

An aerial photograph of a severely arid landscape. The ground is parched and cracked into a complex, irregular pattern of polygonal shapes, resembling a mosaic of dry mud. The colors range from light tan to deep, dark brown, indicating varying degrees of soil dryness and possibly some sparse, dead vegetation. The horizon is visible in the distance under a pale, hazy sky.

Drought, Aridity, Water scarcity, Desertification

(related Land Degradation processes/issues)

Processes in the environment that involve/require water

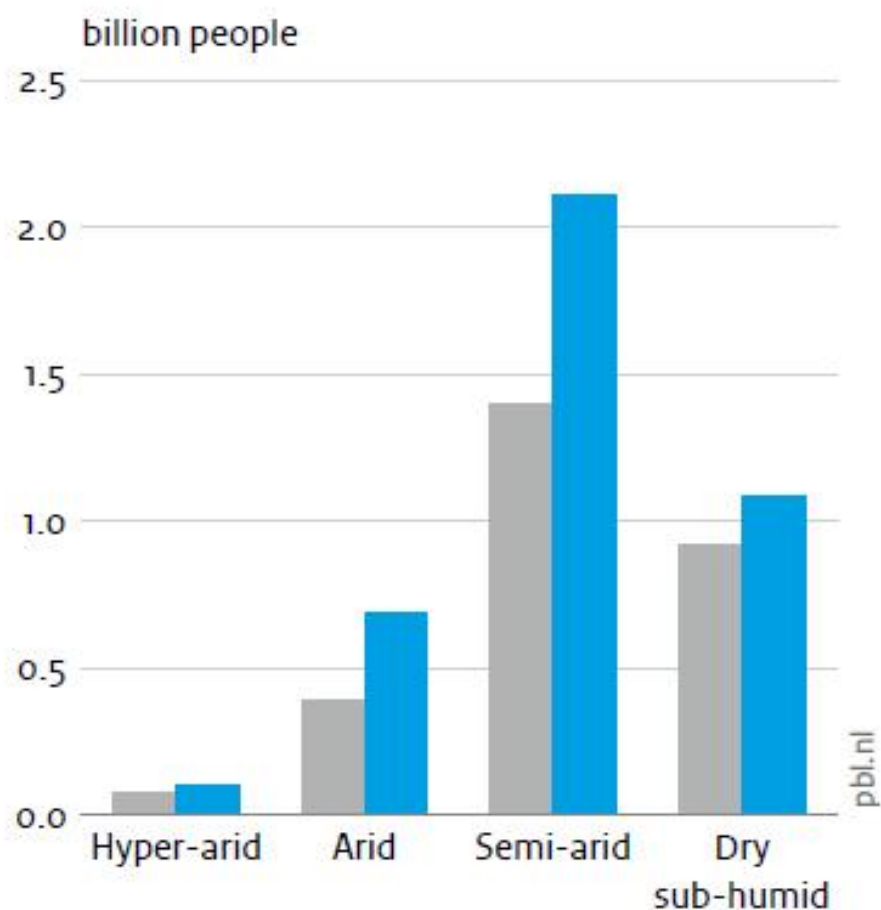
- physiologic processes in plants and animals require water; plants demand water in much higher amounts compared to animals; plants are carrying out the photosynthesis and they are directly exposed to sunlight during the day → they cool themselves through transpiration
- thermoregulation: evaporation and transpiration processes require heat (endothermic) → they cool the surroundings; on the other hand, condensation releases a heat (it warms the surroundings); liquid water has high specific heat capacity (and heat of evaporation) → it prevents T from raising in warm environments (liquid water is efficient cooling medium for the organisms)
- water in soil dissolves minerals → release of nutrients
- transport medium (nutrients, contaminants, energy)
- not only is water essential for all living organisms, but the nutrients in soil are being assimilated by biota mostly in dissolved form (soil solution)
- water in the atmosphere (in gaseous form) contributes to greenhouse effect
- if rainfall rate > rate of infiltration → surface runoff → water erosion → relief (land surface) formation

Consequences of drought (long-term, frequent)

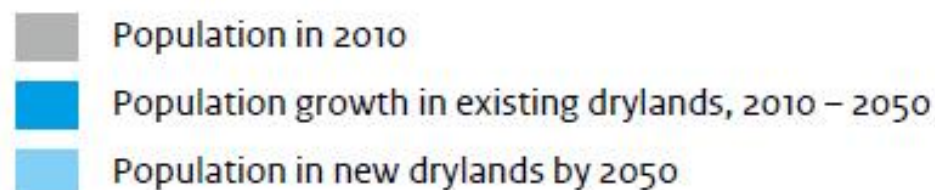
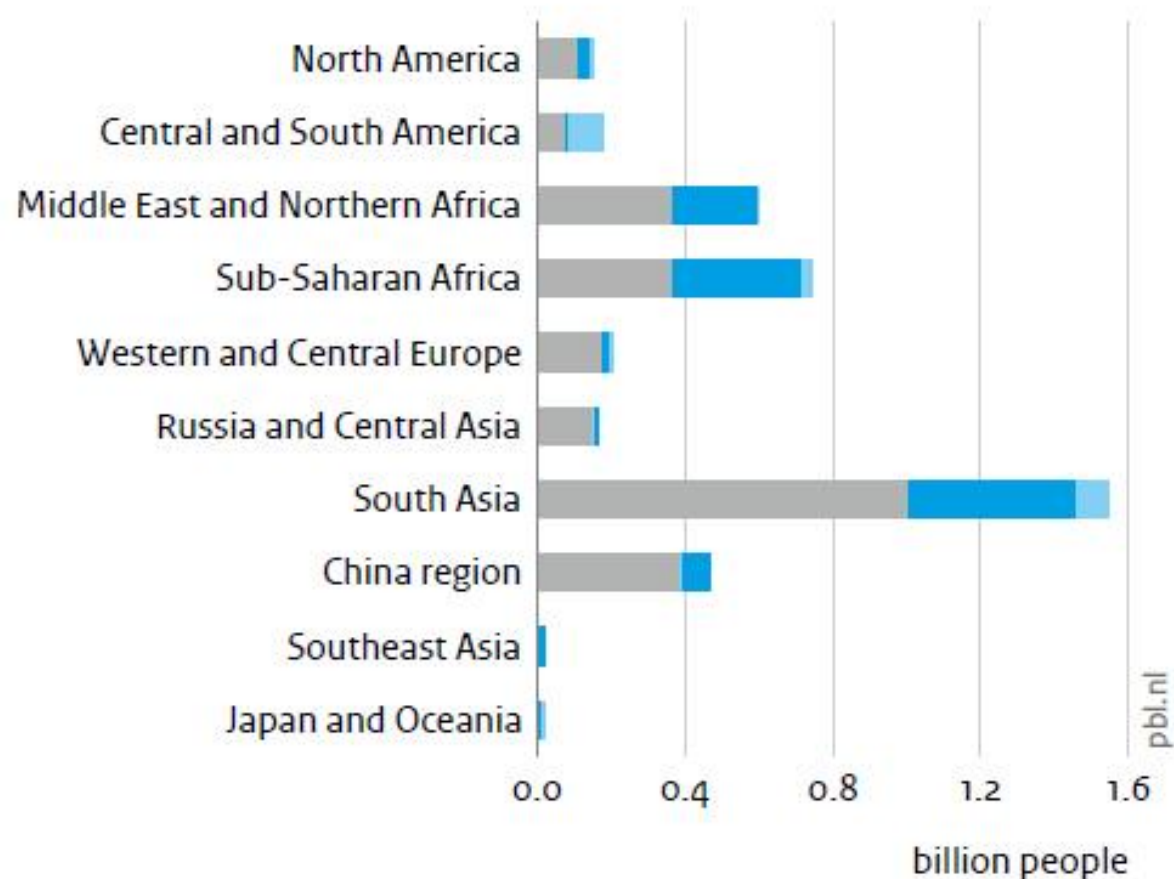
- low net primary production (absence of water → limited photosynthesis)
- soil organic carbon mineralization in formerly humid areas: if the climate in originally humid area becomes dry/drier → carbon accumulated in/at/near the soil surface will be mineralized at higher rate
- increased wind erosion
- higher risk of fire occurrence (if there is a fuel – biomass)
- decrease/absence of thermoregulation: water in soil-plant-atmosphere continuum acts as thermoregulator; plants provide shade and soil-plant-atmosphere system cools surroundings due to the evapotranspiration in the sunlight. On the other hand, it warms the environment in the night → absence of soil-plant-water system results in hot days and cold nights in the desert
- besides lack of precipitation, the desert areas have very limited water retention capacity; even if there is rainfall → water is not retained near the surface (percolates deeper or creates surface runoff)

Population in drylands, under the SSP2 scenario

Global

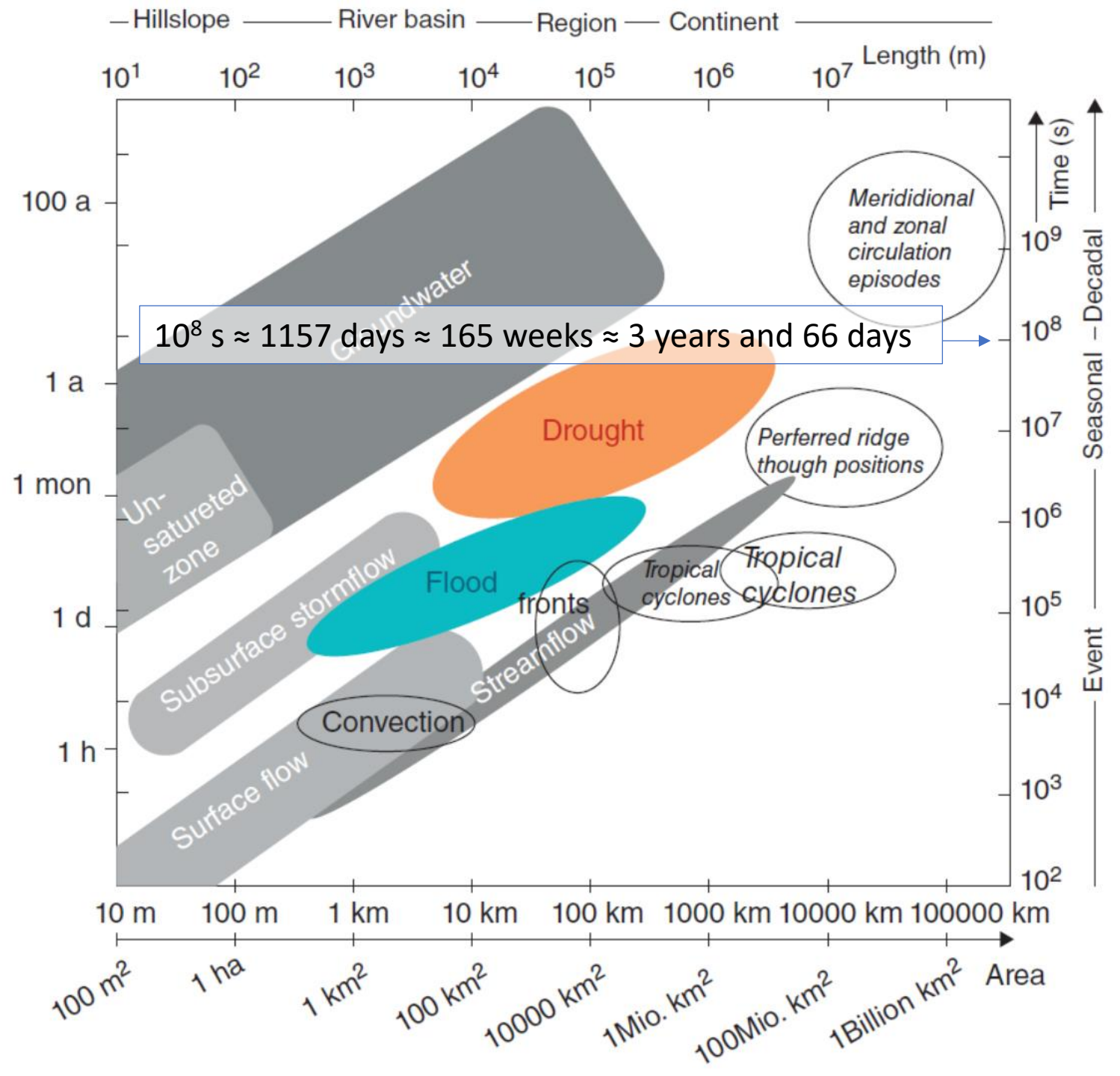


Regional

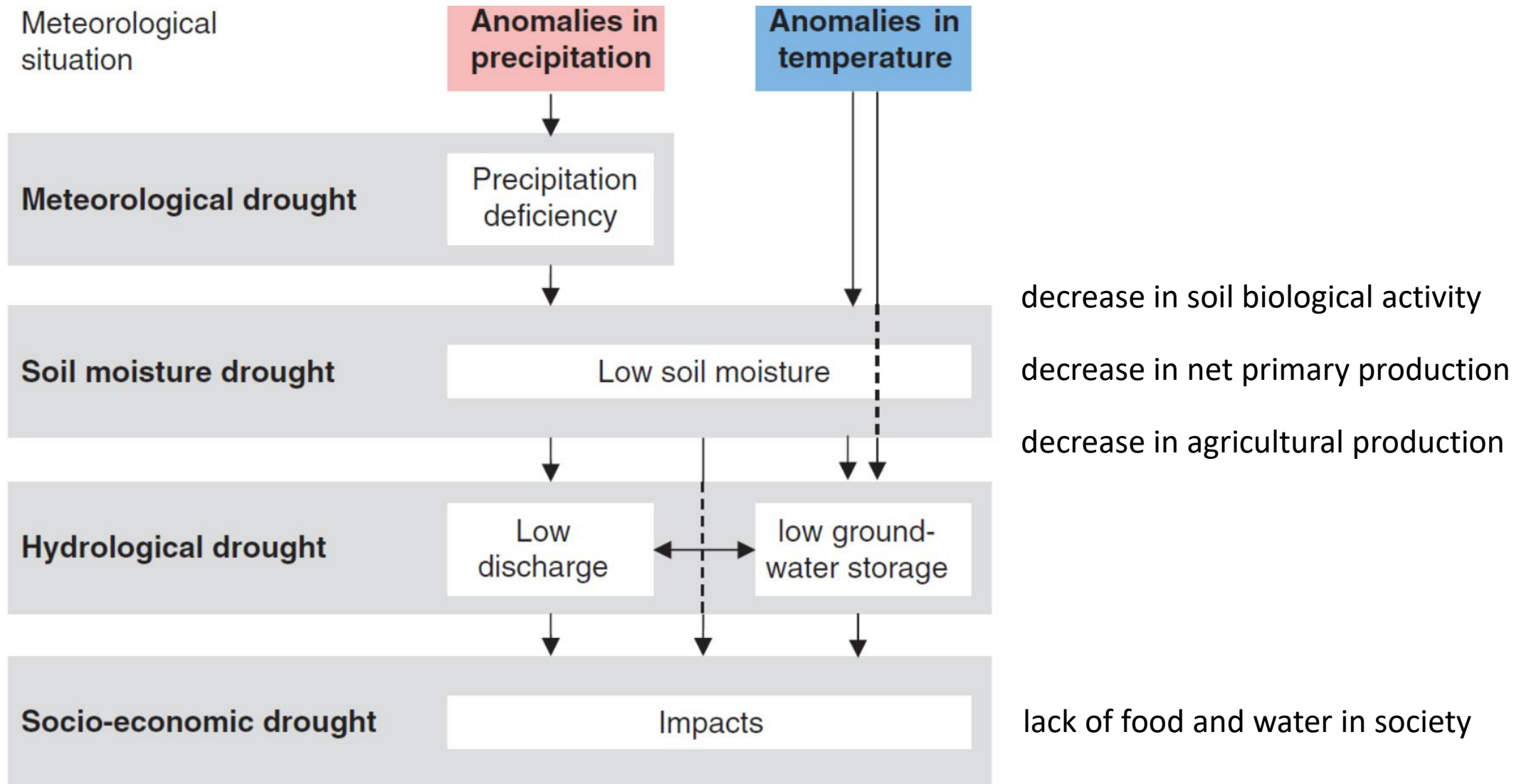


Drought (spatio-temporal context)

- regional/continental level
(app. > 10 km up to 1000 km)
- seasonal/decadal level
(app. > 10 days up to years)
- area: > 100 km² up to several millions km²

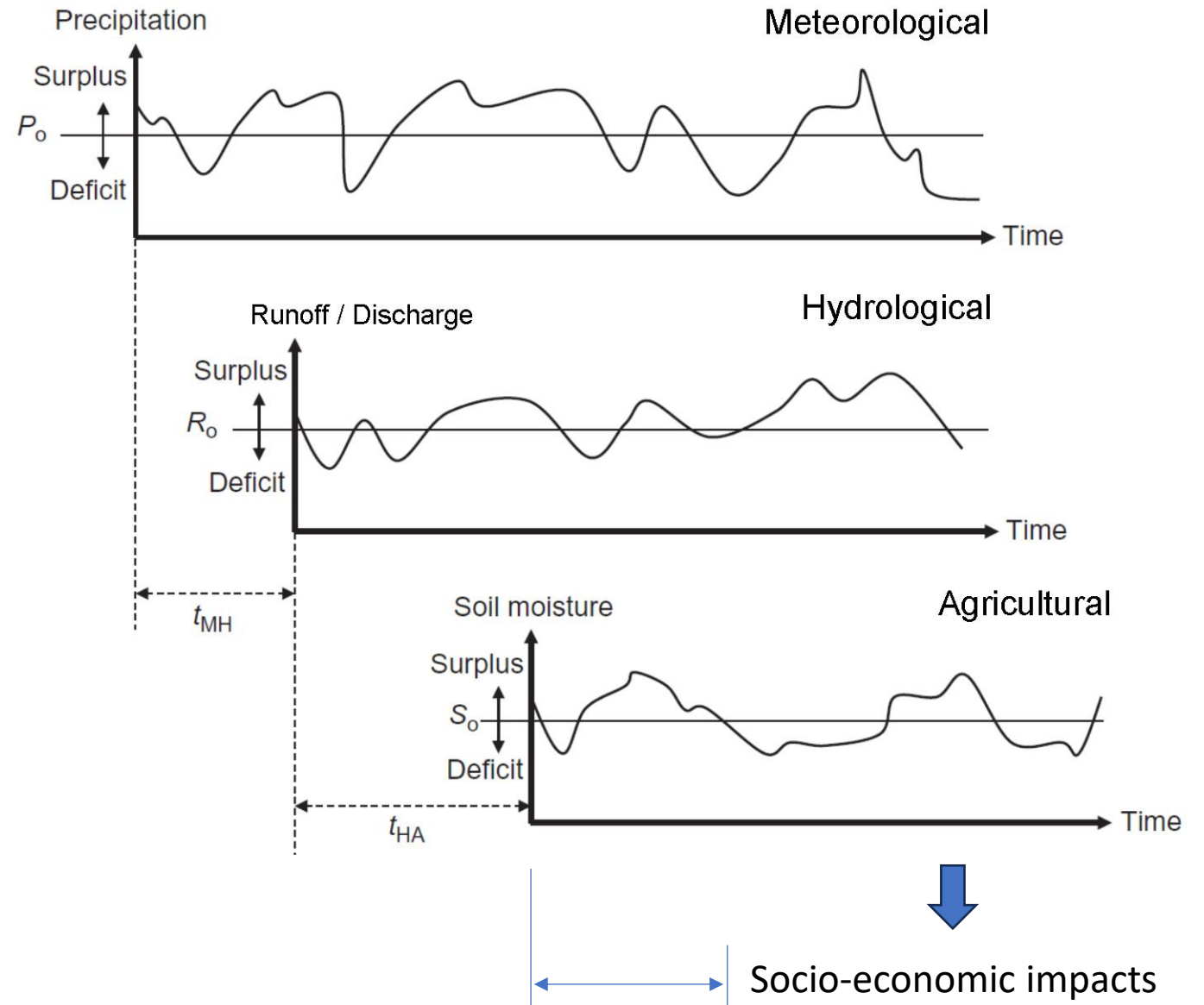
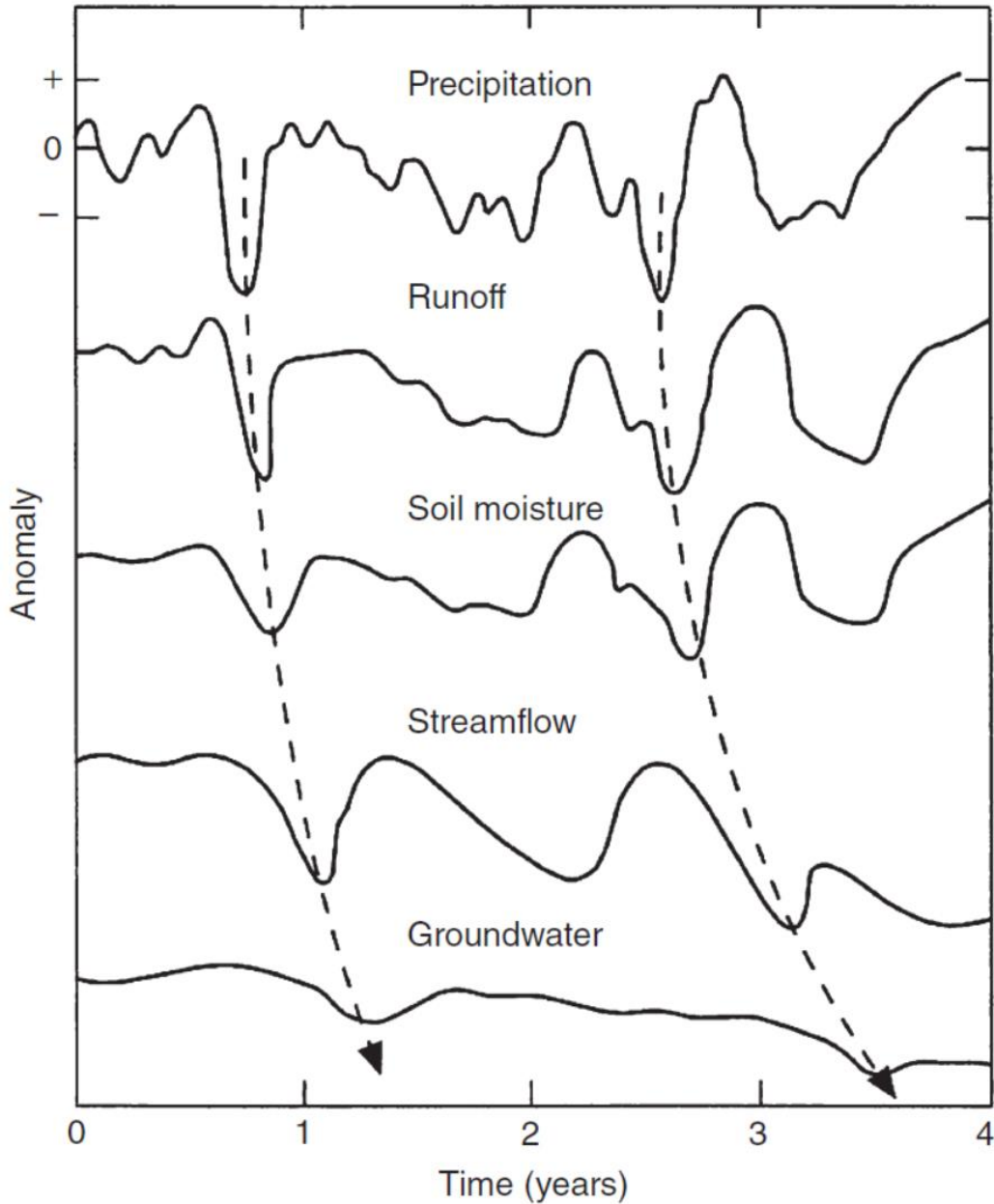


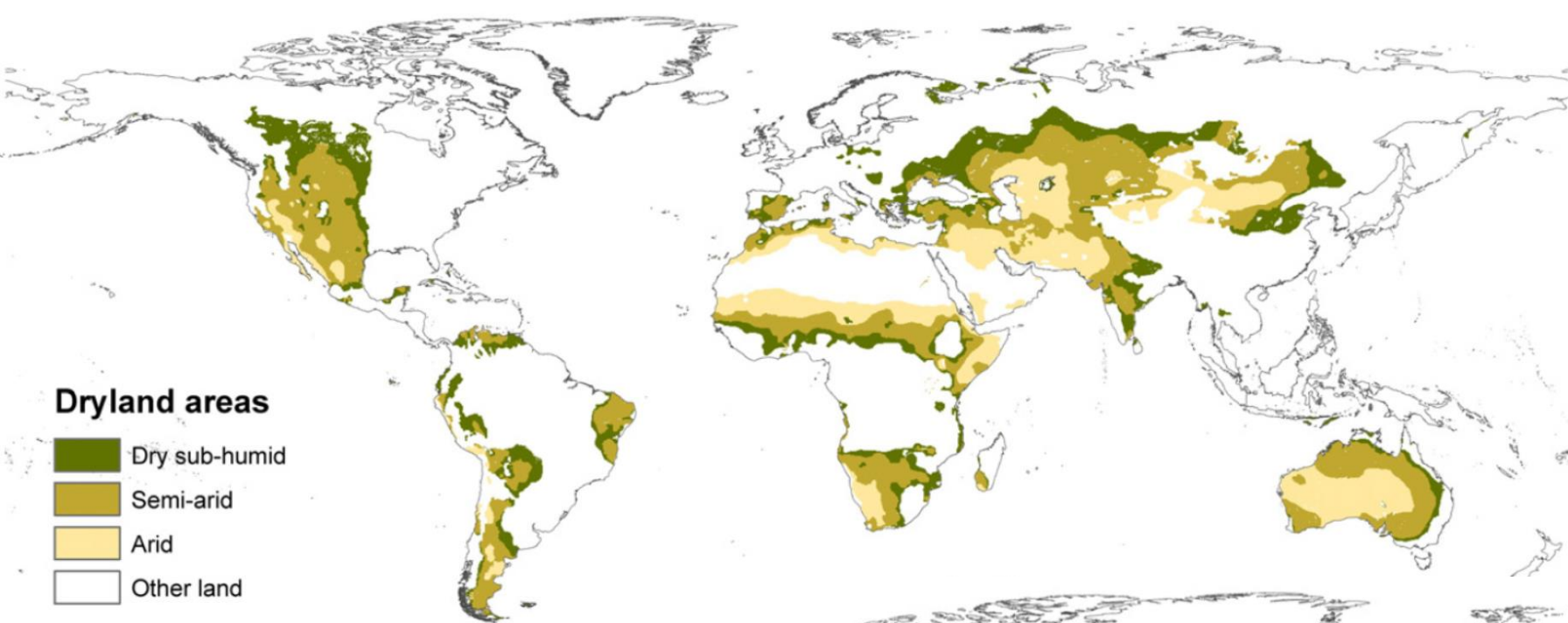
Drought propagation



Scheme representing different categories of drought and their development. (Derived from Peters,⁵³ Van Loon,⁵⁴ Stahl⁵⁵).

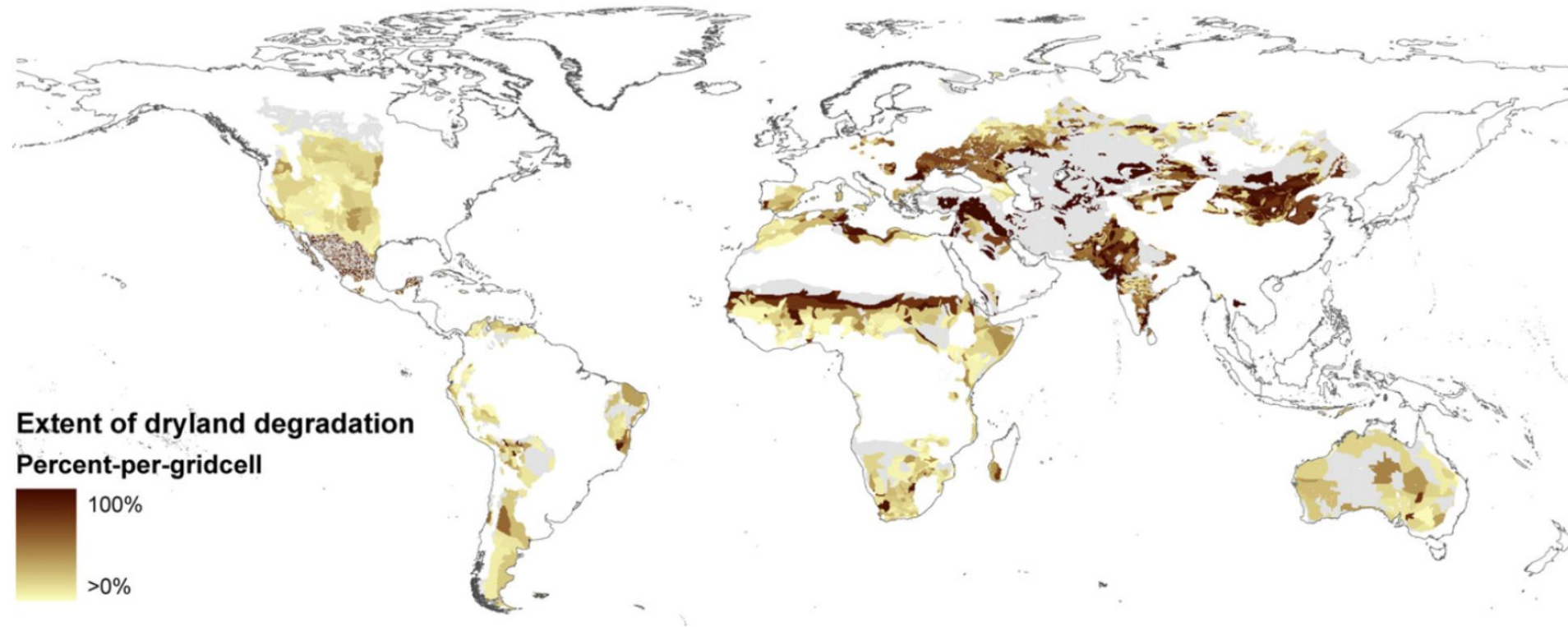
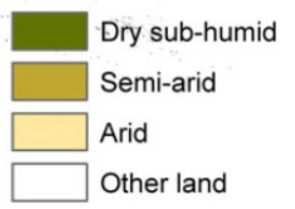
Drought (propagation)



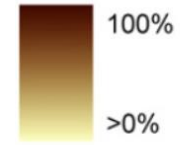


← **Dryland area zones:**
map derived on basis
of the ratio between
annual precipitation
and potential
evapotranspiration

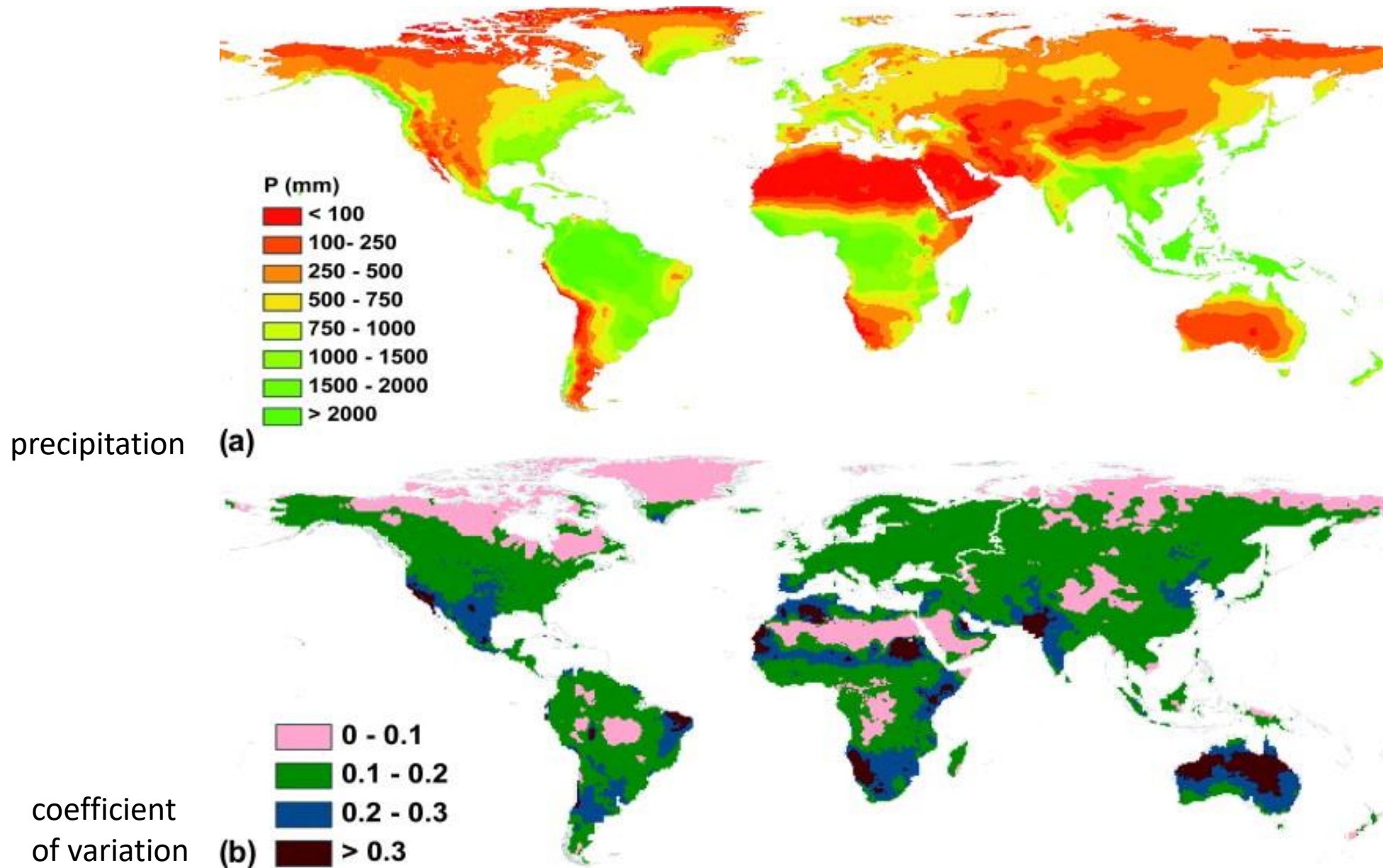
Dryland areas



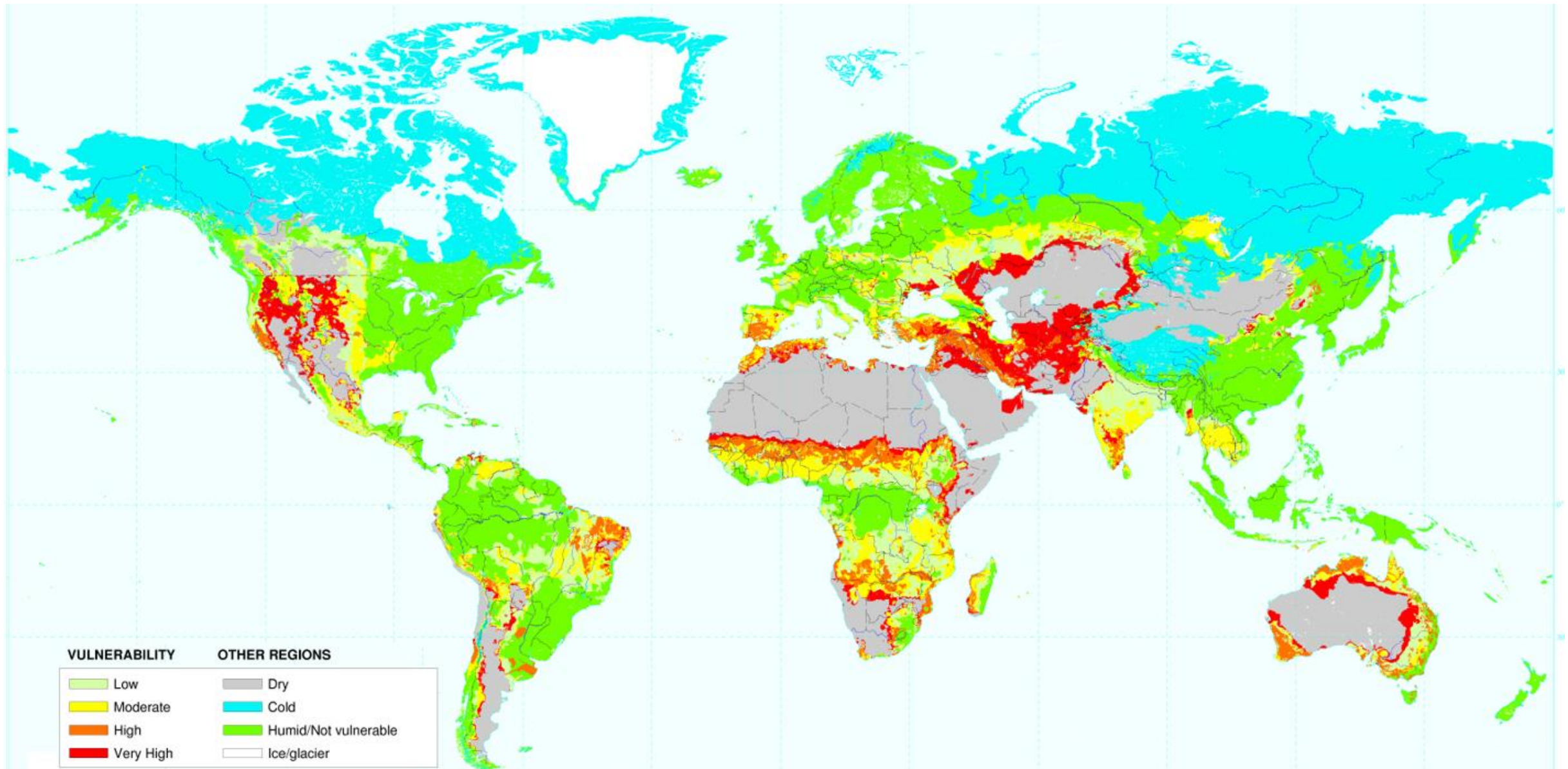
Extent of dryland degradation
Percent-per-gridcell



Natural ecosystems get most water from precipitation



Risk of desertification (vulnerability map)



Map of climate zones

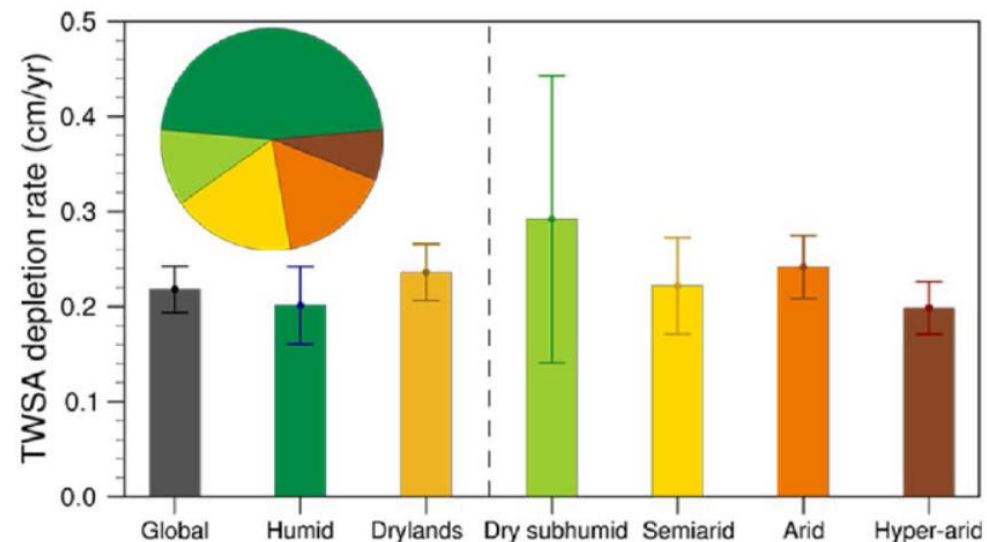
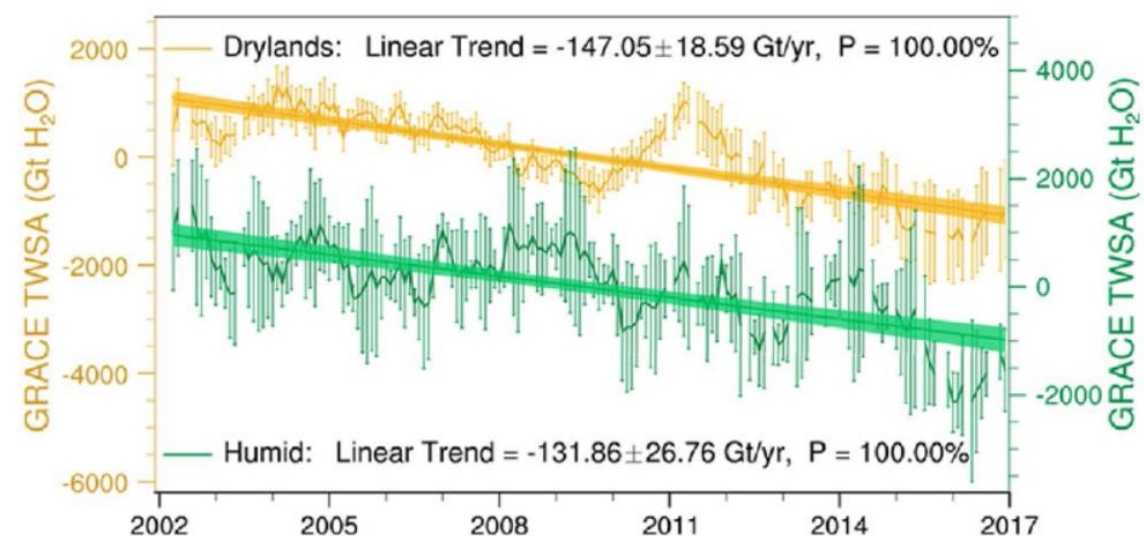
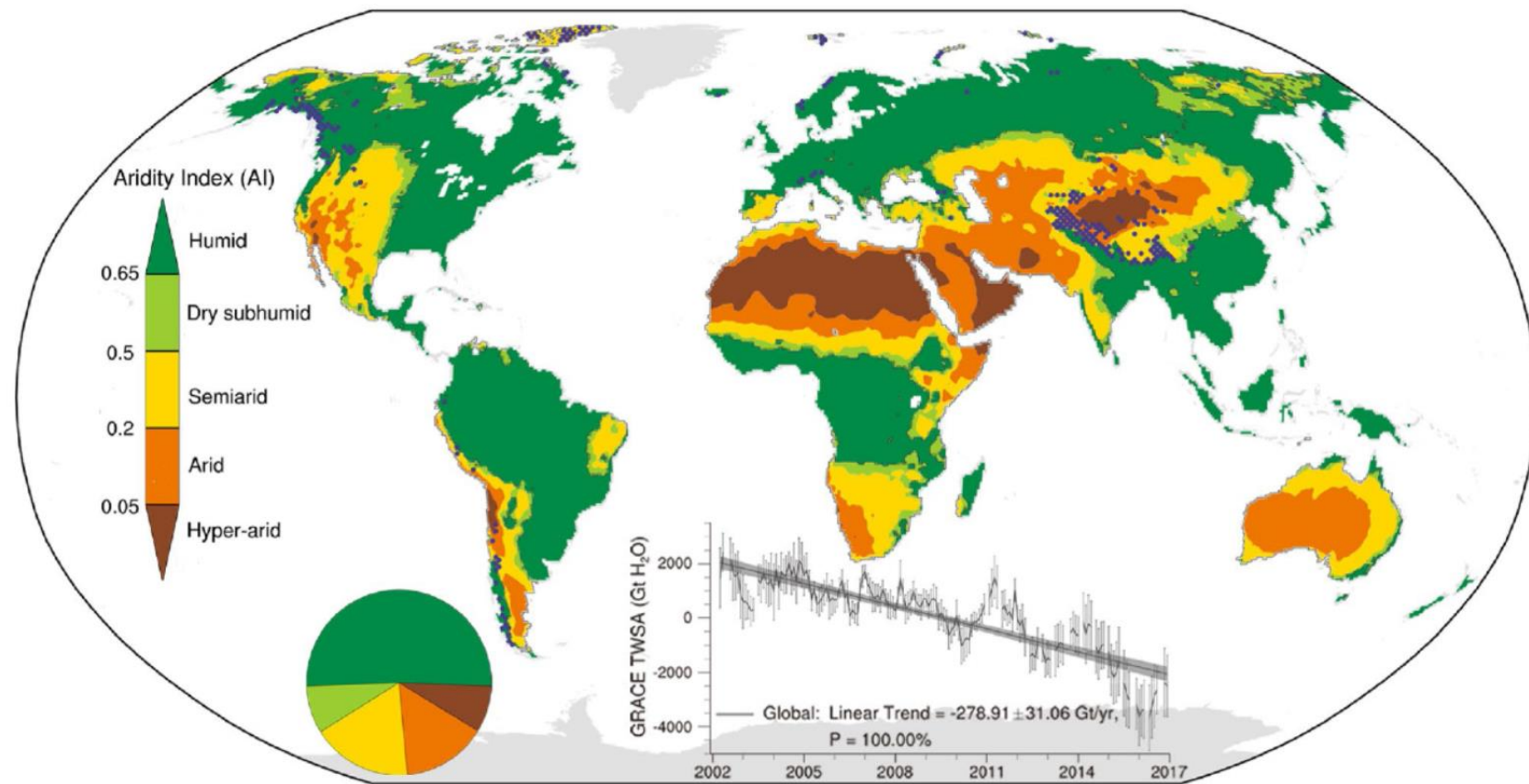
based on the long-term Aridity Index (1961–1990), with pie chart illustrating the proportions of global land area for each climate zone.

Blue dots → glacierized regions.

TWSA – **total water storage** anomaly

TWS has decreased during last several decades

Time series illustrates monthly (deseasonalized) TWS anomalies



Drying of humid/boreal areas → organic C mineralization

- during long-term humid conditions substantial amount of organic C has accumulated in tropical rain forest, in wetlands, in taiga; even in permafrost there is lot of organic C stored (considering global scale)
- organic C turnover proceeds through 1. soil respiration, 2. methanogenesis, 3. soil erosion (physical detachment and transfer of particles → aeration of deeper parts of soil), or 4. via leaching (in liquid form → important in peatland – rapid turnover upon drying)
- soil moisture level is high in the ecosystems with long-term humidity; high portion of soil pore system is filled with water; as soil water content decreases → soil respiration intensity increases
- on global scale soil respiration is the main mechanism of soil organic C turnover → loss in form of CO₂
- in wetlands or thawing permafrost (or in the sediments containing organic C and saturated with water) anaerobic methanogenic bacteria produce CH₄

Drying of humid/boreal areas → organic C mineralization

Bond-Lamberty and Thomson (2010),
Temperature-associated increases in the global
soil respiration record.

- global respiration (the flux of microbially and plant-respired carbon dioxide) increased by 0.1 Pg C yr^{-1} between 1989 and 2008

1 petagram (Pg) = 10^{15} grams

0.1 Pg = 100 million tons

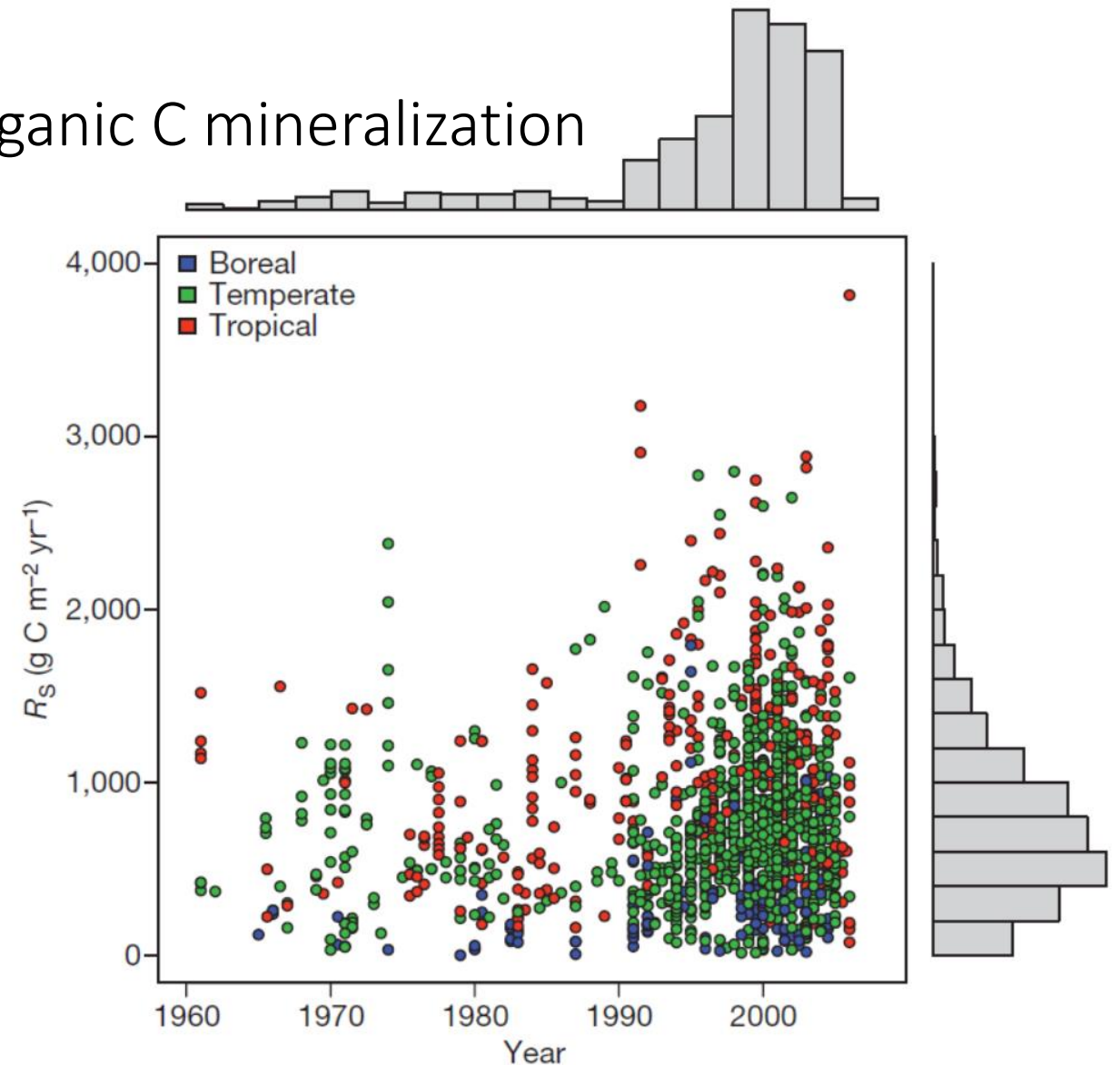


Figure 1 | Collected data on observed R_s , by biome. The 'boreal' biome includes Arctic and high-altitude studies. The histograms show the relative distributions of data along the axes.

Drying of humid/boreal areas → organic C mineralization

Huang et al. 2020, Spatial and temporal variations in global soil respiration and their relationships with climate and land cover.

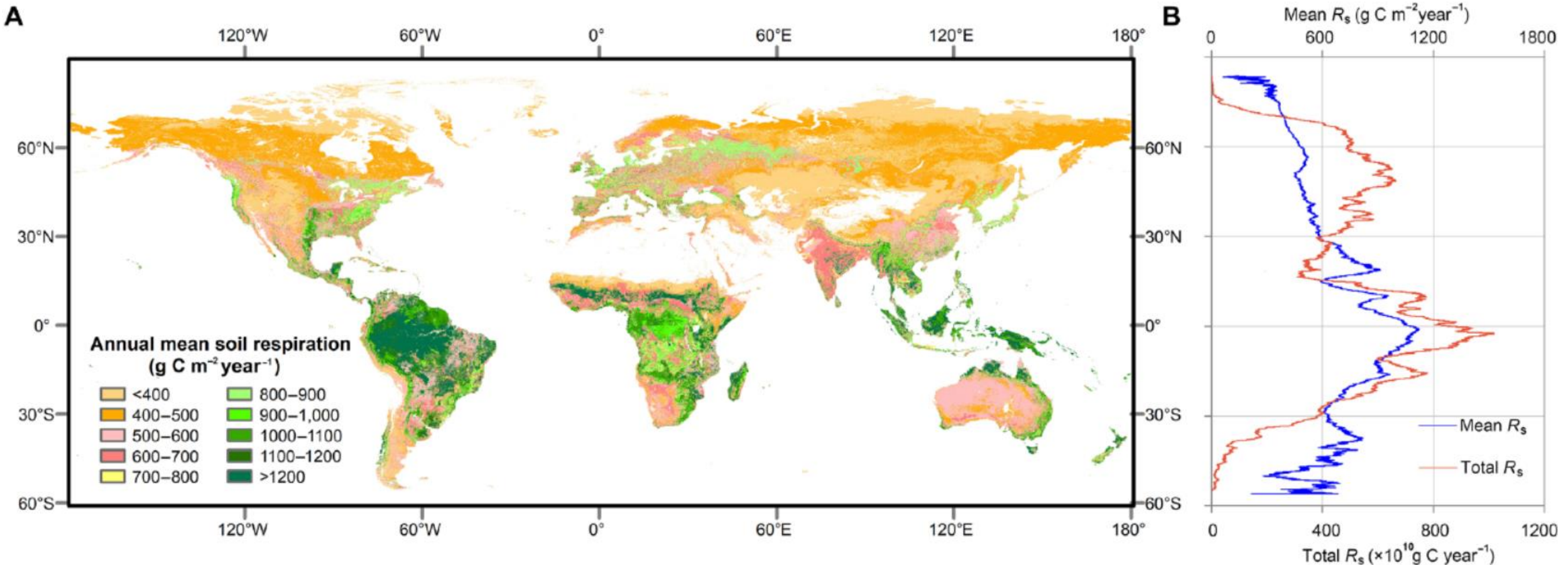


Fig. 1. Global distribution of mean annual R_s between 2000 and 2014. (A) Global map of mean annual R_s at 1 km by 1 km spatial resolution derived using satellite data. (B) Latitudinal distribution of mean annual R_s (blue line) and total annual R_s (orange line). All land grids along a latitudinal row in the global map were averaged to derive mean R_s and summed to derive total R_s .

Huang et al. 2020, Spatial and temporal variations in global soil respiration and their relationships with climate and land cover.

- A) overall trend in annual respiration change over 2000 – 2014 period
- B) spatial trends in respiration change over 2000 – 2014 period
- C) % of area associated with decreasing (green), stable (grey), and increasing (pink) respiration

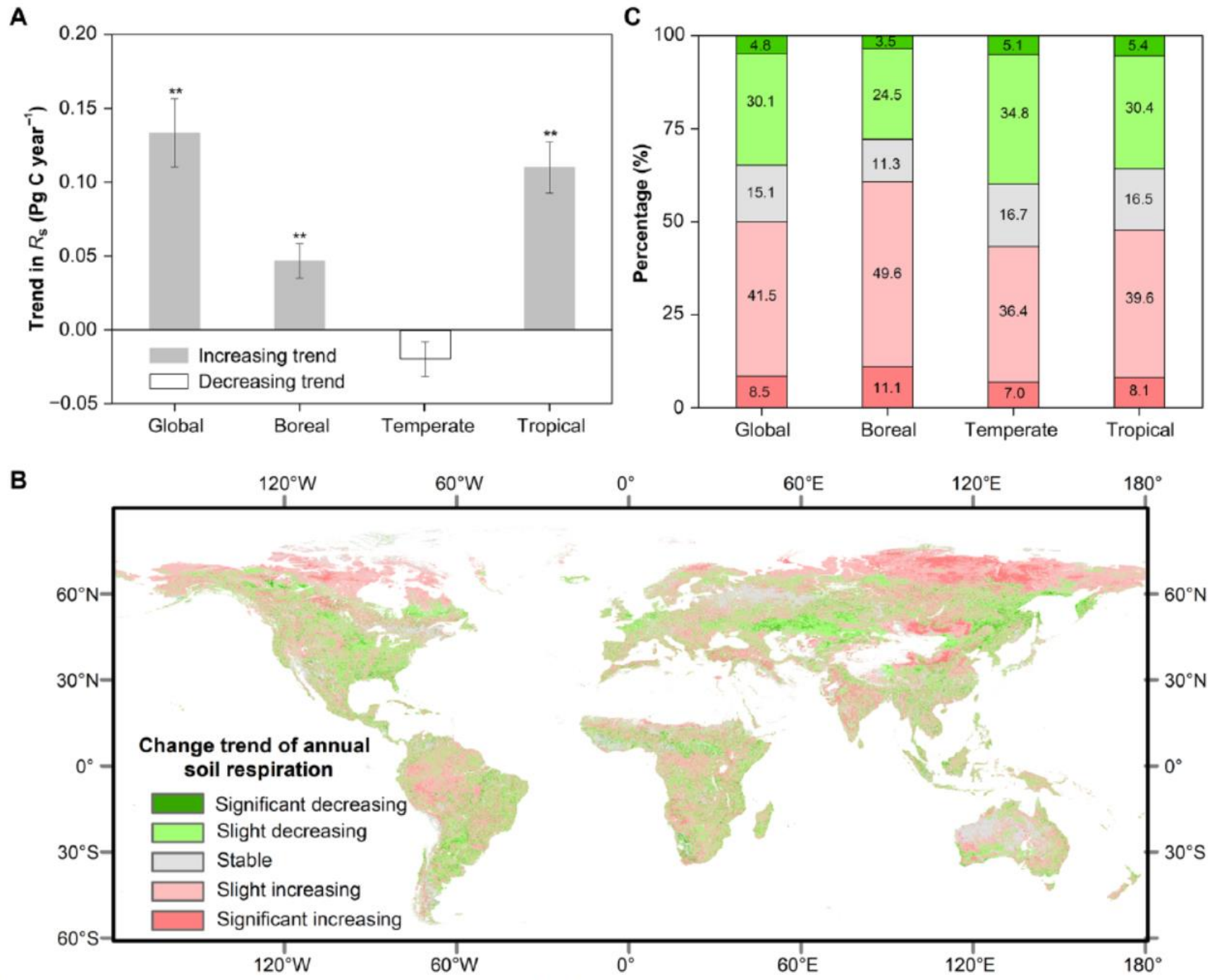


Fig. 2. Trends in annual R_s from 2000 to 2014. (A) Overall trends in annual R_s . To calculate the overall trend at the global scale, global average R_s for each year was first

How much carbon is in the soil? (global estimates)

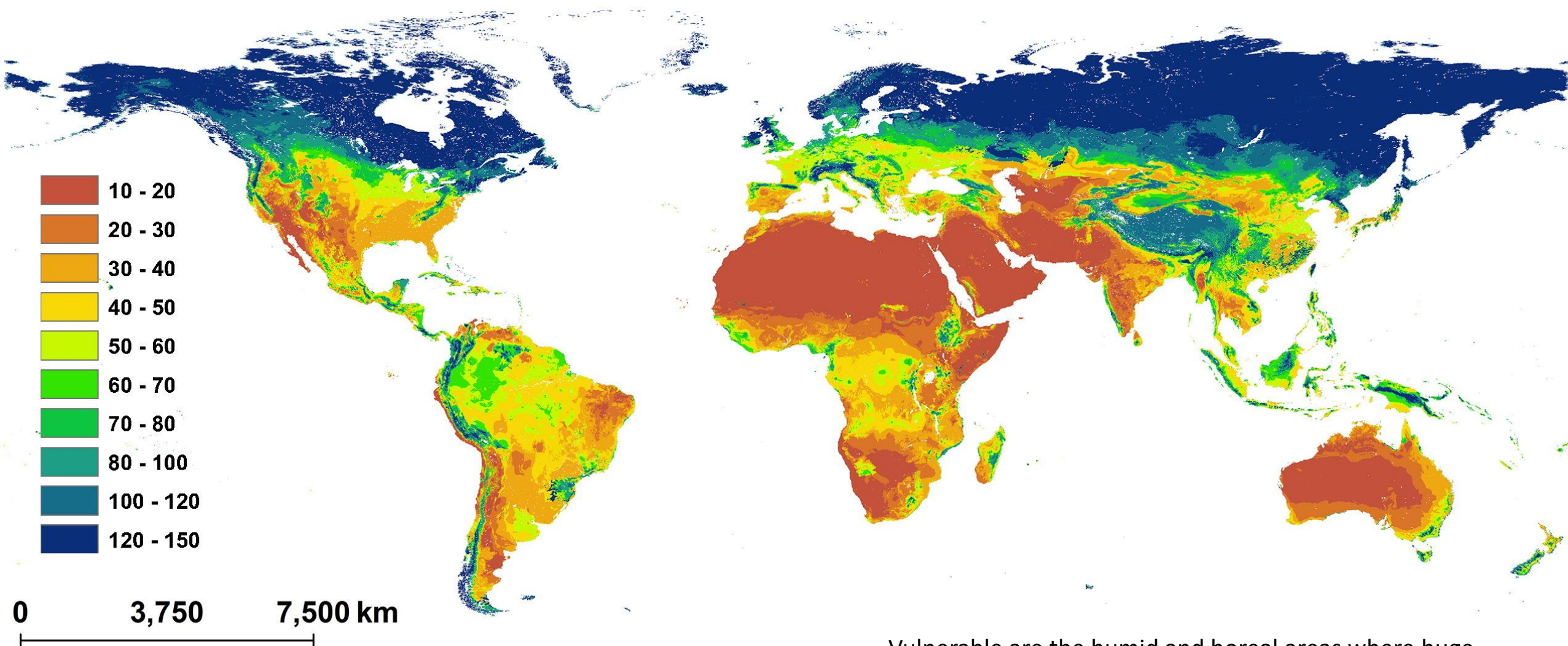
- Organic C – approximately:
 - 684 – 724 Pg (0 – 30 cm)
 - 1 462 – 1 548 Pg (0 – 100 cm)
 - 2 376 – 2 456 Pg (0 – 200 cm)
- Inorganic C (carbonates) – approximately:
 - 695 – 748 Pg (0 – 100 cm)

1 Pg (petagram) = 10^{15} g = 1 billion tons

Although the estimates of soil carbon losses may not seem high, or may be inaccurate in some cases, only few studies reported the opposite trend – an increase in soil organic C content. Vast majority reported net turnover; in other words, on global scale soil organic carbon turnover is much higher compared to soil organic carbon increase.

Degradation / mineralization of soil organic C $\rightarrow$ CO₂ and CH₄ production

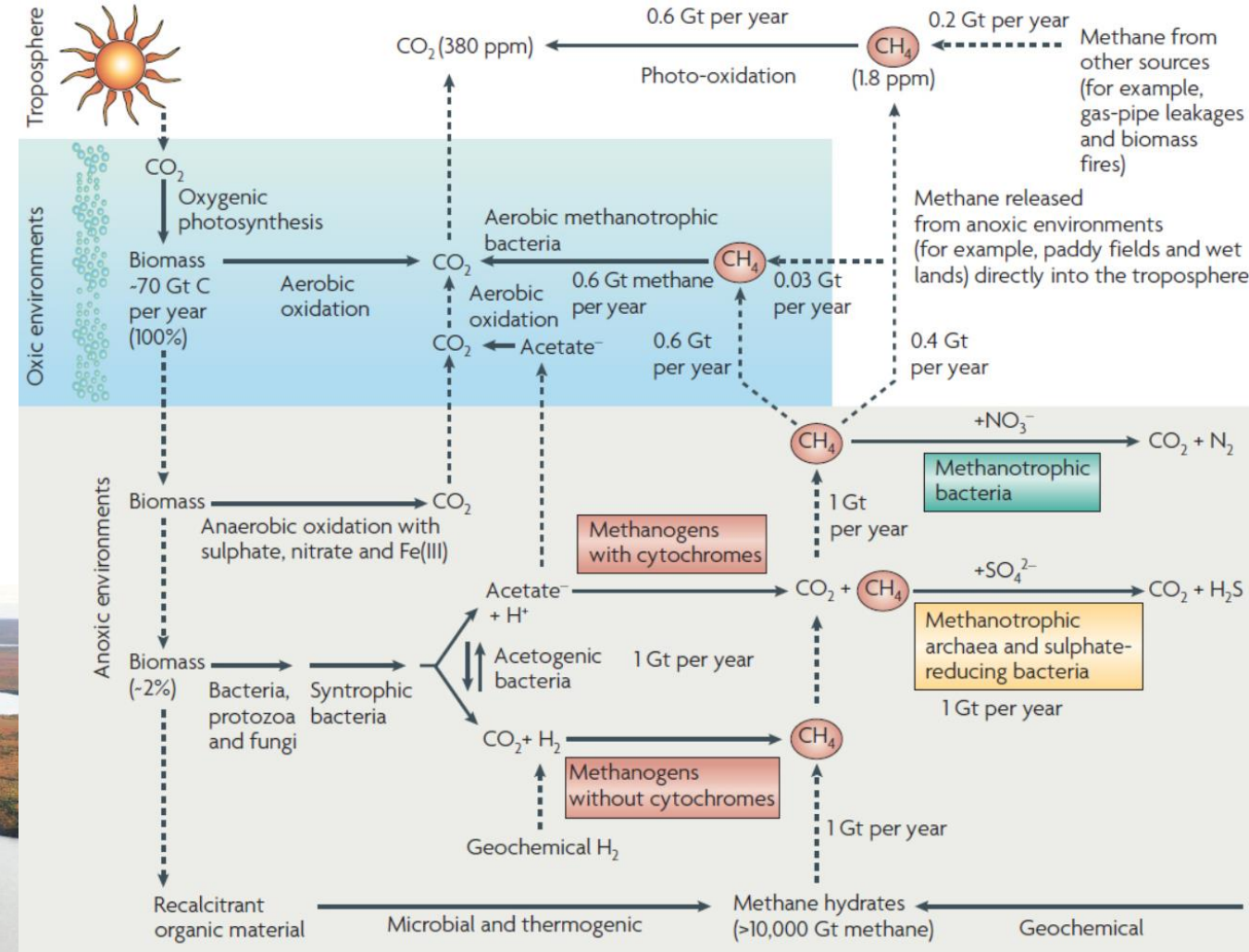
The amount of organic C stored in upper 30 cm of soil – tons per hectare (global estimates)



Minasny et al., 2017. Soil carbon 4 per mille. Geoderma.

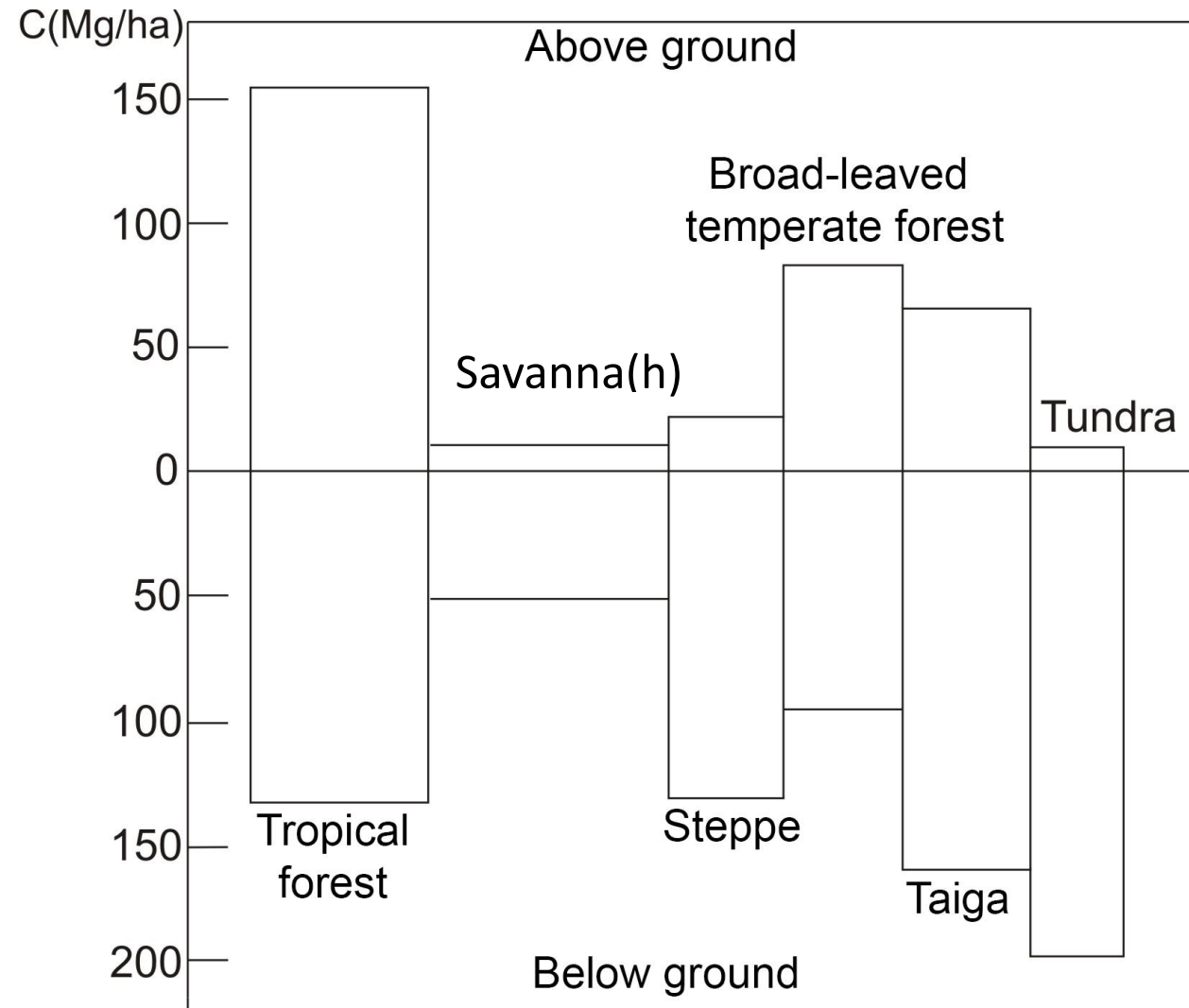
Vulnerable are the humid and boreal areas where huge amounts of relatively labile C are accumulated.

Thawing permafrost → wetland
Wetlands containing higher organic C are producing not only CO₂ but CH₄ as well



Thauer R.K., Kaster A.-K., Seedorf H., Buckel W., Hedderich R., 2008. Methanogenic archaea: ecologically relevant differences in energy conservation. *Nature Reviews Microbiology* 6, 579.

'Vertical' distribution of organic C in the various ecosystems



Soil salinity and sodicity

- accumulation of highly soluble salts in near-surface part of the soil
water evaporates → salts remain in the soil
- occurrence:
arid areas, where annual evapotranspiration >> rainfall
lowlands with shallow water table
subsurface water with higher concentration of dissolved salts
- the problem are sodium salts (NaCl , Na_2SO_4 , NaHCO_3 , $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$, $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$), because of osmotic effect → most plants and microorganisms can not use/utilize water with high concentration of Na salts
additionally, sodium salts cause collapse/deterioration of soil structure
- salinity: accumulation of highly soluble salts
- sodicity: accumulation of highly soluble **sodium** salts

- higher concentration of sodium salts in soil solution imposes stress (physiological drought) for the majority of terrestrial plants and soil microorganisms
- additional negative factor: toxicity of Na, Cl and B

measurement / indicator → electrical conductivity (mS cm^{-1})

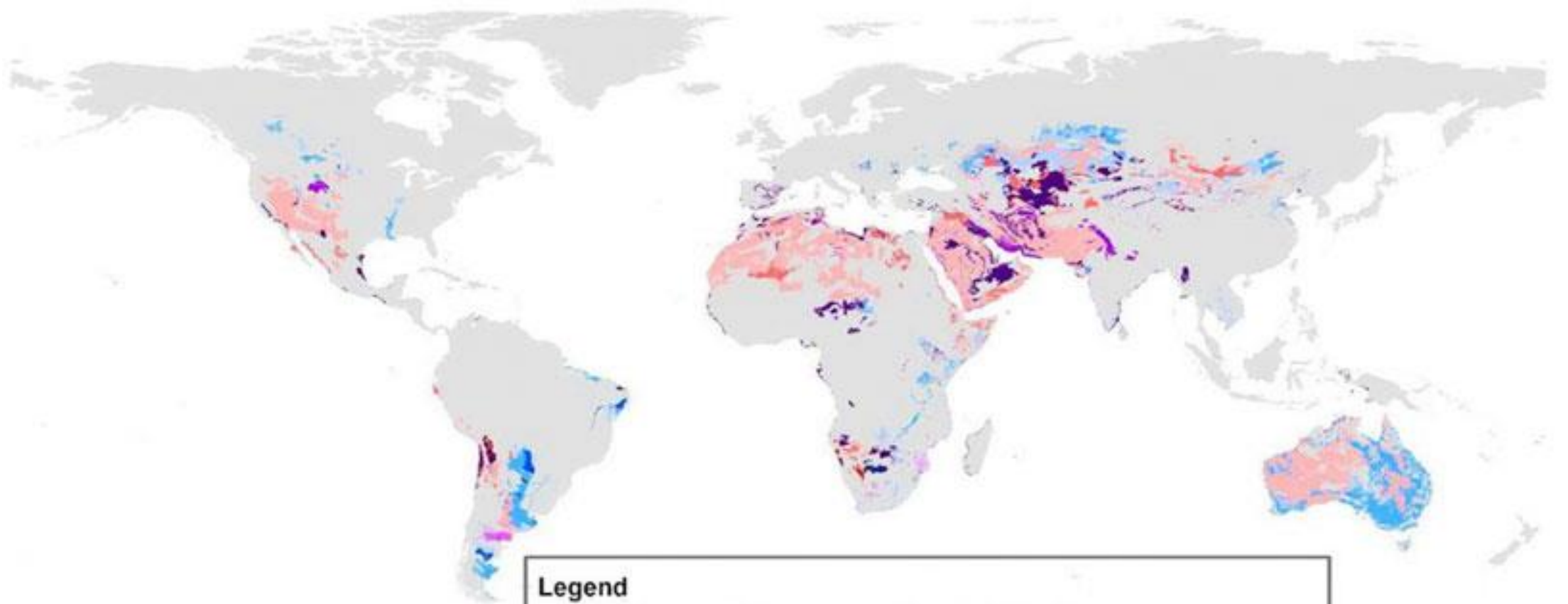


prismatic soil structure

note: cracks in dry soil are not caused by salinity or sodicity;
some clay minerals in soil (smectites) change their volume
with change in soil water content; these swell upon wetting
and shrink upon drying



Global distribution of salt-affected soils

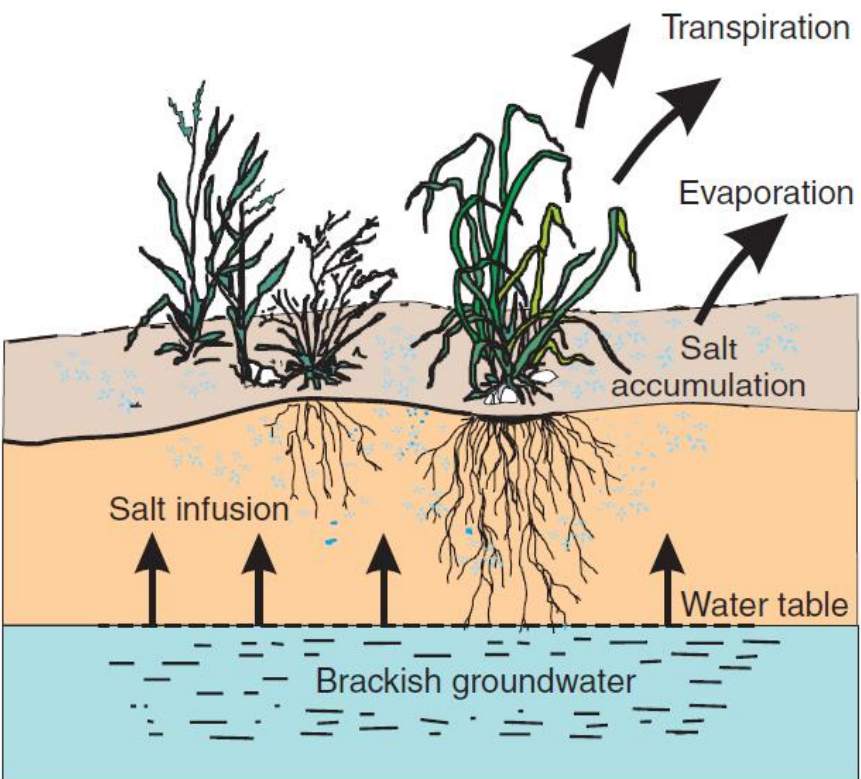
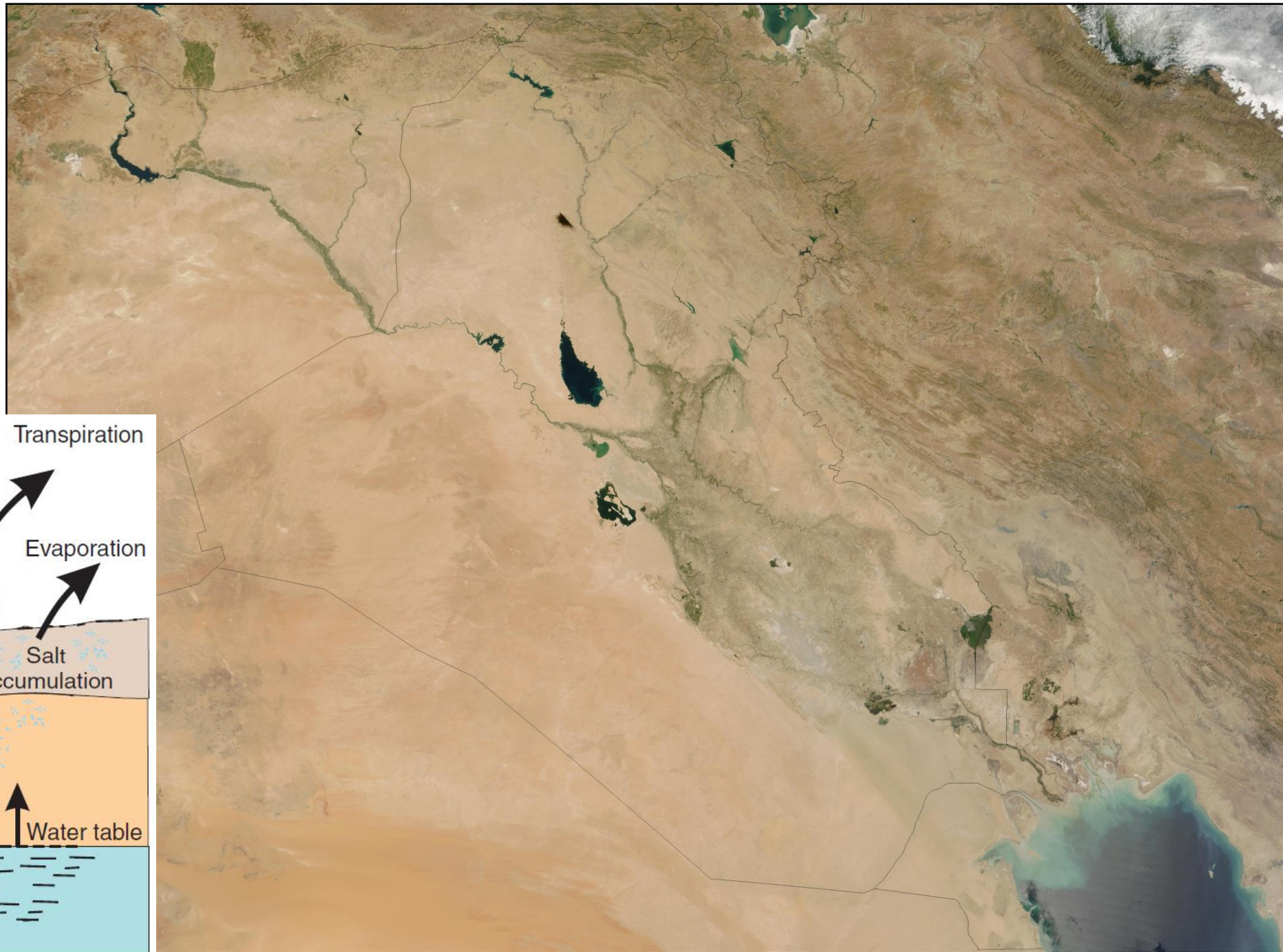


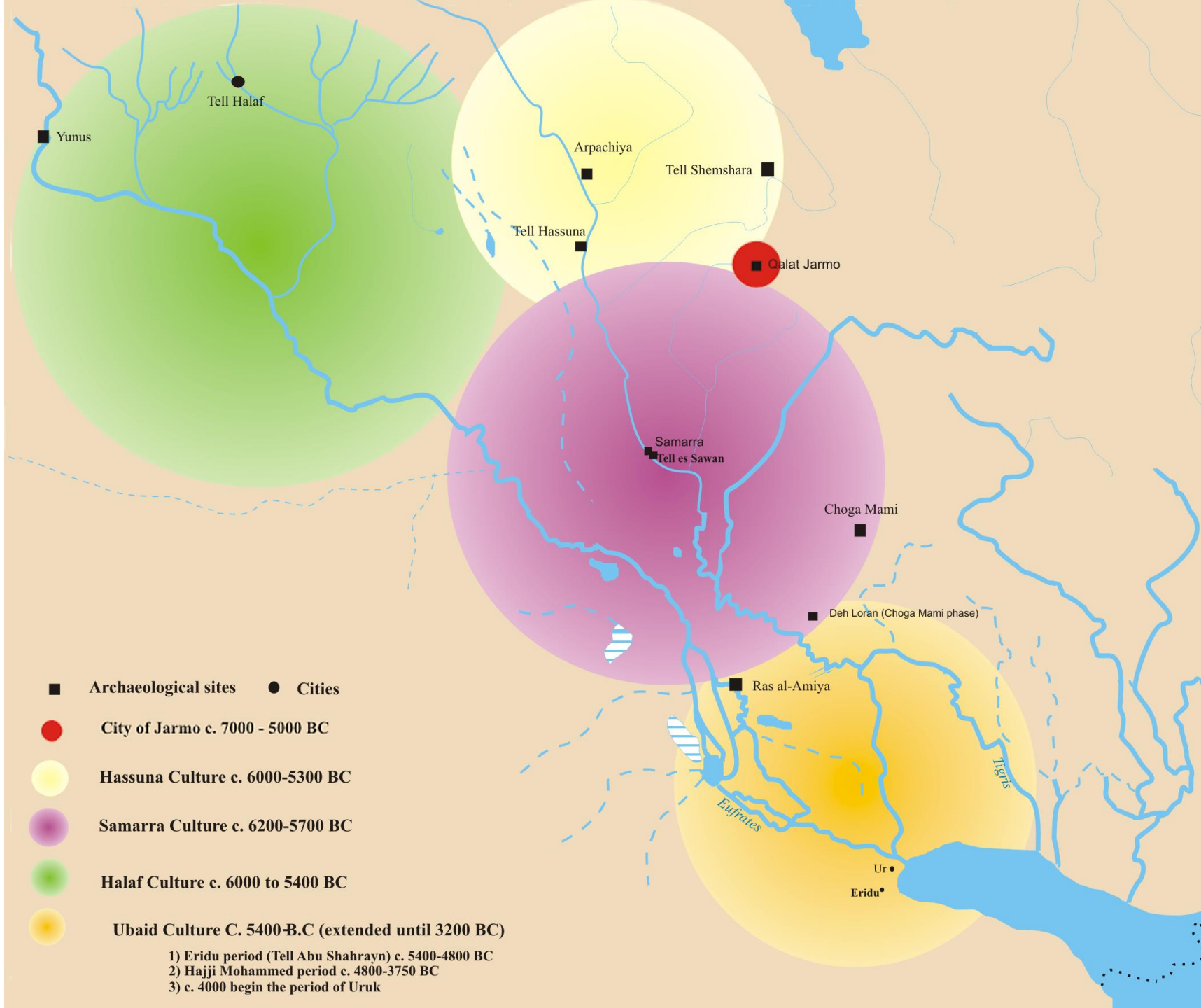
Legend

Type and severity levels of salt-affected soils

 saline slight	 sodic slight	 saline-sodic slight
 saline moderate	 sodic moderate	 saline-sodic moderate
 saline high	 sodic high	 saline-sodic high
 saline extreme	 sodic extreme	 saline-sodic extreme

Mesopotamia



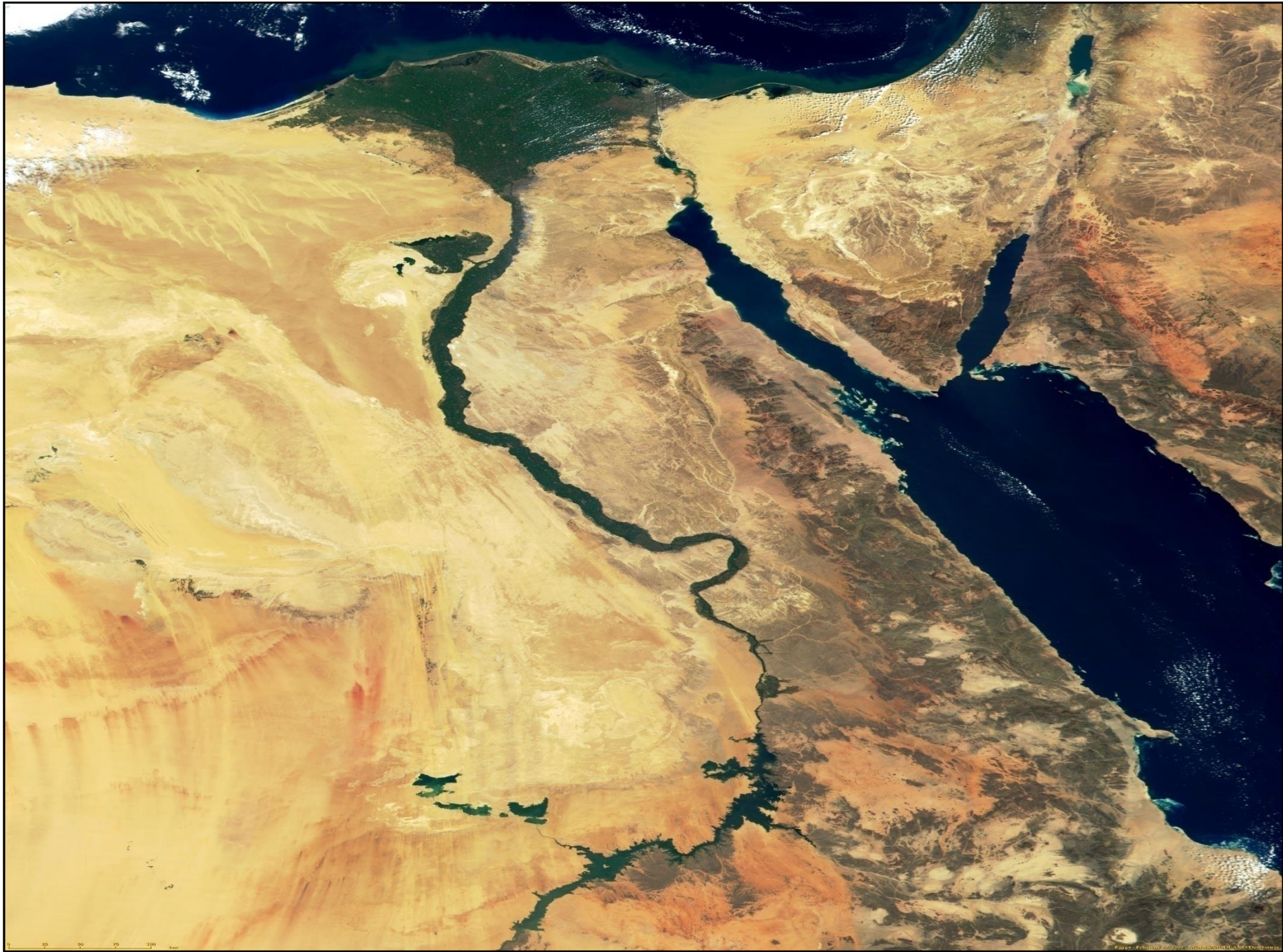


Ancient Mesopotamia

The main constraint to crop production in this arid valley is obviously water (quality and quantity). Fortunately, water is abundant in the twin rivers, the Euphrates and the Tigris. However, the diversion of river water onto valley land led to a series of interrelated problems. The first problem was sedimentation. Early in history, the upland watersheds of the twin rivers were deforested and overgrazed. Erosion resulting from seasonal rains proceeded to strip off the soil of sloping uplands and pour it into the streams. As the floodwaters wound their way toward the lower reaches of the valley, the sediment settled along the bottoms and sides of the rivers, raising their beds and banks above the adjacent plain. During periodic floods the rivers overtopped their banks and inundated large tracts of land. The second insidious problem was salt. It resulted from the inexorable rise in the water table, which, in the absence of adequate drainage, naturally follows the flood irrigation of low-lying lands. Elevated rivers continually seep into the groundwater. So do diversion canals and distribution ditches. Finally, irrigation itself causes seepage from the entire surface of the land. Since all irrigation waters contain dissolved salts, and since crop roots normally exclude salts while extracting soil moisture, the salts tend to accumulate in the soil. Unless leached out, the salts eventually poison the root zone.

In arid regions, natural rainfall is generally insufficient for annual leaching; irrigation must hence be applied in excess of crop water requirements so as to remove Na salts by downward percolation beyond the root zone. For some years or even generations, the processes of groundwater salination and water table rise are invisible and go unnoticed. Then, when the water table comes close to the ground surface, a secondary process of capillary rise comes into play. The rising groundwater evaporates at the surface, thus infusing the topsoil with salt. The civilizations (Sumer, Akkad, Babylonia, and Assyria) each in turn rose and then declined, as the center of population and culture shifted over the centuries from the lower to the central to the upper parts of the valley. (Hillel D., 2004. Introduction to Environmental Soil Physics)

Egypt



Ancient Egypt

There are differences in soil and water regimes in the two river valleys. Neither clogging by silt nor “poisoning” by salt was as severe along the Nile as in the Tigris–Euphrates valley. The silt of Egypt is delivered by the Blue Nile from the volcanic highlands of Ethiopia, and it is mixed with the organic matter delivered by the White Nile from its swampy sources. It was not so excessive as to choke the irrigation canals, but it was fertile enough to add nutrients to the fields. Whereas in Mesopotamia the inundation usually comes in the spring and summer evaporation tends to make the soil saline, the Nile crests at a much more favorable time: after the summer heat has killed the weeds and aerated the soil, and in time to wet the soil for the prewinter planting. The narrow floodplain of the Nile (except in the Delta) precluded the widespread rise of the water table. The water table was controlled by the stage of the river, which, over most of its length, normally lies below the level of the adjacent land. When the river inundated the land, the seepage naturally raised the water table. As the river’s level dropped, it pulled the water table down after it. This annual pulsation of the river and the associated fluctuation of the water table under a free-draining floodplain created an automatically self-flushing cycle by which the salts were leached from the soil and carried away by the Nile itself.

Unfortunately, the soil of Egypt is now threatened with degradation. The Aswan High Dam has blocked the fertile silt that had formerly been delivered by the Nile. Hence Egyptian farmers must rely increasingly on chemical fertilizers. The river, now running clear of silt, has increased its erosivity and has been scouring its own banks. Along the estuaries of the Delta there is no more deposition, so coastal erosion has begun, along with seawater intrusion. The artificial maintenance of a nearly constant water level in the river, needed to allow easy pumping of irrigation water throughout the year, has resulted in raising the water table and making drainage more difficult. (Hillel D., 2004. Introduction to Environmental Soil Physics)

Examples of civilizations affected by drought and related processes

- Mayans prospered from 550 up to app. 770 y AD; drought that occurred between 810 and 910 AD in the Yucatan peninsula in Mexico, was probably linked to collapse of Mayan civilization
- Hittite civilization collapsed around 1198–1196 y BC partially due to the drought impact
- there are records documenting that during Byzantine Empire between 200 and 300 y AD several cities were buried by sands (obviously sandstorms, wind erosion and sand dune movement are not caused directly by drought, but their occurrence is characteristic for arid regions)
- others...

Desertification in Africa during Neogene

Senut et al. (2009)

approximate annual precipitation:

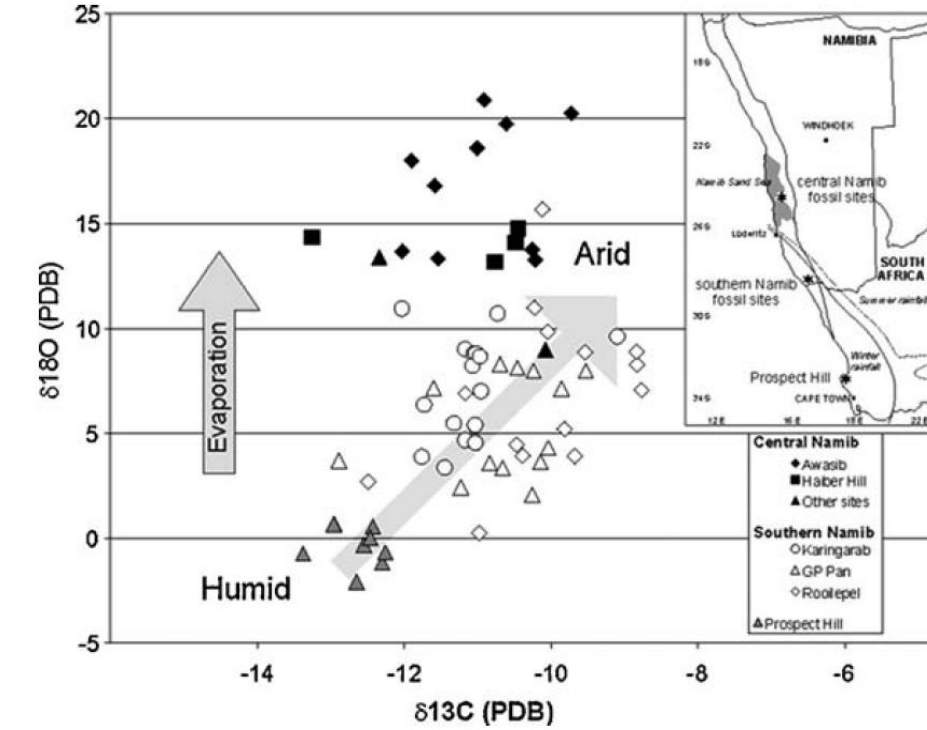
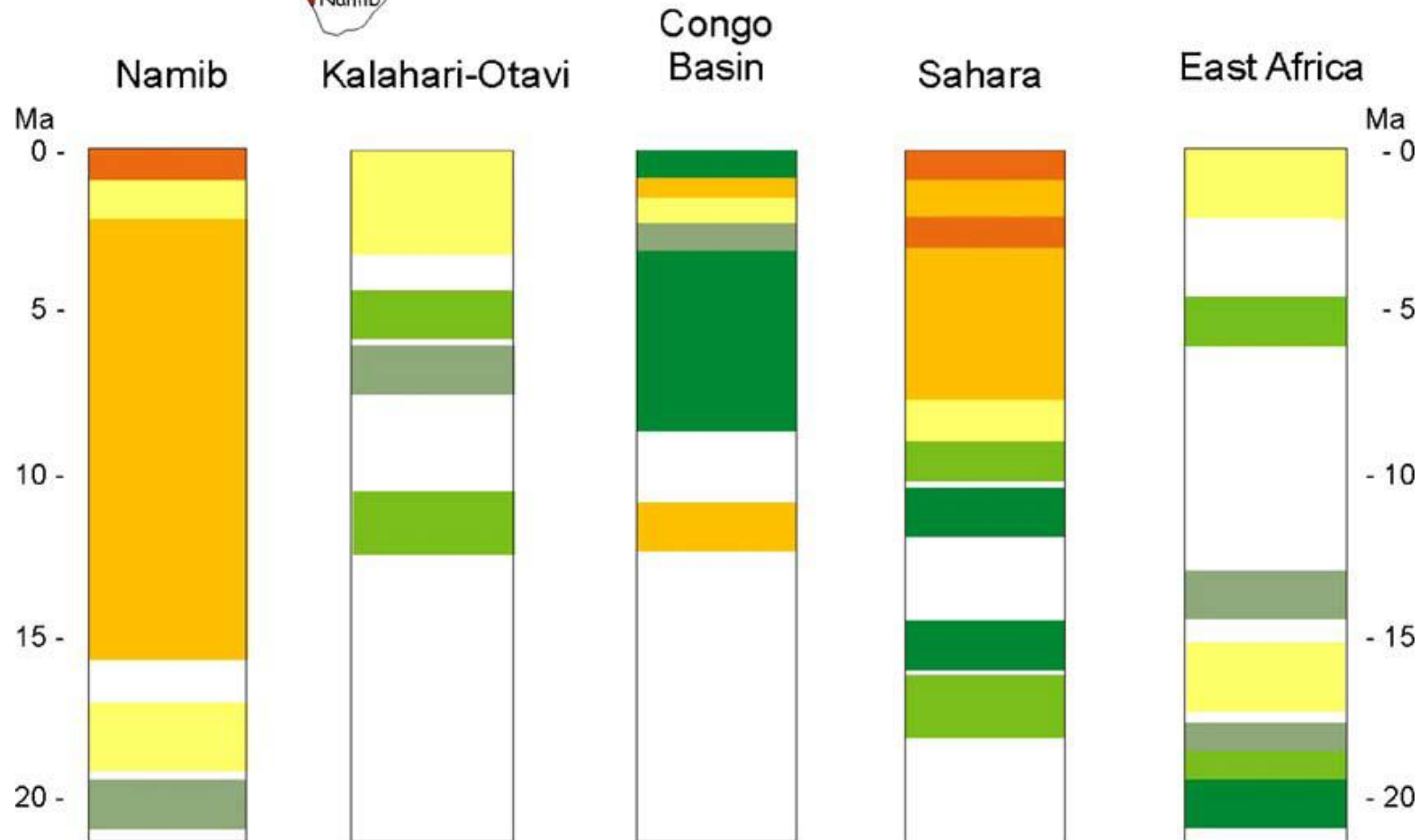
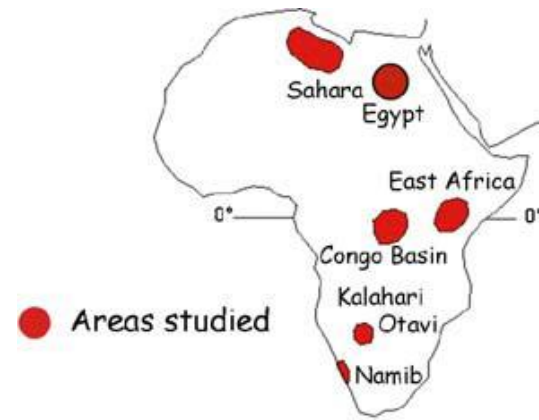


Fig. 4. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of *Diamantormis wardi* eggshells (10–12 Ma) from Prospect Hill (South Africa) and Namib Desert sites.

- results of paleoclimatic studies suggest that even desertification can be reversible
- currently, however, the global extent of desert areas increases

Reclamation of saline/sodic soils

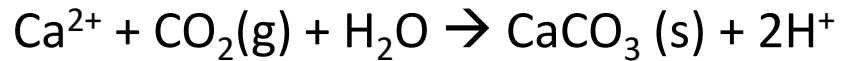
- saline/sodic soils cannot be reclaimed solely by fertilizers or soil amendments
- availability of adequate amounts of **low-salt irrigation water is needed**
- internal soil **drainage must be established**
- important parameter – sodium adsorption ratio (SAR), can be calculated either for soil solution or for irrigation water; it relates the amount of sodium relative to calcium and magnesium in water

$$SAR = \frac{[Na]}{\sqrt{[Ca + Mg]/2}}$$

- if $SAR < 3 \rightarrow$ quality of irrigation water is “safe” considering sodicity hazard
- if only soil salinity is the case (no sodicity) $\rightarrow$ no soil amendments are needed, “only” low-salt water and soil drainage (even these conditions are hard to fulfill in arid areas)
- generally, the amount of water required to remove 70 to 80 percent of salt is proportional to given soil depth (for example, 15 cm water column is needed to remove 70-80% of salts from 15 cm of soil depth)

Reclamation of saline/sodic soils

- in case of sodicity the soil treatment involves use of chemicals (gypsum, lime, CaCl_2 , sulfur)
- gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is perhaps the most used amendment for sodic soil treatment
- the process is based on ion-exchange reactions in soil:



pH decreases to 7.5 – 8; concentration of Ca^{2+} increases, which replaces Na^+ that is subsequently washed away

- the amount of gypsum required (GR , Mg ha^{-1}) can be calculated using following equation:

$$\text{GR} = 0.0086 \ F \ D_s \ \rho_b \ \text{CEC} \ (\text{ESP}_i - \text{ESP}_f)$$

where F is the Ca-Na exchange efficiency factor (unitless), D is the soil depth to be reclaimed (m), ρ_b is the soil bulk density (Mg m^{-3}), CEC is the cation exchange capacity (cmol kg^{-1}), ESP_i and ESP_f are the initial and final ESP values; ESP stands for exchangeable sodium percentage (ESP)

$$\text{ESP} = 100 \left(\frac{\text{Na}_{\text{exch}}}{\text{CEC}} \right)$$