

EcoHydrology: WATER & ECOSYSTEM ECOLOGY, ESPM 111

Dennis Baldocchi
ESPM
University of California, Berkeley



Liquid

2/24/2014



Solid

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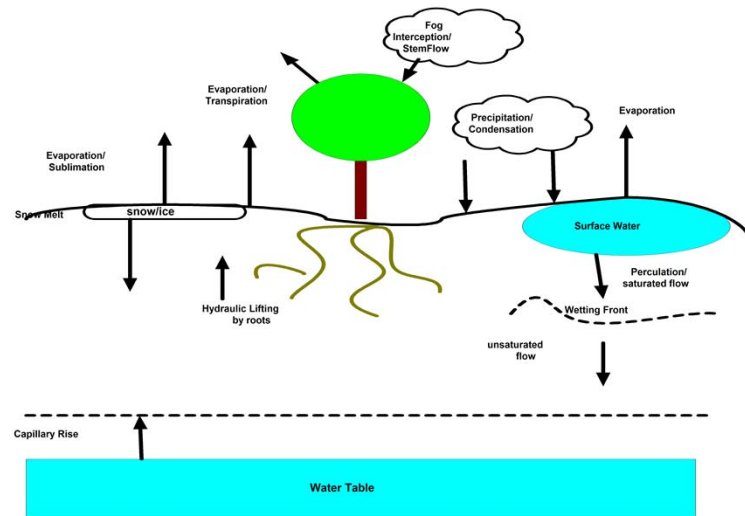
Gaseous

Topics Covered

- Principles
 - Water Balance
 - Water Potential
- Water in the Soil
- Water in the Air
- Evaporation
- BioPhysical Controls on Evaporation

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Hydrological Cycle and Ecosystems

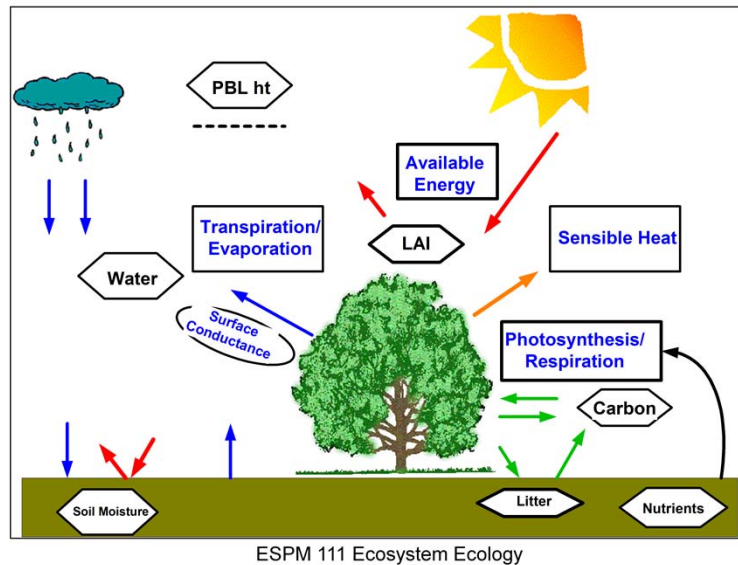


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What are the sources and losses of water through and ecosystem?

Sources of water are through precipitation, snow and fog interception; in dry environments like Chile or the redwoods during the summer fog interception is a significant source of water. Other gains are through access to the water table, phreatic plants, and the soil moisture reservoir through roots and hydraulic lift. Losses include soil evaporation, transpiration, evaporation from water surfaces and sublimation from snow. Sinks tap water through roots

Water and the Environment: Biogeophysical-Ecohydrological View



What controls the water cycle. Again Supply and Demand are themes. I also want to stress the coupling and interconnection between the water, energy, carbon and nutrient fluxes and cycles in regulating water loss. While climate may affect supply and demand, ecology and ecophysiology affects on the controls on the supply and demand. Energy from the sun is primary, but it is absorbed radiation, not radiation per se. So the amount of leaf area index has a profound effect on how much solar energy is absorbed. Plant area also affect the control of water loss through regulating the stomatal aperature. And because stomatal conductance and photosynthesis are closely linked, factors that control photosynthesis have an impact on stomatal conductance (eg leaf nitrogen) and vice versa (humidity deficits and CO₂). Of course the link to N brings in the nitrogen cycle as a secondary control on evaporation, but one that can have big impacts on how and why one ecosystem in a certain climate ecological zone uses water differentlt than another. Together ecosystem ecology helps use describe ecohydrology and have a handle on short and long term feedbacks between plants and the water cycle.

Chemical Potential of Water

Chemical potential quantifies
the driving force for movement of water between two locations



The chemical potential of water is related to the change
in the Gibbs free energy of the system, subjected by pressure, gravity,
temperature and minor constituents
, e.g., salts, .

By convention, Water potential is normalized by V_w , the partial molal volume of
water ($18.05 \cdot 10^{-6} \text{ m}^3 \text{ mol}^{-1}$), giving it units of **Pressure**.

$$\text{kg m}^2 \text{ s}^{-2} / \text{m}^3 = \text{kg m}^{-1} \text{ s}^{-2} = P = F/A = \text{kg m s}^{-2} / \text{m}^2$$

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We must study water through the energy that makes it move. Hence we have to introduce chemical water potential. Because we express it in terms of unit volume it has units of pressure, force per unit area.

Water Potential

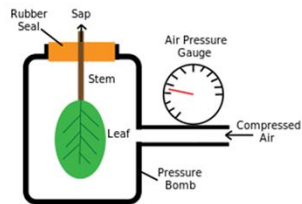
- The **total water potential** of a system consists of the sum of water potentials forces per unit area associated
 - **Pressure (+/-)**
 - **Osmosis (-)**
 - **Soil and Plant Matrix (-)**
 - **Gravitation (+/-)**

$$\psi = \psi_p + \psi_\pi + \psi_m + \psi_g$$

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Total pressure is the additive sum of its components, some you may know (like pressure and gravity) and others that may be new (like osmosis and matric)

Measuring Water Potential



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We use a Scholander pressure 'bomb' to measure total leaf water potential. The leaf is placed in a sturdy metal chamber and the pressure of air is increased. At equilibrium sap will start to exude out the cut petiole. Domestic plants tend to wilt when the water potential is below -1.5 MPa, or -15 atmospheres. Drought adapted oaks can function as low as -6.0 MPa.

- **Turgor (pressure) potential**
 - is related to the hydrostatic pressure, as when someone is blow on or sucking on straw that is inserted in a reservoir of water. Its sign can be positive or negative.
- **osmotic potential**
 - The presence of solutes reduces the activity of water.
- **matric potential**
 - interactions between water and solid surfaces act to reduce the activity of water.
- **gravity Potential**
 - gravitational force is a function of the density of water, the acceleration due to gravity and the height of the water reservoir above or below a reference height:

$$\psi_g = \rho_w gh$$

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Definitions and Terminology

Saturated Flow, Pure Water



$$\psi = \psi_p + \psi_g$$

$$0 = \psi_p + \psi_g;$$

$$\psi_p = -\psi_g$$

Takes Negative Pressure (suction) to lift water against gravity
The Gravitational Burden of Water Overhead Imposes a
Positive Pressures

Dominated by Pressure and Gravity

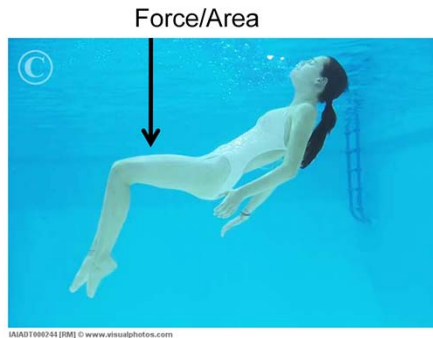
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Let's deconstruct these ideas of water potential. Let's first consider pure water. By definition its water potential is zero. So if you are deep in a pool the pressure potential you feel is the opposite of the gravitation potential that is pushing down on you.

Pressure, or Hydrostatic, Water Potential

Pressure exerted by an overlying water column on an infinitesimal cube of water



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Pressure potential can be positive or negative. Think of the case of the stomatal guard cells, the movement of water into these cells makes the turgid as pressure potential is positive. This leads to their opening. In the reverse case, they can experience negative pressure potential as they become flaccid. The actual potential of a sample of pure water in water is defined as zero

Osmotic/Solute Water Potential

Change in Energy of Pure Water when Solutes are Added



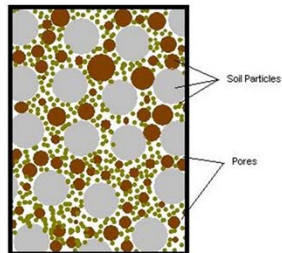
Solutes reduce the free energy of water by reducing the mobility of water molecules as they are attracted to the charged or polar surfaces of the solutes

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Solutes in water reduce its free energy and make its water potential more negative. So a plant in salty water is exposed to a more negative water potential, hence it is harder for it to extract water for its biological use than if its roots were exposed to pure water.

Matric Water Potential

Matric potential refers to the effect of a large polar or charged surface (e.g. soil matrix) on the water system



interactions between water and solid surfaces act to reduce the activity of water. Results from capillary and adsorptive (van der Waal's) forces

Matric effect reduces the free energy of water molecules through attractive forces that reduce their mobility

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Matric water potential is exerted on water in soils, as well as in cells and the plant xylem. So water can be tightly bound to the surfaces of soils. There is moisture there, but a low water potentials it is not biologically available. More over different soil textures will experience different water potentials at the same volumetric water content. This is why it is so important to think about water availability to microbes and plants in terms of water potential than water content. We will explore this later with the topic of water retention curves.

Gravity Potential
= Density of water times Acceleration of Gravity
times Head Differential

$$\psi_g = \rho_w gh$$



It takes Energy to Lift water Up Hill
Energy is Released when Water Flows Down Hill

Conveyance, Storage and Treatment of Water accounts for 19% of CA electricity use

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We are most associated with gravitational potential. Its value depends on the position relative to a reference, known as head

Lifting Water by Suction, 10.3 m at sea level



$$P_{atmos} = -\psi_g = \rho_w gh = 101300 Pa$$

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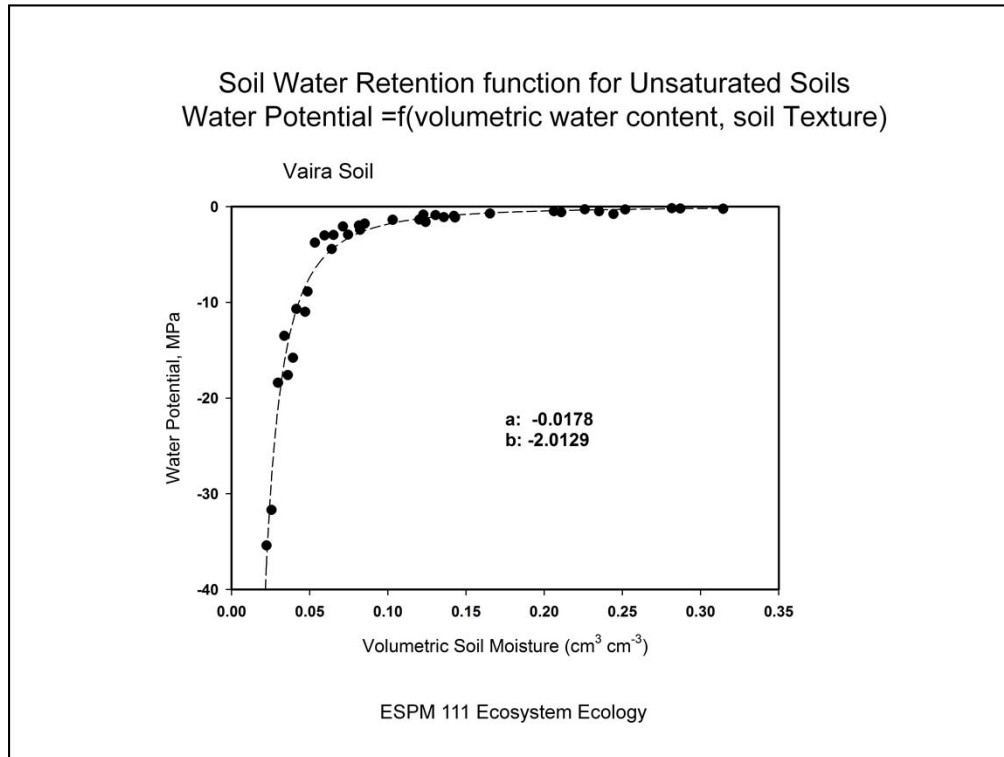
How does a Straw work? Does Paris suck the water out of the glass?; The technical answer is no. Sucking evacuates the atmospheric pressure acting on the water column under the straw. With it evacuated of air pressure, the pressure on the water exposed in the glass pushes it up the straw to a new equilibrium.

What are the Limits on Pumping Water from a Well?
How deep can the Water Table Be?

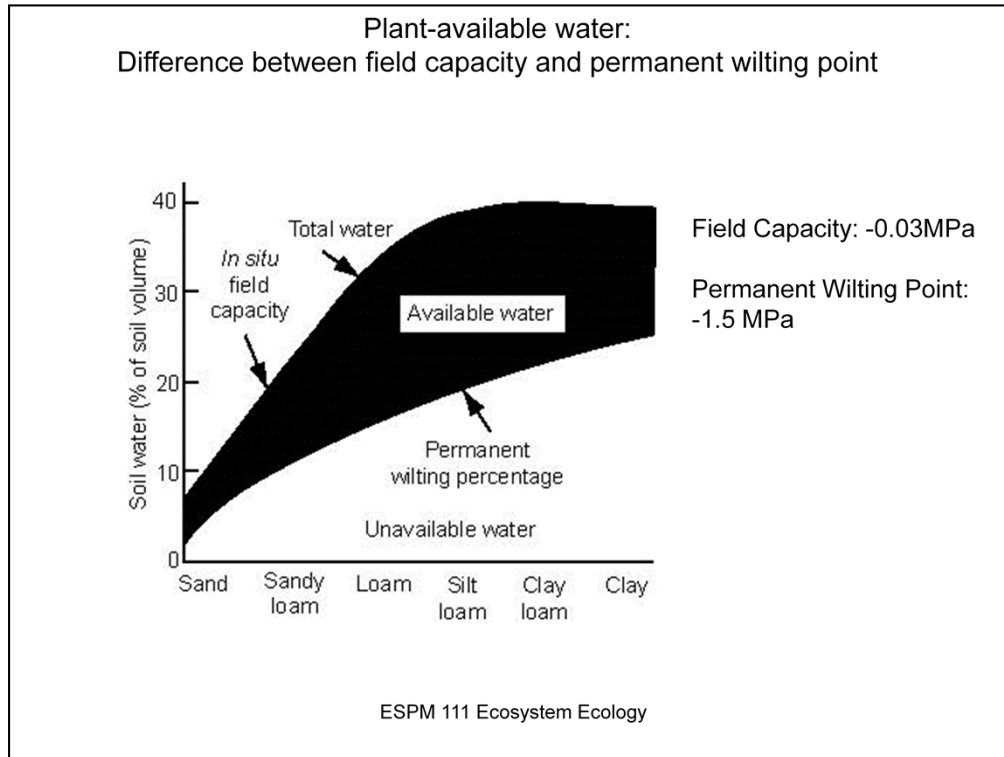


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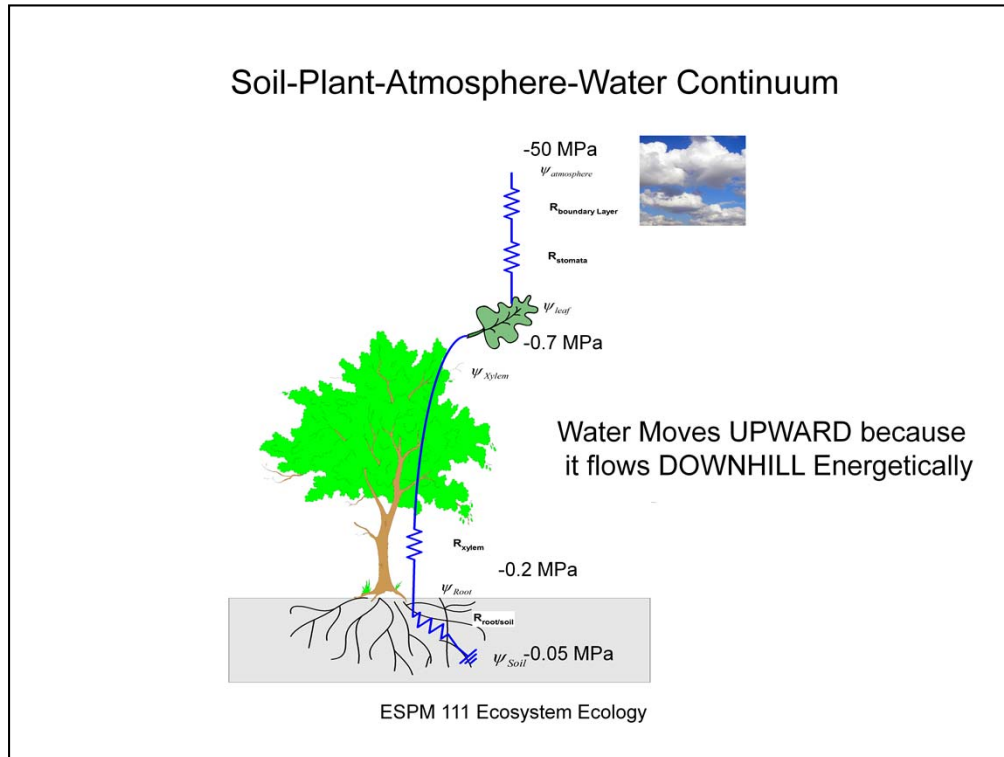
This is an important limit as it also establishes the limit of lifting ground water with a suction pump. If you are interested in doing work for the Peace corp and bring water to underserved people you should know this fact. It is a reason companies like Jacuzzi develop submersible pumps.



While plants cells and microbes sense water potential, we tend to measure volumetric water content, the cubic volume of water in a cubic volume of soil. The relation between water potential and volumetric water content is very non linear. When soils are dry, they hold little water and it takes lots of energy to extract even a little more. When soils are wet, moisture is less tightly bound and is lost with less energy. PedoTransfer functions, like this, describe the relation between these two variables and differ for each soil, like clay, sand, loams, peats.



Consequently, due to energetic arguments different soils hold different amounts of water and gain and lose it at different volumetric water contents. The constant is that most plants function between the field capacity and permanent wilting point, which have well set and quasi university water potentials. Granted a drought adapted plant like an oak leaf will wilt at a much lower water potential than a hydric plant like lettuce.

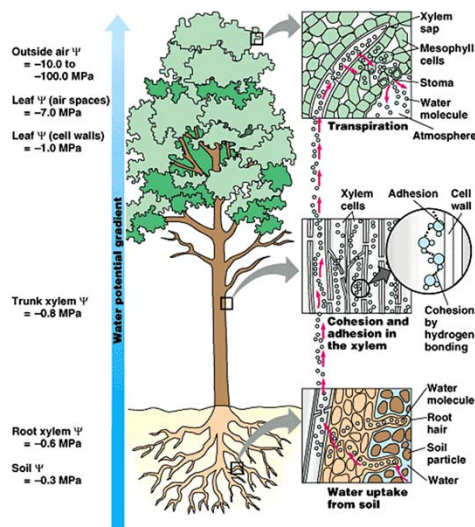


As mentioned above it takes energy to move water. This leads us to define the soil-plant-atmosphere continuum, SPAC. This continuum can be described like an electrical network with resistors in parallel and series, ground states and nodes. We all know water moves down, but in terms of SPAC water moves physically upward, but downward energetically. The key resistances are exerted by the roots, the xylem of the stem, the stomata of leaves and the boundary layer of the atmosphere. This is a very very fundamental concept of this chapter, one that will be tested

Stomatal control is key to prevent plants from evaporating like open water plates they exert control; on a summer day the water potential of a leaf may be -0.7 MPa and it may be exposed to a dry atmosphere with a water potential of -50 MPa . This is a strong gradient unless something is retarding this transfer.

Water potential of pure water is zero by definition

Adhesion-Cohesion Theory



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<http://www.uic.edu/classes/bios/bios100/lectures/f04am/model.gif>
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The idea of matric water potential enables the adhesion-cohesion theory to lift water up the column of xylem cells. Water is polar, so bonds allow adjacent water molecules cohesion with one another, tied together like a long string. Adhesion with the surface of vessels and tracheids in the xylem enable the string of water to work its way upward to the demand by the atmosphere.

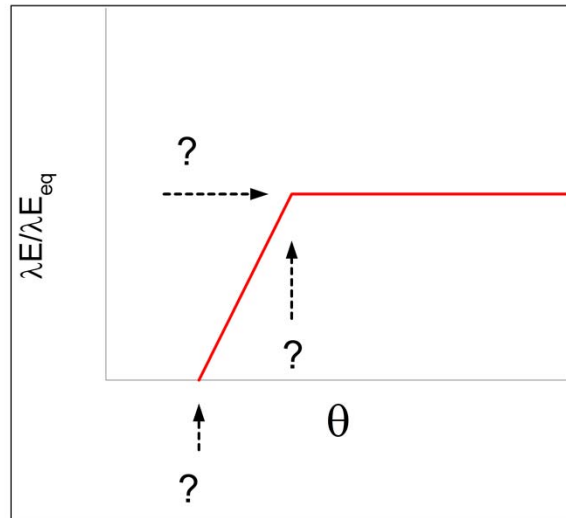
Drought Survival vs Die-Back,
Vulnerability to Embolism and Loss in Hydraulic Conductance
Hydraulic Failure vs Carbon Starvation,
Isohydric vs Anisohydric Plants



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Drought is a reality. In recent years, the Western US and California have experienced prolonged and wide-spread Drought. What does this do to ecosystems, who depend on water?

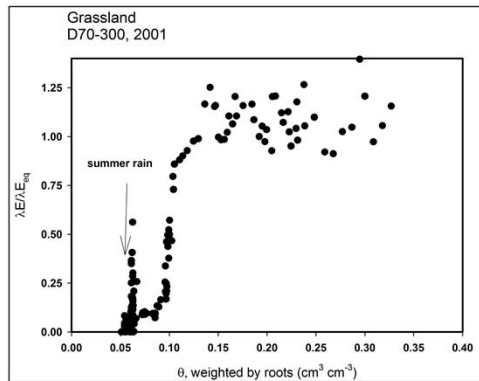
EcoHydrology, Evaporation & Soil Moisture



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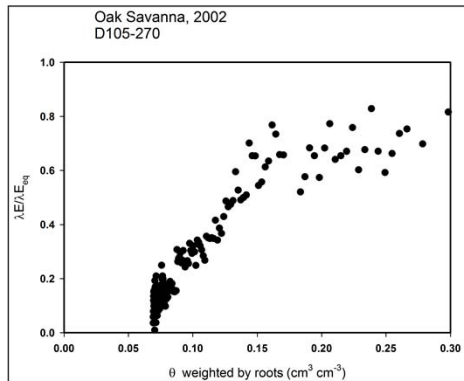
Drought is a reality and constant in California, so knowing how evaporation varies with water content of the soil is critical. The response tends to follow a threshold response.

Evaporation and Drought



Grass Uses Water Quick as Possible,
Then Die; Isohydic

Baldocchi et al. 2004

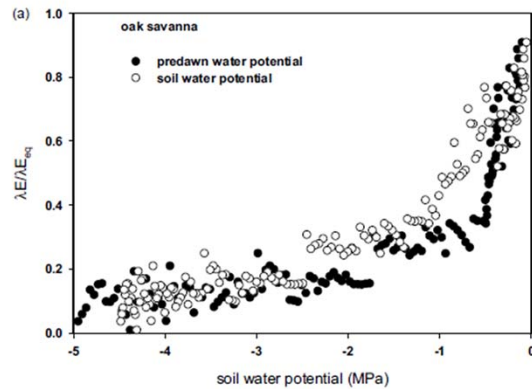


Oaks meter out Water Conservatively;
Anisohydric

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Here are our data for the oaks and grasslands.

D.D. Baldocchi et al. / *Agricultural and Forest Meteorology* 123 (2004) 13–39



Blue Oaks seem
Isohydric in the early
Phase of summer Drought, and
Anisohydric in the later Phase

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The oaks I work tend to be isohydric in the early phase of summer drought. As the soil gets drier and drier, the stomata close to reduce more water loss and keep the predawn water potential in a narrow range. This reduces evaporation, but occurs at the cost of reduced carbon uptake. In the later stage the oaks seem Anisohydric, but it is known that their roots tap ground water.

Vulnerability to Embolism and Loss in Hydraulic Conductance

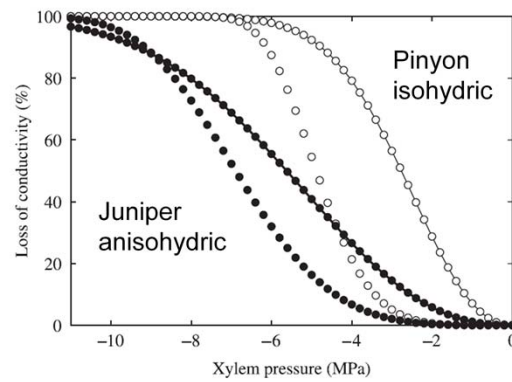
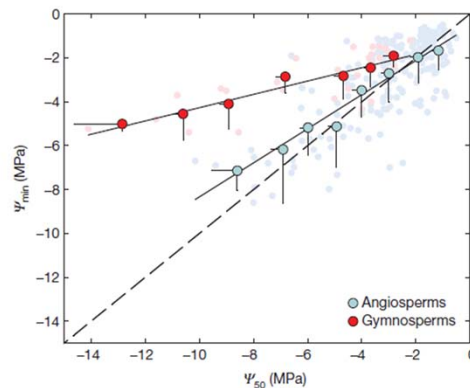


Fig. 4 The percentage loss of conductivity of excised root (connected circles) and stem (unconnected circles) segments of piñon (open circles) and juniper (closed circles) as a function of xylem pressure. These 'vulnerability curves' were obtained by the air-injection method (Linton *et al.*, 1998).

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Pinyon experience 50% loss of conductivity at much higher (less negative) water potentials than Juniper (-4 vs -7 Mpa)

Vulnerability to Embolism differs among Gymnosperms and Angiosperms



Water potential with 50% loss in conductivity

70% of 226 tree species, from 81 sites, operate within
1 MPa of Hydraulic Safety Margin for Injury..
Explains Why Drought Decline is Occurring World-Wide

Choat et al 2012 Nature

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Why would trees take a conservative strategy to close their stomata, reduce transpiration and potential photosynthesis? They have invested in woody biomass with a relatively expensive conducting xylem. If the atmospheric pull is too great it may cause bubbles, air pockets, that would break the thin line of water being pulled through the transpiration stream. Too many embolisms and the tree dies. Angiosperms are less conservative than gymnosperms, hence angiosperms are more vulnerable to death when severe drought occurs. They operate on a tight margin between critical values, like the water potential defining 50% of conductive loss

See Sperry, Tyree and Cochard, Ψ_{50} is water potential where 50% loss of hydraulic conductivity occurs

Evaporation

- Evaporation is the “physical process by which a liquid or solid is converted to a gaseous state” (Glossary of Meteorology).
- Plant canopies introduce water vapor into the atmosphere via **transpiration** and the **evaporation** of water from the soil and free water on the leaves and stems.



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Evaporation consists of evaporation from the soil and transpiration from plants. This is the green water flows

Evaporation: EcoPhysiological View point



Current=potential/resistances

$$I = \frac{V}{R}$$

**Evaporation is a function of the ratio between potential difference
In humidity, V, and the resistances against that potential, R**

$$E = \frac{\rho m_v (e_s(T_s) - e_a)}{m_a \sum R}$$

R = resistances, stomata & boundary layer = 1/G, conductances

m_v and m_a are molecular masses for vapor and dry air

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Flux of water is very important. We can conceptualize it using an analogy to Ohm's law where the flux is determined by the difference in the potential divided by the sum of resistances. The potential is defined by the vapor pressure of the atmosphere and the saturation vapor pressure as the surface temperature of a leaf (the interior of the leaf is essentially wet). The resistances are imposed by the stomata, a physiological resistance, and the boundary layer resistance of the leaf, a function of its size and wind velocity.

EVAPORATION is Energy Driven: Meteorologist Viewpoint



$$\lambda E = R_n - H - G - S - P_s$$

- Net Radiation (R_n) is partitioned into
 - Sensible Heat Exchange (H)
 - Latent Heat Exchange (λE)
 - Soil Heat Exchange (G)
 - Heat Storage in the Air and Vegetation (S)
 - Photosynthesis (P_s)
 - Bowen Ratio, β , $\lambda E/H$

$$\lambda E = \frac{R_n - G}{1 + \beta}$$

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The amount of possible water loss is determined by the energy balance and the energy consumed by latent heat exchange, LE.

Potential Evaporation

- “the evaporation from an extended surface of a short grass that is supplied with water and the canopy covers the ground completely.”

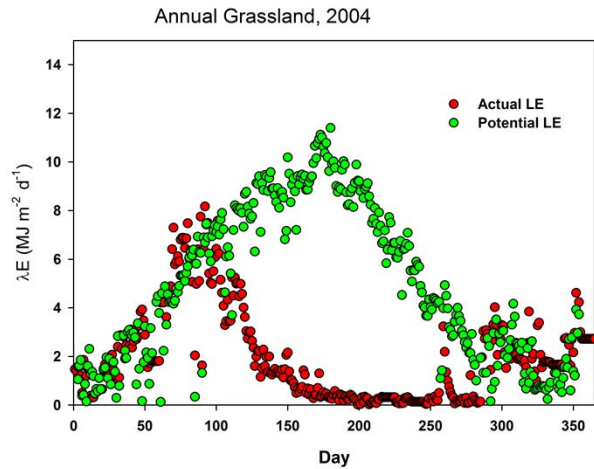


UC Davis Lysimeter

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Potential evaporation is important for managing crops and understanding the limitations imposed by physiological control

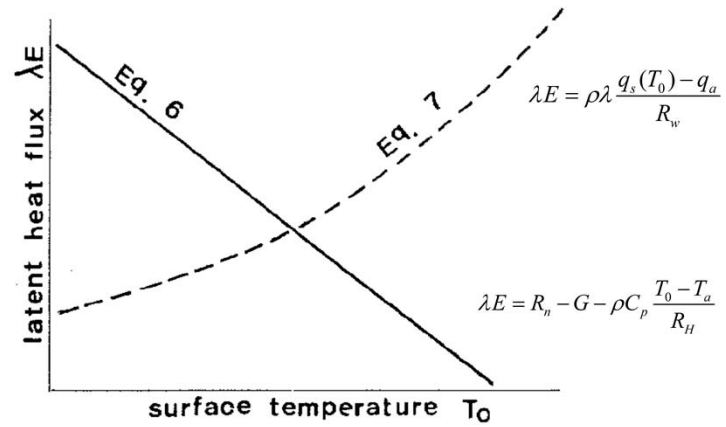
Potential vs Actual Evaporation



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Grasslands don't have enough water to operate full bore at their potential rates. They do so in the spring when there is water, then the plants dry up and die during the period with the greatest evaporative demand.

Conflicting Controls on Evaporation,
Supply of Water vs Demand by Available Energy



Monteith, 1981 QJRMS

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Penman Monteith Eq

- λE is a Balance between the supply and demand for moisture
- Reconciles the Meteorological and Physiological Viewpoints

$$\lambda E = \frac{s(R_n - S) + \rho \cdot C_p \cdot G_H \cdot D}{s + \gamma + \gamma \frac{G_H}{G_s}}$$

s: slope of $e_s(T)$ and T curve

γ : psychrometric constant

G_s & G_H : surface and aerodynamic conductances

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This is the most famous and important equation in biometeorology. It blends physiological control of evaporation, as defined by Ohms law, with meteorological control, as defined by the energy balance. It is a highly non linear function but in essence it tell us how evaporation changes with available energy, the vapor pressure deficit of the atmosphere and resistances (the inverse is conductance, G) imposed by the surface and atmospheric boundary layer and turbulence.

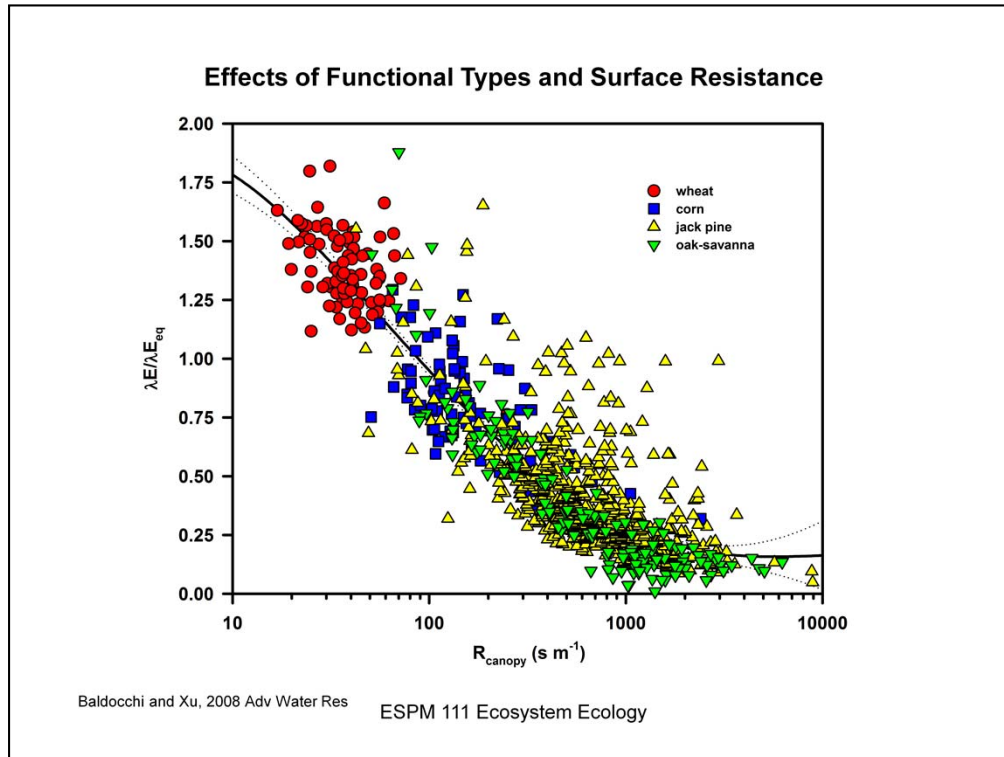
Big-Leaf Surface Conductance, G_s



$f(\text{LAI, soil moisture, photosynthetic capacity}(N))$

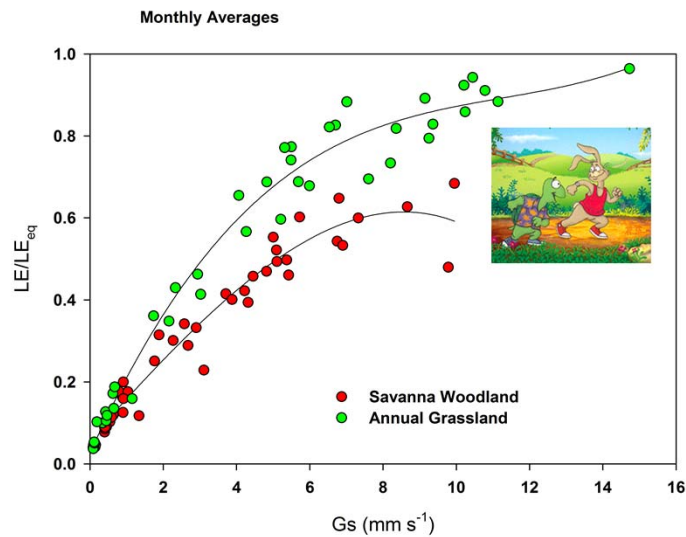
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The big leaf conductance is affected by the amount of leaf area index sustained and the opening of stomata. These are functions of soil moisture, photosynthetic capacity, leaf nitrogen.



Here are data I collected showing the ranking of the surface conductance with different plant types. Through evolution and limitations in environmental conditions they impose different resistances to water loss. The wheat is most open and the jack pine and oak savanna are most conservative. C4 corn has a greater resistance than C3 wheat for physiological reasons.

Landscape Differences on Evaporation Rates, normalized by Available Energy
On Short Time Scales, Grass ET > Forest ET

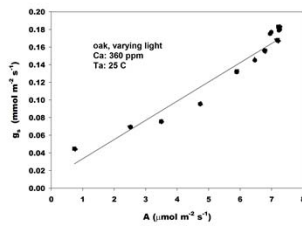


Ryu, Baldocchi, Ma and Hehn, JGR-Atmos, 2005
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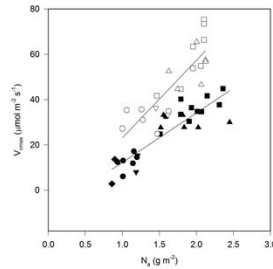
Same world different ways of operating. The oak and grass are 2 km away and yet they evaporate much differently.

Stomatal Conductance Scales with N, via Photosynthesis

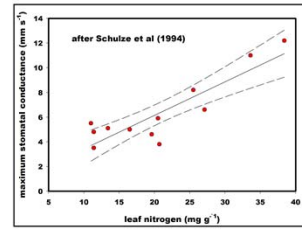
Stomatal Conductance Scales with Photosynthesis



Photosynthetic Capacity Scales with Nitrogen



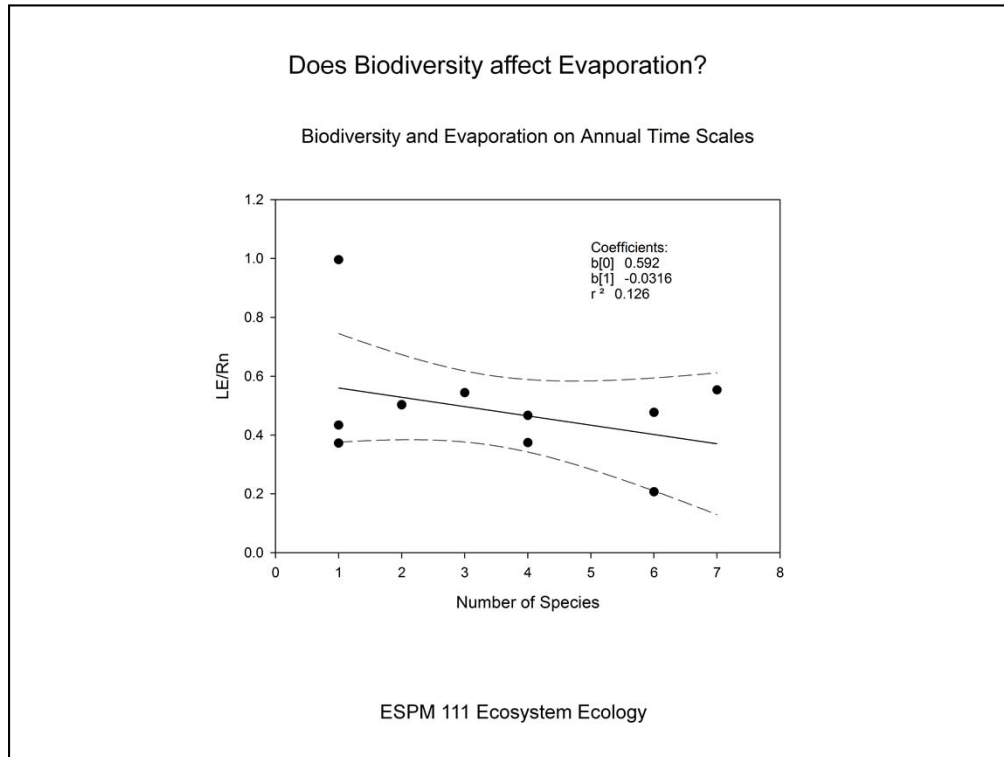
Stomatal Conductance scales with Nitrogen



Wilson et al. 2001, Tree Physiology
Schulze et al 1994, Annual Rev Ecology

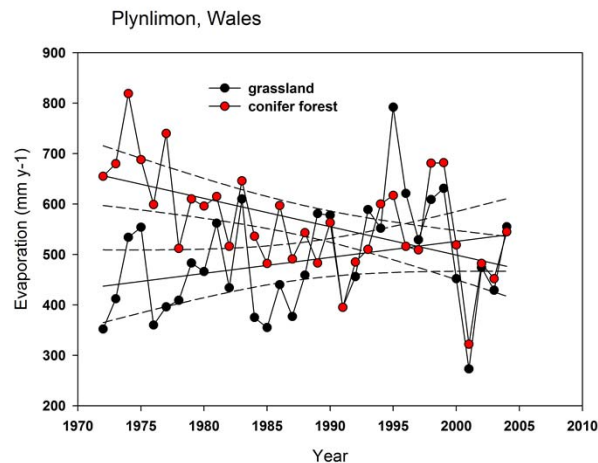
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This is the ecophysiological logic on how and why surface conductance can rank amount plant types. Stomatal conductance scales with photosynthesis. So plants with the greatest capacity will have greater conductances. This capacity is a function of N which dominates the photosynthetic enzyme Rubisco.



Does biodiversity affect evaporation? Should it, based on the discussion we had? We have to think of scaling on a plant vs plant level vs plant vs land area. Energy is available at the land area basis and plants fill this niche occurringly. Because species is a human construct and it says nothing about plant traits, we find little correlation between water loss and biodiversity, per se. Not to say diversity is not important. Just that the number of species may not affect water loss.

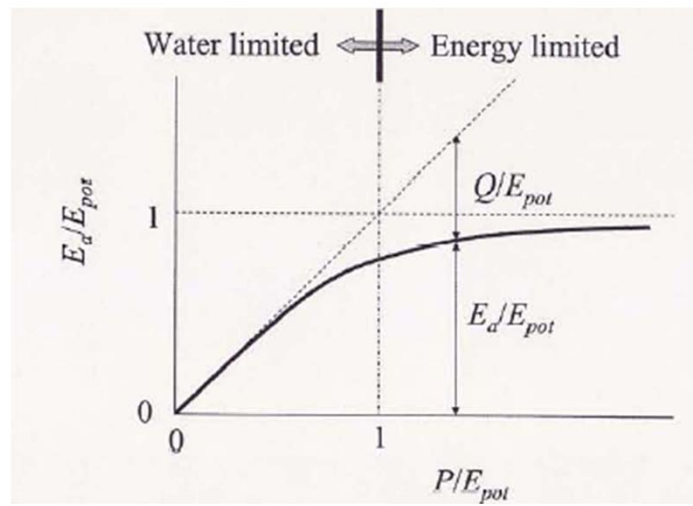
Stand Age also affects differences between
ET of forest vs grassland



Marc and Robinson, 2007 HESS
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What about grasses vs forests? The conventional wisdom was that forests used more water, so water managers in the UK would favor deforestation to increase water yield. Yet this long term study shows the results depend upon the age of the forest. Over 30 years the trends intersected and crossed. Here is an important set of evidence supporting the need for long term ecological studies.

Budyko Evaporation-Precipitation Relationship

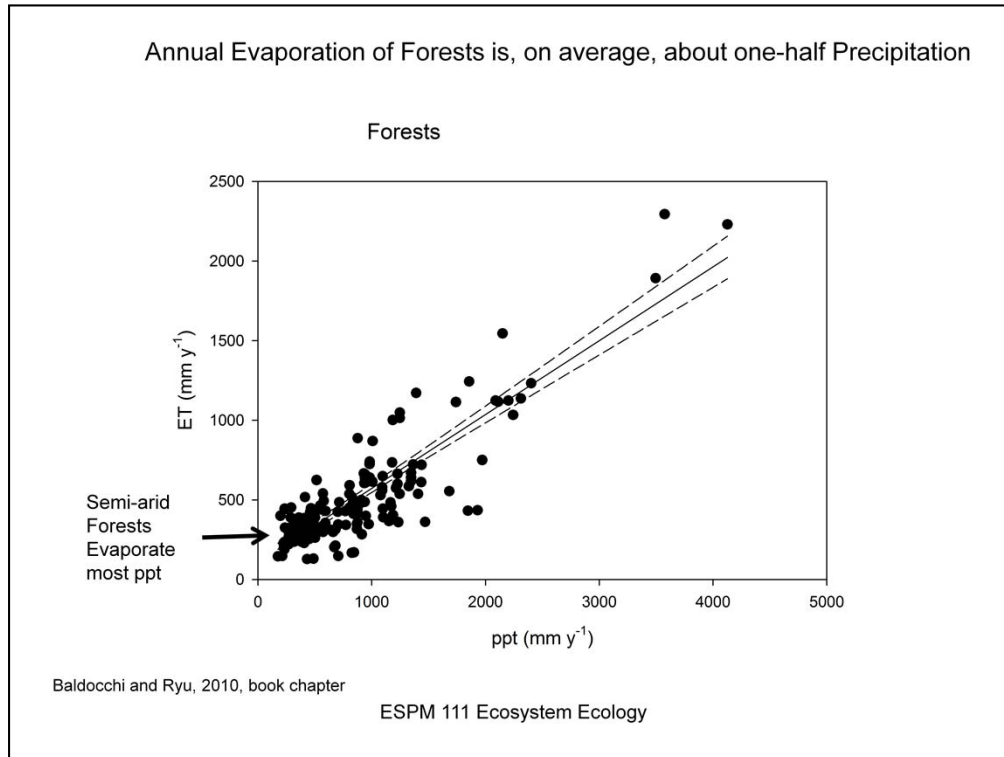


From Farquhar and Roderick, 2007

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Globally annual evaporation can be ranked with limitations imposed by limited precipitation, or in wet areas limited energy.



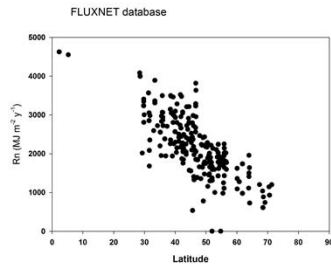
This gives one a sense how much water is evaporated by forests across the world.

Points to Ponder

- Why is the Arctic so wet if it gets the rain of a desert?
- How does land use (conifer/deciduous forests vs grasslands) affect energy and water balances?
- How does biodiversity affect evaporation and water yield?
- What will happen to Evaporation with Global Warming and Higher CO₂ concentrations?
- How does evaporation differ across the world by climate and ecosystem or plant functional grouping or trait?

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Why is the Arctic so Wet, if it can be Classified as a Desert by its Meager Rainfall (< 300 mm/y)?



Equilibrium Evaporation

$$E_{eq} = \frac{1}{\lambda} \frac{s}{s + \gamma} R_n$$

$$\frac{s}{s + \gamma} \sim 0.432 + T_a \cdot 0.0116$$

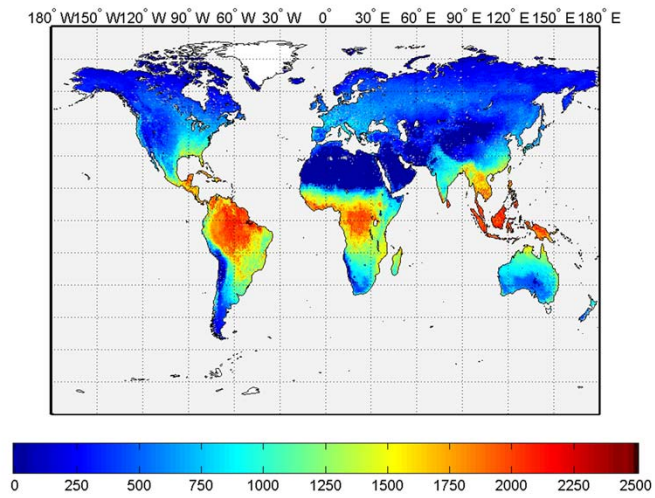
$$E_{eq} = \frac{1}{2.41 MJ / kg} 0.39 \cdot 1000 MJ m^{-2} y^{-1} = 161 mm$$

ppt >> E_{eq}

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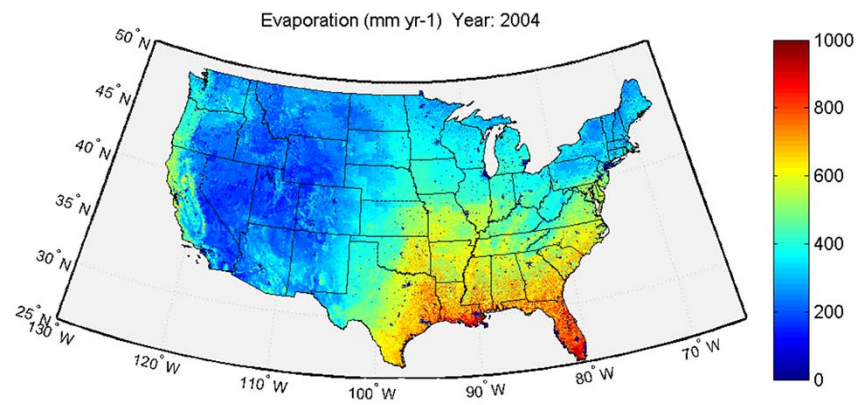
$$\langle ET \rangle = 500 \text{ mm/y} \Rightarrow 63,000 \text{ km}^3/\text{y}$$

Evaporation (mm yr⁻¹) Year: 2003



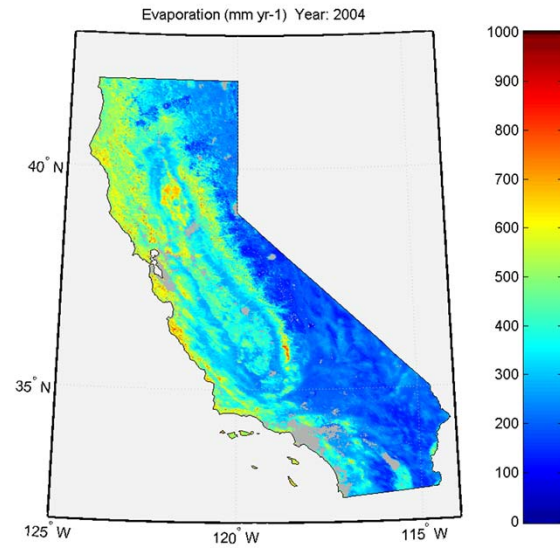
Ryu, Baldocchi et al. Global Biogeochemical Cycles 2012

MODIS-Driven Product Using Biophysics via Cloud Computing



Ryu, Baldocchi et al. Global Biogeochemical Cycles, 2012
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Down-Scale to Regions for Policy and Management Decisions



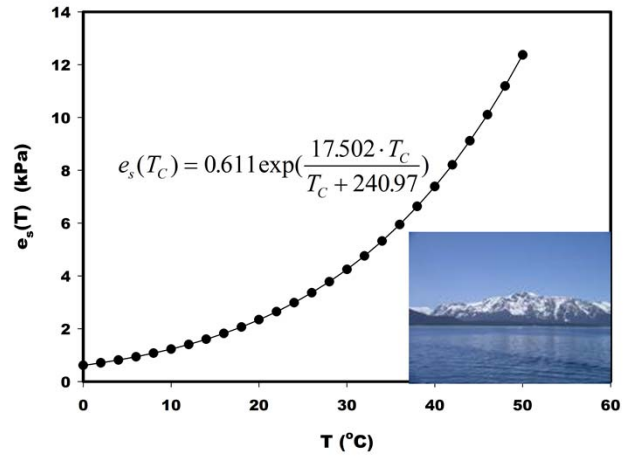
Ryu, Baldocchi et al. Global Biogeochemical Cycles 2012

Atmospheric Humidity

- Relative Humidity, $h_r = \frac{e_a}{e_s(T)}$
 – Ratio between ambient, e_a , and saturated vapor pressures, $e_s(T)$
- Absolute Humidity $\rho_v = \frac{e_a m_v}{R T_k}$
- Dew Point Temperature, T_d $T_d = \frac{240.97 \cdot \ln(e_a / 0.611)}{17.502 - \ln(e_a / 0.611)}$
- Wet Bulb Psychrometry $C_p(T_a - T_w) = \frac{\lambda(e_s(T_w) - e_a)}{P}$

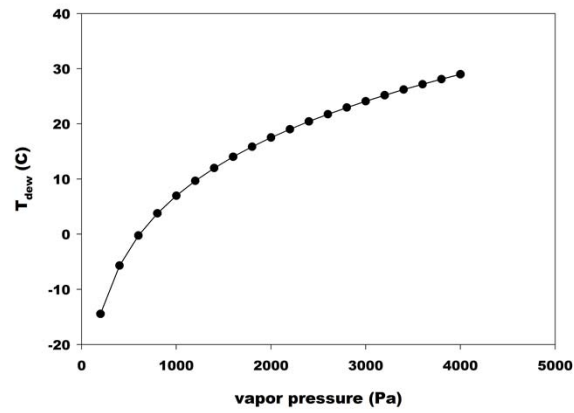
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SATURATION VAPOR PRESSURE



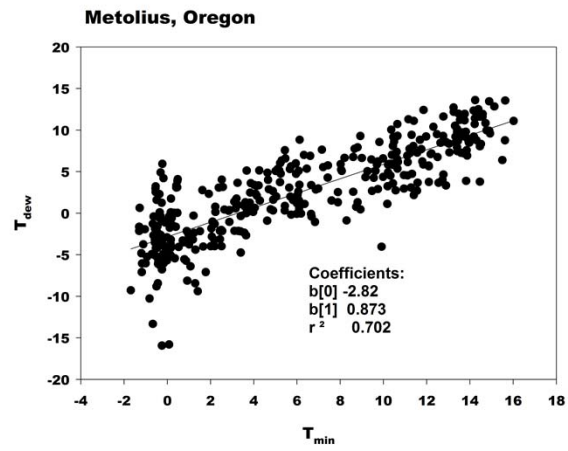
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Dewpoint Temperature and Vapor Pressure



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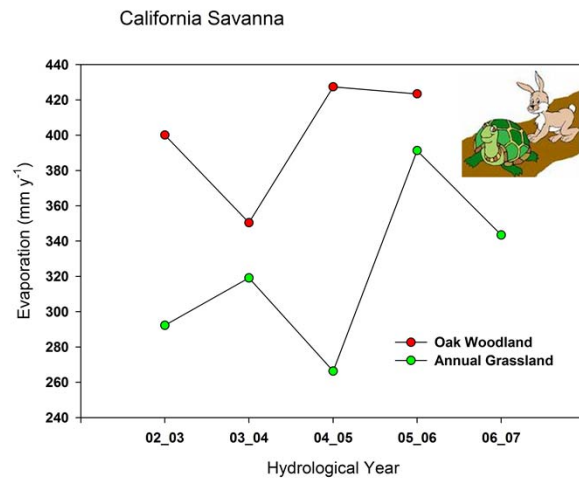
Dewpoint Scales with Minimum Temperature



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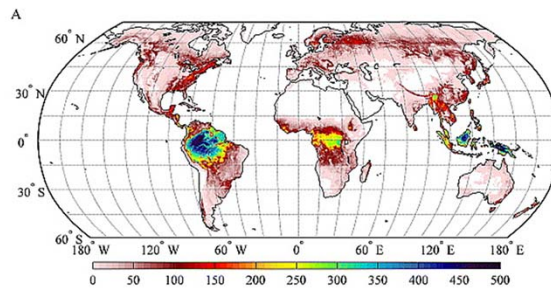
Role of Land Use on ET:
On Annual Time Scale, Forest ET > Grass ET



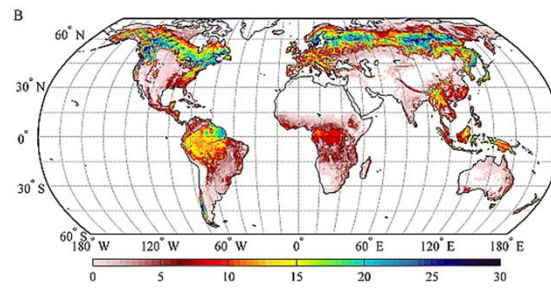
Ryu, Baldocchi et al, JGR-Atmos, 2010

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Forest Rainfall Interception



Mm/yr

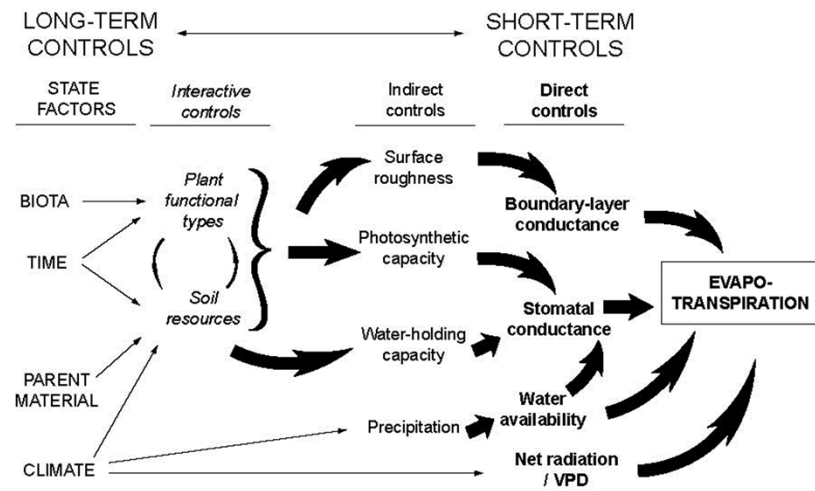


% of Rainfall

Miralles et al 2010 JGR Atmos

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Summary



Chapin et al.

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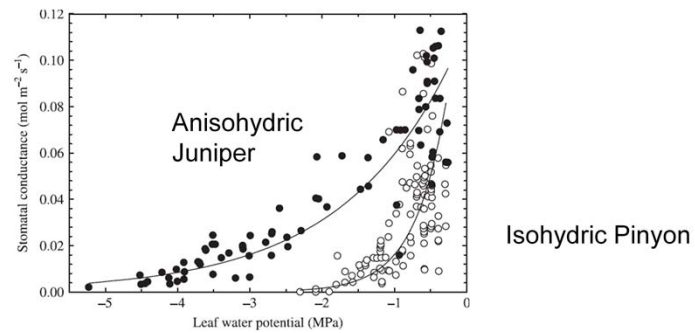


Fig. 8 Stomatal conductance vs leaf water potential for piñon (open circles) and juniper (closed circles) at Mesita del Buey, Los Alamos, New Mexico. Data from Barnes (1986).

Plants with **Isohydric** regulation of water status avoid of drought-induced hydraulic failure via stomatal closure, but the consequence can be carbon starvation and a cascade of downstream effects such as reduced resistance to biotic agents.

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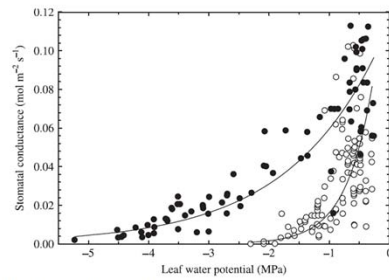
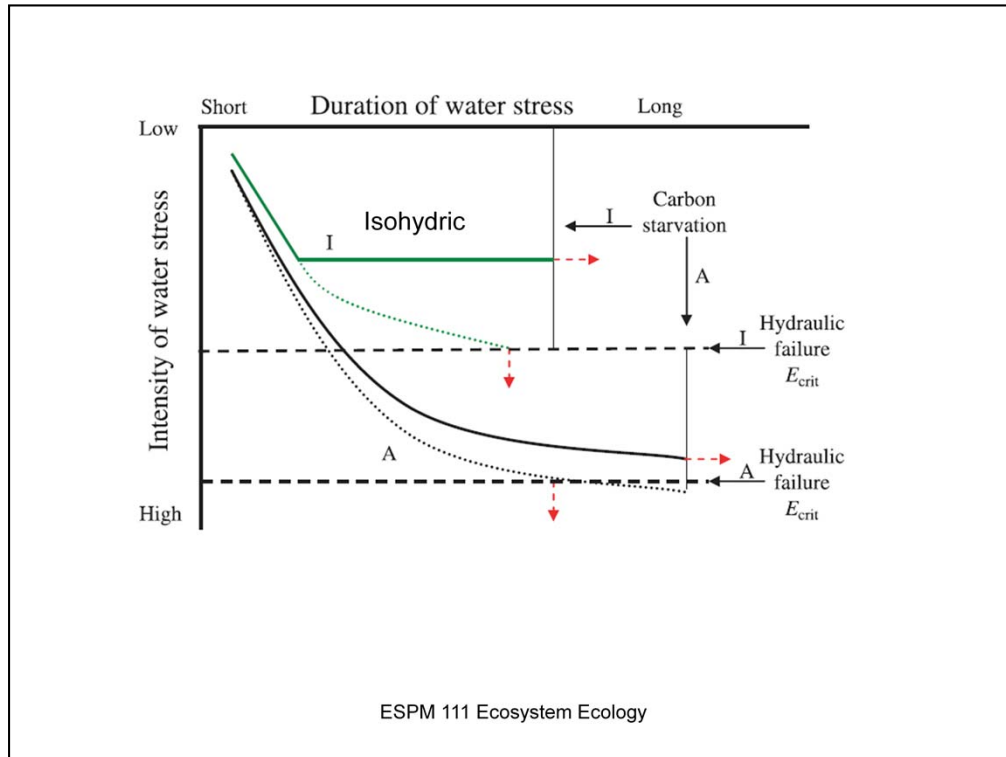


Fig. 8 Stomatal conductance vs leaf water potential for piñon (open circles) and juniper (closed circles) at Mesita del Buey, Los Alamos, New Mexico. Data from Barnes (1986).

Anisohydric species, by contrast, allow midday Ψ to decline as soil Ψ declines with drought; Anisohydric species tend to occupy more drought-prone habitats compared with isohydric species; Anisohydric plants are relatively drought-tolerant, they are predisposed to hydraulic failure because they operate with narrower hydraulic safety margins during drought.

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McDowell et al. Tansley Review

Anisohydric plants operate at a tighter safety margin to the point of hydraulic failure.

Isohydric plants are more vulnerable to embolism, but they are more adept at avoiding hydraulic failure, but at the cost of carbon starvation.