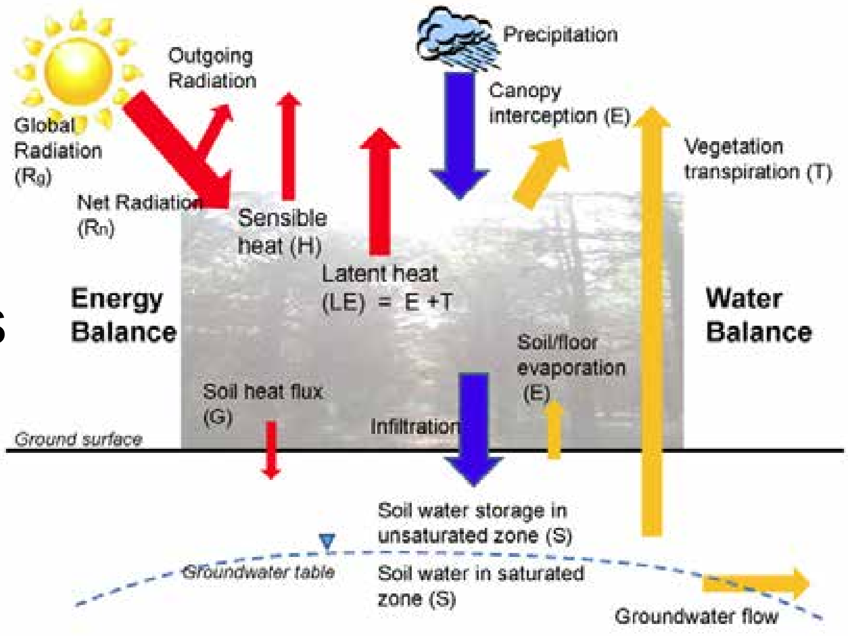
Terrestrial H_2O and Energy Balance

- Objectives
  - To gain a basic understanding of:
    - Terrestrial ecosystem energy balance
    - Terrestrial ecosystem hydrologic balance

Terrestrial H_2O and Energy Balance

- H_2O & Energy balances are **very** interdependent
  - –Conservation of energy/mass
  - –Solar energy is the base of energy balance, and also drives hydrologic cycle
    - •**Evapotranspiration (i.e., LE)**
  - –Hydrologic cycle accounts for ~80% of turbulent energy transfer from surface to the atmosphere
    - •**Evapotranspiration (i.e., LE)**



(Sun *et al*. 2010)

Terrestrial H_2O and Energy Balance

- H_2O cycle exerts large control on biogeochemical cycles
  - Influences biotic processes
  - Dissolution/transfer of nutrients within/among ecosystems

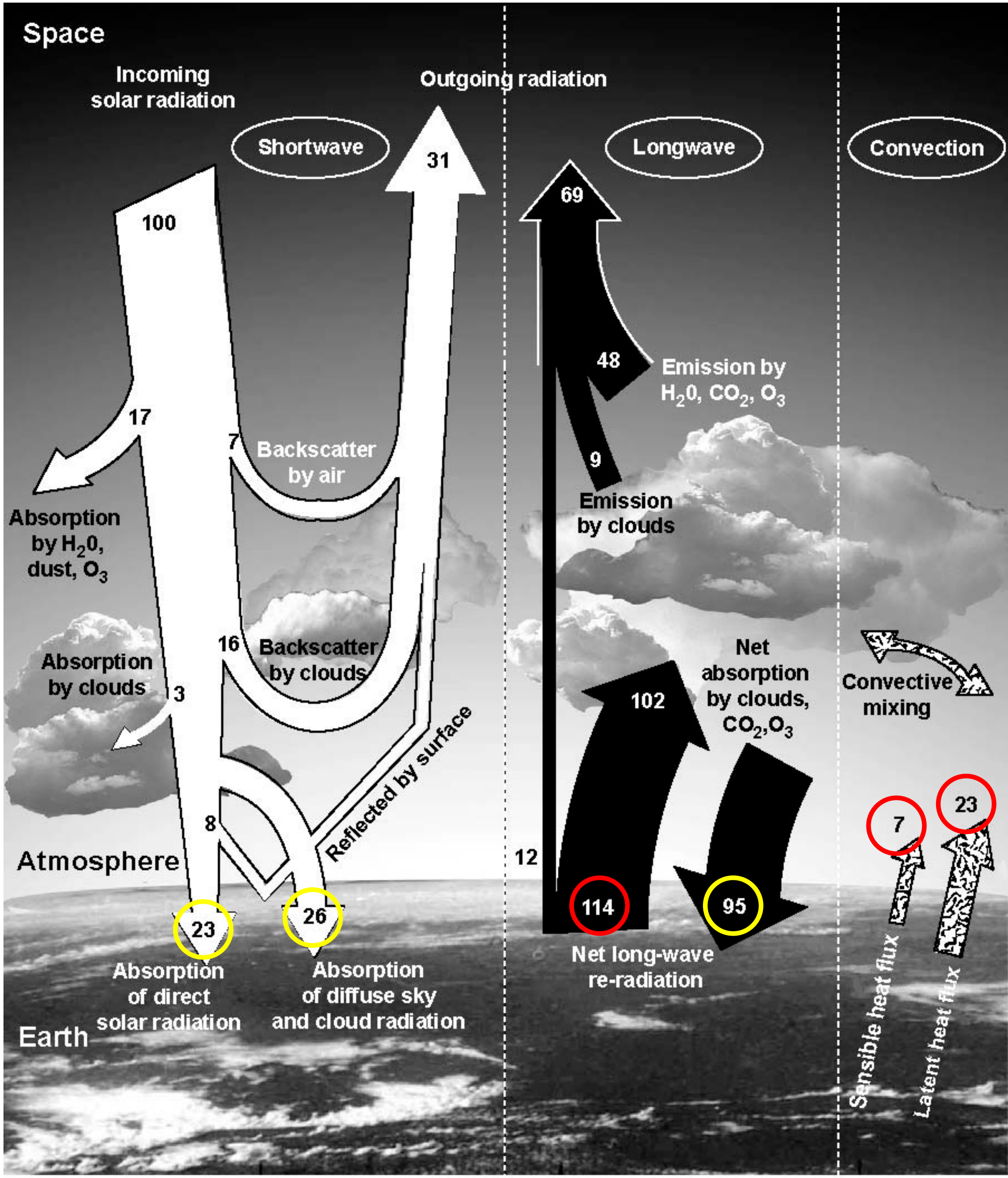
- Humans have greatly modified the hydrologic cycle
  - Use ~50% of readily available fresh water (70% by 2050)
  - Decreased streamflow & groundwater supplies
  - Regional and global climate impacts of LULC change
  - Sea level rise (thermal expansion and melting of ice)
  - “Water vapor feedback”

- Critical to understand the controls over energy and water exchange (i.e., budgets)

- Energy budget of an ecosystem can be viewed much as we did for the Earth system

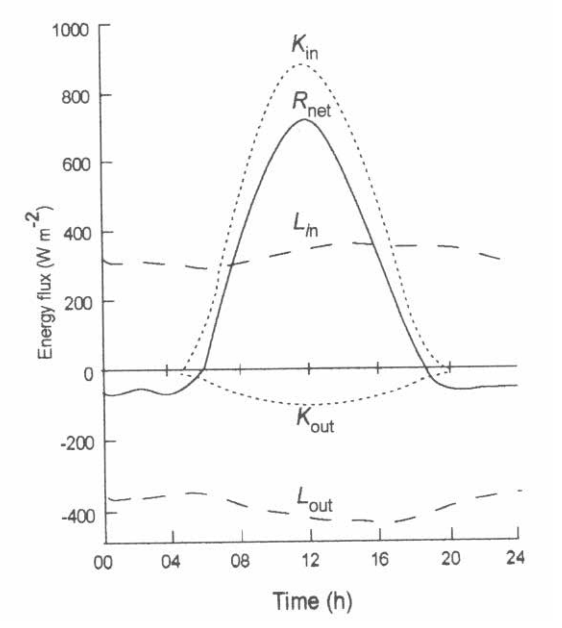
In = Out

23+26+95 = 114+7+23



Net radiation (R_{net})

- R_{net} = energy input to ecosystem
  - Energy available to an ecosystem
- Surface energy absorption is a balance between
  - Input (long- & shortwave radiation)
  - Output (long- & shortwave radiation)
    - True for ecosystems, leaf surface, globe, etc.
    - $R_{net} = (K_{in} - K_{out}) + (L_{in} - L_{out})$



Net radiation (R_{net})

- K_{in}
  - Direct (~90%), diffuse, and reflected shortwave radiation
- K_{out}
  - Proportion of K_{in} absorbed depends on surface properties
    - albedo (a): 0-1 (1 most reflective)
    - $K_{out} \approx a * K_{in}$
      - More complex canopies → lower a (and lower K_{out}) → higher R_{net}

Table 4.1 Typical values of albedo for the major surface types on Earth

Surface type	Albedo
Ocean and lakes	0.03–0.10[a]
Bare soil	
Wet, dark	0.05
Dry, dark	0.13
Dry, light	0.40
Evergreen conifer	0.08–0.11
Deciduous conifer	0.13–0.15
Evergreen broadleaf	0.11–0.13
Deciduous broadleaf	0.14–0.15
Arctic tundra	0.15–0.20
Grassland	0.18–0.21
Savanna	0.18–0.21
Agricultural crops	0.18–0.19
Desert	0.20–0.45
Sea ice	0.30–0.45
Snow	
Old	0.40–0.70
Fresh	0.75–0.95

Data from Oke (1987), Sturman and Tapper (1996), Eugster et al. (2000), Hollinger et al. (2010)

[a]Albedo of water increases greatly (0.1–1.0) at solar angles less than 30°

Net radiation (R_{net})

- L_{in}
  - Determined by T_{sky}
    - Most absorbed radiation is reemitted (emissivity is high)
- L_{out}
  - Determined by $T_{surface}$ and emissivity
  - Emissivity in vegetated ecosystems is ~1, so largely driven by $T_{surface}$
- Both L_{in} and L_{out} depend on K_{in} and $T_{surface/sky}$
  - Also depends on a and evapotranspiration rates
- Why are cloudy nights warmer than clear nights?

Net radiation (R_{net})

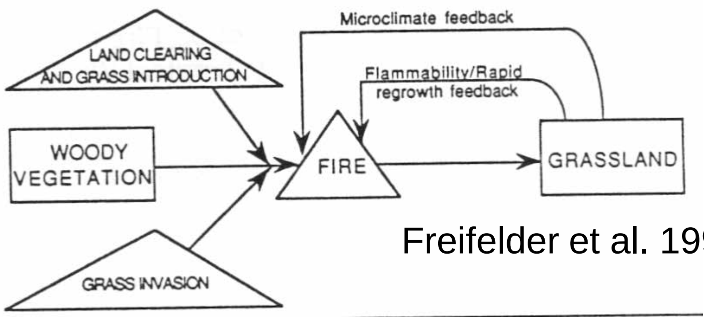
- R_{net} = (1-a)(K_{in}) + $\sigma(\varepsilon_{sky} T_{sky}^4 - \varepsilon_{surf} T_{surf}^4)$
  - σ = Stefan-Boltzman constant; ε = emissivity
  - K_{in}, a, surface roughness, and T_{surf} have largest impact on R_{net}
- Canopy structure strongly influences T_{surf} and, therefore, energy exchange
  - a ↓ as canopy complexity ↑
  - Roughness → mechanical turbulence that transfers energy from surface to atmosphere

•HI Tropical Dry Forest Conversion

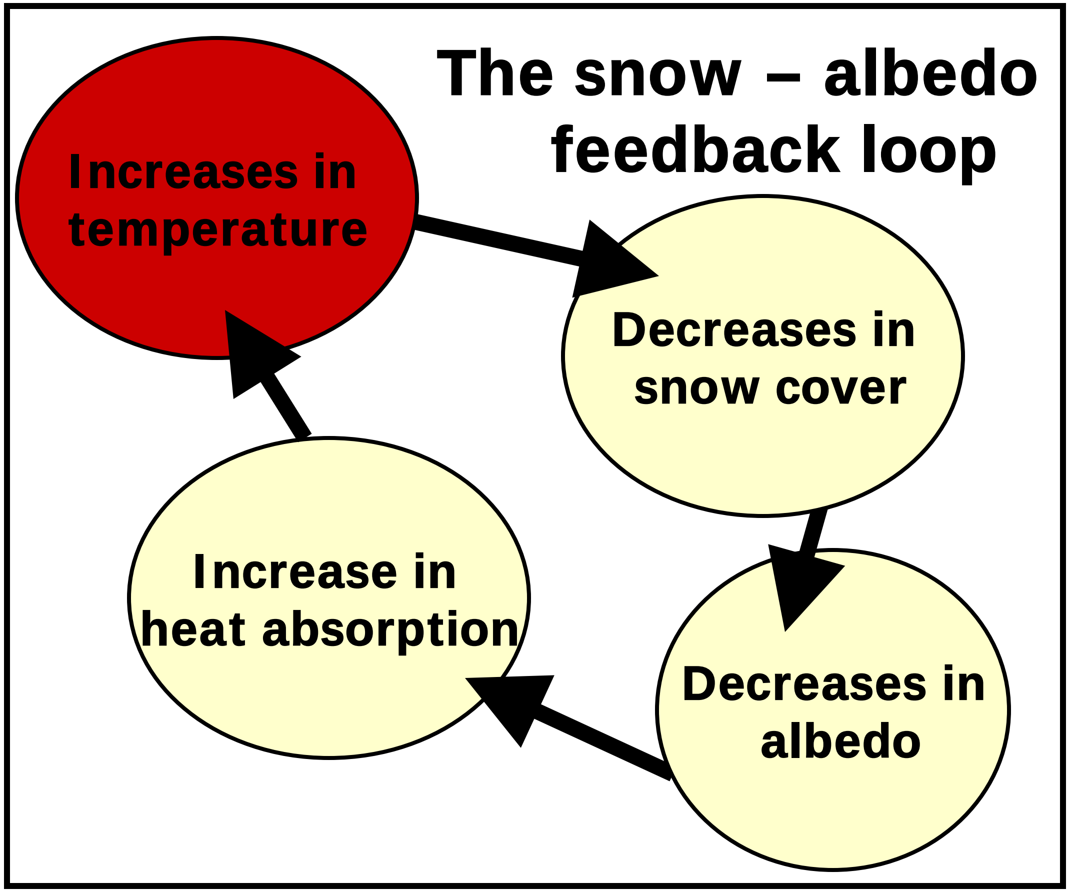
- T_{surf}?
  - ↑
- Roughness?
  - ↓
- a?
  - ↑

$R_{\text{net}} = (1\text{-a})(K_{\text{in}}) + \sigma(\varepsilon_{sky}T_{\text{sky}}^{4} - \varepsilon_{surf}T_{\text{surf}}^{4})$

•Windspeed ↑, but less mechanical turbulence



Freifelder et al. 1998



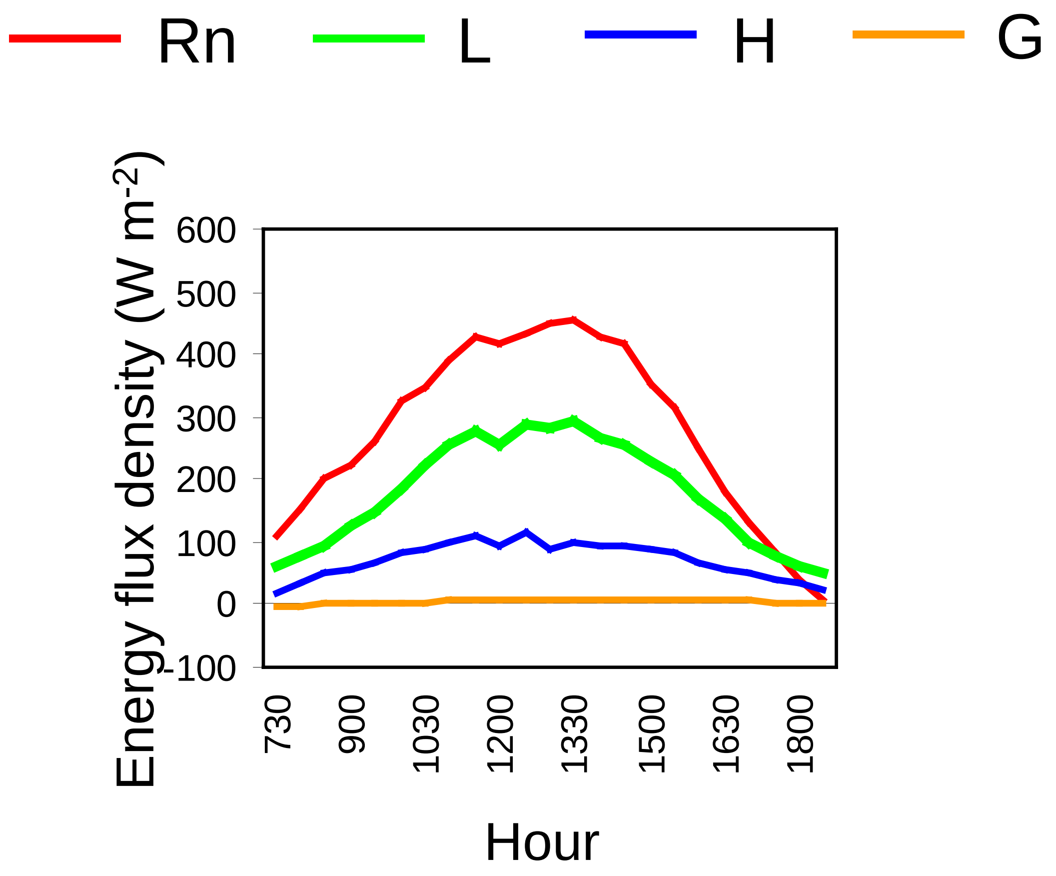
Do variations in seasonal snow cover and associated changes in albedo and atmospheric heating result in a positive feedback to the climate system?

Recent studies have found reductions in high-latitude snow cover.

(Dye, 2002; Stone et al., 2002; Chapin et al., 2005; Euskirchen et al., 2006)

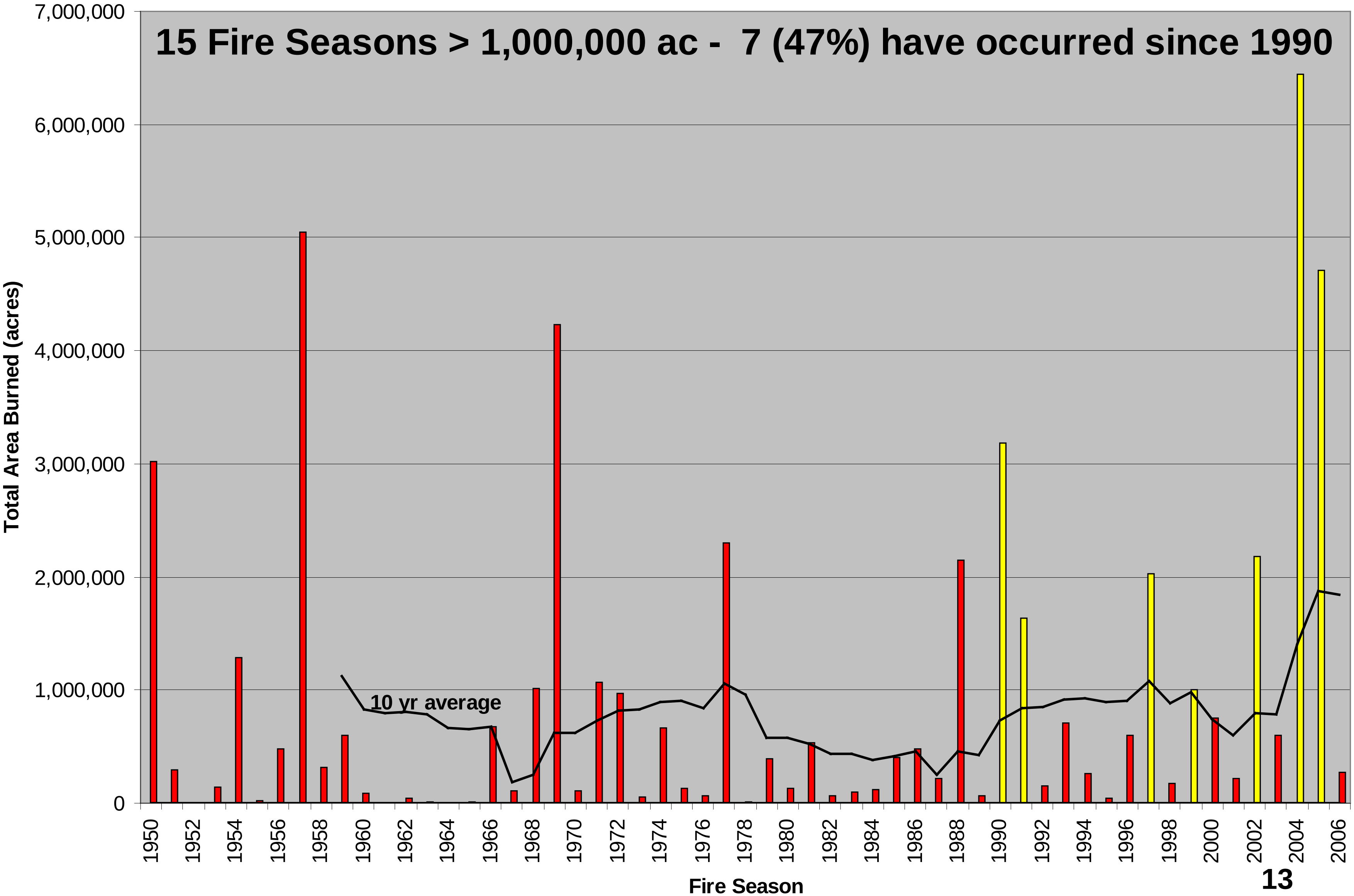
Net radiation (R_{net})

- Energy input ≈ Energy loss
  - Radiative energy absorbed ≈ Non-**radiative energy lost**
- $R_{net} = H + LE + G + P + \mathrm{D}S$
  - sensible, latent, & ground heat flux; photosynthesis, Dstorage in biomass
- $R_{net} = H + LE + \cancel{G} + \cancel{P} + \cancel{\mathrm{D}S}$
  - G balances over 24 hrs
  - P ~1-5% of K_{in}
  - DS typically small & balances over 24 hours
  - $R_{net} = H + LE$



Rn
L
H
G
Energy flux density (W m-2)
600
500
400
300
200
100
0
-100
730
900
1030
1200
1330
1500
1630
1800
Hour

Total Annual Area Burned in Alaska 1950-2006

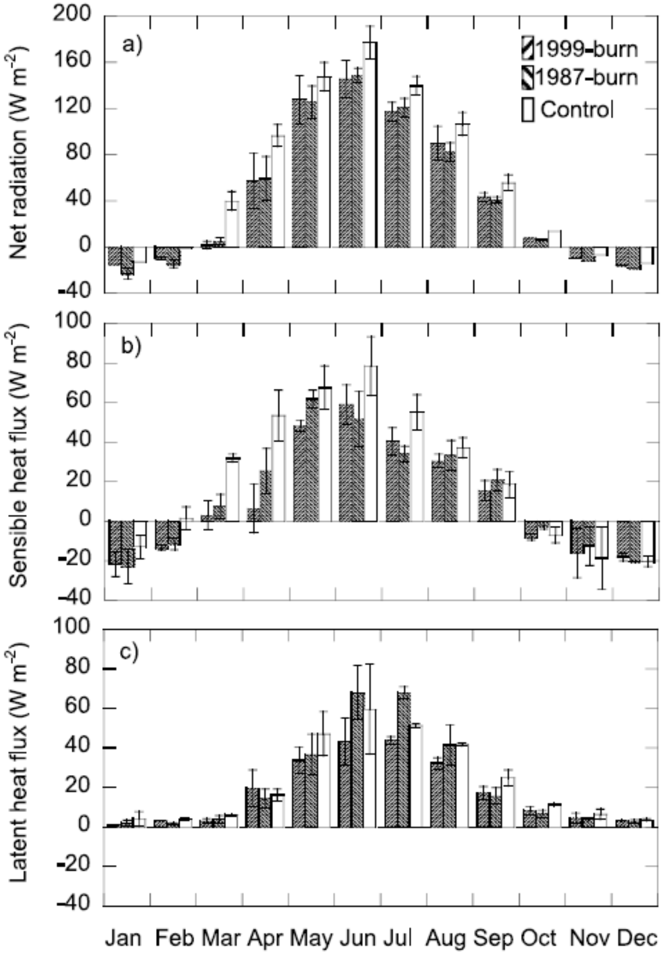


Fire, stand structure, and surface energy exchange

- Fire release large amounts of greenhouse gases to the atmosphere
  - Also changes energy and water balances
- How do post-fire shifts in stand structure impact climate via changes in surface energy exchange?
- R_{net}, H, LE, a, and T_{surf} in a 1999-burn (3 yrs), 1987-burn (15 yrs), and 1920-burn (82 yrs; Control = “unburned”)
  - 1999-burn = grasses; 1987-burn=deciduous forest; Control = spruce forest

Liu & Randerson 2007

Fire, stand structure, and surface energy exchange



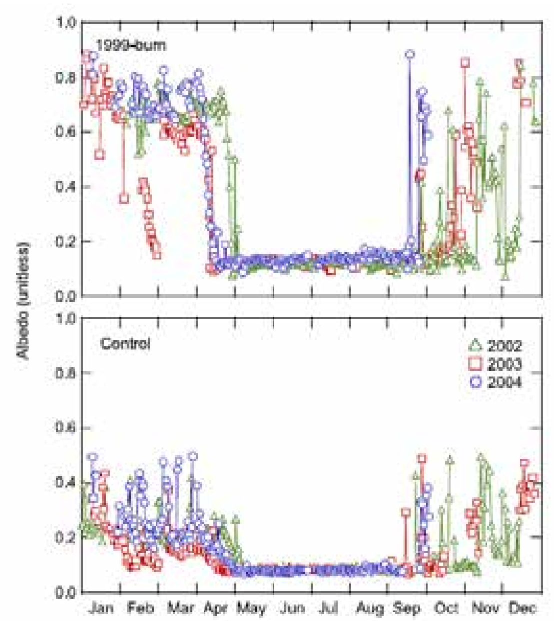
R_{net} ↓ 32% and 34% for 1999-burn and 1987-burn (less energy available for ecosystem processes, and heating the atmosphere)

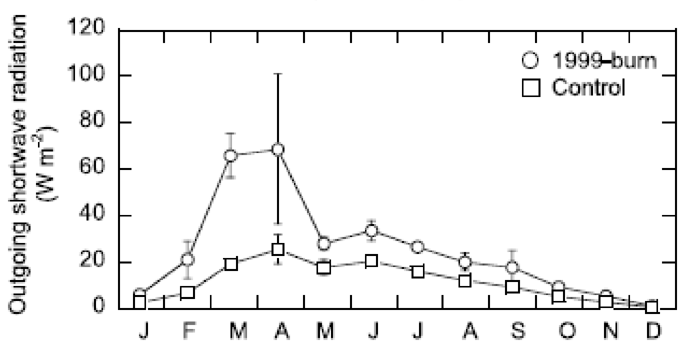
H ↓ 61% and 39% for 1999-burn and 1987-burn

LE ↓ 18% and 21% for 1999-burn and 1987-burn

Liu & Randerson 2007

Fire, stand structure, and surface energy exchange

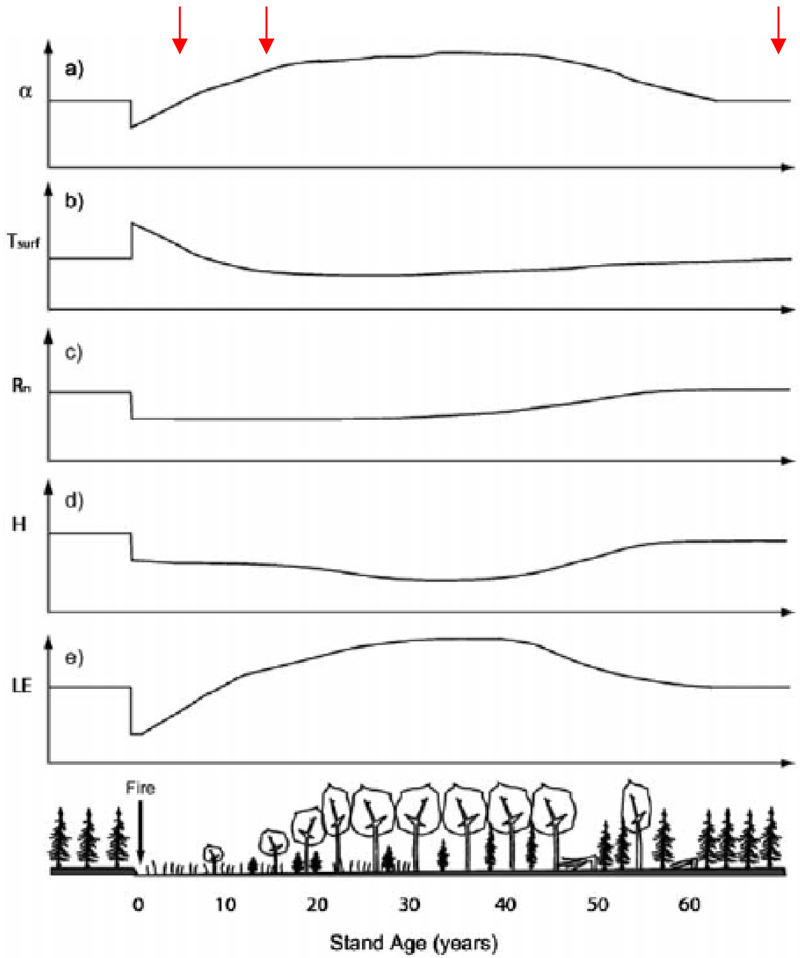




Driven largely by changes in a, which altered the amount of surface energy available to drive *H* and *LE*

Liu & Randerson 2007

Fire, stand structure, and surface energy exchange

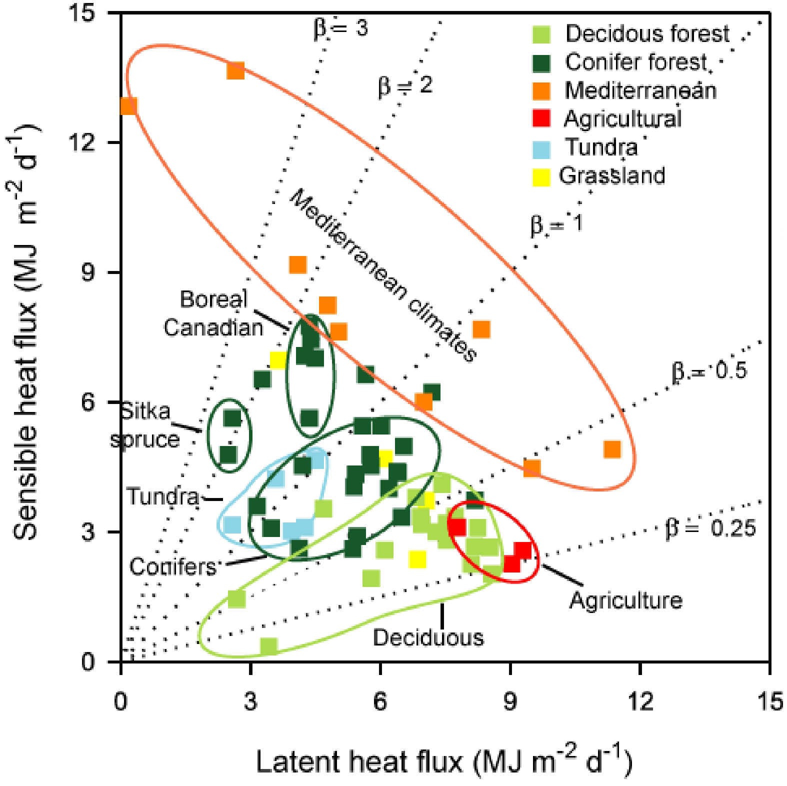


Fire-induced changes in the surface energy budget led to overall climate cooling due to increased a and decreased Bowen ratio (*β*) in recently burned stands

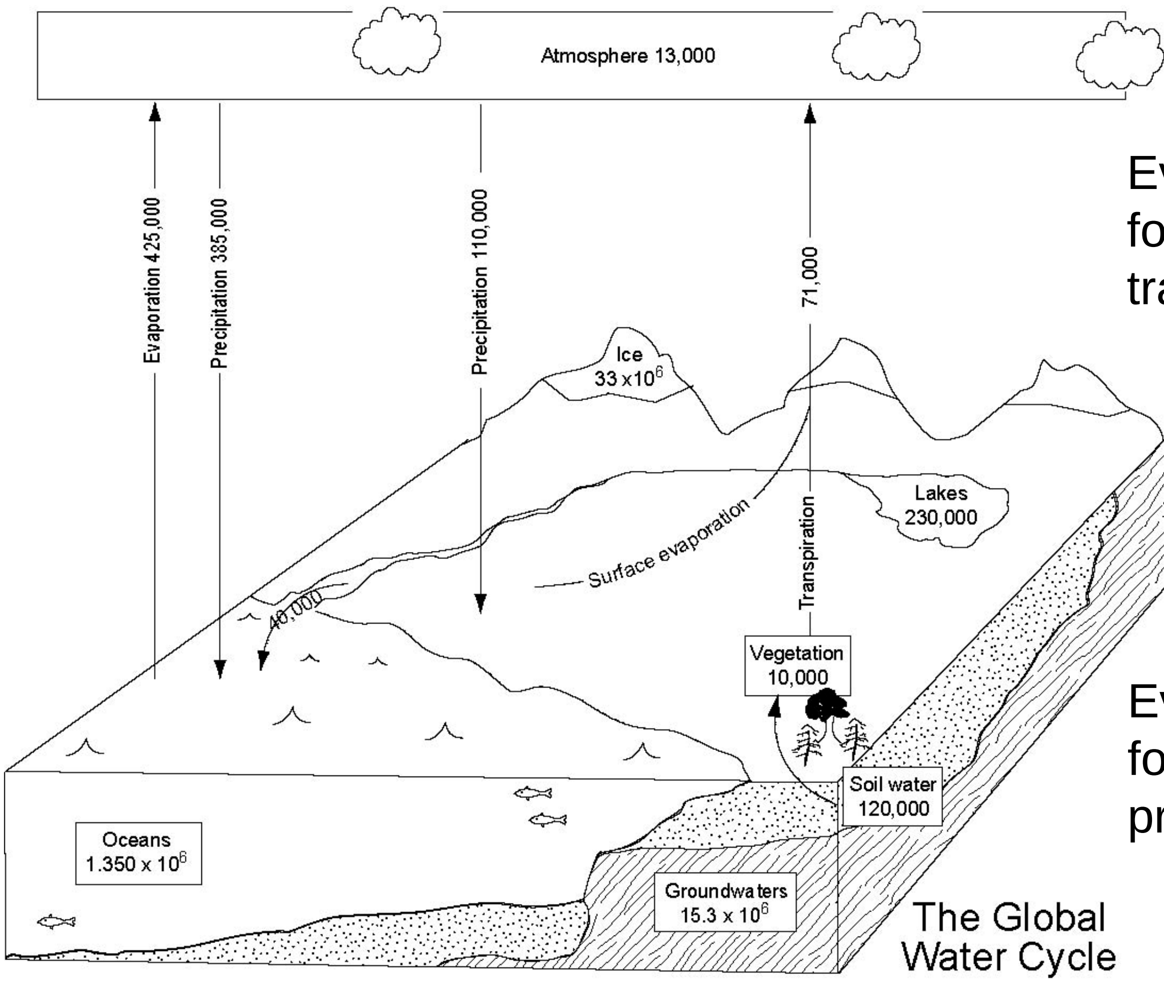
Liu & Randerson 2007

Net radiation (R_{net})

- Bowen ration (β): *H*/*LE*
  - Important interactions between *H* and *LE*
    - LE cools surface & ↓ H
    - H warms surface air & ↑ LE
  - β: Index of strength of linkage between energy & H_2O cycles
    - Lower $\beta \rightarrow$ the tighter the linkage
  - <0.1 to >10
  - *H* or *LE* can dominate
    - *LE* dominates (i.e., β < 1):
      - Moist env., active vegetation, rough canopy/strong winds



Hydrologic Cycle

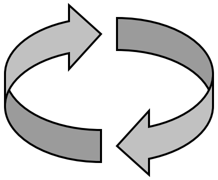


Evapotranspiration accounts for ~80% of turbulent energy transfer to the atmosphere

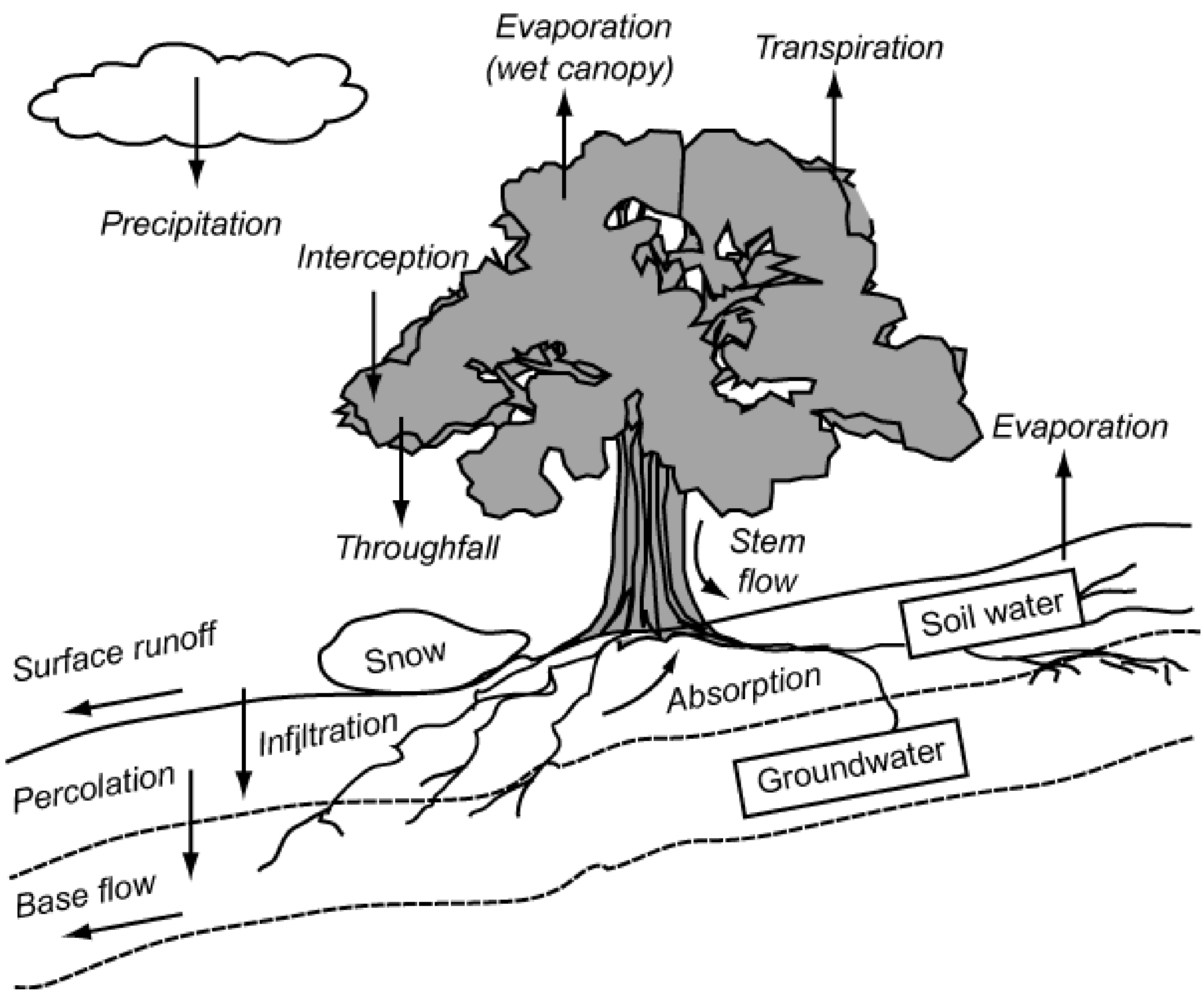
Evapotranspiration accounts for loss of ~65% of incoming precipitation on land

Hydrologic Cycle

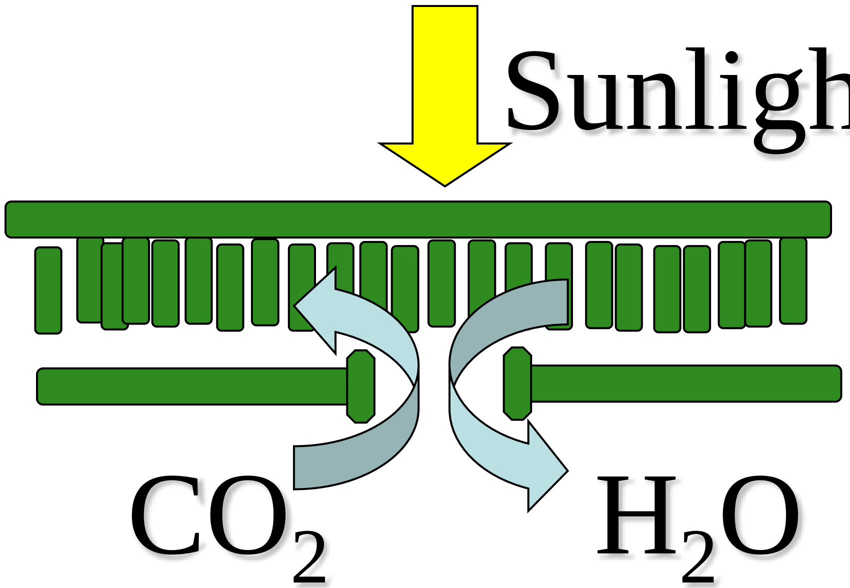
- H_2O is essential to biological processes
- H_2O is the MAJOR greenhouse gas
  - Water-vapor feedback to warming
    - Warm air holds more water & warming causes more water to evaporate
    - ↑ Water content of atmosphere
    - Absorbs more infrared radiation
    - Warms the atmosphere



- Terrestrial Ecosystem Water budget:
  - Inputs and outputs (vertical and lateral)
  - Internal transfers



Why do plants use so much water?



- Constant tradeoff between CO_2 uptake & H_2O loss for photosynthesis

- Driven by strong gradients in water potential along the soil-plant-atmosphere continuum

Hydrologic Cycle

- Ecosystem ≈ bucket (Inputs = Outputs + DStorage)
- Inputs
  - Precipitation, Cloud/Fog water, Groundwater, Dew
- Outputs
  - Evaporation and Transpiration (& sublimation)
  - Runoff
  - Drainage / base flow
- Storage
  - Soil (and vegetation)
    - Primarily a function of soil depth & soil texture
  - Balance between inputs and outputs

Water inputs to ecosystems

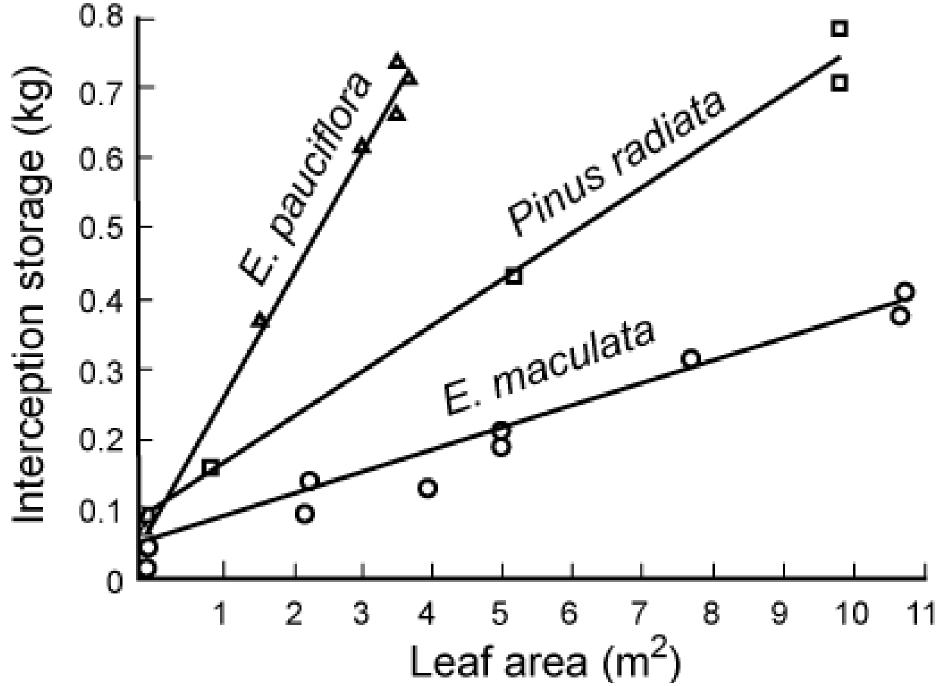
- Precipitation
  - Major water input to most ecosystems
- Groundwater
  - Phreatophytes; stream-side communities
- Fog deposition / cloud interception
  - ≥50% of input in some systems (e.g., montane cloud forests)
- Dew

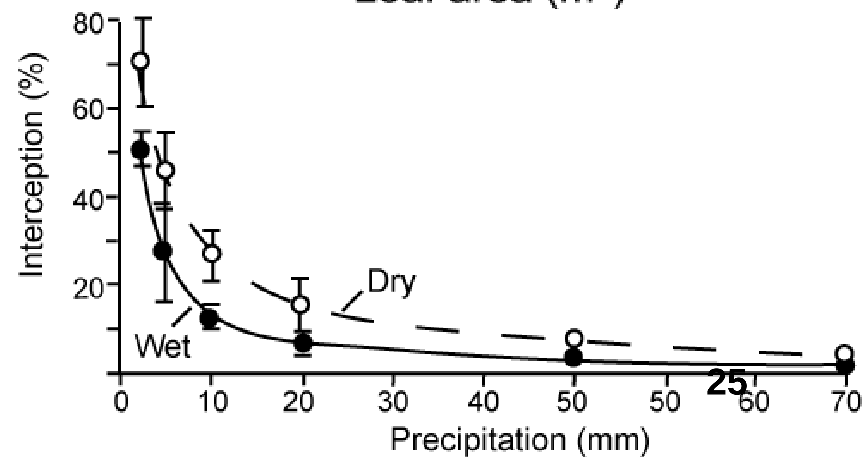
Canopy interception

- Canopies intercept a large proportion of precipitation (10-20%) and cloud/fog H_2O

- Ecosystems differ in canopy interception/storage
    - Depends mainly on LAI
    - Depends on precip size & wet vs. dry canopy

- Intercepted H_2O can be:
    - Evaporated, absorbed, throughfall, or stemflow





Water movement in ecosystems

- Water moves along energy gradients
  - From high to low potential energy
    - Less negative to more negative water potential
- What controls energy status of water?
  - Pressure
    - Gravity
    - Forces created by organisms
  - Osmotic gradients (solute concentrations)
  - Matric forces (adsorption)

$$y_t = y_p + y_o + y_m$$

Water movement in soil

$$J_s = L_s \frac{\Delta y_t}{l}$$

J_s = Water flux rate through soil

Δy_t = Water potential gradient (gravity and matric forces predominate)

L_s = Hydraulic conductivity (resistance)

l = Path length (resistance)

Water movement in soil

- Infiltration depends largely on hydraulic conductivity (L_s)
  - Texture
  - Aggregate structure
  - Macropores made by animals and roots
  - Impermeable layers
    - Calcic layer in desert
    - Permafrost in cold climates

- When infiltration rate is < precipitation rate, runoff (overland flow) occurs

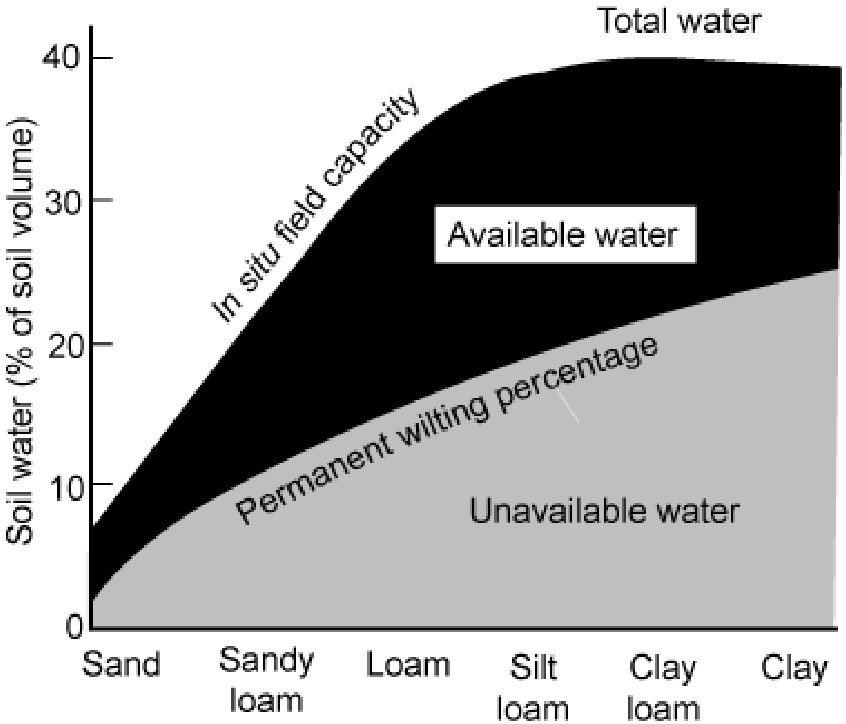
Water movement in soil

- Water holding capacity

WHC = Field Capacity (FC) - Permanent Wilting Point (PWP)

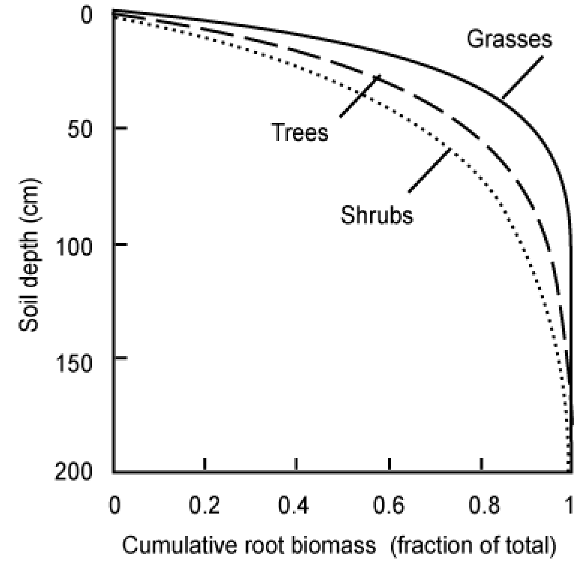
  - FC = amount of water left after drainage from gravity
  - PWP = point at which roots can no longer remove water from soil particle surfaces

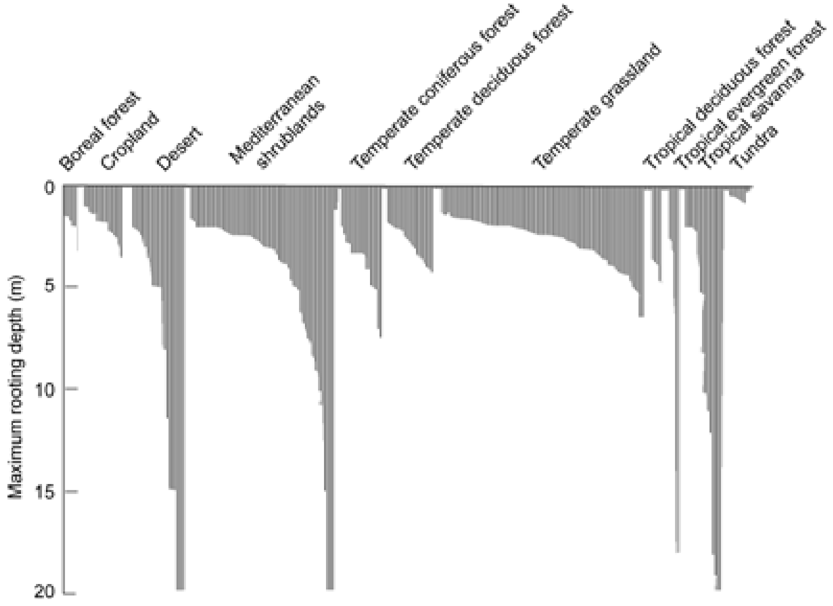
- Texture has very large impact on WHC and plant available water



Water movement in soil

- Roots
  - Most roots are in upper soil
  - Roots can extend far into soil
  - Water moves into roots when roots have lower y than soil (more -)
  - As roots draw water away from adjacent soil, water flows thru soils towards roots
  - Continues until matric potential is too high
  - Root hairs and mycorrhizae provide low-cost ways to explore large volumes of soil





Water movement in plants

$$J_p = L_p \frac{\Delta y_t}{l}$$

J_p = Water flux rate through plants

Δy_t = Water potential gradient

L_p = Hydraulic conductivity (resistance)

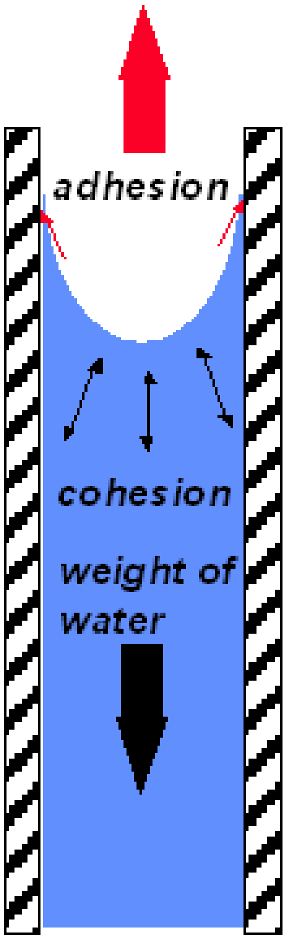
L = Path length (resistance)

Water movement in plants

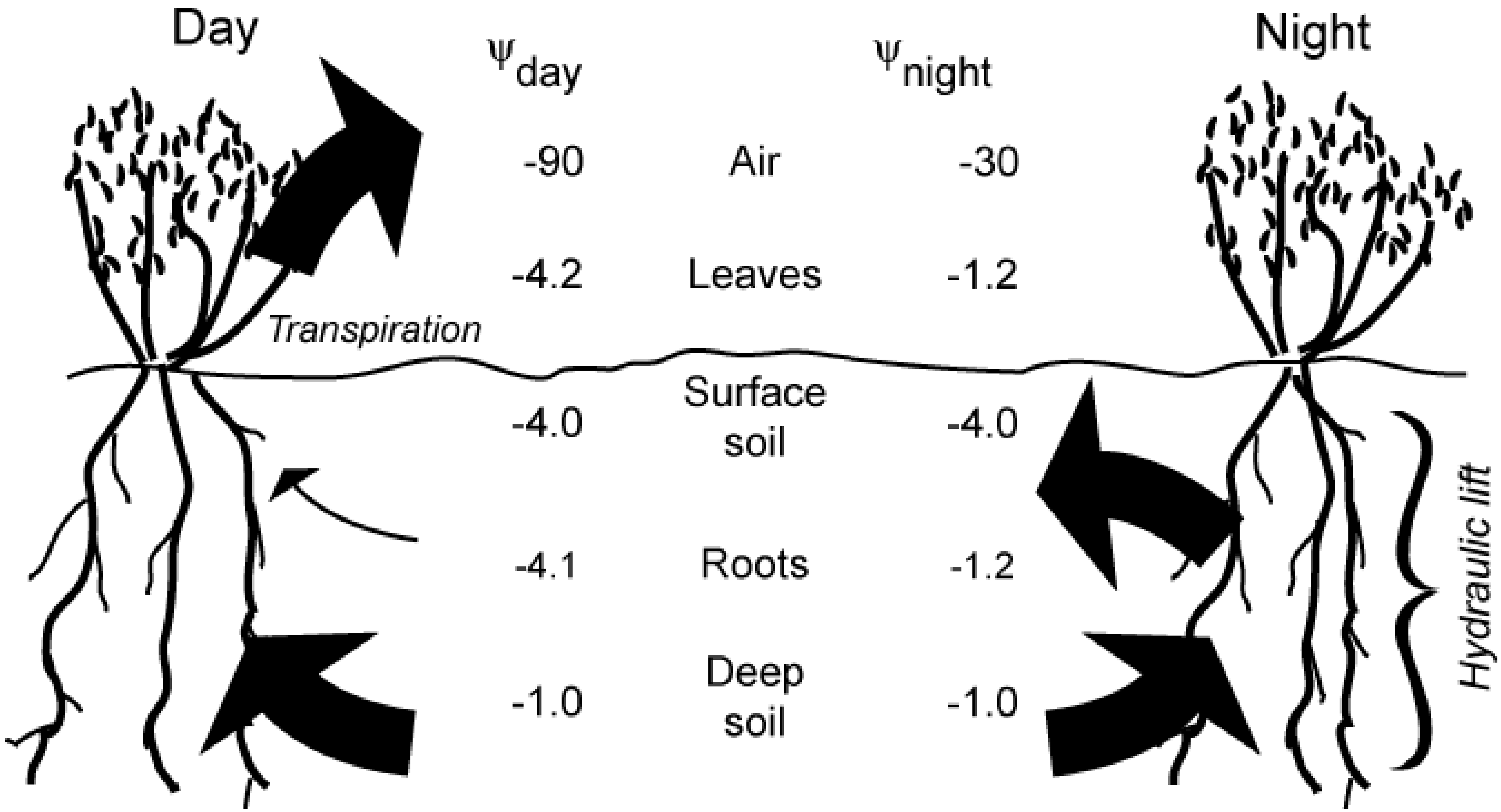
- Water moves in continuous column from soil pores or film on soil particles → roots → stem → leaf → atmosphere
- Plant expends <u>no energy</u> in transporting water
  - Passive transport driven by <u>transpiration</u>
  - *Very different from the considerable metabolic energy used by plants to acquire C, N, P, etc.*

Water movement in plants

- Upward movement enabled by strong cohesive forces among water molecules and adhesion to conduit
  - Counteracts gravity
  - Allows H_2O to move up trees as tall as 100m



Water movement in plants



- Water moves along pressure/energy gradient
- Pressure gradients typically differ in day vs. night

Water movement in plants

- Hydraulic lift 1st shown by Richards & Caldwell (1987) for *Artemisia tridentata*
- Since shown for many species
  - Widespread phenomenon
- Important implications for:
  - Recharge upper soil layers
  - Facilitating nutrient mineralization
  - Neighboring plant utilization
  - Prolong / enhance fine root activity

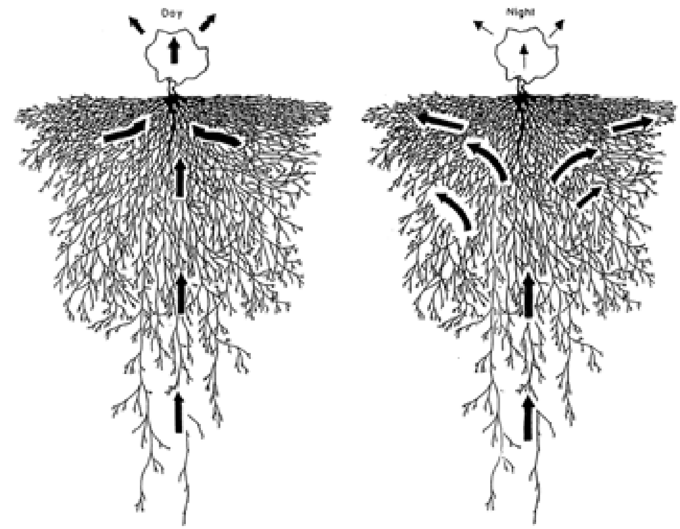


Table 2 Species exhibiting hydraulic lift in the field

Species	Reference	Nature of evidence
Artemisia tridentata (sagebrush)	Richards and Caldwell 1987, Caldwell and Richards 1989	Ψ_s fluctuations, daytime bagging experiment, deuterium labeling, nighttime lighting experiments
Agropyron desertorum (crested wheatgrass)	Caldwell 1990	Ψ_s fluctuations, nighttime lighting experiments
Gutierrezia sarothrae (broom snakeweed)	Wan et al. 1993	Water accumulation in upper root zone, soil water content fluctuations
Acer saccharum (sugar maple)	Dawson 1993, 1996	Ψ_s fluctuations, natural abundance of deuterium
Dipterocarps (three species)	P. Becker, personal communication	Natural abundance of stable isotopes
Quercus douglasii (blue oak)	C. Millikin and C. Bledsoe, personal communication	Ψ_s fluctuations
Sarcobatus vermiculatus (greasewood), *Quercus douglasii* (blue oak), *Artemisia filifolia* (sand sagebrush)	J.H. Richards, personal communication	Ψ_s fluctuations
Yucca schidigera (Mojave yucca), *Larrea tridentata* (creosote bush), *Ephedra nevadensis* (Nevada joint-fir), *Ambrosia dumosa* (white bur sage) *Lycium pallidum* (pale thornbush)	C. Yoder and R. Nowak, personal communication	Ψ_s fluctuations, nighttime lighting and daytime bagging experiments

Caldwell et al. (1998)

Water movement in plants

•Hydraulic lift can be reversed

•"Hydraulic Redistribution"

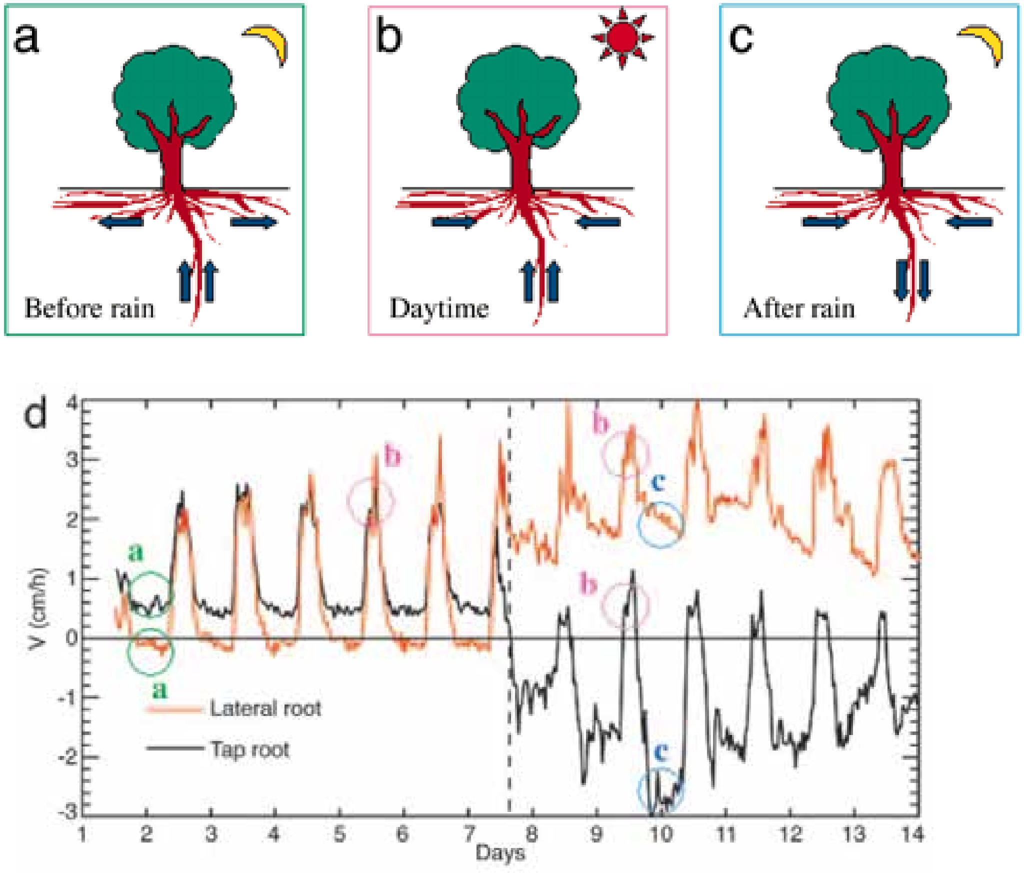
•Transports surface moisture to deeper soil layers

•Potentially important for:

- Phreatophytic species
- Tolerance of water stress during droughts

•Hydraulic redistribution increases dry season transpiration in the Amazon by ~40%

- Direct link between plant roots and regional climate via *LE*

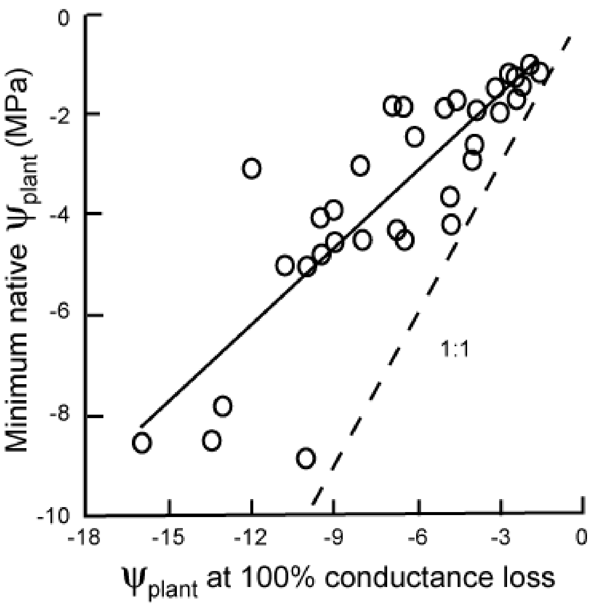


Lee et al. (2005)

Water movement in plants

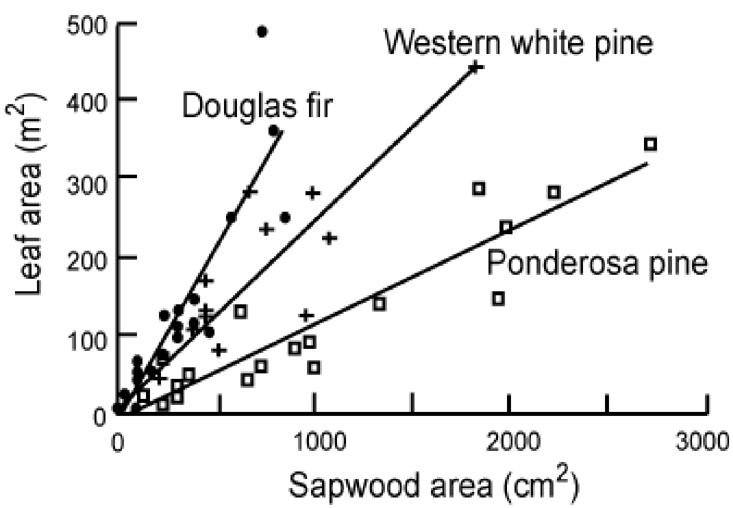
- In stems, water moves upward through xylem
  - Capillaries composed of functionally dead cells
- Cavitation (embolism) when enough pressure is applied to break water columns under tension
  - Largely irreversible in many species
    - Diffuse-porous (can) vs. ring-porous (cannot)
- Several “safety factors” keep cavitation from being common
  - Fine roots act as “hydraulic fuse”
    - More vulnerable to cavitation, but more easily replaced

Water movement in plants



•"Safety Factors"

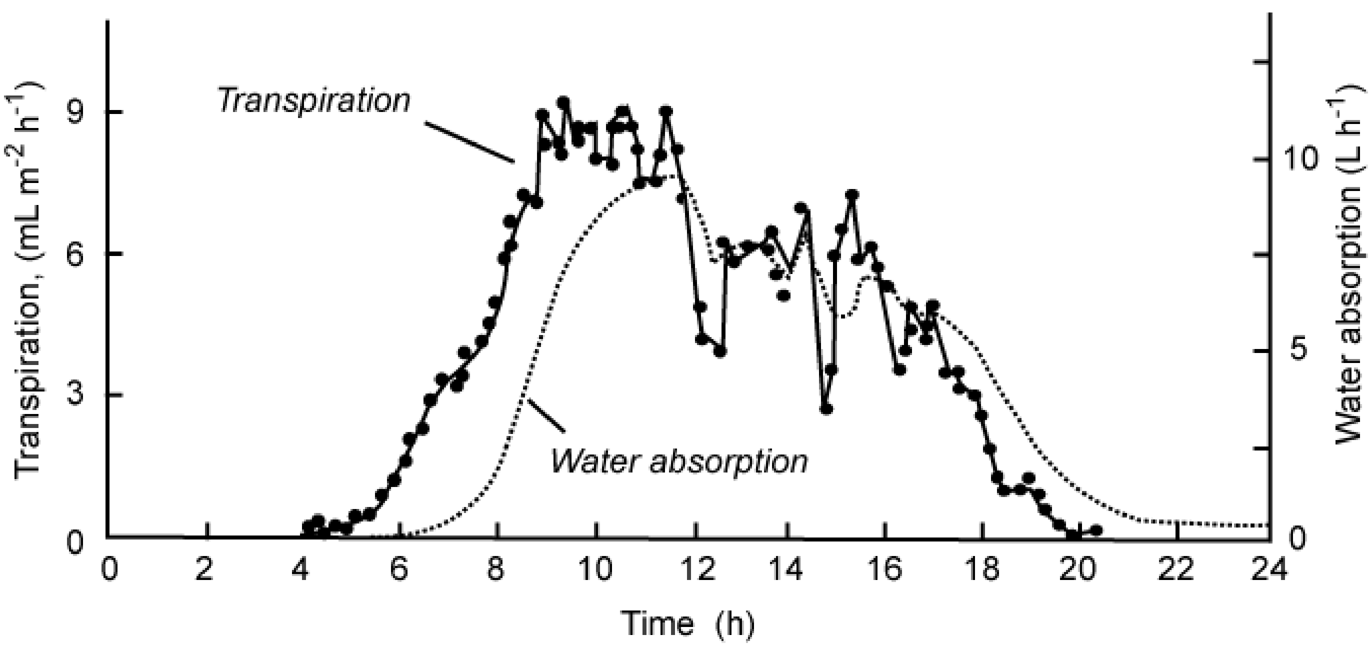
•Plants tend to produce stems that resist cavitation at lower potentials than typically experienced



•Area of conducting tissue (sapwood area) varies by species, but is linearly related to leaf area

Water movement in plants

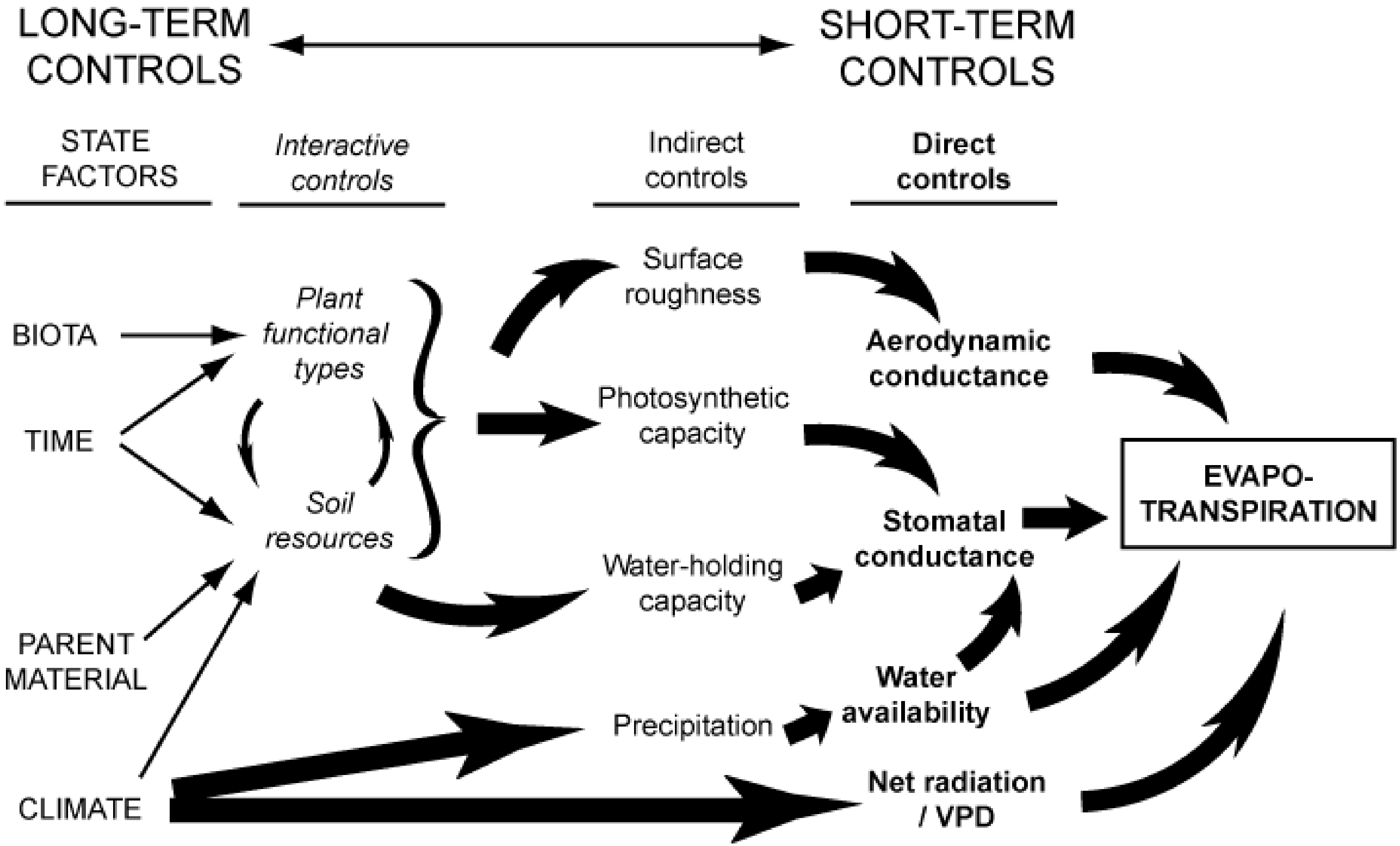
- “Safety Factors”
- Water storage in stems (from hours to 5-10 days of water)
- Recharged at night
    - Predawn leaf water potential is a good index of soil water status & degree of drought experienced by plants



Water movement in plants

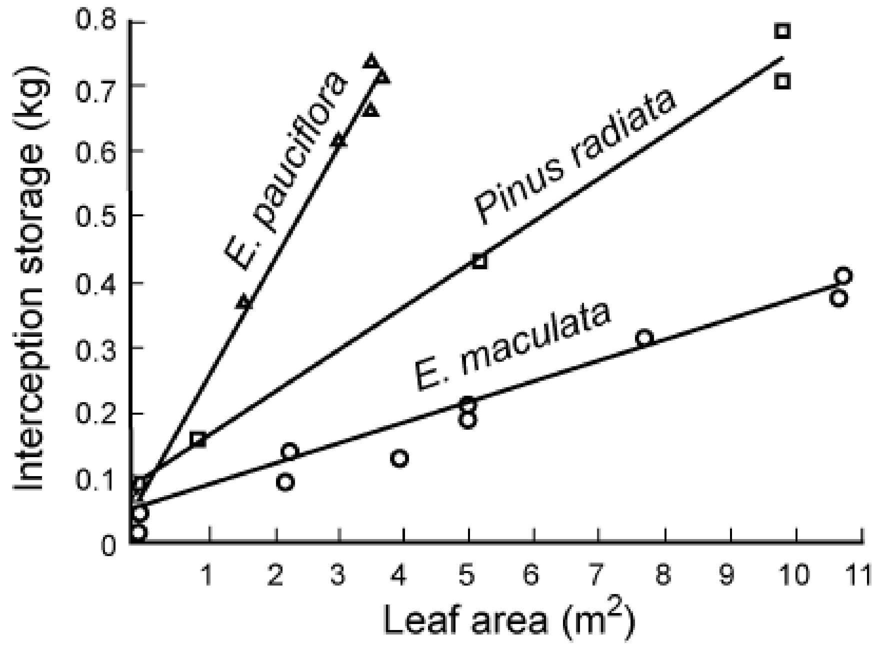
- Driving force for water loss from leaves is vapor pressure gradient
  - Depends on temperature and water vapor in bulk air
  - Vapor pressure deficit (VPD)
- Plants control H_2O loss directly by creating resistance to H_2O movement between leaf & air
  - Stomatal conductance
  - Boundary layer
  - Pubescence
  - Leaf orientation

Water movement in plants



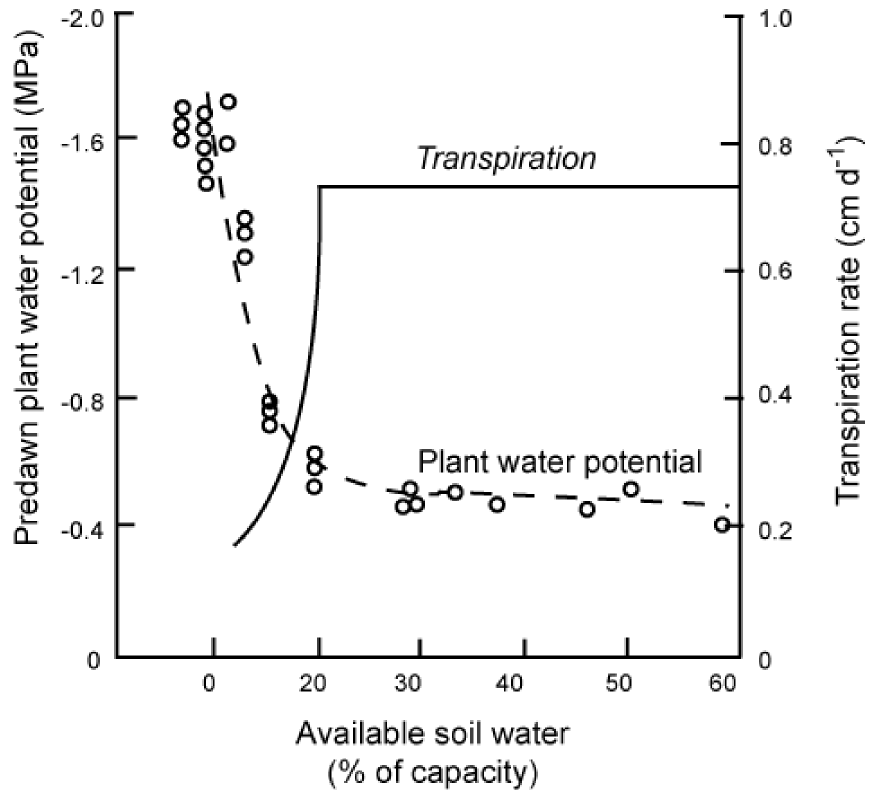
Water losses

- Evaporation from wet canopies
  - Can be a large fraction of precipitation
  - Depends on:
    - Interception (leaf area)
    - Surface roughness (mechanical turbulence)
    - Climate (VPD)



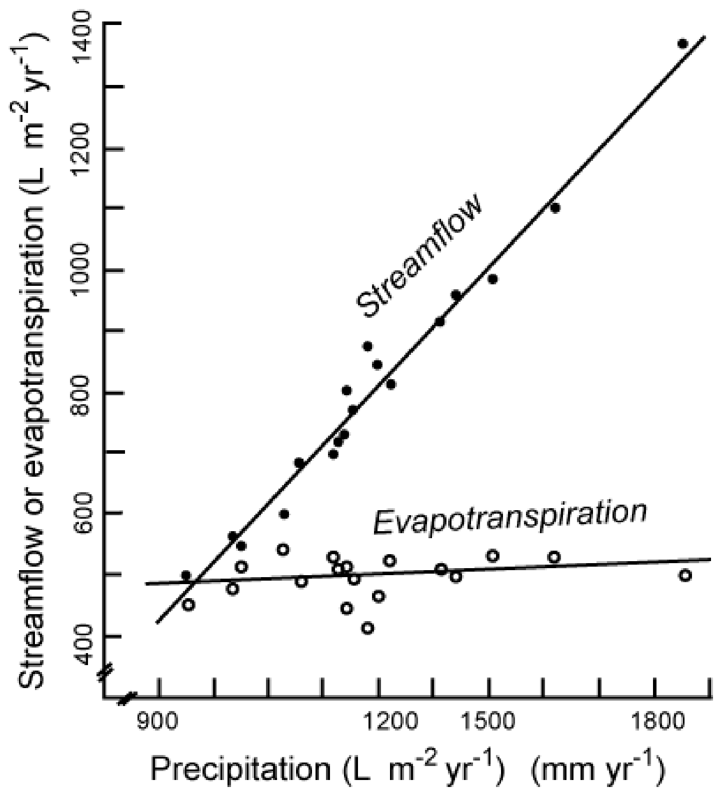
Water losses

- Soil water availability limits ET from dry canopies
  - Insensitive until ~75-80% of soil available water is gone



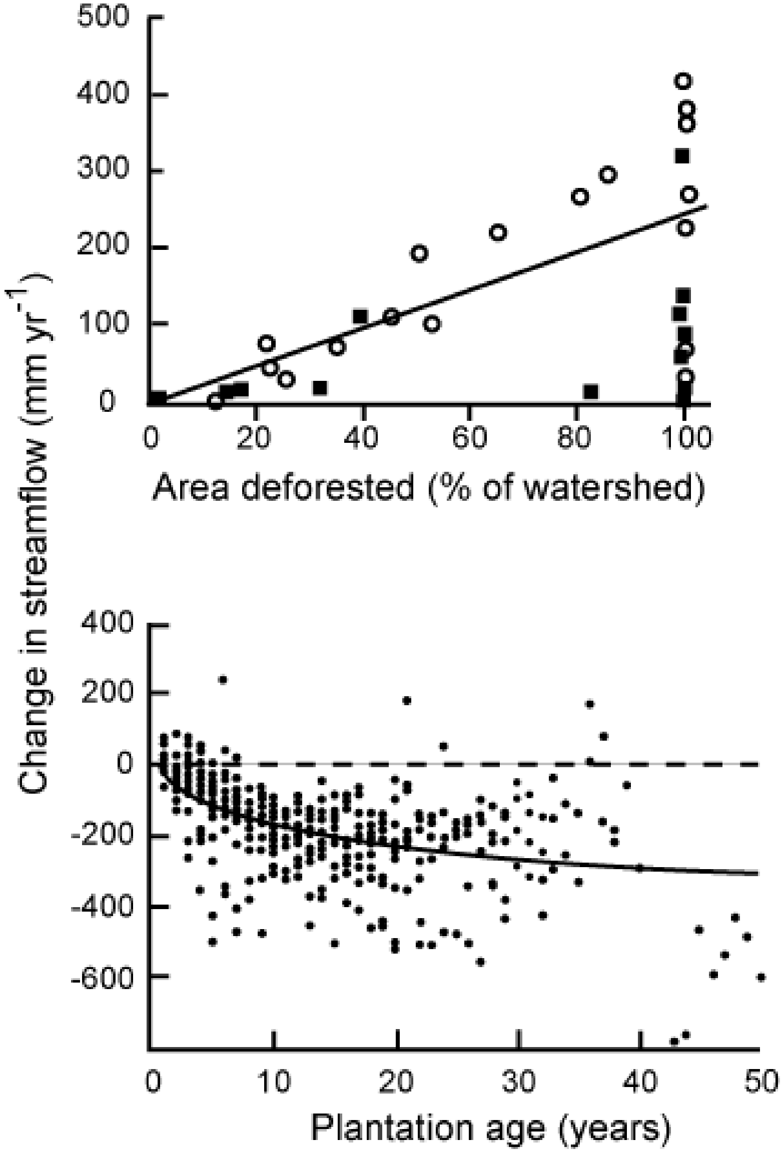
Water losses

- $P = ET + R \pm DS$
  - $P \pm DS = ET + R$
  - $P \approx ET + R$
  - $P - ET \approx R$
- Runoff is the "leftovers" after *ET*
  - Also determined by infiltration
    - Particularly in arid ecosystems
    - In moist ecosystems, *R* driven primarily by *P*



Water losses

- Management (e.g, deforestation) impacts balance of inputs & outputs
  - Deforestation
    - ↓ *ET*
    - ↓ interception, stemflow, and throughfall → ↓ infiltration and ↑ runoff → ↑ streamflow
  - Reforestation / afforestation should be the opposite



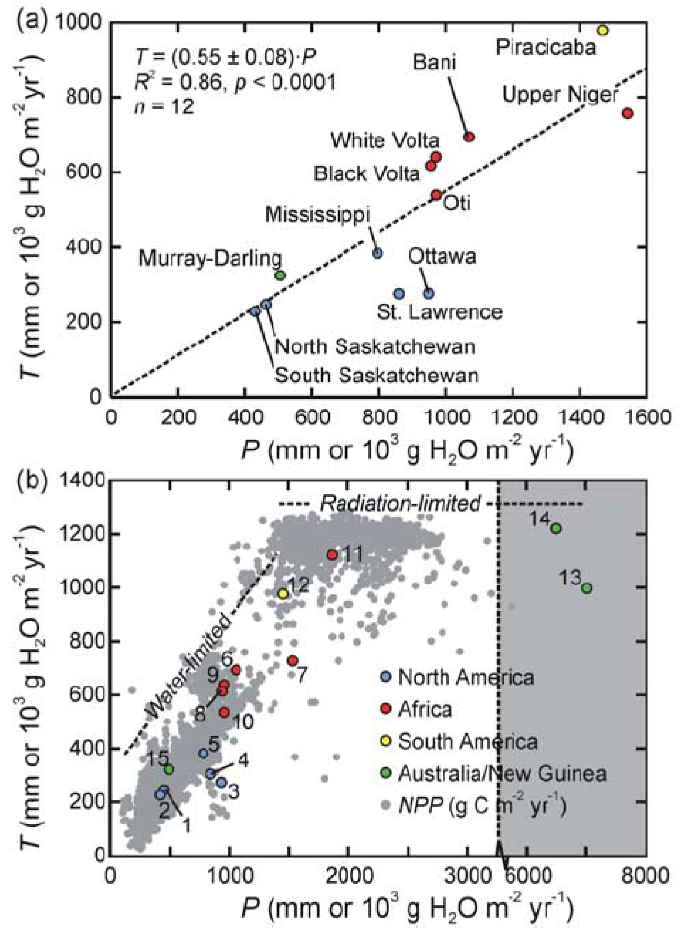
Water losses

- What proportion of watershed evapotranspiration is evaporation vs. transpiration?
  - Used ^{2}H and ^{18}O isotopes to partition ET into transpiration and evaporation (soil, canopy, and water)
  - 15 large watersheds with MAP from <500 to >6000 mm

Ferguson & Veizer 2007

Water losses

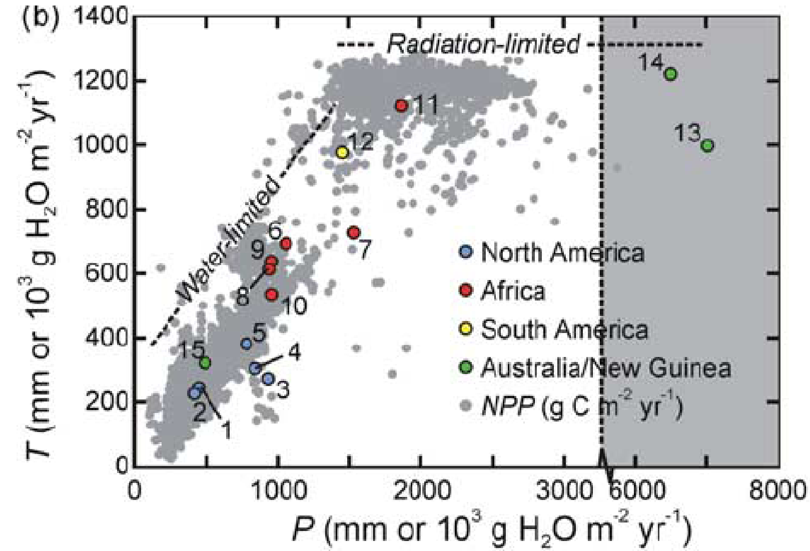
- Water limited (<1500 mm)
  - Linear increase in T with P (water limited)
  - *T* is ~71% of *ET* and 55% of *P*
- At MAP >1500 mm
  - Plateau (radiation limited)
  - *T* is ~71% of *ET* and 10-15% of *P*
    - By balance, *R* ↑

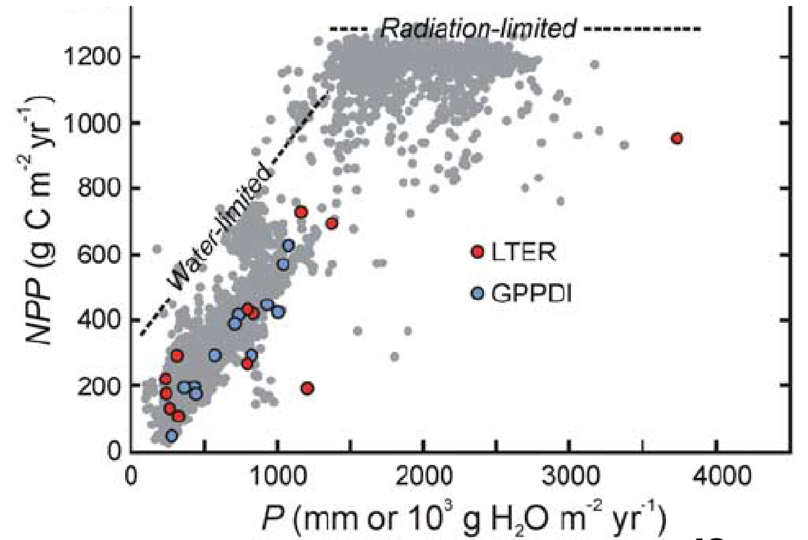


Ferguson & Veizer 2007

Water losses

- Very tight coupling between hydrologic and carbon cycles
  - C cycle limited by *T*?
  - *T* limited by C cycle?
  - Both limited by same factors?
- *T* was <u>3 orders of magnitude</u> larger than NPP





Ferguson & Veizer 2007