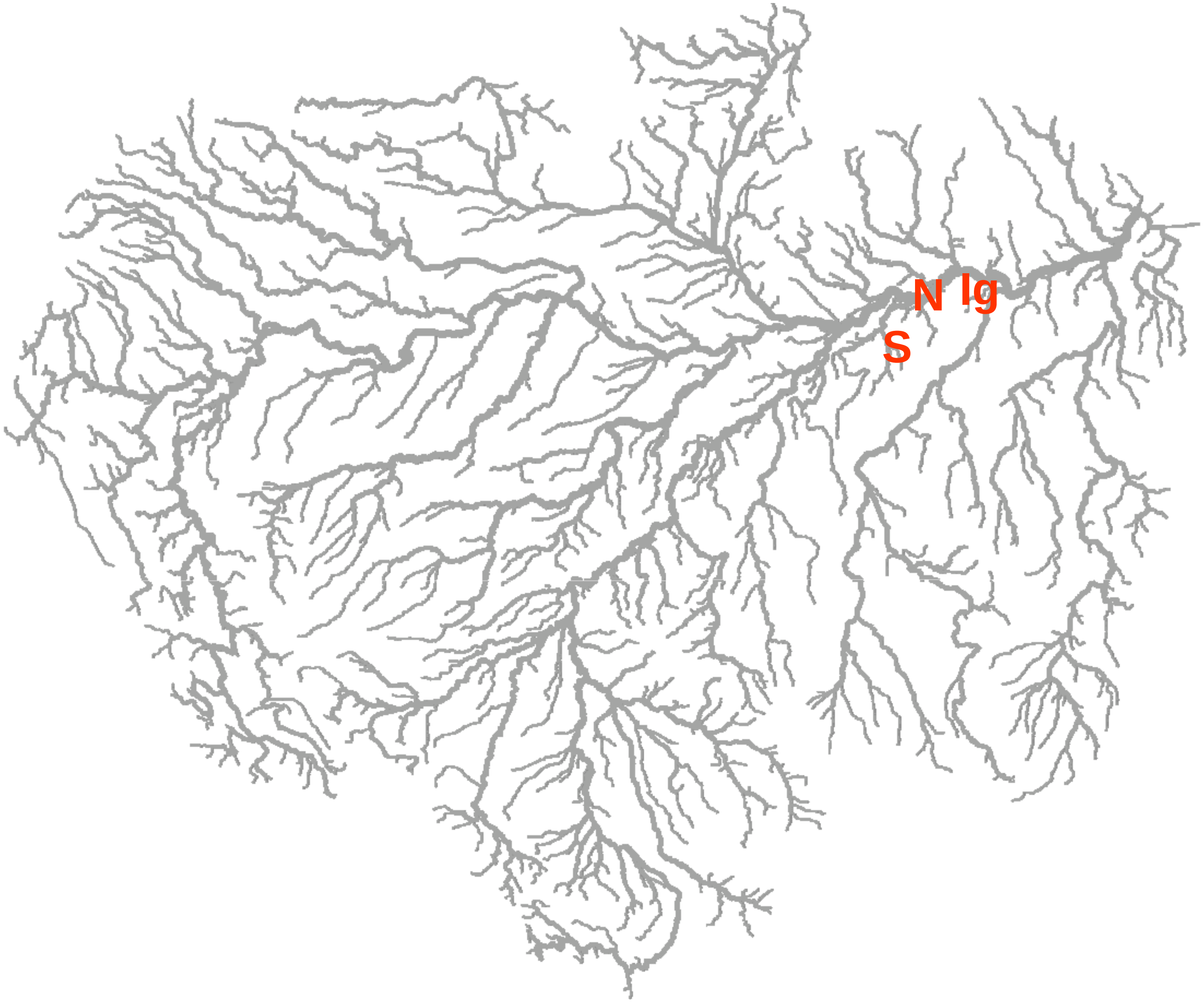
Rede Beija Rio in prep



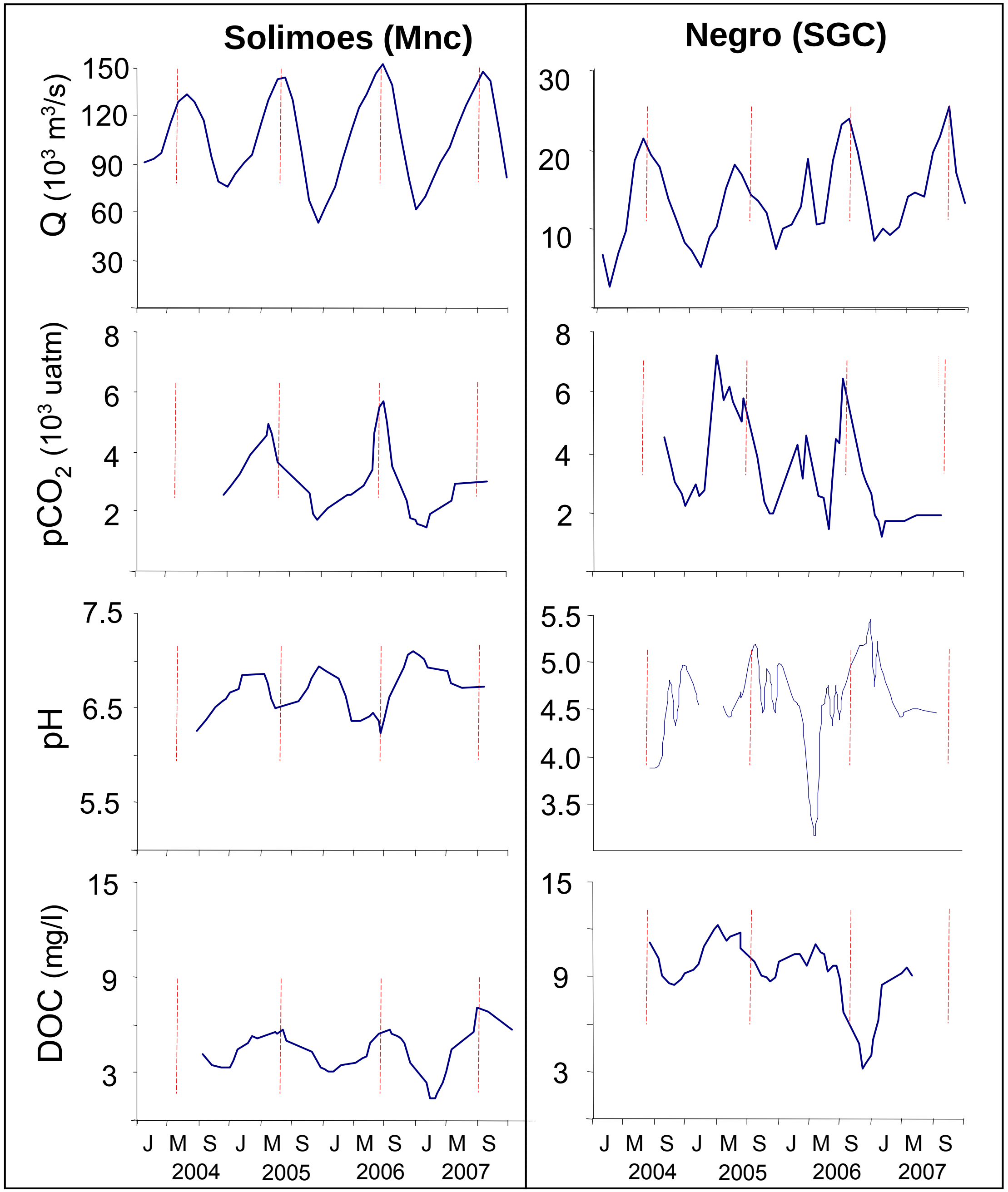
COM 2
PB-2
Urupa
Jip-1 (JP)
Jip-2 (Tab)
Madeira (PV)
Q (10^3 m³/s)
pCO2 (10^3 uatm)
pH
DOC (mg/l)
M
J
P,C
J M S J M S J M S J M S
2004 2005 2006 2007



***Rede Beija Rio* in prep**



Rede Beija Rio in prep



Solimoes (Mnc)
Negro (SGC)
Q (10^3 m^3/s)
150
120
90
60
30
30
20
10
pCO$_2$ (10^3 uatm)
8
6
4
2
pH
7.5
6.5
5.5
5.5
5.0
4.5
4.0
3.5
DOC (mg/l)
15
9
3
J M S J M S J M S J M S
2004 2005 2006 2007

Gas Transfer Velocity

$$F_{CO2} = \boldsymbol{k}\, s\, (pCO_{2(water)} - pCO_{2\,(air)})$$

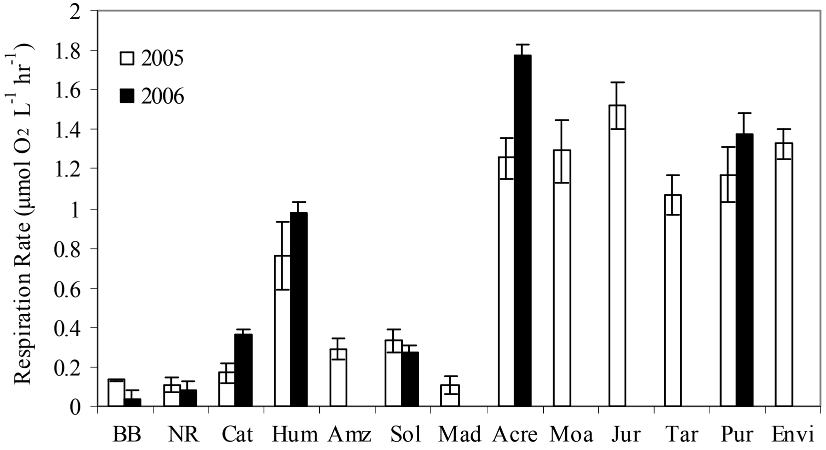
where:

k = gas transfer or piston velocity (cm hr^{-1})

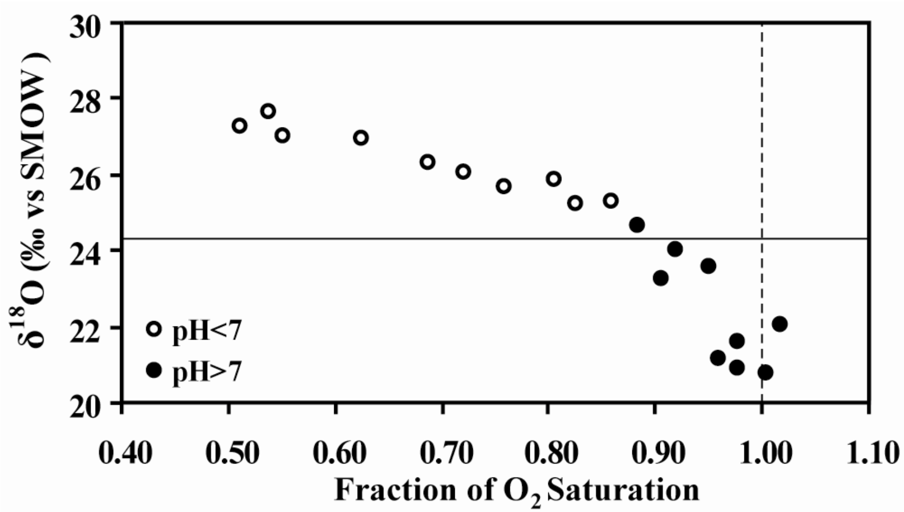
s = solubility of CO_2

RIVER METABOLISM IN AMAZON WATERS

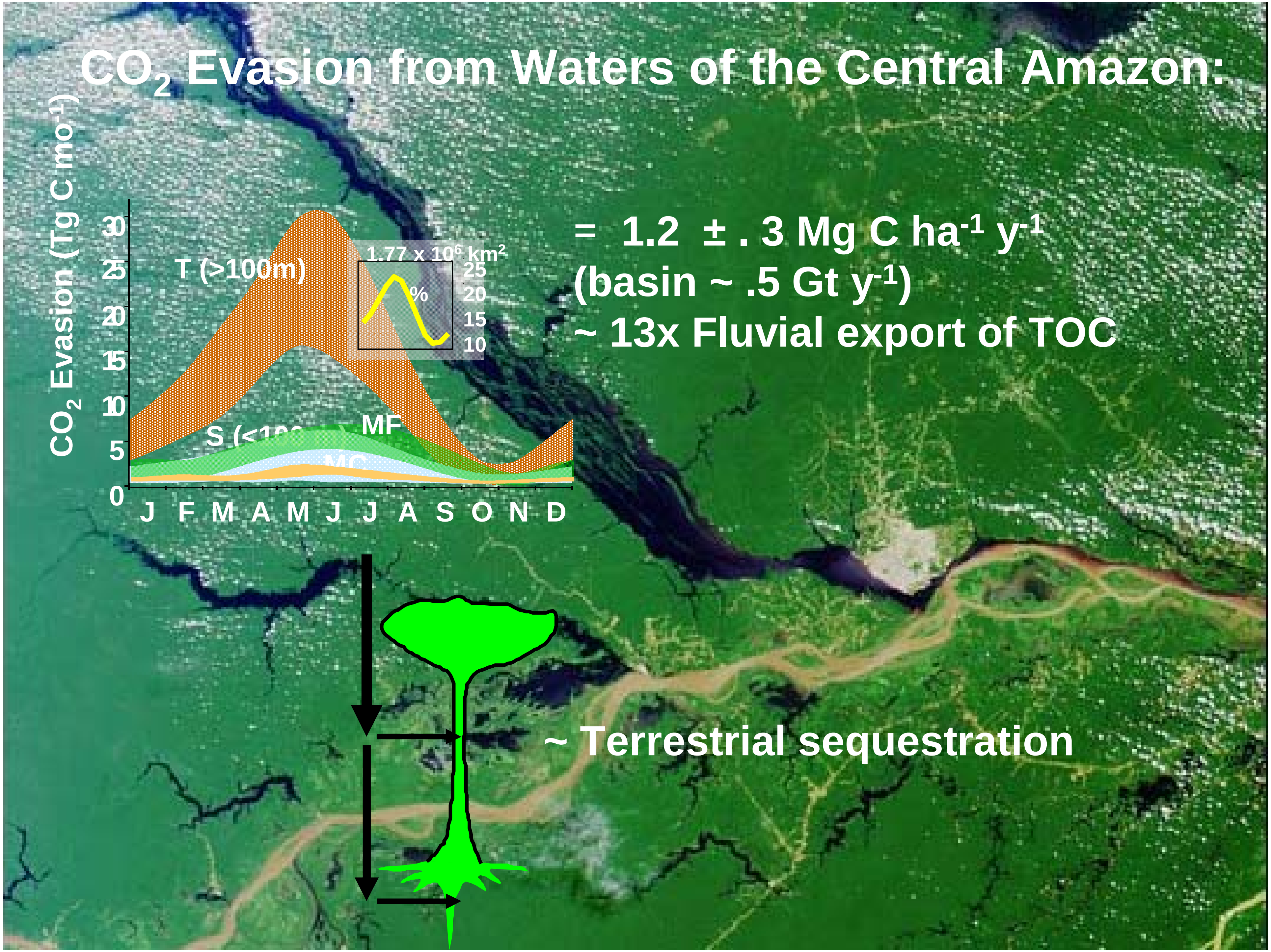
Respiration rates



$\delta^{18}O$ vs O_2 saturation



Respiration dominates over photosynthesis when $\delta^{18}O$ values are greater than 24.2‰ and are undersaturated, whereas photosynthesis dominates over respiration when $\delta^{18}O$ values are less than 24.2‰ and the fraction of oxygen saturation is greater than 1


CO2 Evasion from Waters of the Central Amazon:
= 1.2 ± . 3 Mg C ha-1 y-1
(basin ~ .5 Gt y-1)
~ 13x Fluvial export of TOC
~ Terrestrial sequestration
CO2 Evasion (Tg C mo-1)
30
25
20
15
10
5
0
J F M A M J J A S O N D
T (>100m)
MF
1.77 x 10^6 km^2
%
25
20
15
10

•Patterns of Hydrograph/pCO_2/pH/DOC exhibits a high degree of “environmental coherence” across scales, from seeps to big rivers; likely differentiated by local/regional landscapes

•Original outgassing estimate seems conservative (implications)

•How to dial in to overall basin Carbon budget – is the land/water coupling and fluvial system ‘de-coupled” to some extent from the upland, and how do you “count” it?

• Óbidos does *not* represent the definitive freshwater endmember to the Atlantic; relevant dynamics occur below

•*Think of “Amazon Ecosystem” as coupled watershed & plume*


Any questions?
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STANFORD
TRACK & FIELD
09.11.2004 23:52