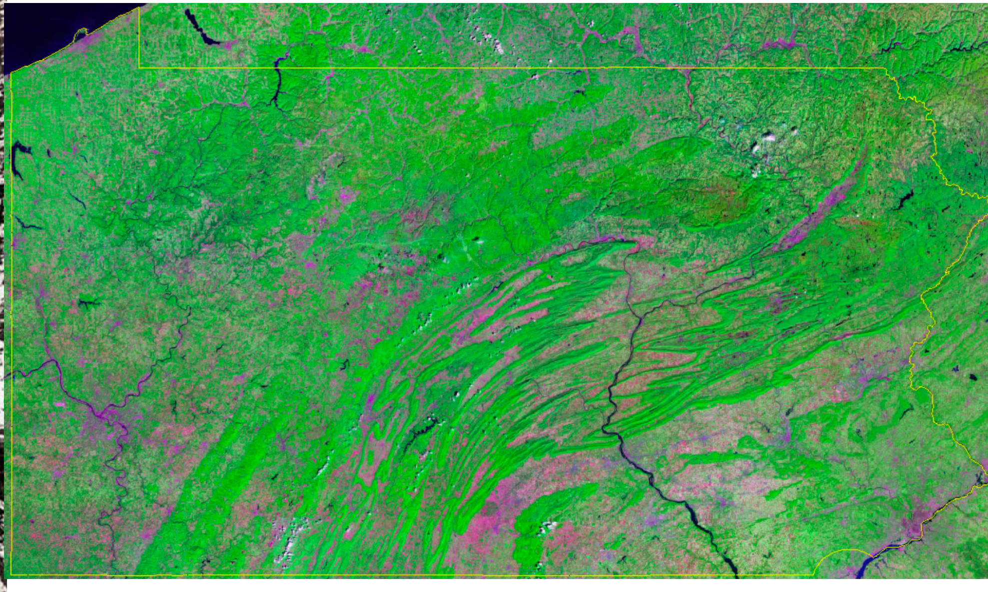
National CZO Program

http://criticalzone.org

Critical Zone science – A *transdisciplinary* approach to Earth surface and environmental science

Tim White
Earth and Environmental Systems Institute
The Pennsylvania State University

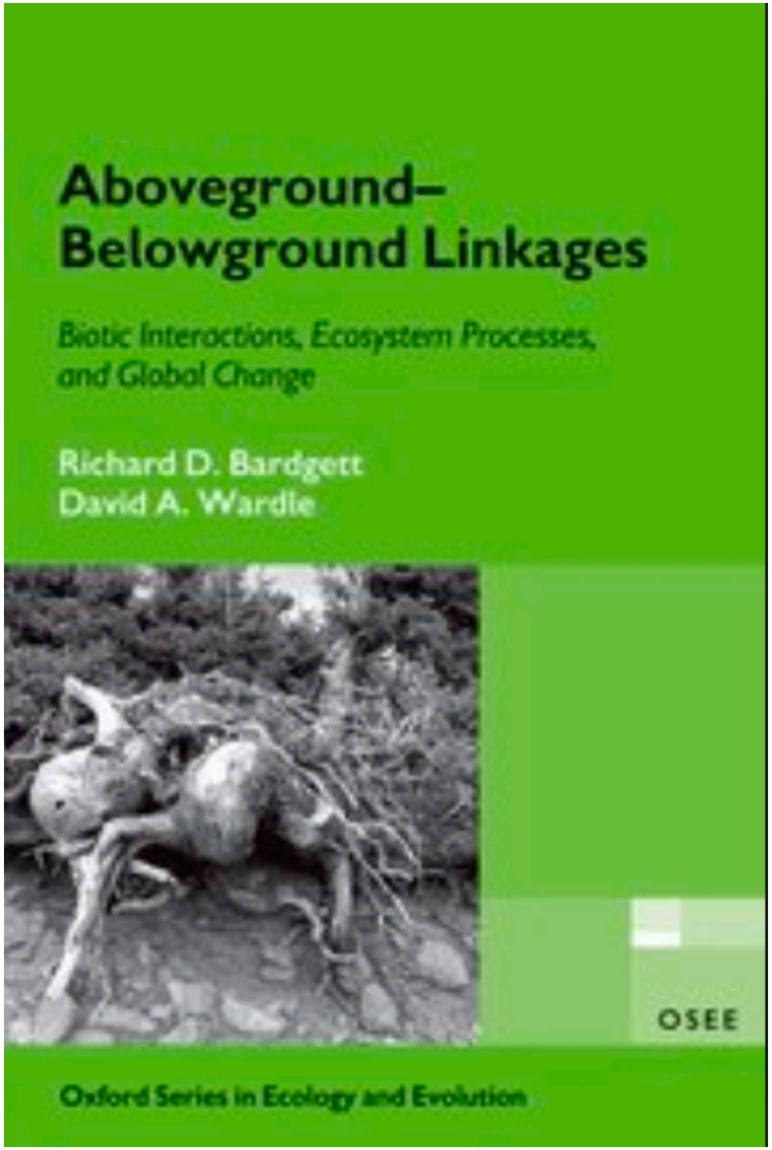
The history of humanity's relationship with varied landscapes and ecosystems has waxed and waned through the ages often in synch with the needs and mores of dominating cultures and industries.



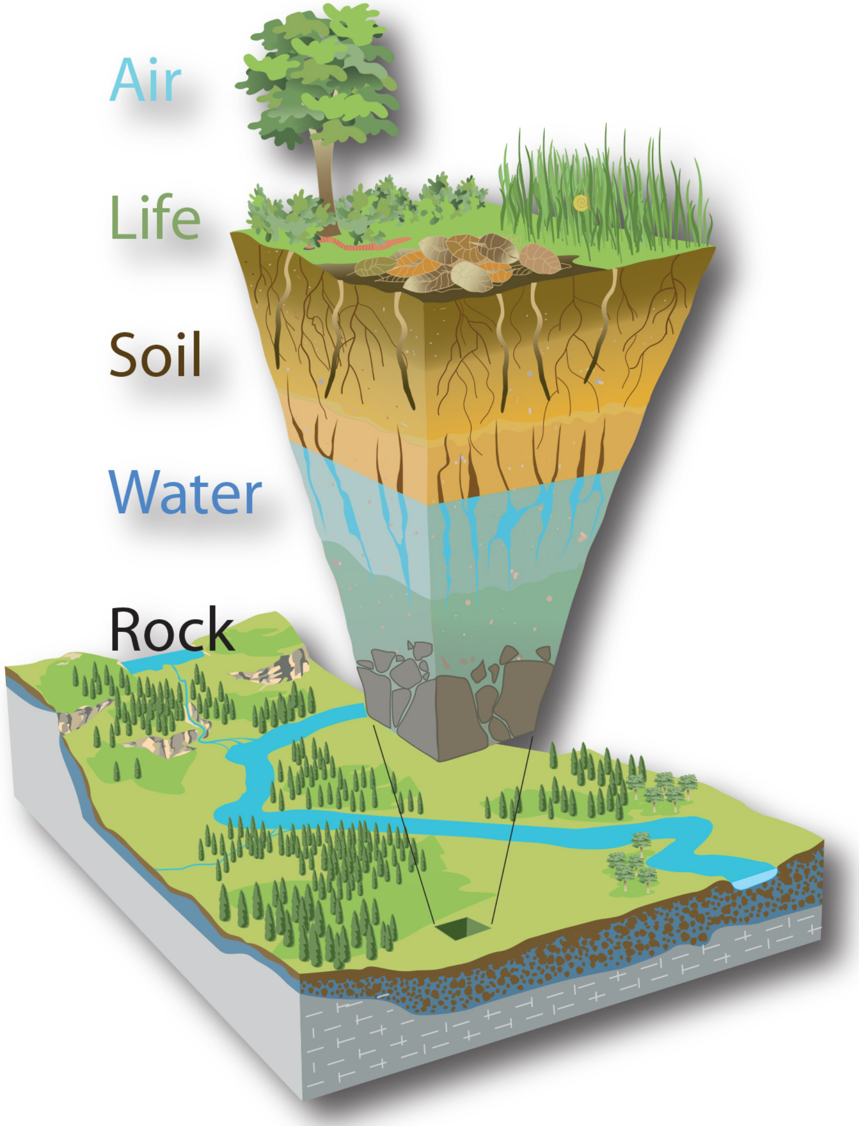
During the 20th century, scientists began to more formally consider the complex relationships between life and the environment.

- Tansley (1935) coined the term “ecosystem” and described the intimate link between **organisms and their abiotic environment**
- Bardgett and Wardle (2012)
- Richter and Billings (2015)
- wonderful reviews and consideration of other early scientists work in understanding biotic-abiotic relationships.

- Integrated approaches were stifled by subdivision of terrestrial ecosystem science into aboveground and belowground realms
- But, the concept that interactions *between* aboveground- and belowground-organisms and their abiotic environment is again accepted.



Now a diverse array of Earth surface and environmental scientists are considering the Critical Zone – “where rock meets life” – the next evolutionary step in defining humanity’s relationship to and understanding of the terrestrial Earth.



Biogeosciences, 15, 4815–4832, 2018
https://doi.org/10.5194/bg-15-4815-2018

Biogeosciences
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Ideas and perspectives: Strengthening the biogeosciences in environmental research networks

Daniel D. Richter[1], Sharon A. Billings[2], Peter M. Groffman[3], Eugene F. Kelly[4], Kathleen A. Lohse[5], William H. McDowell[6], Timothy S. White[7], Suzanne Anderson[8], Dennis D. Baldocchi[9], Steve Banwart[10], Susan Brantley[11], Jean J. Braun[12], Zachary S. Brecheisen[1], Charles W. Cook[1], Hilairy E. Hartnett[13], Sarah E. Hobbie[14], Jerome Gaillardet[15], Esteban Jobbagy[16], Hermann F. Jungkunst[17], Clare E. Kazanski[18], Jagdish Krishnaswamy[19], Daniel Markewitz[20], Katherine O'Neill[21], Clifford S. Riebe[22], Paul Schroeder[23], Christina Siebe[24], Whendee L. Silver[25], Aaron Thompson[26], Anne Verhoef[27], and Ganlin Zhang[28]

Critical Zone science and CZ Observatories

Critical Zone – What is it?

- Why is it critical?
- What is CZ science?
- What is a CZ Observatory?

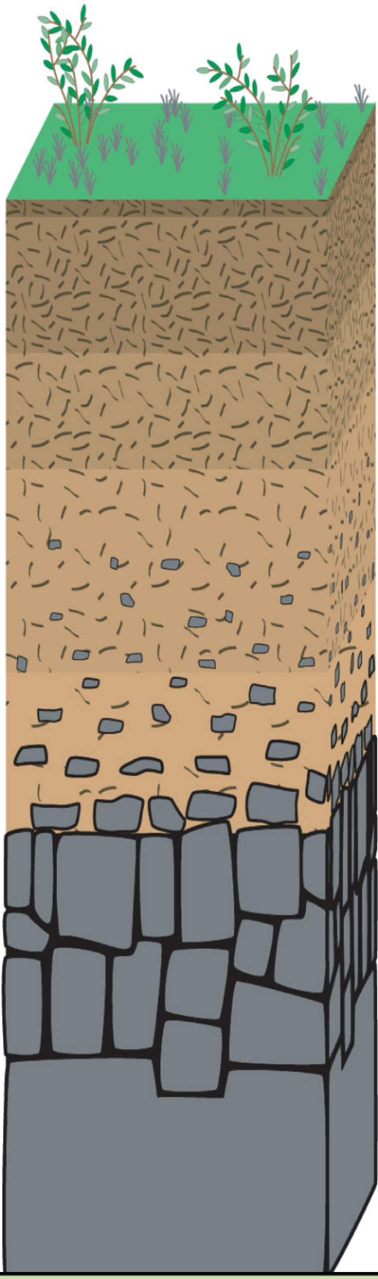
Critical Zone:

• Term published in 1999 GSA abs. by Gail Ashley (Rutgers U. geologist), and more formally by US NRC in 2001 BROES report.

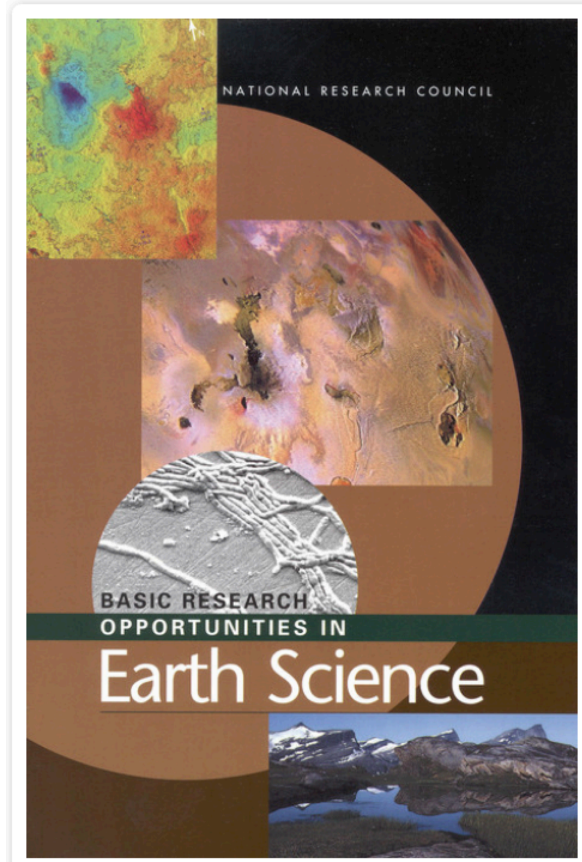
= Thin veneer at Earth’s surface spanning from the top of vegetation canopy through soil to the bottom of fresh groundwater zone.

• Where “rock meets life”, and most terrestrial life exists and depends upon.

• **Critical Zone –versus- critical zones?**



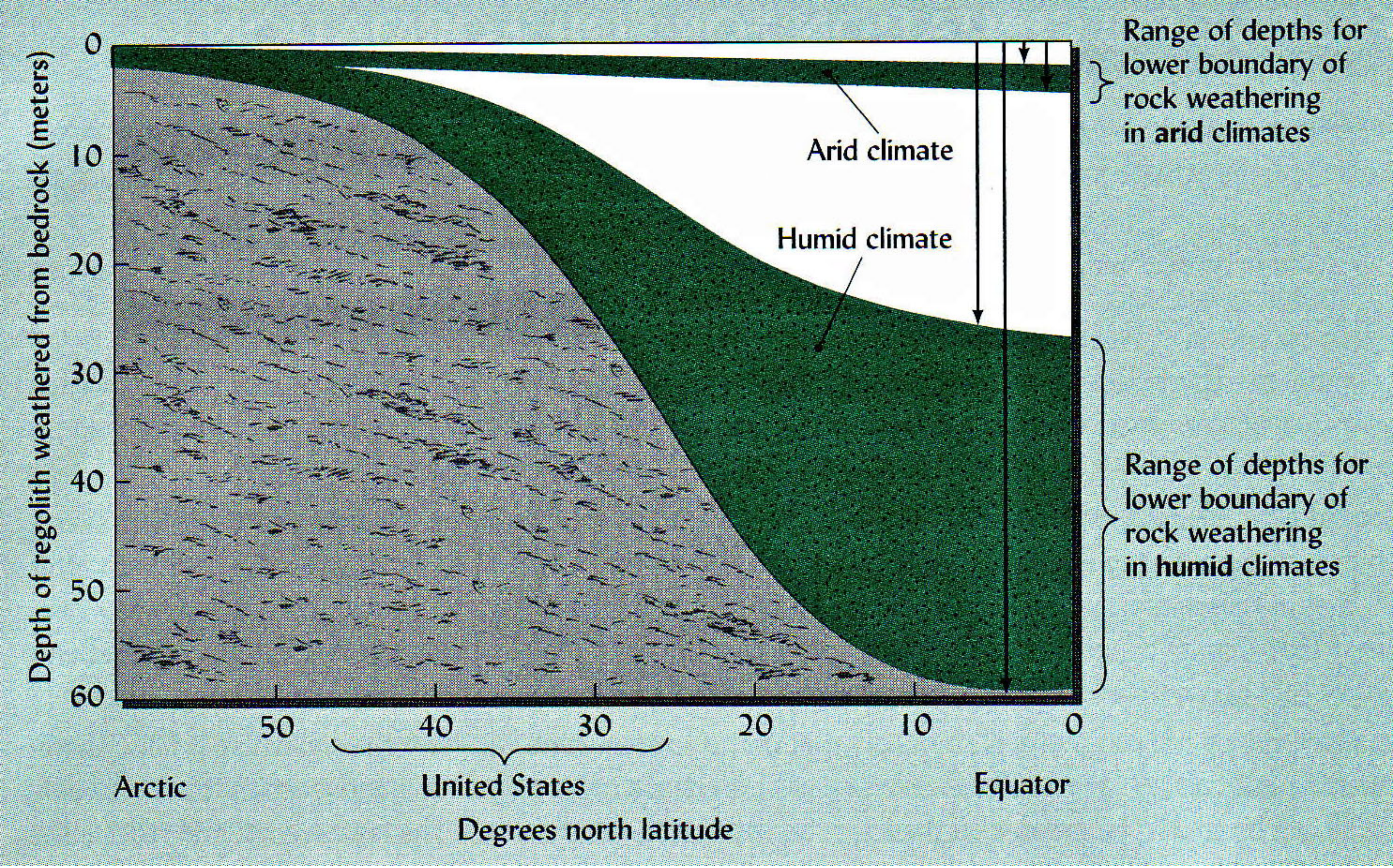
U.S National Research Council report: Basic Research Opportunities in the Earth Sciences



The Critical Zone: Earth’s near surface environment

Free download:
Google US NRC BROES

www.nap.edu/catalog/9981/basic-research-opportunities-in-earth-science



From Brady and Weil, 2008, The nature and property of soils

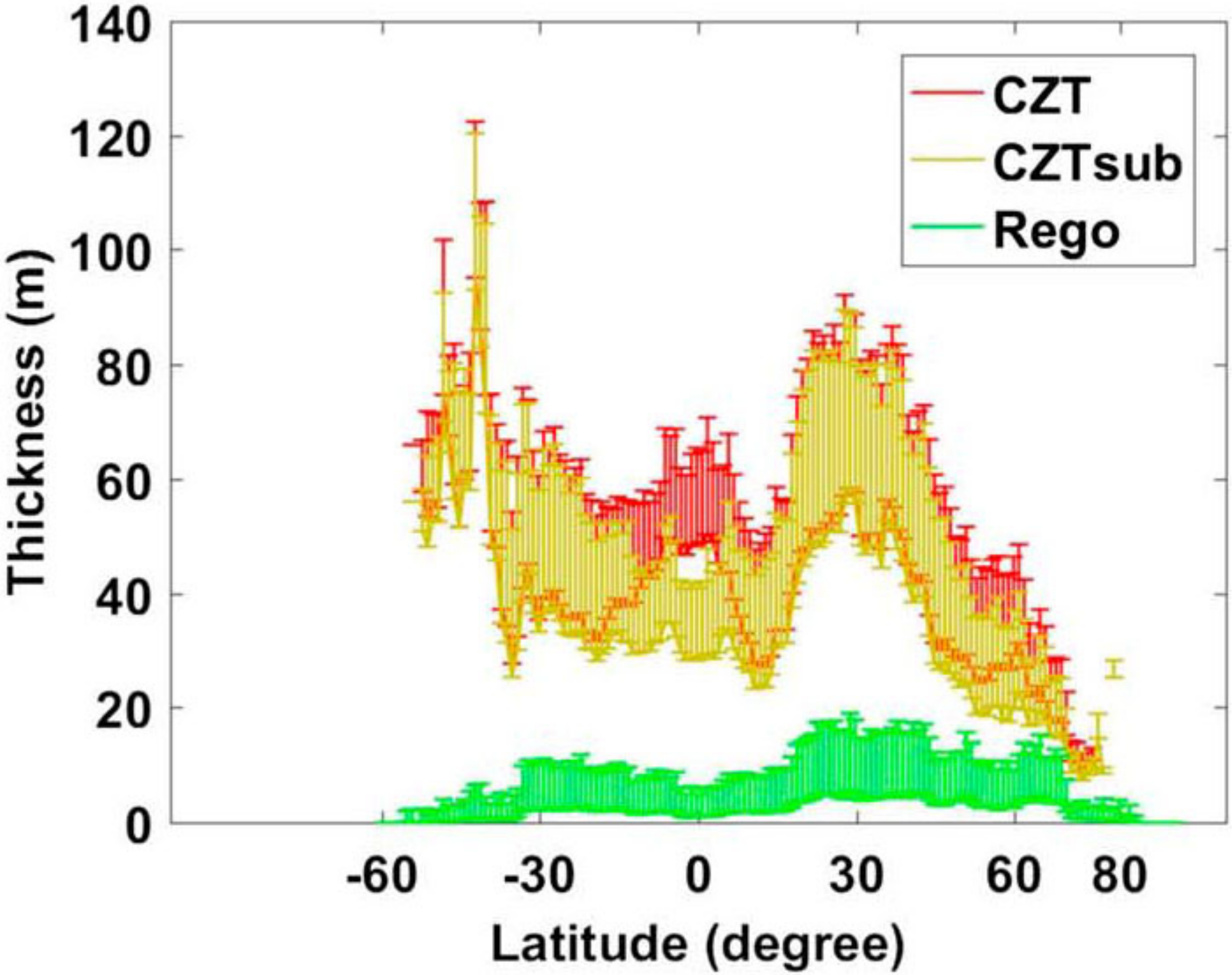
Tropical rainforest:

- Extensive forest canopy w/ complex understory
- Thick mature soils and deep weathered regolith
- Potentially deep aquifers

Polar realm:

- Stunted vegetation
- Glaciers and their debris
- Bare bedrock
- Thin discontinuous soils
- Permafrost

Longyearbyen Valley,
Spitsbergen

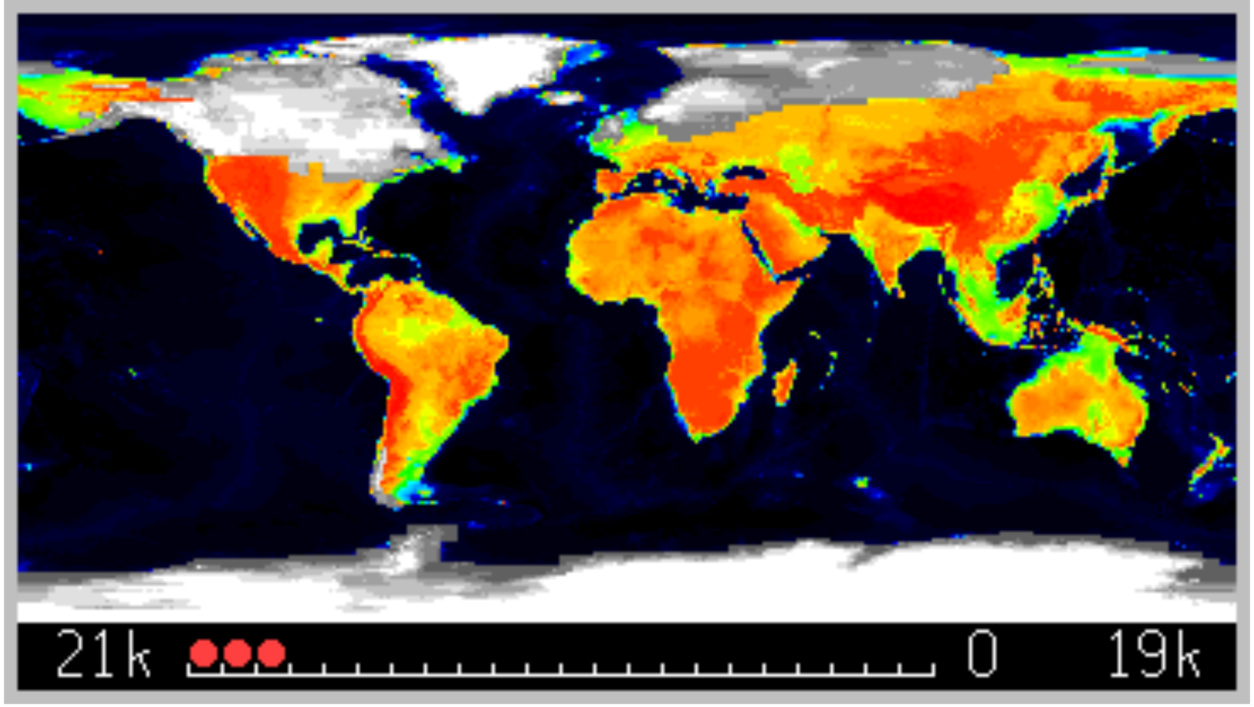


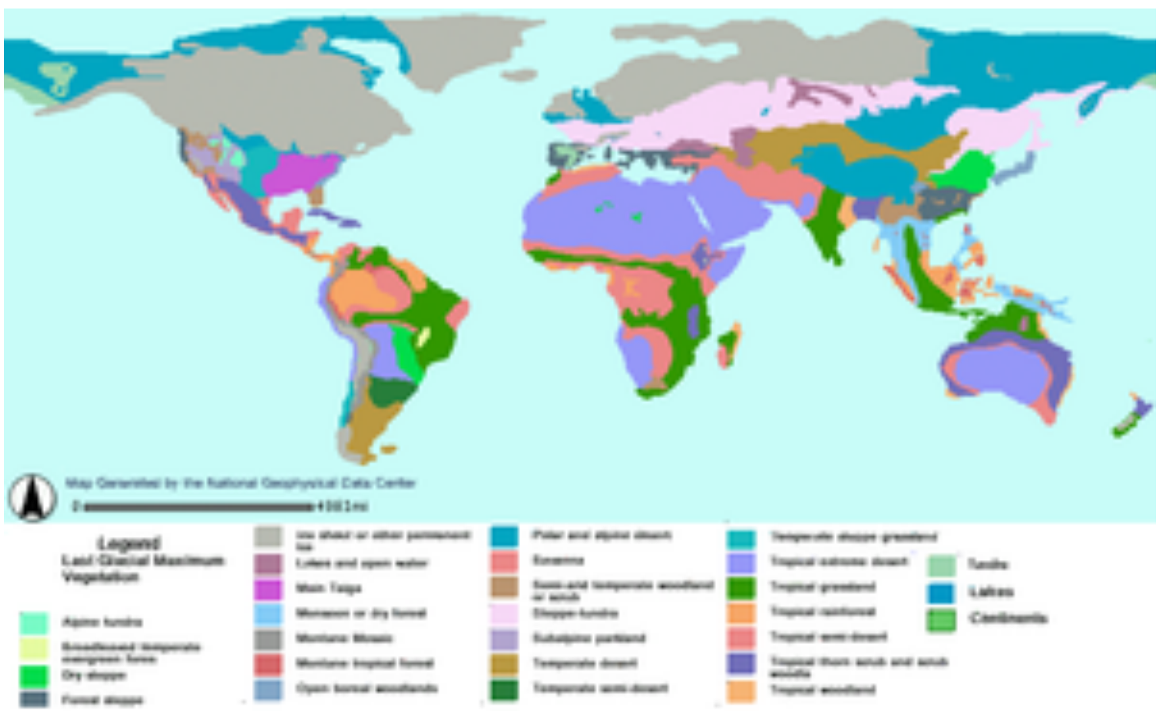
Thickness (m):

- global ave 36.8 (0.7-223.5)
- vegetation 5.6 (0-59.9)
- GW depth 24.9 (0-219.6)
- GW zone 6.7 (0-143.3)

On average,
above ground ~20%,
belowground ~80%.

Xu and Liu, 2017, The global distribution of Earth's critical zone and its controlling factors, Geophys. Res. Letters





Thickest CZ in mid latitudes – WHY?

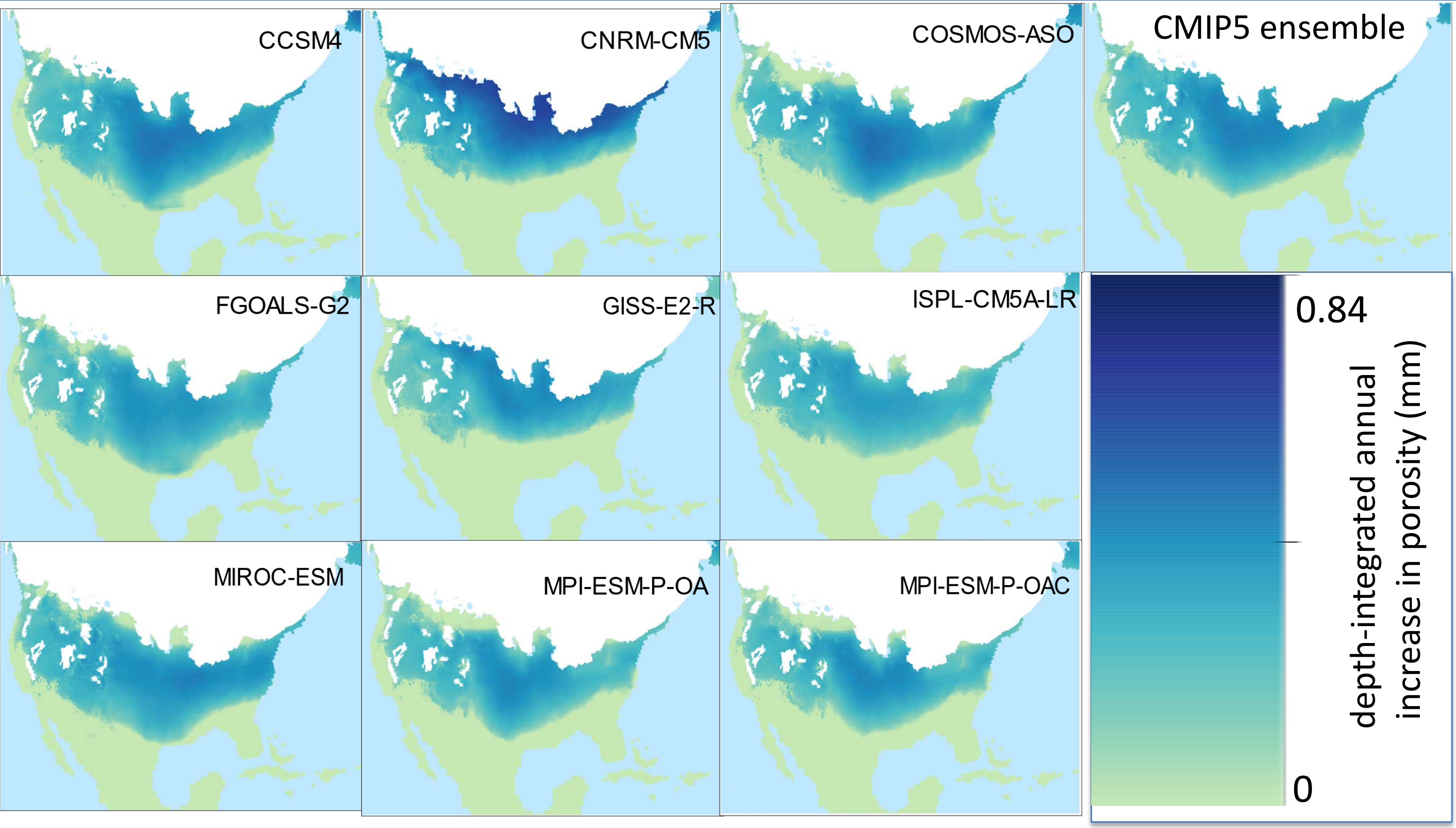
PALEOCLIMATE!? DEEP TIME PERSPECTIVE

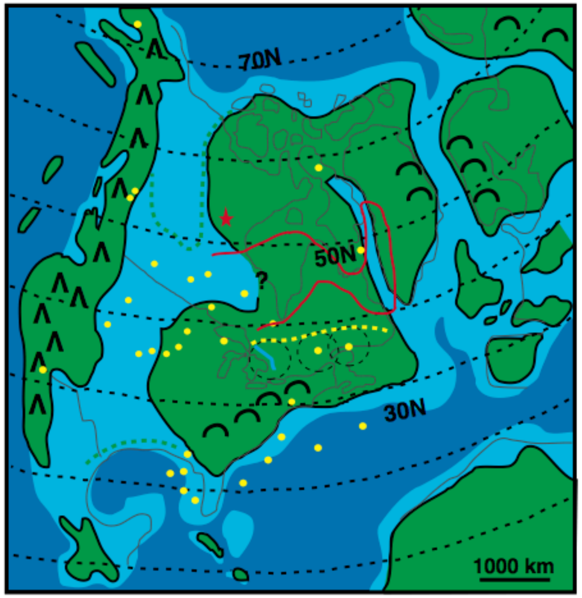
Poleward, continental glaciers periodically scrape away weathered rock and redistribute to mid latitudes

But also……..

All models predict extensive frost cracking 21 ka in unglaciated lands

Downscaled paleo climate simulations (10 km) and frost cracking model





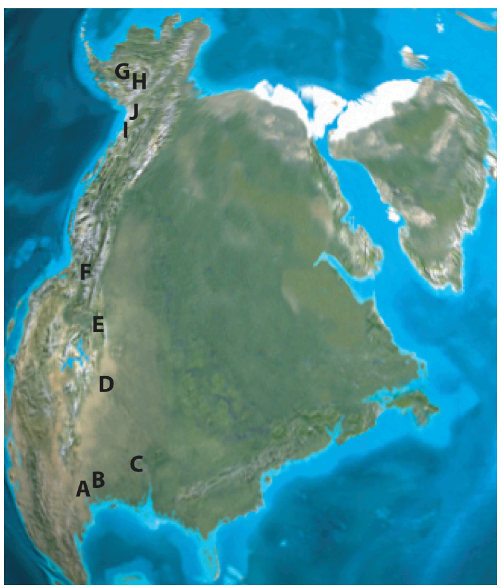
Mid to Late Albian Highstand Paleogeography of North America (Kiowa-Skull Creek Cycle; 98-106 Ma)

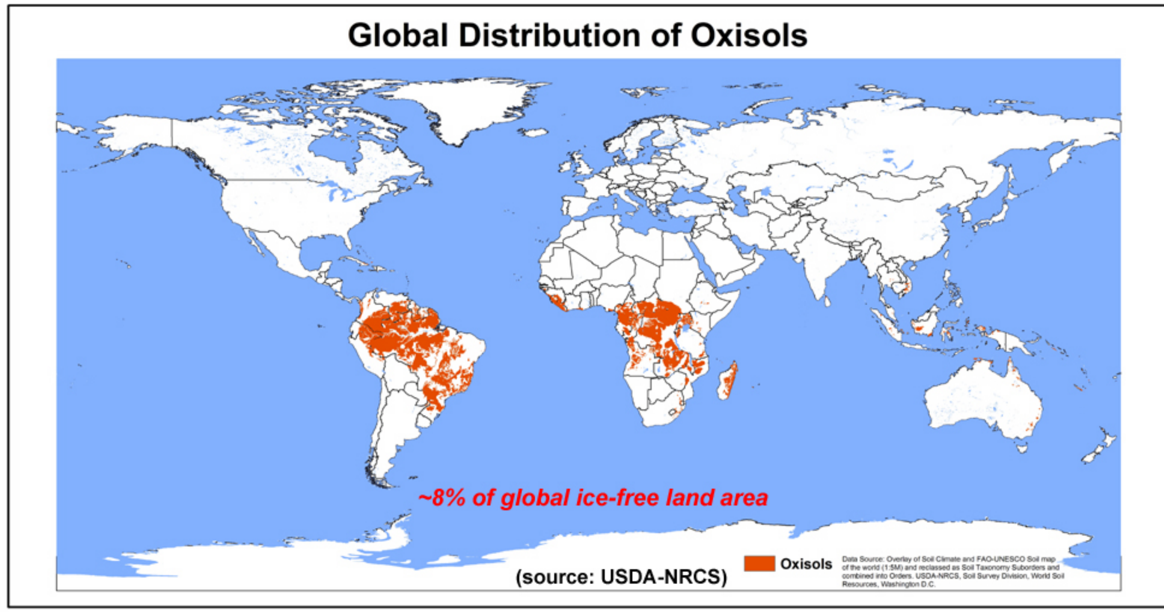
= lowstand seaway extent

= known kaolin paleosol locales

= southern shoreline of Hudson Arm

= 250-km radius circle estimating distance to marine environs





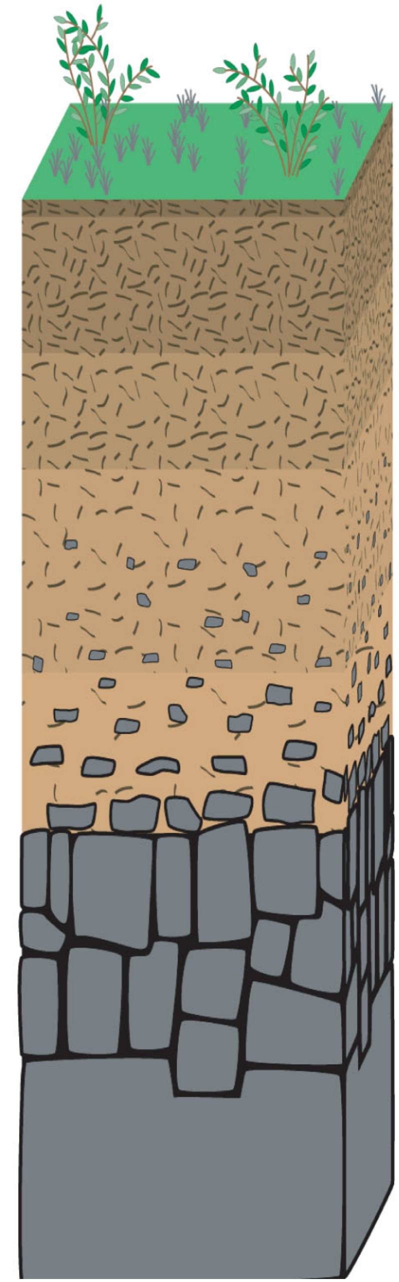
Early Eocene North America (~50 Mya)

Societal relevance: Why “critical”?

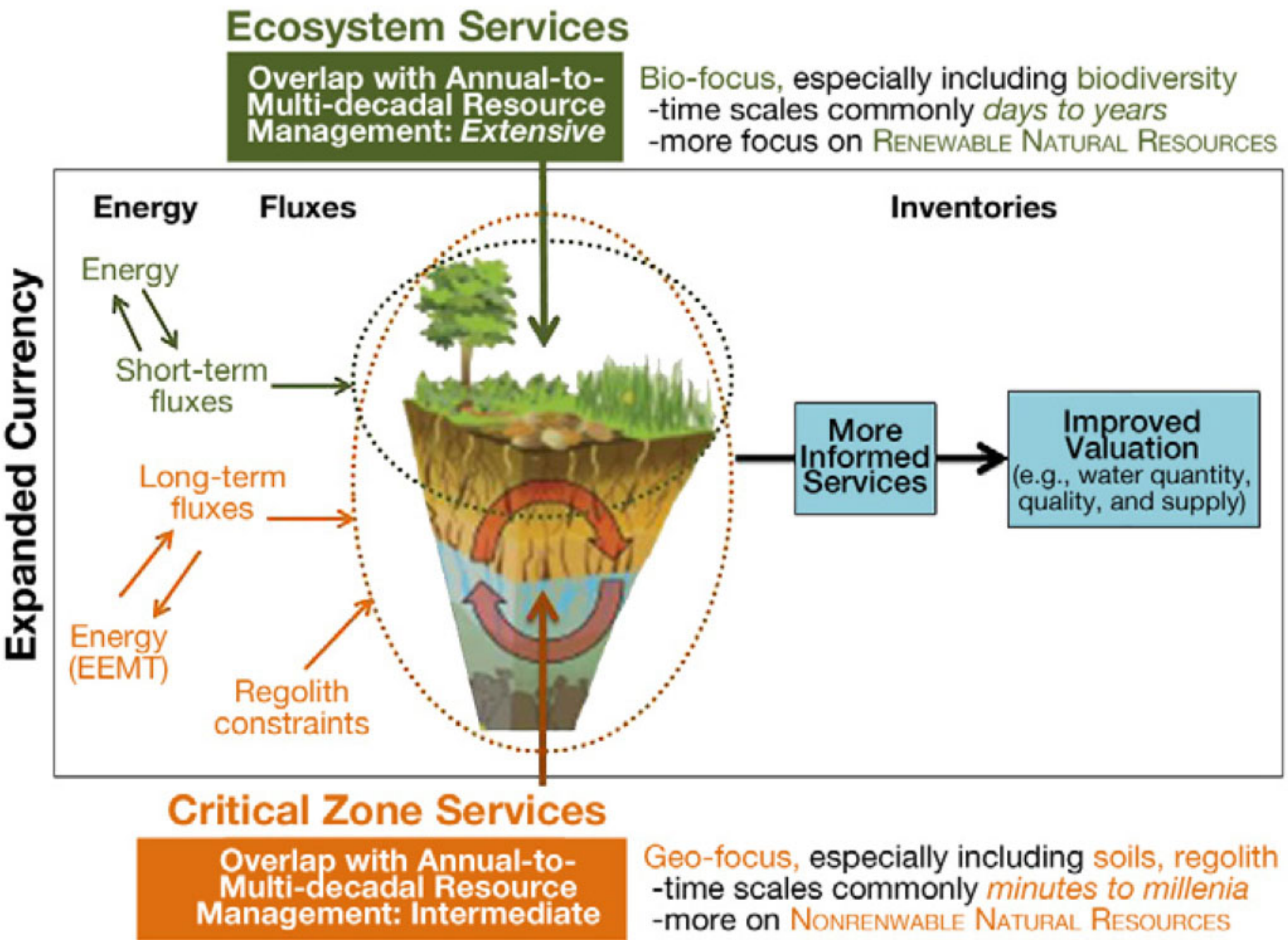
The zone within which most terrestrial life exists and depends on, for:

- solid substrate we live on
- food and fiber
- water and nutrients
- biodiversity

Ongoing climate and land use changes to the zone may stress terrestrial life including humanity – thus a better understanding of CZ processes and function may aid adaptation to change.



Why Critical? Provides services! The CZ perspective extends <u>context</u> of ecosystem services by addressing how CZ structure provides a broader spatial and temporal template that determines coevolution of physical and biological systems that result in societal benefits.

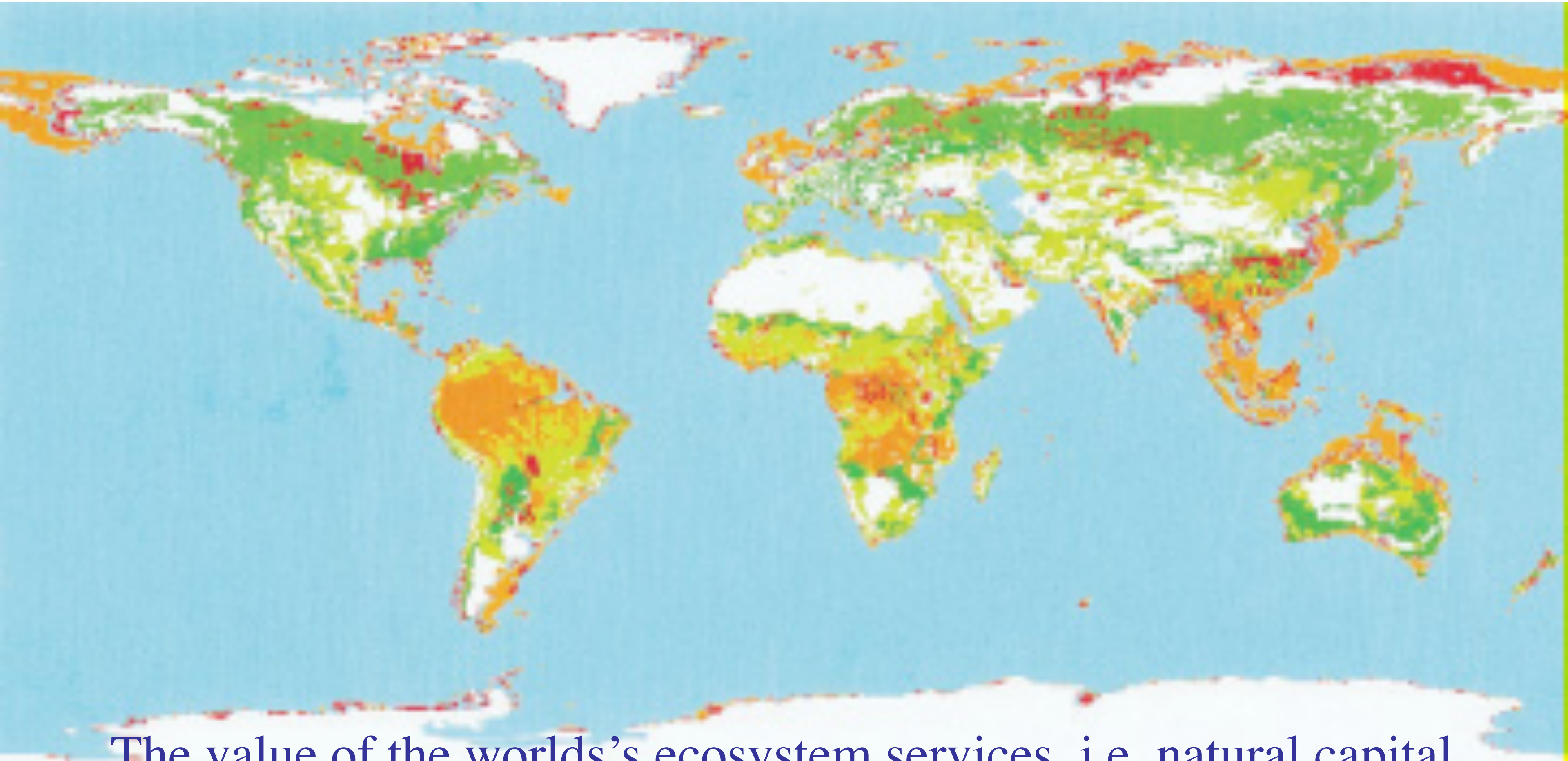


***Rates at which ecosystem services are provided are <u>constrained</u> by rate-limited CZ processes that are non-renewable on human life spans**

Field et al., 2015, Critical Zone Services: Expanding Context, Constraints, and Currencies beyond Ecosystem Services, Vadose Zone Journal

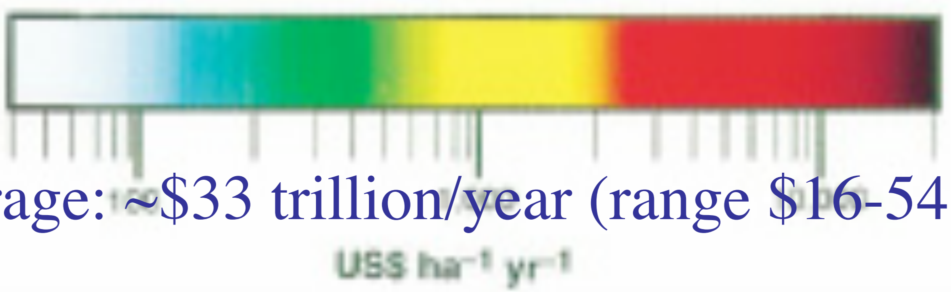

Ecosystem and Critical Zone Services
* Pollination
* Fulfillment of cultural, spiritual/intellectual needs
* Regulation of climate
* Insect pest control
* Maintenance and provision of genetic resources
* Maintenance and regeneration of habitat
* Provision of shade and shelter
* Prevention of soil erosion
* Maintenance of soil fertility
* Maintenance of soil health
* Maintenance of healthy waterways
* Water filtration
* Regulation of river flows and groundwater levels
*Waste absorption and breakdown
If we allow natural assets to decline, so do the benefits.
But if we care for and maintain natural assets, we reap greater returns.

Why Critical? Because it is threatened by human activity……

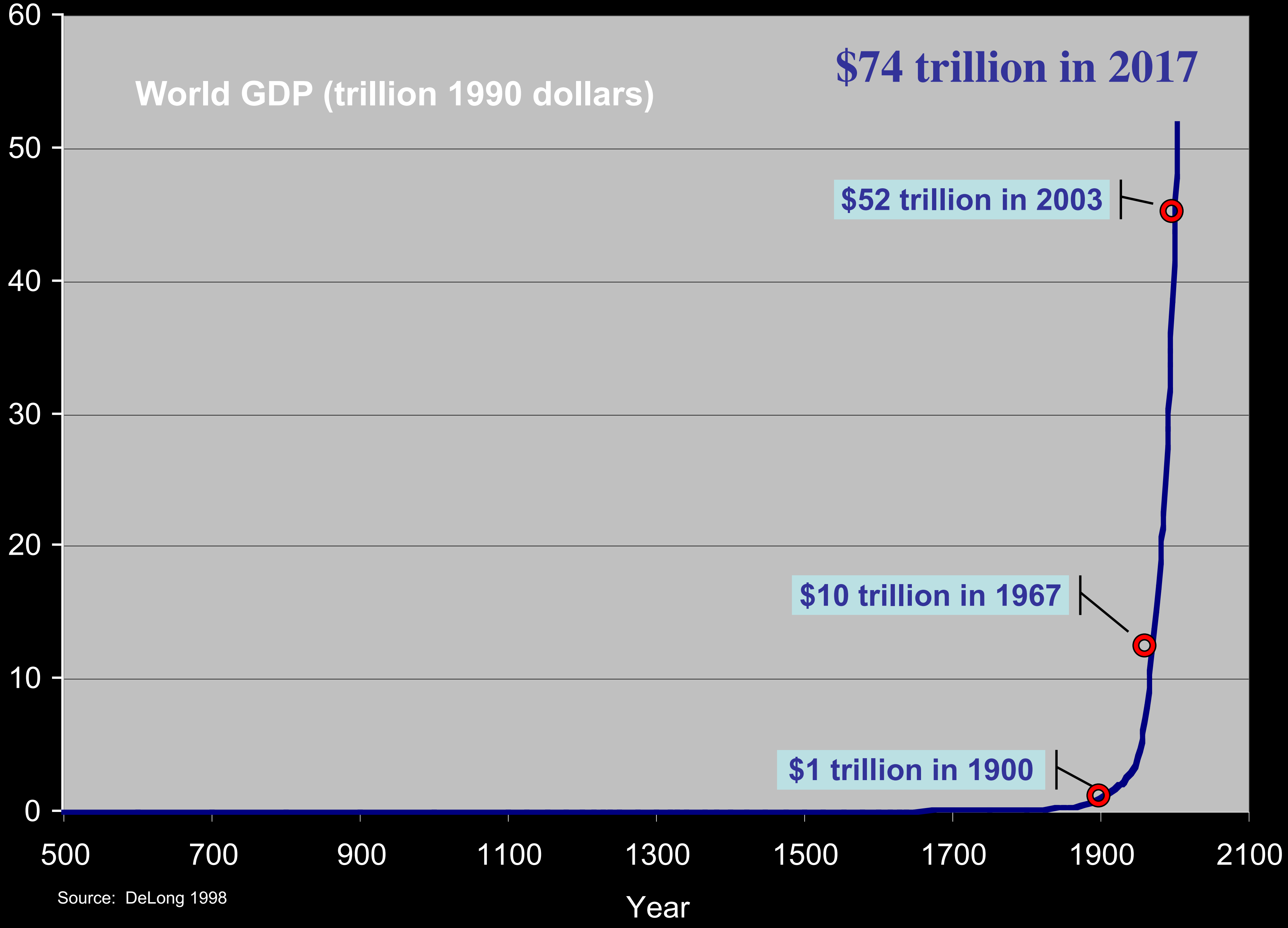


The value of the worlds's ecosystem services, i.e. natural capital

• Costanza et al., 1997, Nature, 387, 253-260.



Average: ~$33 trillion/year (range $16-54 t/y)


World GDP (trillion 1990 dollars)
$74 trillion in 2017
$52 trillion in 2003
$10 trillion in 1967
$1 trillion in 1900
60
50
40
30
20
10
0
500
700
900
1100
1300
1500
1700
1900
2100
Year
Source: DeLong 1998

“Critical” because it is threatened by human activity

Global Environmental Change 26 (2014) 152–158

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Changes in the global value of ecosystem services

Robert Costanza[a,*], Rudolf de Groot[b], Paul Sutton[c,d], Sander van der Ploeg[b], Sharolyn J. Anderson[d], Ida Kubiszewski[a], Stephen Farber[e], R. Kerry Turner[f]

[a] Crawford School of Public Policy, Australian National University, Canberra, Australia
[b] Environmental Systems Analysis Group, Wageningen University, Wageningen, The Netherlands
[c] Department of Geography, University of Denver, United States

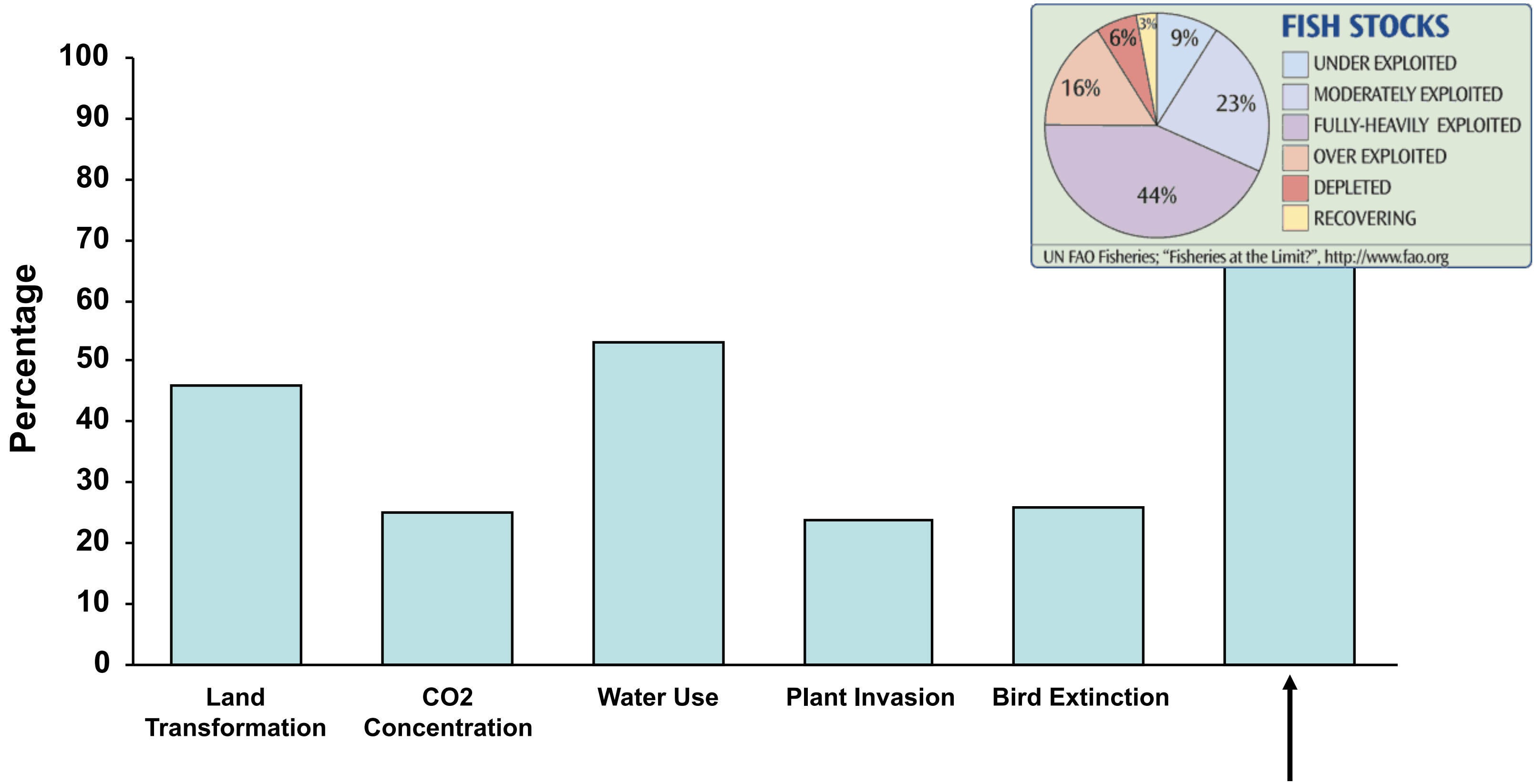
the estimate for the total global ecosystem services in 2011 is $125 trillion/yr (assuming updated unit values and changes to biome areas) and $145 trillion/yr (assuming only unit values changed), both in 2007 $US. From this we estimated the loss of eco-services from 1997 to 2011 due to land use change at $4.3–20.2 trillion/yr, depending on which unit values are used. Global estimates expressed in monetary

Received in revised form 18 February 2014
Accepted 1 April 2014

Keywords:
Ecosystem services
Global value
Monetary units
Natural capital

ecosystem service values and land use change estimates between 1997 and 2011. We also address some of the critiques of the 1997 paper. Using the same methods as in the 1997 paper but with updated data, the estimate for the total global ecosystem services in 2011 is $125 trillion/yr (assuming updated unit values and changes to biome areas) and $145 trillion/yr (assuming only unit values changed), both in 2007 $US. From this we estimated the loss of eco-services from 1997 to 2011 due to land use change at $4.3–20.2 trillion/yr, depending on which unit values are used. Global estimates expressed in monetary accounting units, such as this, are useful to highlight the magnitude of eco-services, but have no specific decision-making context. However, the underlying data and models can be applied at multiple scales to assess changes resulting from various scenarios and policies. We emphasize that valuation of eco-services (in whatever units) is not the same as commodification or privatization. Many eco-services are best considered public goods or common pool resources, so conventional markets are often not the best institutional frameworks to manage them. However, these services must be (and are being) valued, and we need new, common asset institutions to better take these values into account.

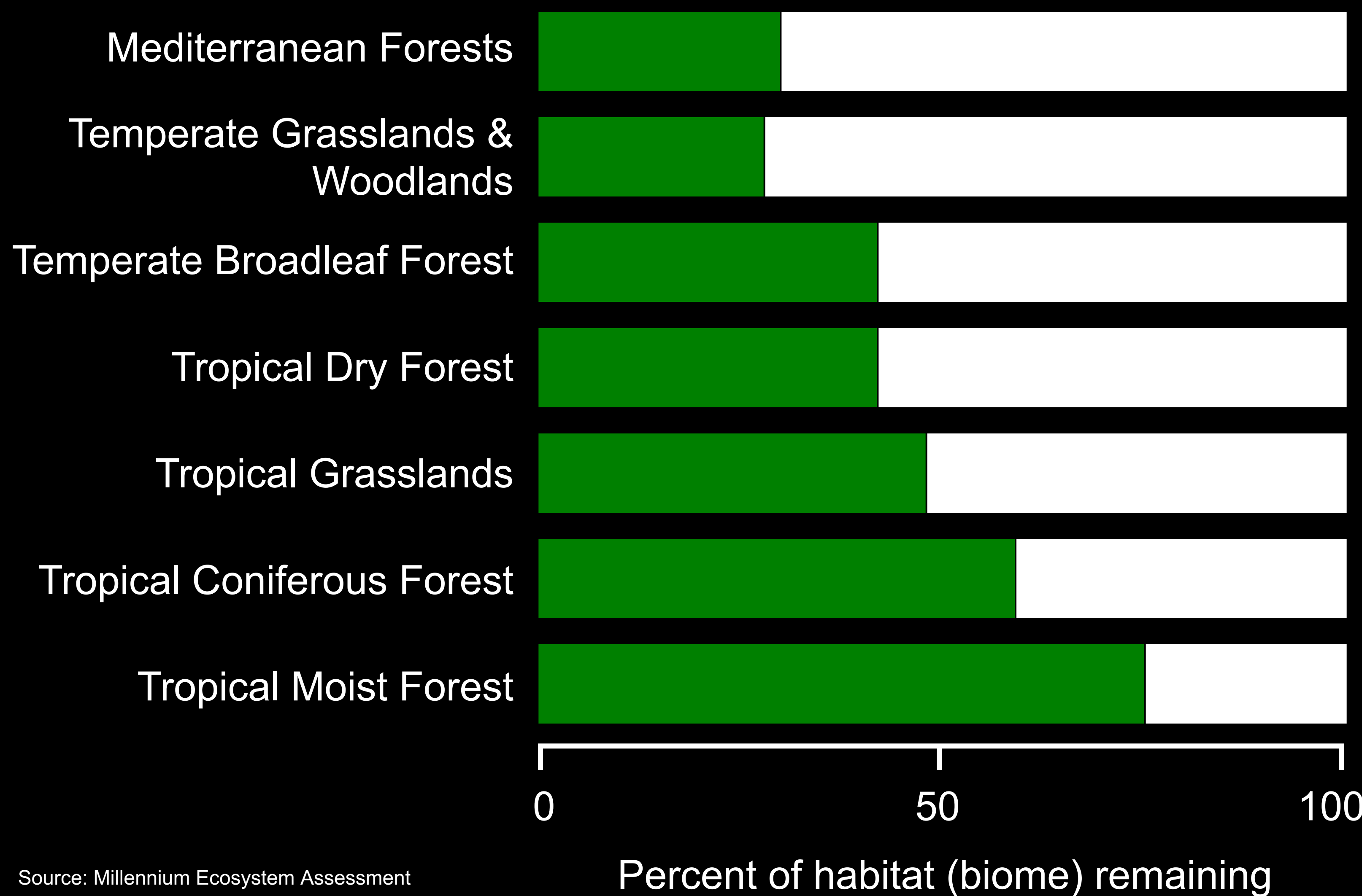
Human Dominance or Alteration of Several Major Components of the Earth System



Percentage of major marine fisheries that are fully exploited, overexploited, or depleted

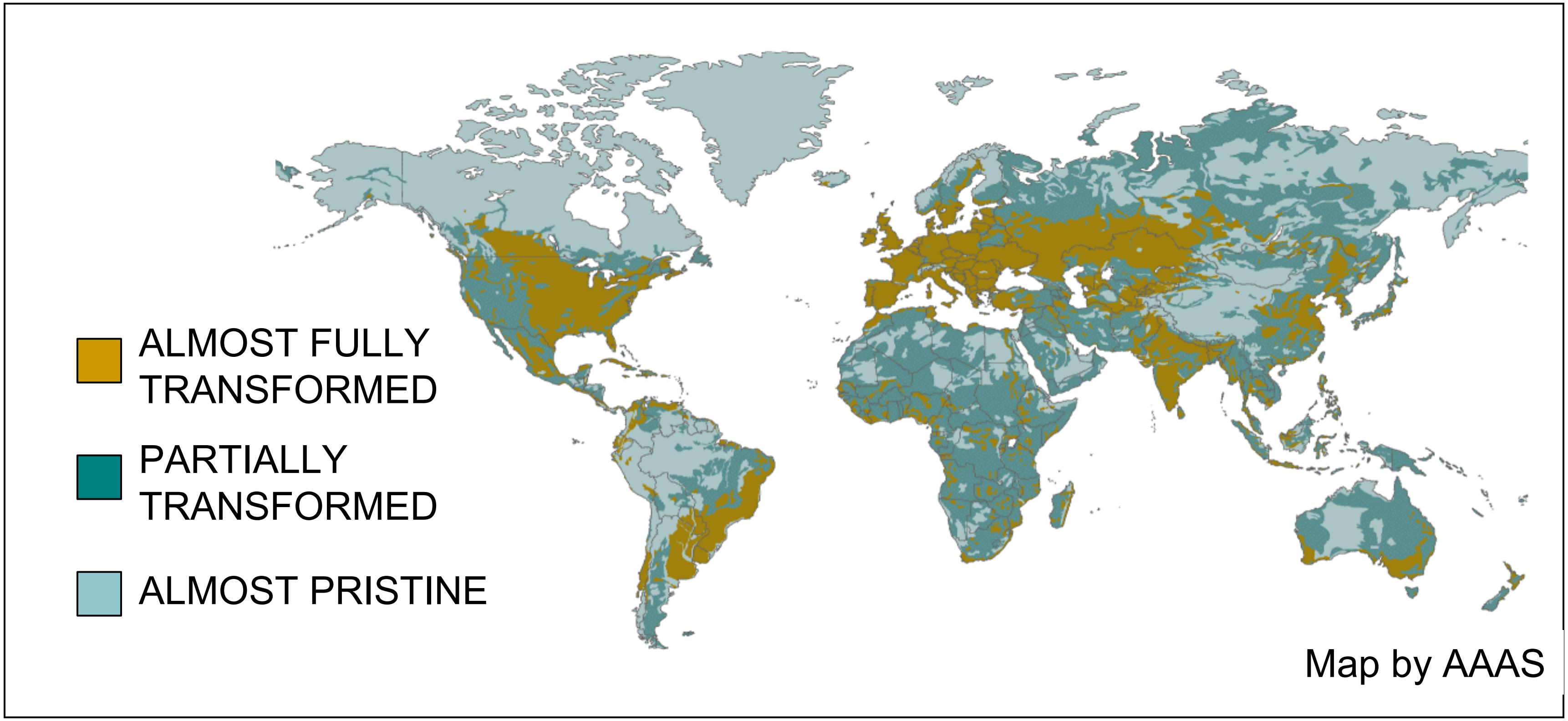
Source: Vitousek et al. 1997

Habitat Loss to 1990

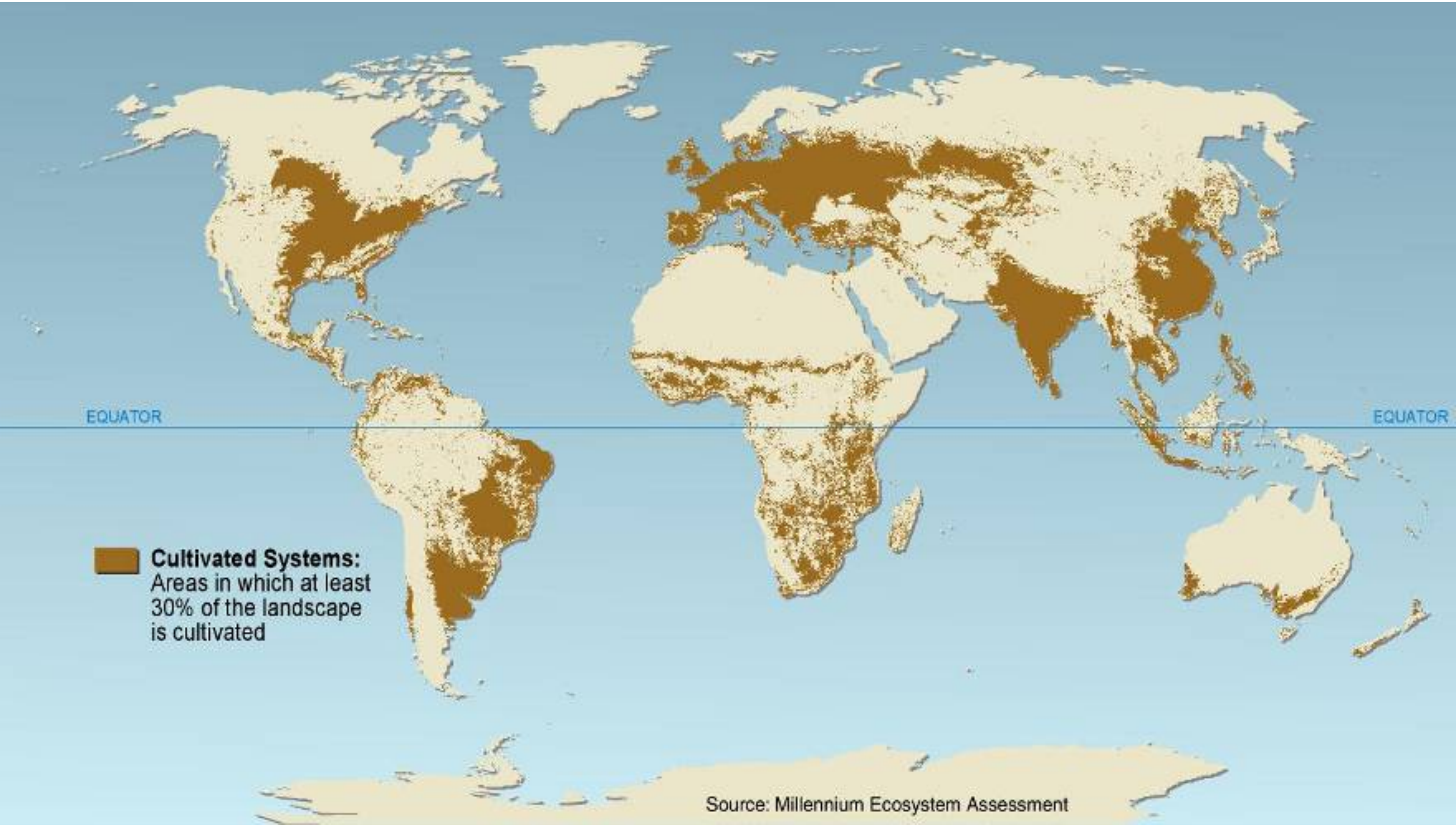


Source: Millennium Ecosystem Assessment

Humans have already transformed 40-50% of ice-free land on Earth

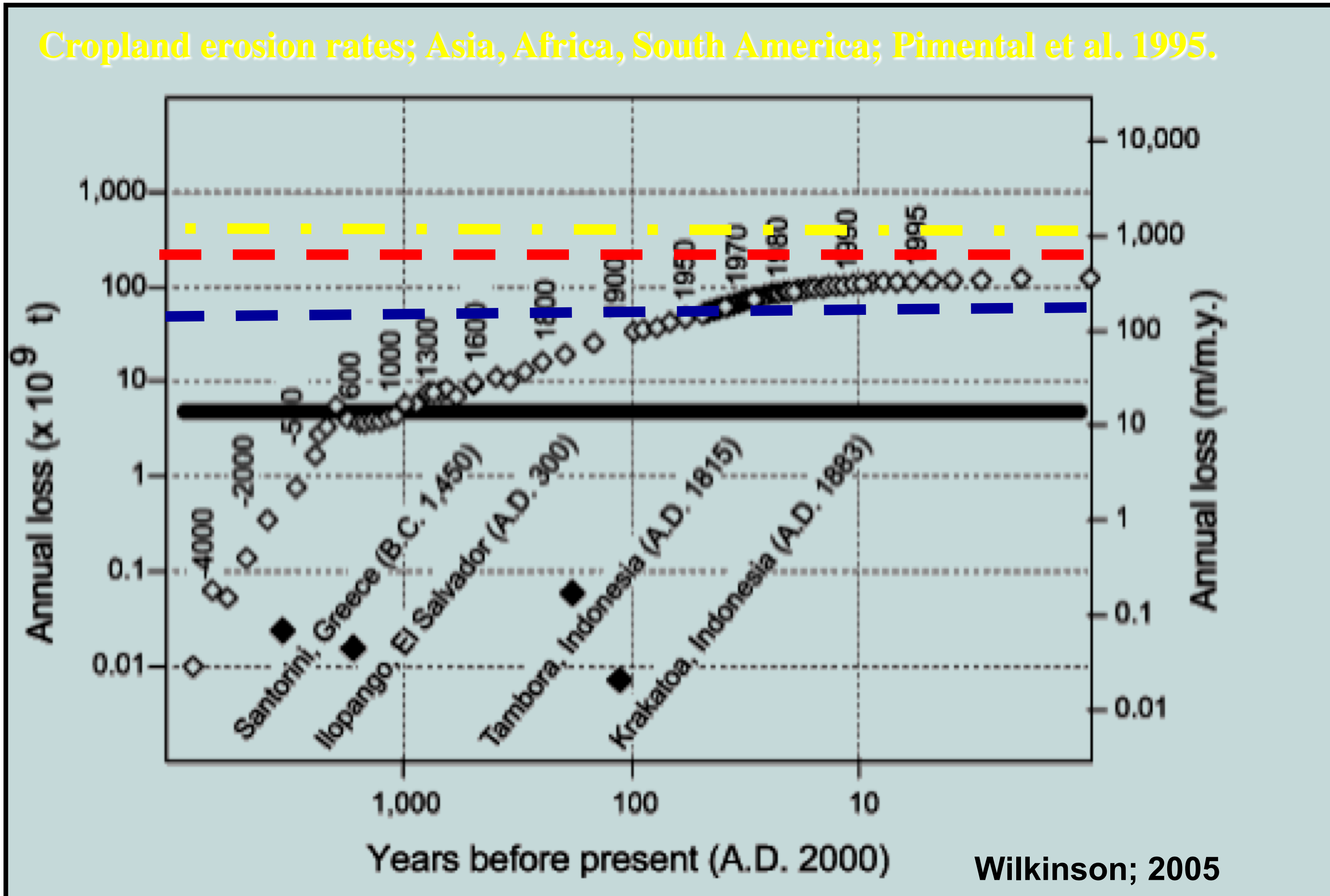


Map from "AAAS Atlas of Population & Environment"


EQUATOR
EQUATOR
Cultivated Systems:
Areas in which at least
30% of the landscape
is cultivated
Source: Millennium Ecosystem Assessment


PARDON OUR DUST...
AS WE CONTINUE TO REMODEL EVERY SQUARE INCH OF PLANET EARTH!
HUMANKIND INC.
A PAN-GLOBAL ORGANIZATION
"WE'RE EVERYWHERE YOU ARE!"
CartoonStock.com

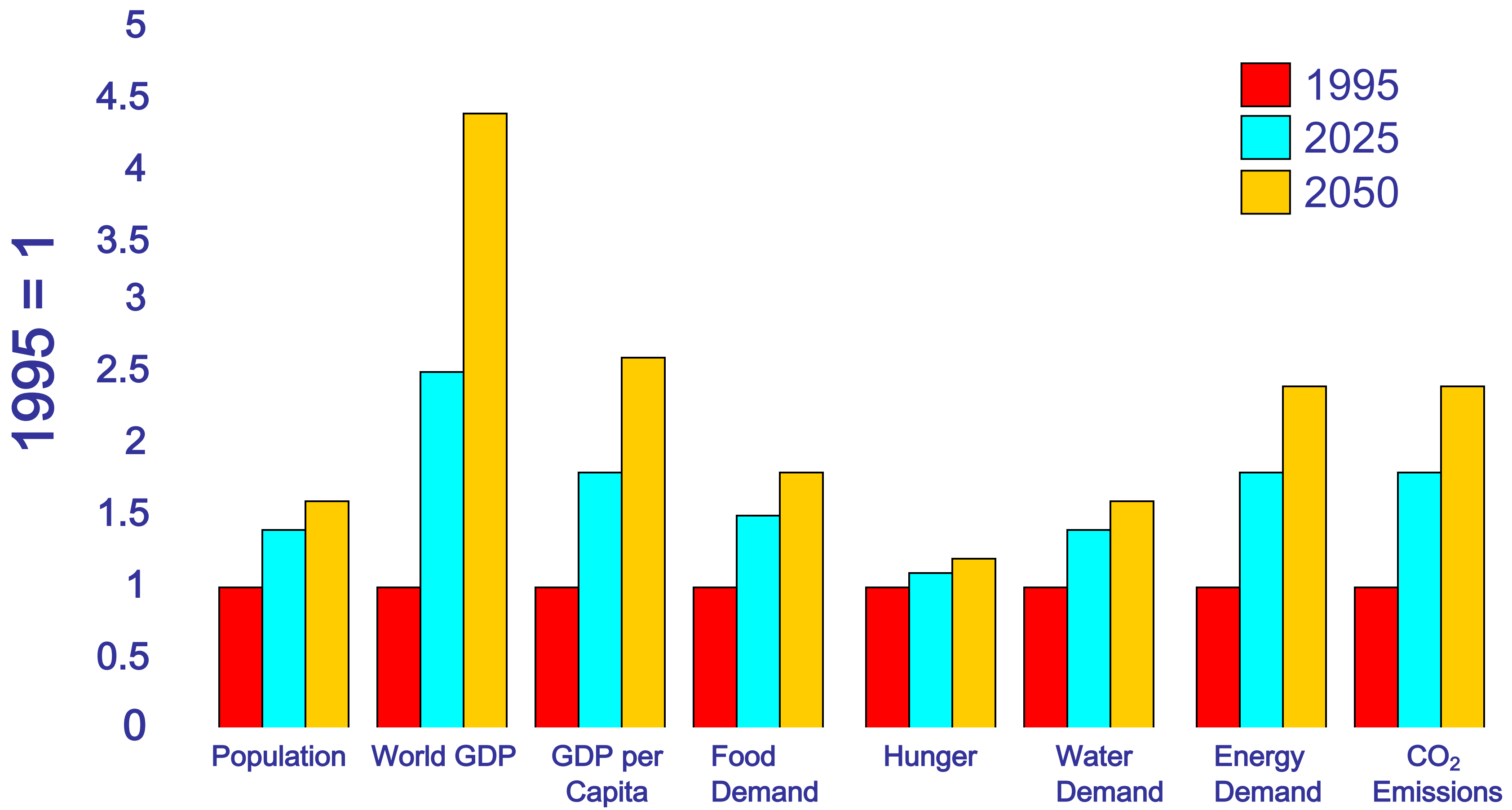
Humans are now an order of magnitude more important at moving sediment than the sum of all other natural processes



Mean cropland soil loss from US (11% of global land area); Wilkinson and McElroy, 2007

Mean pastureland soil loss from US (26% of global land area); Wilkinson and McElroy, 2007

Global Trajectories of Human Forcing of the Environment 1995-2050 (indexed to 1995)



Source: National Academy Press, Our Common Journey (1999)

CZ science evolved from the recognition that many similar scientific questions were being asked by diverse groups of Earth surface and environmental scientists who did not typically collaborate……..

but needed to if they wanted to answer pressing questions and advance solutions.

SoilCritZone

CZ science aims to understand how interactions among rock, soil, water, air, and terrestrial organisms influence Earth as a habitable system.

CZ observatories bring diverse and disparate communities together to build cross-science alliances to answer societally relevant transdisciplinary questions.

Atmosphere

How do processes that nourish ecosystems change over human and geologic time scales?

What processes control fluxes of carbon, particulates, and reactive gases over different timescales?

Nutrients

Landform Evolution

How do biogeochemical processes govern long-term sustainability of water and soil resources?

How do variations in and perturbations to chemical and physical weathering processes impact the Critical Zone?

Chemistry of Water

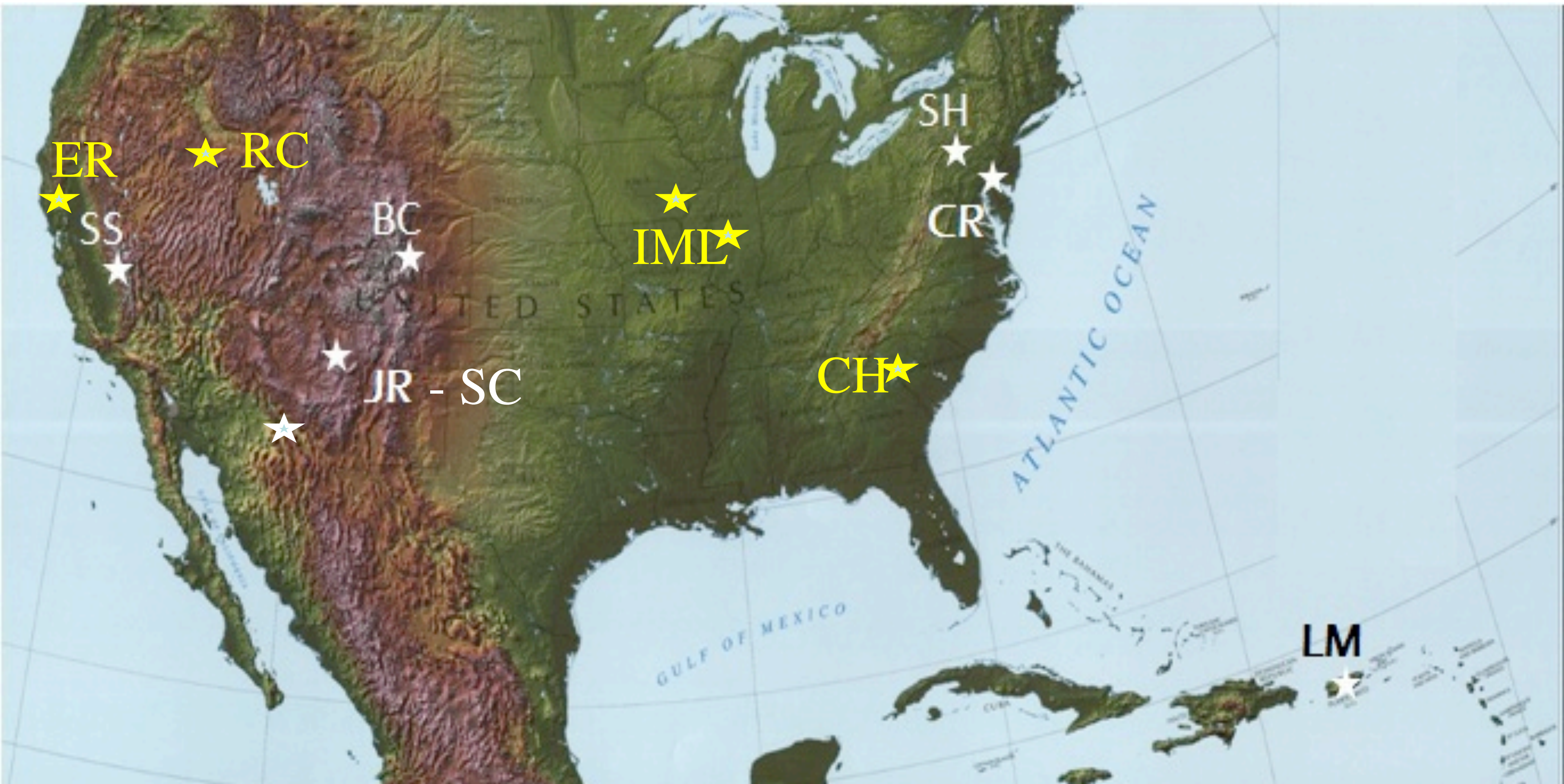
Not all CZ science is new.

For example:

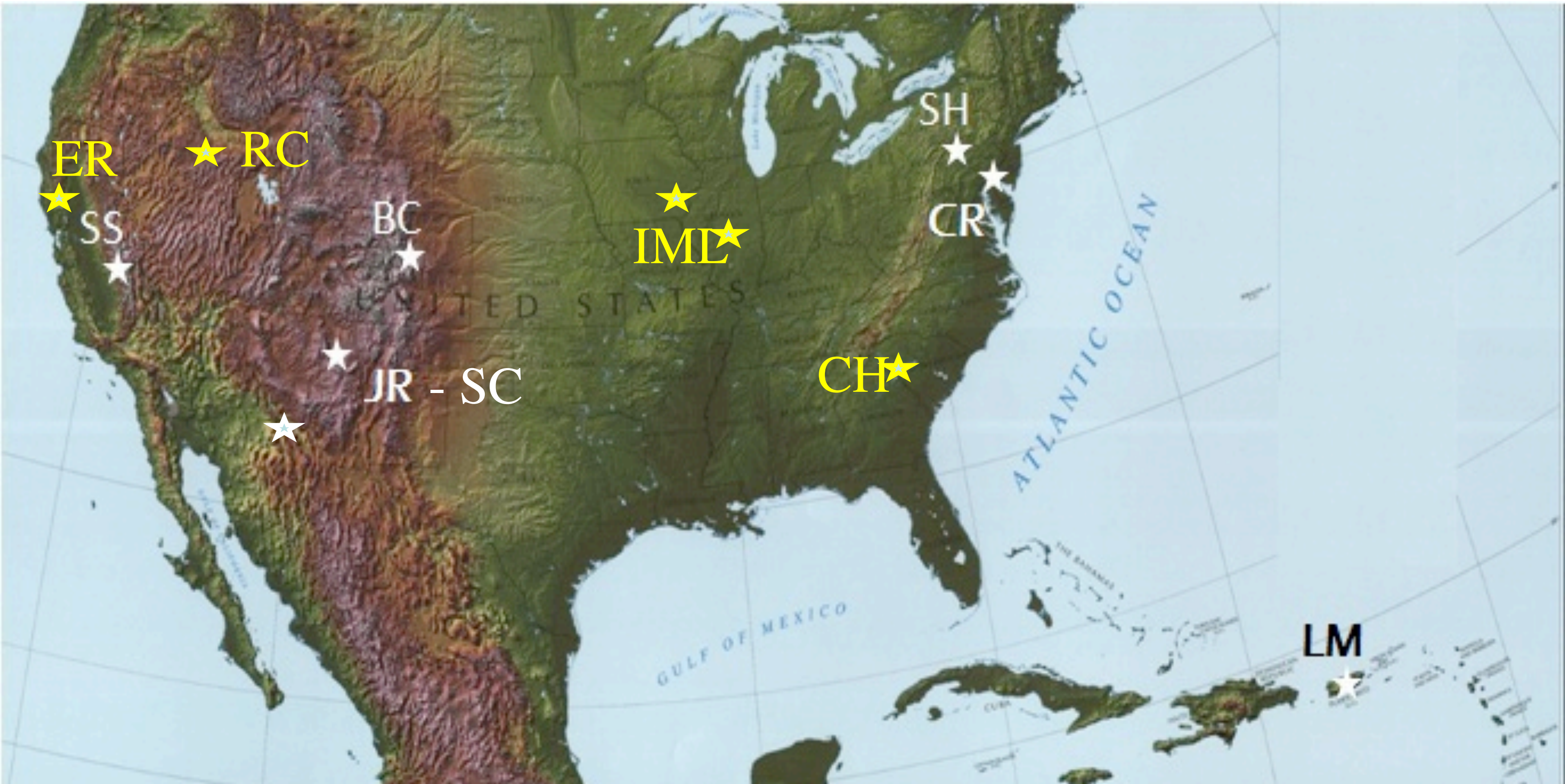
- Research on rainfall-runoff is hillslope hydrology,
on soil development is pedology, and so on……
- New (CZ) science emerges through integration, and/or
when very different timescales are connected.

- **The challenge and potential is to get disparate disciplines to value those connections, e.g.:**
  - **top 10 cm of soil and weathering front at 10 m, or**
  - **between patterns of precipitation and erosion across a mountain range.**

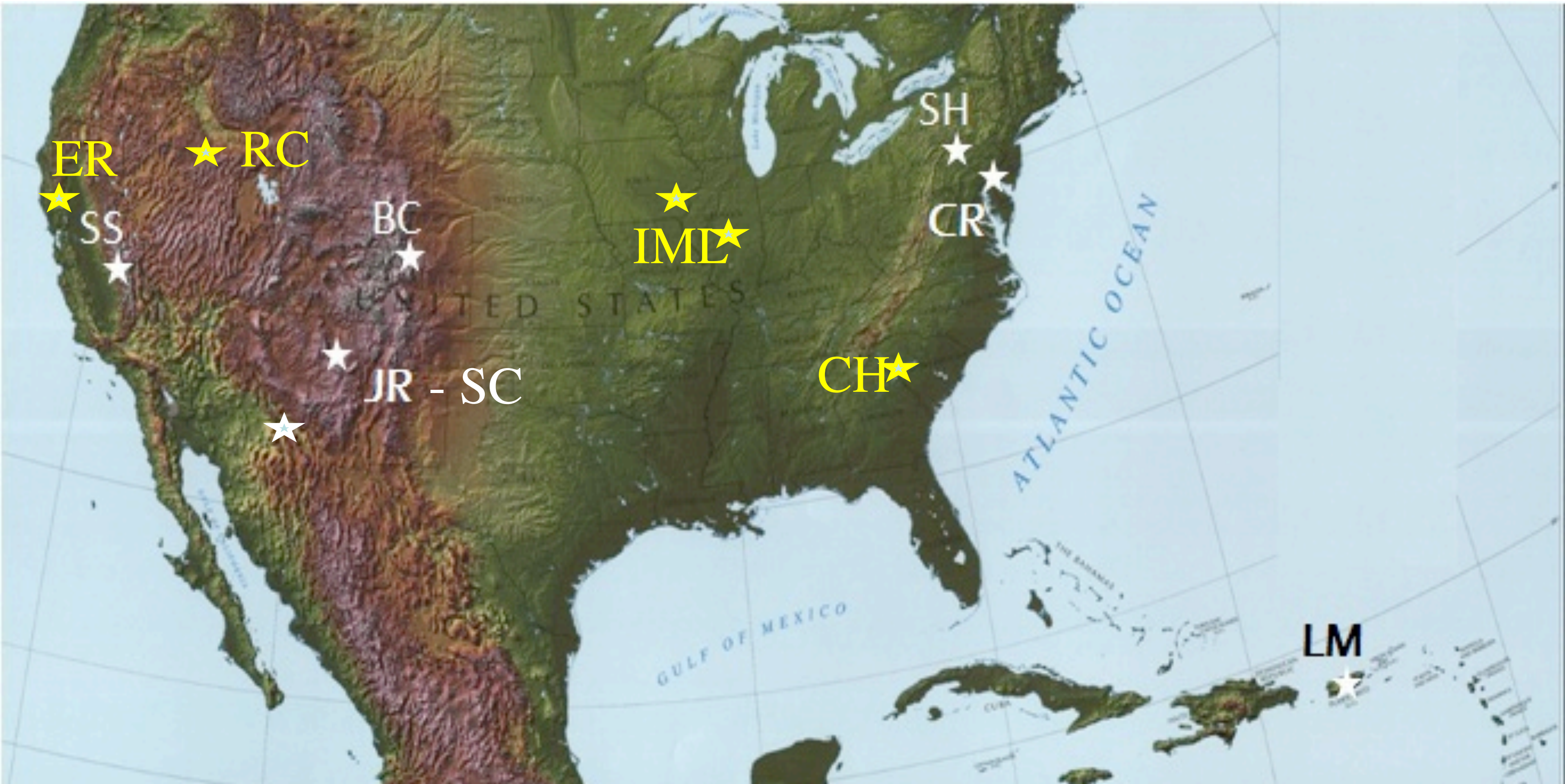
State of CZ science in US: 9 CZOs cover an array of geologic, climatologic and ecologic settings in which a variety of CZ processes can be studied from the vegetation canopy into bedrock.



The sites promote site-specific research and education activities and have created a strong community among a diverse group of CZ scientists (CUAHSI, geomorphology, CZEN, geobiology….



The sites are building a network that can attract a diverse group of Earth scientists to advance CZ science by answering questions like: *How has the CZ changed and how will it change in the future?*



CZOs seek to develop <u>COMMON MEASUREMENTS</u> to quantify:

- 1. CZ structure and evolution
- 2. Event-based and continuous fluxes of energy, water, solutes and sediments across CZ interfaces
- 3. Changes in storage of energy, water, solutes and sediments

CZO →	Boulder Creek	Calhoun	Catalina-Jemez	Christina River	Eel River	IML	Luquillo	Reynolds Creek	Shale Hills	Southern Sierra
Land-Atmosphere										
LiDAR	X	Z	X	X	X	X	X	Y, Z	X	X
Eddy flux	Y	Z	X			X, Y, Z		Y	X	X, Z
Wind speed and direction	X	Z	X	X	X	X, Y	Y	Y	X	X
Precipitation and throughfall	X	X, Z	X	X	X	X, Y	Y	Y	X	X, Y, Z
Wet and dry deposition	Y	X, Z	X	X		Y	Y	Y	X	X
Snowpack distribution and duration	X		X					Y	X	X
Vegetation and Microbiota										
Structure and function above and below biomass	X	X	X	X	X, Z	X	Y	Y, Z	X	X, Y, Z
Microbial composition above and below ground	X	X, Z	X	X	X	X	Y	Z		X, Z
ET - species composition and structure relationships	Y	Z	X		X	y		Y, Z	X	X
Soil (Vadose Zone)										
Solid - elemental composition and mineralogy	X	X, Z	X	X	X	X	X	Y, Z	X	X, Y
Solid - texture and physical characterization	X	X, Z	X	X	X	X	X	Y, Z	X	X, Y, Z
Solid - organic matter content	X	X, Z	X	X	X	X	X	Y, Z	X	X, Z
Solid - radiogenic isotope composition	X		X	X		X	X		X	X, Z
Fluid - soil moisture (sensors)	X	X, Z	X	X	X	X	X	Y, Z	X	X, Z
Fluid - soil temperature (sensors)	X	Z	X	X	X	X	X	Y, Z	X	X, Z
Fluid - soil solution chemistry (samplers)	X	X, Z	X	X	X	X	X		X	X, Y, Z
Fluid - soil gas chemistry (samplers/sensors)		X, Z	X	X	X		X, Y	Z	X	Z
Saprolite and Bedrock (Saturated Zone)										
Solid - petrology and mineralogy	X	X, Z	X	X	X	Y	X	Z	X	X, Z
Solid - elemental composition and OM content	X	X, Z	X	X	X	X	X	Z	X	X, Z
Solid - texture, physcial/architectural constraints	X	X, Z	X	X	X	X	X	Z	X	X, Z
Fluid - potentiometric head, temperature (sensors)	X	Z	X	X	X	X	X	Y	X	X
Fluid - groundwater chemistry (samplers/sensors)	X	X, Z	X	X	X	X	X	Z	X	X, Z
Fluid - saprolite/weathered bedrock gas chemistry		X, Z			X					X
Geophysical surveys - depth to bedrock	X		X	X	X		X	Y	X	X
Surface Water										
Instantaneous discharge	X	X, Z	X	X	X	X, Y	X, Y	Y	X	X, Y, Z
Stable isotopes of water	X	Z	X		X		X		X	X
Stream water chemistry (samplers/sensors)	X	X, Z	X	X	X	X	X, Y, Z	Z	X	X, Y
Sediments (samplers/sensors)	X	Z	X	X	X	X	X	Y, Z	X	Y, X
Extent of wetted channel		Z			X					Y, X
Aquatic biota (invertebrates, fish, etc.)					X		Y			Y
Age or rate constraints										
Cosmogenic radionuclides	X	X	X		X		X		X	X
^{14}C ages	X	X	X				X			
Optical Stimulated Luminescence ages	X									

CZO Common Measurements

Land-Atmosphere
LiDAR
Wind speed and direction
Precipitation and through-fall
Wet and dry deposition
Eddy flux
Snowpack distribution and duration

Soil (vadose zone)
Solid- elemental composition and mineralogy
Solid- texture and physical characterization
Solid- organic matter content
Fluid- soil moisture (sensors)
Fluid- soil temperature (sensors)
Fluid- soil solution chemistry (samplers)
Fluid - soil gas chemistry (samplers/sensors)
Solid- radiogenic isotope composition

Vegetation and Microbiota
Structure and function above and below biomass
Microbial compostion above and below ground
ET-species composition and structure relationships

CZO Common Measurements

Saprolite and bedrock (saturated zone)

Solid- petrology and mineralogy
Solid- elemental composition and organic matter content
Soild- texture and other physical and architectural traits
Fluid- potentiometric head, temperature (sensors)
Fluid- groundwater chemistry (samplers/sensors)
Geophysical Surveys- depth to bedrock
Fluid- saprolite/weathered bedrock gas chemistry (samplers/sensors)

Surface water

Instantaneous discharge
Stream water chemistry (sample/sensors)
Sediments (samplers/sensors)
Stable isotopes of water
Extent of wetted channel
Aquatic biota (invertebrates, fish, etc.)

Age or rate constraints

Cosmogenic radionuclides
^{14}C ages
Optical Stimulated Luminescence

The lower boundary of the Critical Zone generally equates to the base of the groundwater zone, a diffuse boundary of variable depth extending up to a km or more below the surface.

- more difficult to define and access than upper boundary
- relative paucity of life and lack of atmosphere simplifies study (somewhat)
- lower frequency information to understand.

Deep drilling at some CZOs has been accomplished but not at all CZOs.

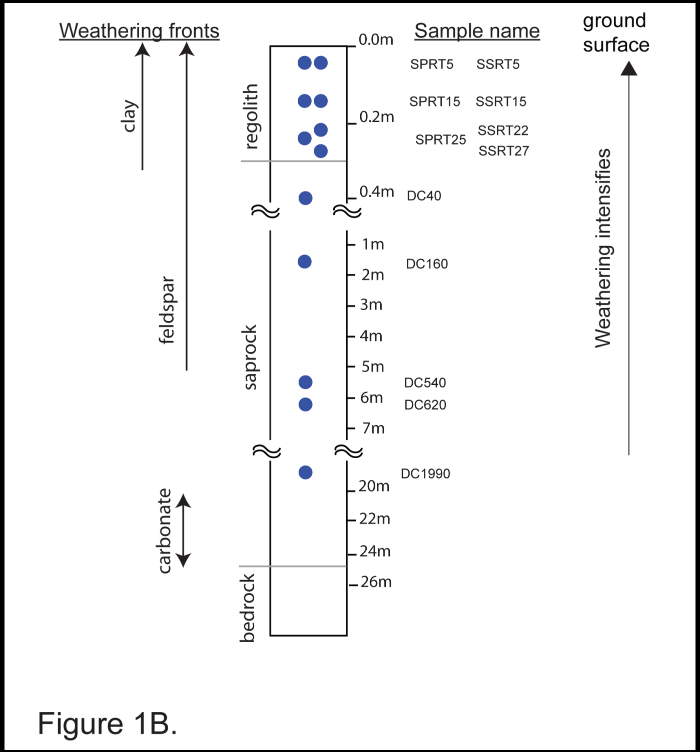
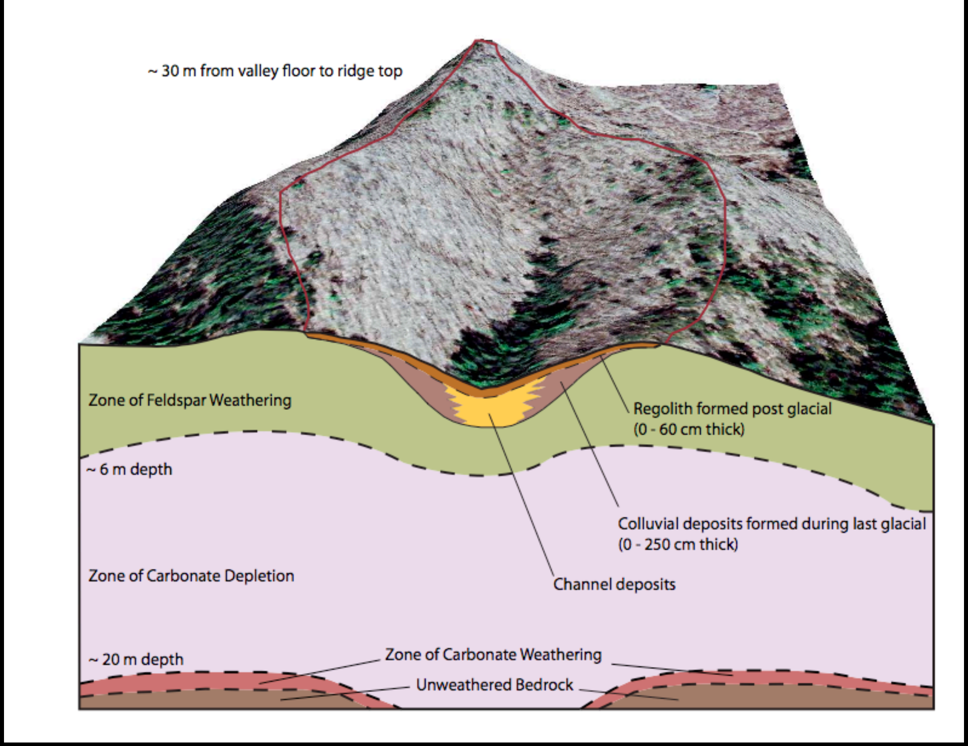


Figure 1B.



We use deep wells to for example obtain samples of fresh bedrock, consider fracture density, and sample water and gas, and to address questions:

1. What is the composition of fresh bedrock?
2. To what depth does groundwater freely circulate?
3. What controls circulation?
4. Does life exist at these depths?
5. If so, what biogeochemical processes occur?
6. Does weathering occur?
7. What role do these processes play in overall flux of energy, water, nutrients, gases?

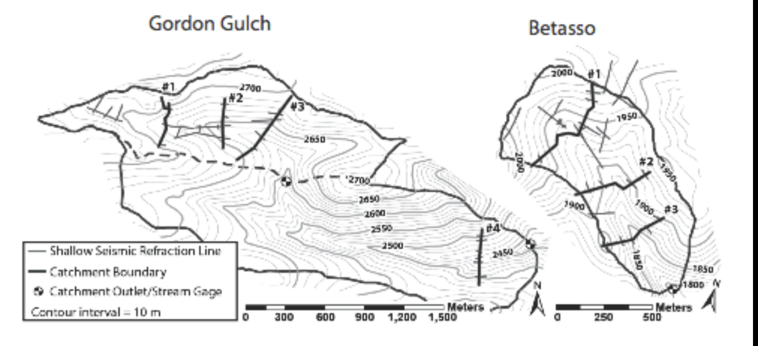
Similarly we use networks of shallow groundwater wells to:

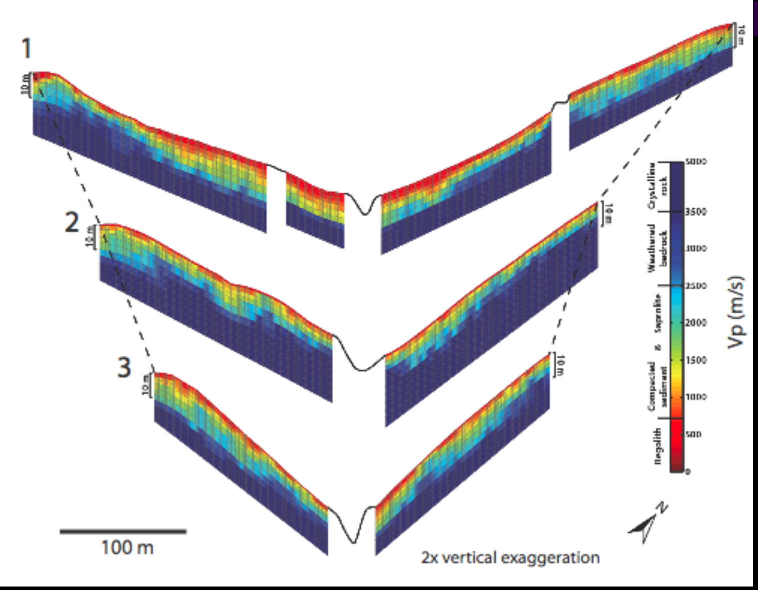
- sample soil, shallow bedrock and groundwater
- define recharge pathways to the subsurface
- provide portals for instrumentation and high frequency monitoring

Geophysical surveys to:

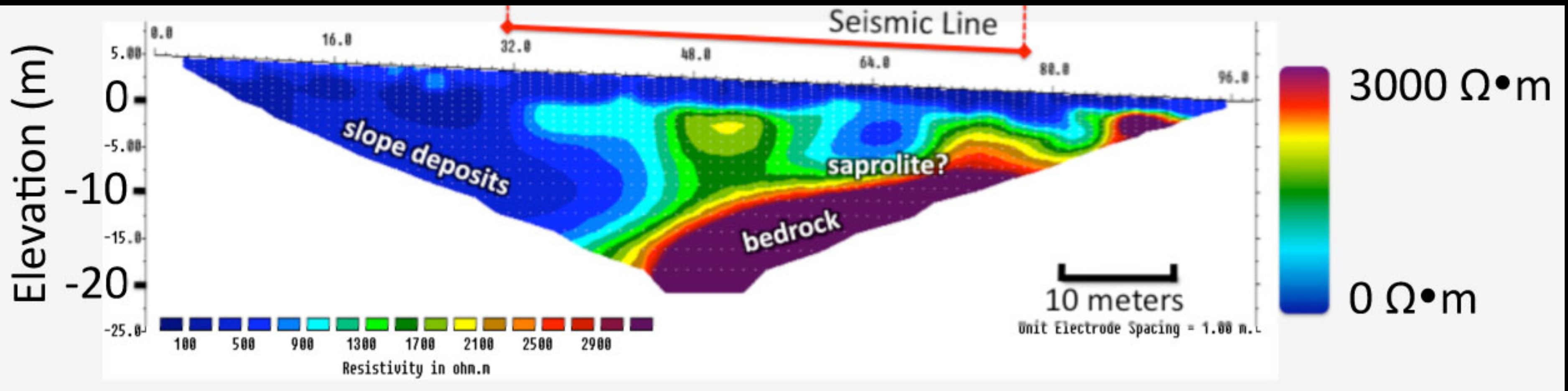
- **Help define well sites and design well networks**
- **Map spatial distributions of subsurface material and soils, distribution of hydraulic conductivity and groundwater flow paths**
- **Ground truthed by shallow well drilling**

Shallow geophysical surveys from BoulderCreek CZO help delineate and map subsurface materials.





Below: relatively high resistivity values for bedrock, low values for overlying slope deposits, and intermediate values for weathered material/saprolite.



The upper boundary of the Critical Zone extends to the top of the vegetation canopy.

- relatively easy to see

- but is heterogeneous and complex

- requires high frequency information to fully understand.

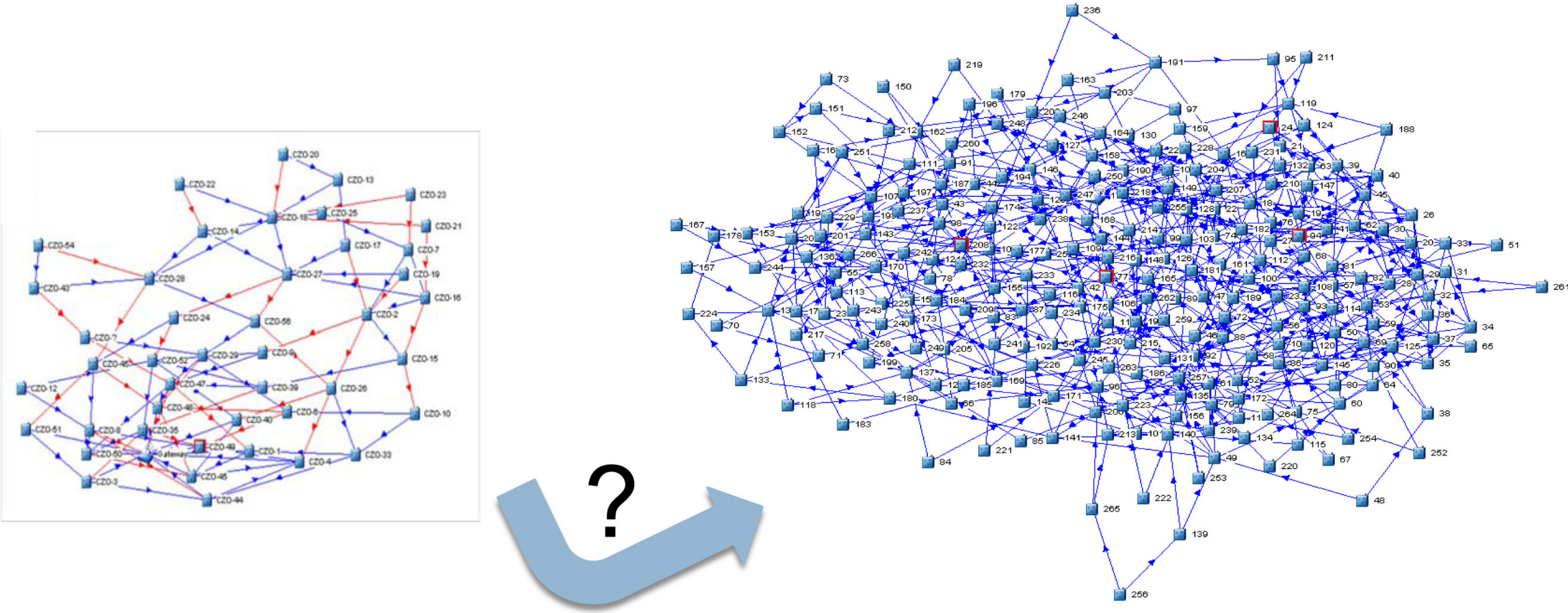
State-of-the-art sensors with wireless communication networks

- Provide high frequency real time monitoring
- Thus far not coordinated between CZOs.
- Can link subsurface to surface

How do various measured parameters fluctuate?
What do fluctuations teach us about processes?

General Challenge

- We would like to provide a wireless infrastructure that will allow simple and practical instrumenting of large-scale areas (10-100 sq. km)
- We have shown that it possible to successfully monitor catchments of 1-2 sq km, but our tools (hardware and software) need to be improved to ensure successful operations at larger scales
- What is required to transition from a 60 node wireless sensor network to a 1000+ node network?



Canopy Towers provide:

• High frequency and high quality meteorological and hydrological measurements, including but not limited to:

- eddy covariance systems to measure the exchange of water, energy, and carbon between biosphere and atmosphere
- webcams to record phenological state of the canopy.

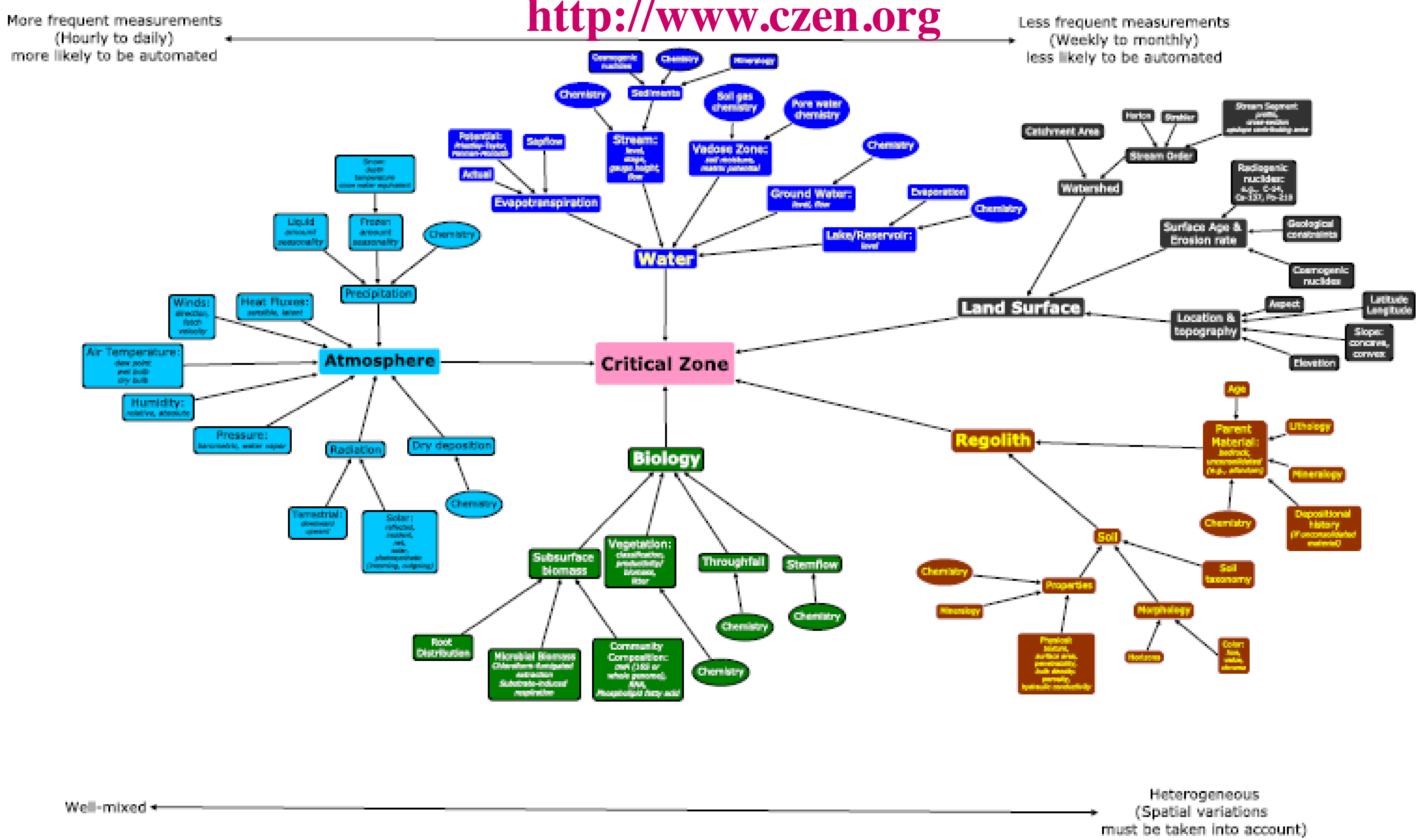
To answer CZ questions requires shared data

- We have a great variety of data types that vary with space and time
- We need to be able to share data

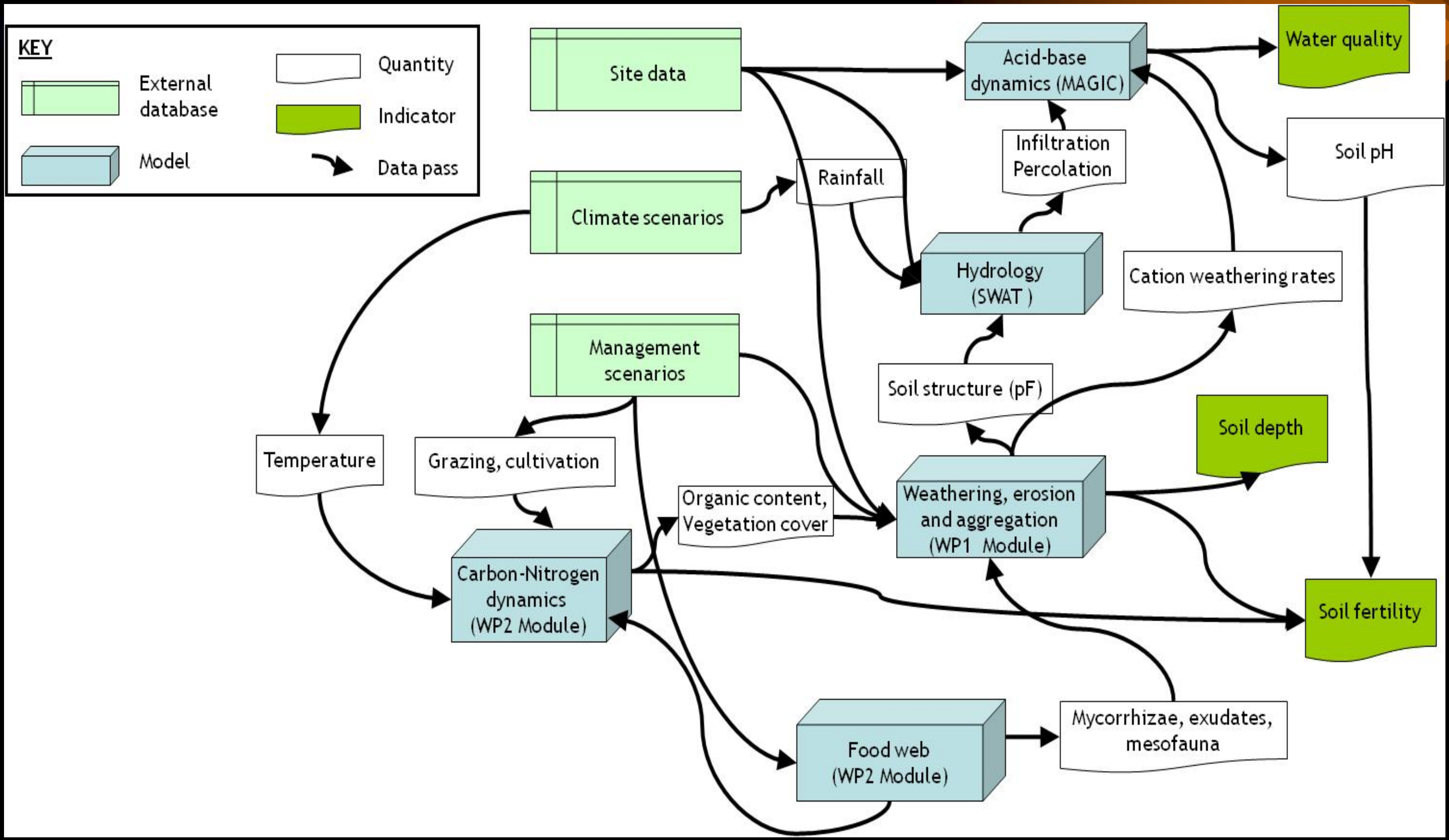
CZEN has drafted an ontology that describes the structure of the data.

http://www.czen.org/content/critical-zone-ontology

http://www.czen.org



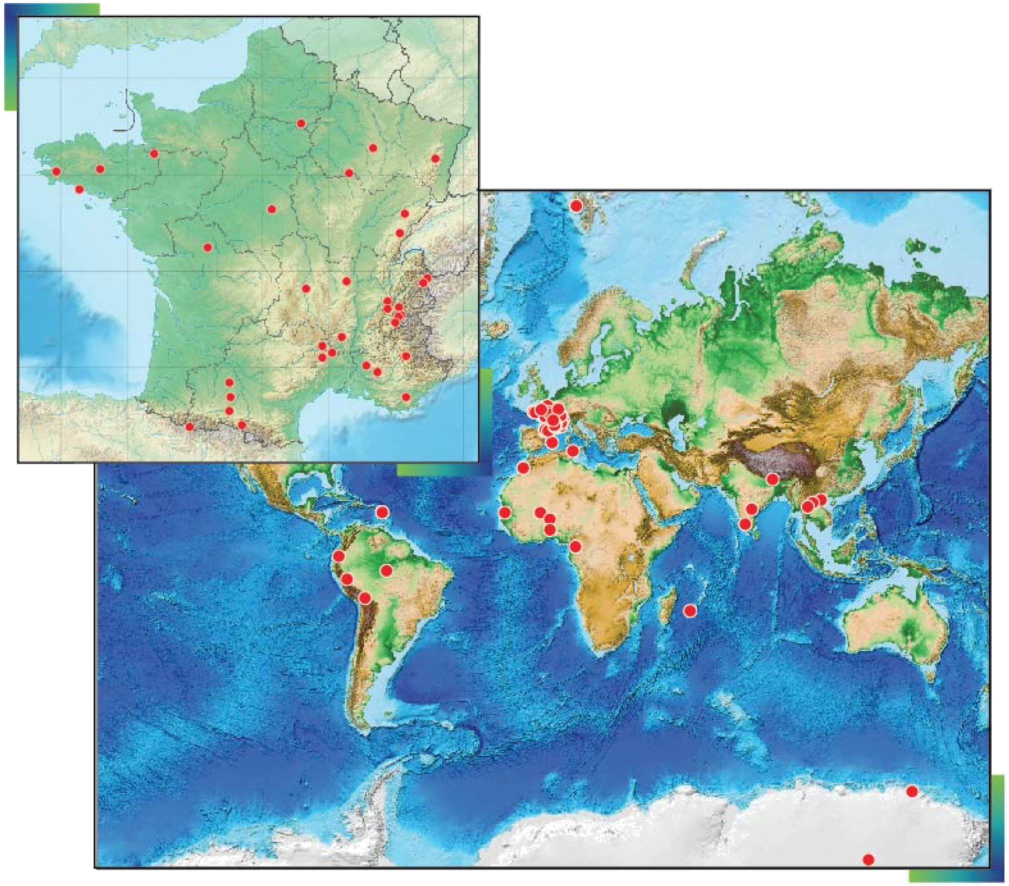
Open-Source Modeling Framework



French network of CZOs; Research and Applications

Networks associated with OZCAR observatories:

- CRYOBS-CLIM Observatories
- RBV network
- H+ Observatories
- Tourbières Observatories
- Regional Space Observatories
- ROSES Observatories
- OPE Observatories



UK – China
Critical Zone Observatory

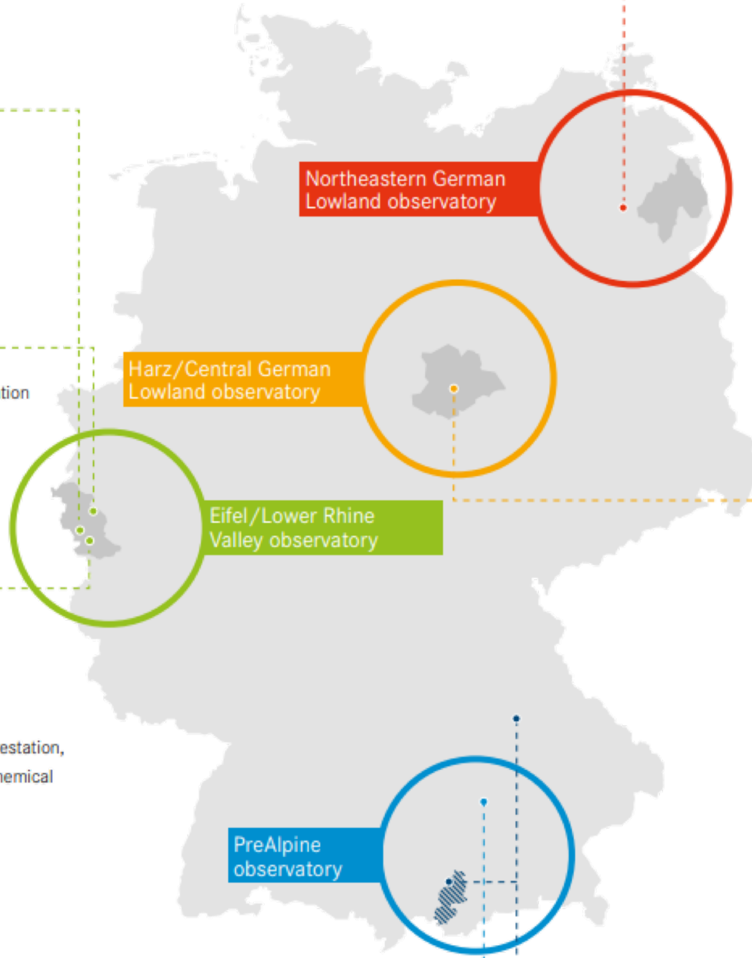
UK-

TERENO
TERRESTRIAL ENVIRONMENTAL OBSERVATORIES

Ellebach CZO
Area: 101.3 km²
Fertile Börde landscape, primarily farmland
Average yearly temperature: 10 °C
Precipitation: 705 mm/year
Main areas of research: Matter fluxes, land use, greenhouse gas emissions, subsurface patterns

Kall CZO
Area: 19 km²
Low mountains, predominantly grassland vegetation
Average yearly temperature: 7 °C
Precipitation: 1200 mm/year
Main areas of research: Climate change, water quality, organic matter dynamics

Erkensruhr CZO
Area: 41.7 km²
Low mountains, predominantly forest coverage (Eifel National Park)
Average yearly temperature: 7 °C
Precipitation: 1080 mm/year
Main areas of research: Land-use change/deforestation, soil-groundwater-river interactions, soil biogeochemical processes



Fürstensee CZO
Area: 40 km²
Lowlands with numerous forests
Average yearly temperature: 8 °C
Precipitation: 584 mm/year
Main areas of research: Effects of global change, water budget, hydrogeology, groundwater recharge, vadose zone hydrology, groundwater-lake-interactions, groundwater-tree-interactions, dendrochronology, palaeohydrology of lakes, past land use impacts, carbon cycling and storage, geomicrobiology of peatlands

Selke CZO
Area: 458 km²
Low mountains with forest and farmland
Average yearly temperature: 8.5 °C
Precipitation: 550 mm/year
Main areas of research: Water and matter fluxes, climate variability, extreme events, bio-geochemical transformation, soil-landscape modeling, hyporheic processes, groundwater-surface water interactions, mobilization of dissolved organic carbon (DOC)

Scheyern/Pudelbach CZO
Area: 13.5 km²
Rolling hills, primarily farmland
Average yearly temperature: 7.4 °C
Precipitation: 803 mm/year
Main areas of research: Climate change, land use, greenhouse gas emissions

TUM-CZO
Area: Ammer catchment 709 km²/Otterbach catchment 91 km² Alps and foreland
Average yearly temperature: 4-8 °C (Ammer catchment)/ 7 °C (Otterbach catchment)
Precipitation: 1,100–2,000 mm/year (Ammer catchment)/ 800 mm/year (Otterbach catchment)
Main areas of research: Water and matter fluxes, climate change, land use, greenhouse gas emissions

Germany

Critical Zone Exploration Network (2018) – 233 sites
czen.org; Site Seeker

National CZO Program

CRITICAL ZONE OBSERVATORIES

funded by NSF

studying the zone where rock meets life