Física do Solo
CCR/UFSM

Temperatura (Calor) do Solo

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Soil Temperature

- Critical factor that influences important physical, chemical, and biological processes in soil and plants:
  - Soil hydraulic properties
  - Organic matter decomposition and mineralization
  - Biodegradation of pesticides
  - Seed germination
  - Plant growth

In roots, respiratory energy is used for nutrient uptake, and root growth and maintenance, as well as for symbiotic processes and defence (Martinez et al., 2002). Root respiration accounts for 33–60% of total soil respiration (Bowden et al., 1993; Pregitzer et al., 1998), and consumes 8–52% of carbon fixed by photosynthesis (Lambers et al., 1996).

Roots exert a strong influence on the temperature sensitivity of soil CO_2 efflux (Boone et al., 1998) and provide an important reference for global warming caused by an increase in atmospheric CO_2 concentration (Atkin et al., 2000).

Copiado de:
Journal of Experimental Botany, 56:2651–2660, 2005

What is temperature?

- Measure of the average random kinetic energy of the molecules of a substance
- Physical property that determines the direction of heat flow between two substances in thermal contact
- T ≠ Heat Content
- Heat Content = $(T - T_{ref}) \times C$ — *heat capacity – we'll get to it later.*

Modes of energy transfer

- **Radiation**: emission of energy in the form of electromagnetic waves
- **Conduction**: transfer of heat by molecular exchanges of kinetic energy
- **Convection**: transfer of heat by bulk fluid motion

Radiation

- All objects at a temperature T > 0 K emit radiation: energy in the form of electromagnetic waves
- Total amount of radiation emitted strongly depends on T.

Radiation

- **Stefan-Boltzmann law:**

$$J_t = \varepsilon \sigma T^4$$

J_t: total energy emitted, W m^{-2}
ε: emissivity (unitless)
= 1 for a "black body"; 0.9 to 1.0 for soil
σ: Stefan-Boltzmann constant
= 5.67 x 10^{-8} W m^{-2} K^{-4}
T: temperature of the emitter (K)

Note: by convention, little *t* is time, big *T* is Temperature.

Radiation

- **Emissivity** is the fraction of blackbody emittance at a given wavelength emitted by a material
- A **blackbody** is a body whose surface absorbs rather than reflects incoming shortwave radiation, and that emits long-wave radiation at maximum efficiency

Radiation

- **Wien's law**

$$\lambda_m = \frac{2900\,\mu m \cdot K}{T}$$

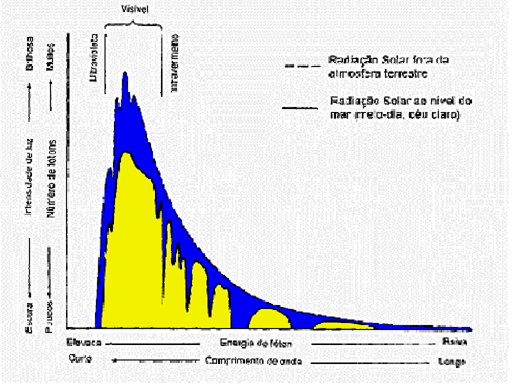
λ_m is the wavelength of maximum radiation intensity

- λ_m is inversely proportional to temperature

Radiation

- **Wien's law** $$\lambda_m = \frac{2900\,\mu m \cdot K}{T}$$
- Sun Surface Temperature ≈ 5760 K
- Earth Surface Temperature ≈ 288 K
- **λ_m for the sun** is about 0.5 µm. 99% of solar radiation is in the wavelengths 0.3 - 4.0 µm and is called **shortwave**
- **λ_m for the earth** is about 10 µm (range of 3 - 50 µm), and is called **infrared or long-wave radiation**

DISTRIBUIÇÃO ESPECTRAL DA RADIAÇÃO SOLAR



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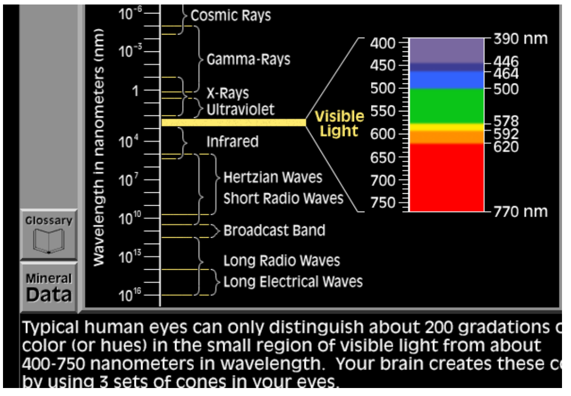
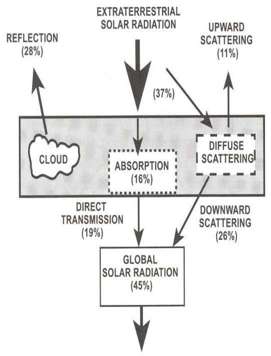
DISTRIBUIÇÃO ESPECTRAL DA RADIAÇÃO SOLAR



Solar Radiation

- Only a fraction of the solar radiation emitted by the Sun that reaches the Earth's atmosphere is available for warming the soil



FONTE ENERGÉTICA

SOL- **Energia radiante através de radiação de onda curta (0,2 a 4 μm).**

Do total da energia irradiada pelo sol,

*** 45% incide na superfície da terra- 19 sol+26 céu**

*** 28% é refletida pelas nuvens**

*** 16% é absorvida por moléculas de dióxido de C, ozônio e vapor de água na atmosfera**

*** 11% é dispersa e retorna ao espaço exterior**

100%

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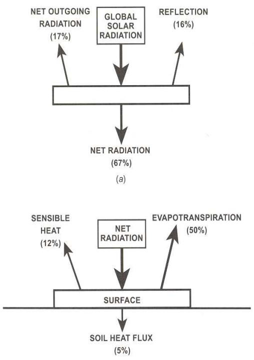
Net radiation at the soil surface

- The global solar radiation as it reaches the land is further partitioned
- Net radiation at the soil surface:

$J_n = (J_s + J_a)(1-\alpha)+J_{il} - J_o$

J_n = net radiation
J_s = direct beam incoming short-wave
J_a = diffuse incoming short-wave
α = albedo: the fraction of incoming short-wave radiation reflected by the surface
J_{il} = incoming long-wave
J_{lo} = outgoing long-wave



Albedo (α)

- Shortwave reflectivity
- For soils, α varies from 0.1 - 0.4 (unitless)
- Depends on:
  - Soil color
  - Surface roughness
  - Sun angle (latitude, time of day)
  - Soil wetness
  - Slope and aspect

3. FATORES FÍSICOS QUE ALTERAM A RADIAÇÃO SOLAR

- Diferença entre regiões geográficas

A quantidade de energia que chega ao solo em um determinado local varia em função da constituição da atmosfera, da latitude e época do ano.

- Equador - Latitude zero

- Pequena amplitude durante todo o ano

- Incidência vertical

- Menor percurso

- Energia máxima

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3. FATORES FÍSICOS QUE ALTERAM A RADIAÇÃO SOLAR

Com aumento da latitude

- Amplitude de variação dentro do ano aumenta

- Menores valores atingidos no inverno e maiores no verão

Regiões com baixas temperaturas

*** Adotar práticas para aumentar temperatura do solo.**

Regiões tropicais e subtropicais com altas temperaturas

*** Amenizar as temperaturas a fim de otimizar (ou viabilizar) desenvolvimento vegetal.**

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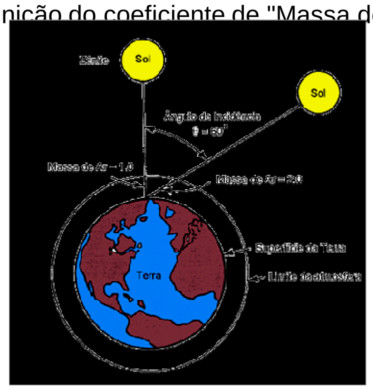
Trajetória dos raios de Sol na atmosfera e definição do coeficiente de "Massa de Ar"



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3. FATORES FÍSICOS QUE ALTERAM A RADIAÇÃO SOLAR

3.4 DISTRIBUIÇÃO DE SOLO E ÁGUA

ÁGUA TENDE A DIMINUIR A AMPLITUDE TÉRMICA

3.5 VEGETAÇÃO

Altera o albedo

- ✓ **Diminui a profundidade de penetração da radiação global**
- ✓ **Aumenta a remoção do calor latente por evapotranspiração**
- ✓ **Diminui a taxa de perda de calor do solo por isolar a superfície**

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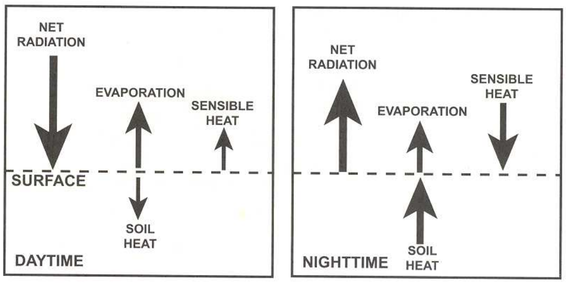
Surface energy balance

- **Energy balance at the soil surface:**

$$J_n = S + A + LE$$

J_n = net radiation at the surface
S = heat flux into the soil
A = sensible heat flux to the atmosphere
L = latent heat of vaporization
E = rate of evaporation
(all in W m^{-2})

Surface energy balance



Heat flow in soil

- Radiation is how energy gets from the sun to the soil surface.
- Convection and conduction are the two most important mechanisms of heat transport under normal conditions
- A third mechanism, latent heat movement (latter we will comment).

Convection

- Convection: transfer of heat by a flowing liquid or gas
- 2 forms:
  - Convection of sensible heat (heat in the form of a change in temperature)
  - Convection of latent heat (heat in the form of a change of phase)

Convection of sensible heat

- Liquid water has a high volumetric heat capacity

C_L = 4.17 X 10^6 J m^{-3} K^{-1} (at 20 ° C)

- Convection of sensible heat can significantly alter the soil thermal regime when liquid water fluxes are relatively large

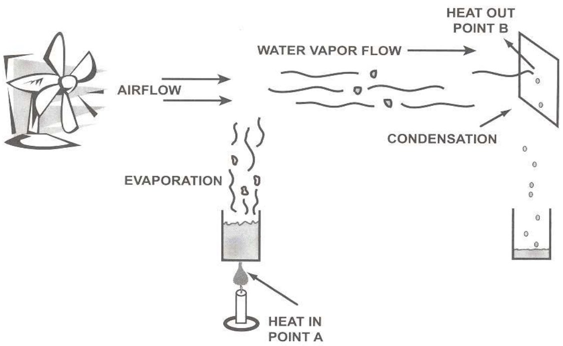
Convection of latent heat

- Convective transport of latent heat energy, usually in the form of water vapor.

H_v = latent heat of vaporization
= 2450 J/g (at 20 ° C)

- A temperature gradient in moist soil can induce a vapor pressure gradient, which can drive water vapor transport

Convection of latent heat



Heat conduction

- Fourier's Law: the heat flux is proportional to the temperature gradient

$$q_h = -\kappa \frac{dT}{dz}$$

q_h = heat flux by conduction (W m^{-2})

κ = thermal conductivity (W m^{-1} K^{-1})

T = temperature (K or °C)

z = position (m)

Transient heat conduction

- Heat conservation equation

energy in - energy out = change in heat stored

$$C\frac{\partial T}{\partial t} = -\frac{\partial q_h}{\partial z}$$

- ***C*** = Volumetric heat capacity

also written $c\rho_t$: <u>mass-based</u> heat capacity, times the wet bulk density (to convert to a volume basis)

Transient heat conduction

- Combine Fourier's law: $q_h = -\kappa \frac{dT}{dz}$

with the heat conservation equation:

$$C\frac{\partial T}{\partial t} = -\frac{\partial q_h}{\partial z}$$

to describe transient heat conduction:

$$C\frac{\partial T}{\partial t} = -\frac{\partial q_h}{\partial z} = -\frac{\partial}{\partial z}\left(-\kappa\frac{\partial T}{\partial z}\right)$$

Soil thermal properties

- Volumetric heat capacity
- Soil thermal conductivity
- Soil thermal diffusivity

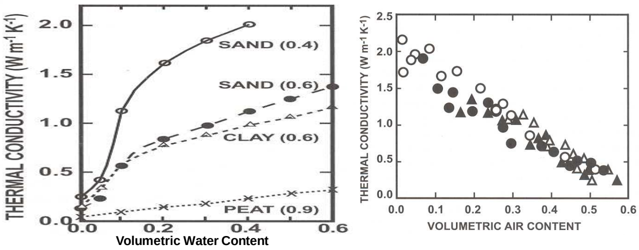
Soil thermal conductivity, κ

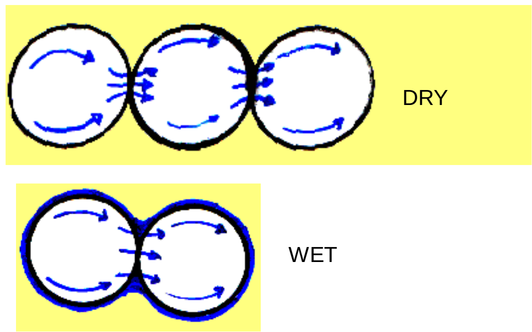
- κ is the rate of heat transfer through a unit area of soil under a unit temperature gradient (W m^{-1} K^{-1})
- Typical values are between

$$0.1 \leq \kappa \leq 5 \text{ W m}^{-1} \text{ K}^{-1}$$

- Varies with
  - Mineralogy
  - Air-filled porosity
  - Temperature
  - Spatial arrangement
  - Organic matter content
  - Water content
  - Bulk density

Soil thermal conductivity





Volumetric heat capacity, *C*

- *C*, the volumetric heat capacity, is the energy required to heat a unit volume of soil by one degree. Units: J m^{-3} K^{-3}
- *C* varies with
  - *Water content*
  - *Bulk density*
  - *Mineralogy*
  - *Organic matter content*
  - *temperature*

Volumetric heat capacity

- *C* can be estimated by (*f* is volume fraction)

$$C = f_m C_m + f_o C_o + f_w C_w$$

- or by $C = \rho_w c_w \theta + \rho_b c_s$
- Typically, $0.8 \leq C \leq 3$ MJ m^{-3} K^{-1}

- **Tubelis (1972)**
- Latossolo Vermelho-Escuro = 210 cal/kg ºC
- Latossolo Vermelho-Amarelo = 190 cal/kg ºC

Soil thermal diffusivity, D_T

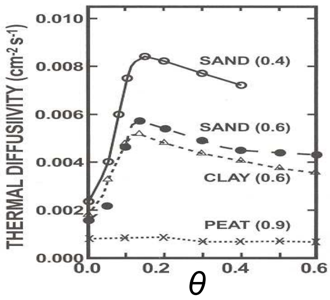
- Change in temperature produced in a unit volume by the quantity of heat flowing through the volume in unit time under a unit temperature gradient.
- Units: $m^2\ s^{-1}$ (same as molecular diffusion)
- More useful definition: the ratio of the thermal conductivity to the volumetric heat capacity:

$$D_T = \kappa / C$$

- Makes the heat flow equation more convenient: $\frac{\partial T}{\partial t} = -D_T \frac{\partial^2 T}{\partial z^2}$

Soil thermal diffusivity

- Used to characterize the rate of transmission of heat through the soil
- Influenced by anything that changes κ or C.



Calor específico gravimétrico, condutividade térmica e massa específica de constituintes do solo

Constituinte	C_g [1]	K [2]	ρ_p
	cal/kg ºC	mcal/cm s ºC	kg/m³
Quartzo	170	21	
mineral	170	7	2650
orgânica	460	0,6	1400
água	1000	1,37	1000
ar	240	0,06	1,3

[1] Prevedello (1996)
[2] Hillel (1998)

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Soil thermal regime

Steady-state $q_h = -\kappa \frac{\Delta T}{\Delta z}$

Transient $\frac{\partial T}{\partial t} = -D_T \frac{\partial^2 T}{\partial z^2}$

Instantaneous change
(like infiltration)

Cyclical change
New! Improved! Dynamic!

Basic heat flow equation or **Fourier's Law**

$q_H = -k \text{ grad } T$

$q_h = -kz\ dT / dz$ R[1] vertical

q_h = heat flux, cal / cm² sec
k = thermal conductivity, cal / cm s ° C
dT / dz = thermal gradient, ° C / cm

$dT / dz = (T_1 - T_2) / (z_1 - z_2)$

q_h = [cal / cm s ° C] [° C / cm] = cal / cm² s

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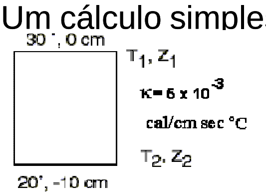
Um cálculo simples



q_h = -5 X 10 $^{-3}$ cal / cm s ° C [(30° - 20°) /(0cm -10cm)]

q_h = -5 X 10 $^{-3}$ cal/cm sec ° C [10° /10 cm]

=-5 X 10 $^{-3}$ cal/cm ^{2} sec

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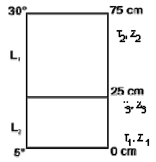

T_2 = 30 ° C
Z_2 = 75 cm
T_3 = ? ° C
Z_3 = 25 cm
T_1 = 5 ° C
Z_1 = 0 cm

$(L_1 + L_2)/ k_{eq} = L_1/ k_1 + L_2 / k_2$

$75 / k_{eq} = 50 / 5 \times 10^{-3} + 25 / 2.5 \times 10^{-3}$
$75 / k_{eq} = 10000 + 10000$
$75 = 20000\ k_{eq}$

$k_{eq} = 3.75 \times 10^{-3}$ cal / cm s ° C

Therefore, for the full column:
$q_h = - k_{eq} [(T_2 - T_1) / (L_2 - L_1)]$
$q_h = - 3.75 \times 10^{-3}$ cal/cm s ° C [(30° - 5°) / (75cm - 0cm
$q_h = -1.25 \times 10^{-3}$ cal / cm^2 s

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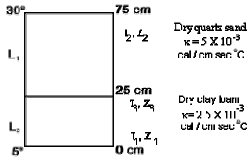

Now for lower 1/3 of column to find temperature at T_3

-1.25×10^{-3} cal/cm^2 s
$= -2.5 \times 10^{-3}$ cal/cm s ° C [(T3-5°)/(25cm-0cm)]
T3 = 17.5 ° C

Now for the upper 2/3 of column:

-1.25×10^{-3} cal/cm^2 s
$= -5 \times 10^{-3}$ cal/cm s ° C [(30° -T3)/(75cm-25cm)]
T3 = 17.5 ° C

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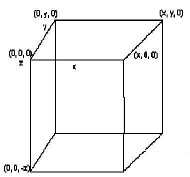

- Heat conservation equation: i.e. heat is conserved; neither gained nor lost without reaction.

  Unit volume of soil used to calculate temperature balance equation:

  Heat balance equation:

Amount of heat energy flowing into soil volume during a small time interval, Δt, is equal to

Amount of heat energy flowing out of a soil volume during Δt

Plus increased of heat energy stored in soil volume during Δt

Plus amount of heat energy that has disappeared from volume during Δt by reaction.

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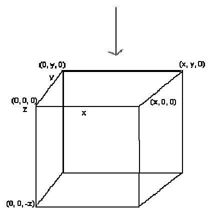
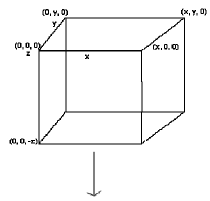
A. Amount of heat energy flowing into soil volume during a small time interval, Dt

B. Amount of heat energy flowing out of a soil volume during Dt





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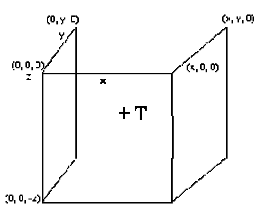
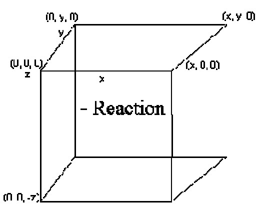
C. Plus increased of heat energy stored in soil volume during Dt

D. Plus amount of heat energy that has disappeared from volume during Dt by reaction.





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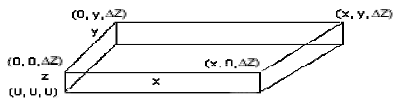
A = B + C + D



q_h = Soil heat flux, cal / cm^2 time:

A = q_h (x, y, z, t + ½ Δt) Δx Δy Δt
B = q_h (x, y, z + Δz, t + ½ Δt) Δx Δy Δt
C = [H (x, y, z + ½Δz, t + Δt) - H (x, y, z + ½Δz + t)] Δx Δy Δz
D = r_h Δx Δy Δz Δt

Where:
H = heat content per unit volume, cal / cm^3
H = CT
r_h = heat loss from volume during Δt

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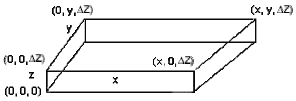
A = B + C + D
0 = B - A + C + D



0 = [q_h (x, y, z + Δz , t + ½Δt) - q_h (x, y, z, t + ½ Δt)] Δx Δy Δt
+ [H (x, y, z + ½Δz, t + Δt) - H (x, y, z + ½Δz, + t)] Δx Δy Δz
+ r_hΔx Δy Δz Δt

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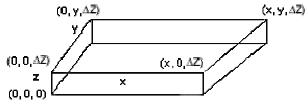

[q_h (x, y, z + Δz, t + 1/2 Δt) - q_h (x, y, z, t + 1/2 Δt)] / **Δz**
+ [H (x, y, z + 1/2 Δz, t + Δt) - H (x, y, z + 1/2 Δz, + t)] / Δt
+ r_h = 0

Note: Δx and Δy are arbitrarily small
As the volume shrinks allows Δz → 0 and time gets small Δt → 0

This equation is know as the heat conservation equation

This assumes q only one dimentional heat flow or heat flow is the only function of z

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in ^3R

H / ∂ t + ∂ q_{hx} / ∂ x + ∂ q_{hy} / ∂ y + ∂ q_{hz} / ∂ z + r_h = 0

r_h can be zero:

∂ H / ∂ t + ∂ q_h / ∂ z = 0

Heat content per volume:

H = C_v (T - T_{ref})

C_v = Volumetric heat capacity
T_{ref} is where H ≡ O

Replace H with Cv T

Cv ∂ T / ∂ t + ∂ q_h / ∂ Z = 0

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Remember from last time that:

q_h = -k dT / dz or heat flux equation.

Inserting the heat flux equation and heat content per volume equation into the heat conservation equation gives:

Cv ∂T / ∂ t = ∂ / ∂z (k ∂T / ∂ z)

if z dependence upon k is neglected then

Cv ∂T / ∂t = k ∂ ^{2}T / ∂ z^2

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This is very non-linear partial differential equation.

To overcome this problem, we introduce the term D_T

D_T = thermal diffusivity, cm^2 / s
Diffusivity = thermal conductivity / volumetric soil heat capacity

DT = k / Cv
Where : D_T = cm^2 / s, k = cal / cm s ° C
Cv = cal / cm^3 ° C

Therefore:
qh = - D_T dT / dz
or
∂ T / ∂ t = D_T d^2 T /dz^2

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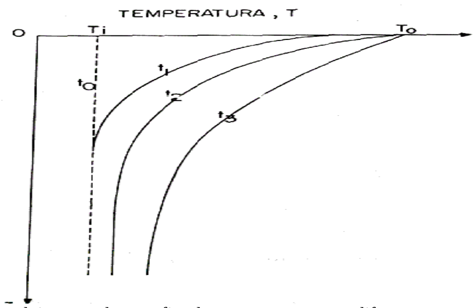
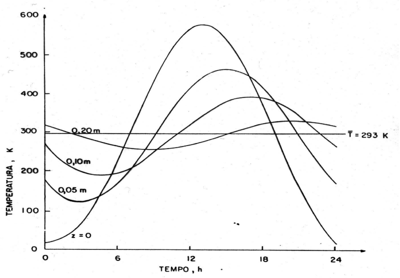
Como explicar este comportamento?



Desenvolvimento dos perfis de temperatura em diferentes tempos de propagação de calor numa coluna de solo termicamente homogêneo, quando a temperatura inicial da coluna (T_i) foi substituída por T_0 na superfície.

Ou este?

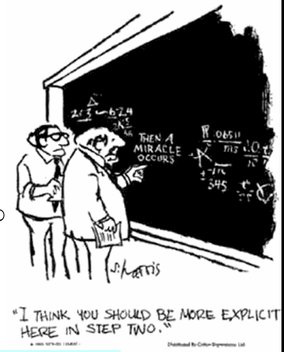


Simple soil heat model

Given: $\frac{\partial T}{\partial t} = -D_T \frac{\partial^2 T}{\partial z^2}$

Assume:

- 1-D soil
- D_T constant
- Constant temperature T_a at $z = \infty$
- Sinusoidal temperature at $z = 0$, with amplitude A_0



Then:

$$T(z,t) = T_a + A_0 \sin\left(\omega t - \varphi_0 - z/d\right) e^{-z/d}$$

Some new terms

$$T(z,t) = T_a + A_0 \sin\left(\omega t - \varphi_0 - z/d\right) e^{-z/d}$$

- 1-D soil (depth z, positive down)
- D_T constant in z and t
- Constant temperature T_a at $z = \infty$
- Sinusoidal temperature at $z = 0$, with amplitude A_0

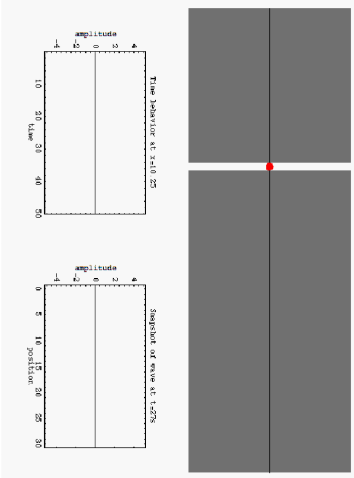
ω = 2π / period (say, 24 hours): normalizes the "clock time" ***t*** to the 2π sine wave period.

d = depth z at which thermal amplitude is A_0/e: normalizes "physical depth" ***z*** to exponential function depth. Specifically, $d = \sqrt{\frac{2D_T}{\omega}}$

The sine part

$$T(0,t) = \sin(\omega t)$$

This is about the soil surface warming during the day, and cooling at night.



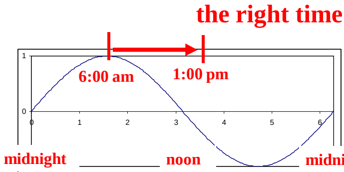
More sine stuff

$$T(z,t) = A_0 \sin\left(\omega t - \varphi_0 - z/d\right)$$

Clock time at the surface

Phase shift with depth

Phase constant: adjust so peak is at the right time of day



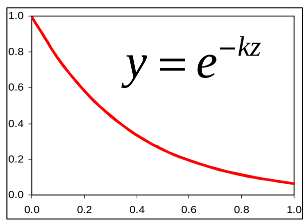
For a period of 24 hours, and a peak at the surface at 1:00 pm (the 13th hour),

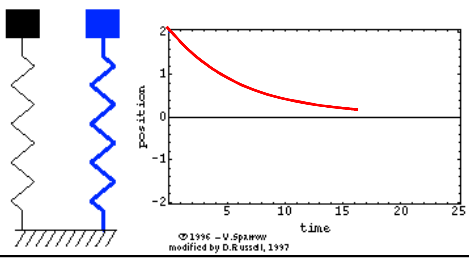
$$\varphi_0 = 2\pi \frac{7}{24}$$

The e^{-z} part

$$T(z) = T_a + A_0 e^{-z/d}$$

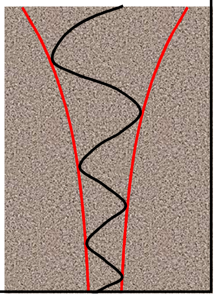
exponential decay, half-lives, etc.





Summary

- Thermal properties (specifically D_T) appear **only** in the definition of damping depth: $d = \sqrt{\dfrac{2D_T}{\omega}}$
- Phase shifts (delays) as sine wave propagates downward
- Amplitude decreases as the wave propagates downward
- Temperature constant at infinite depth



Applications

$$T(z,t) = T_a + A_0 \sin\left(\omega t - \varphi_0 - z/d\right)\, e^{-z/d}$$

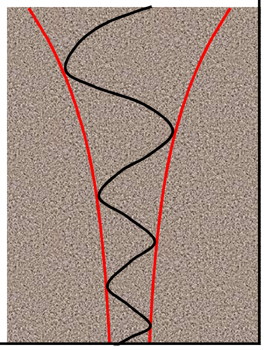
The questions we ask this equation are usually about either

- timing and phase shift, or
- amplitude

but not both.

When it's a timing question, you only need the sin() part

When it's about amplitude, you only need the $e^{-z/d}$ part



Example application

On the coldest day of the year, at what depth is the warmest soil found?

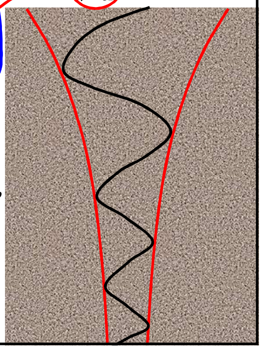
$$T(z,t) = T_a + A_0 \sin\left(\omega t - \varphi_0 - z/d\right)\, e^{-z/d}$$

Translation: what depth ***z*** is ½ cycle (i.e., π) later than the surface?

½ cycle delay requires that $z/d = \pi$,

where $d = \sqrt{\dfrac{2D_T}{\omega}}$ and $\omega = \dfrac{2\pi}{\text{period}}$,

so $z = \pi\sqrt{\dfrac{2D_T\ 365\text{ days}}{2\pi}}$



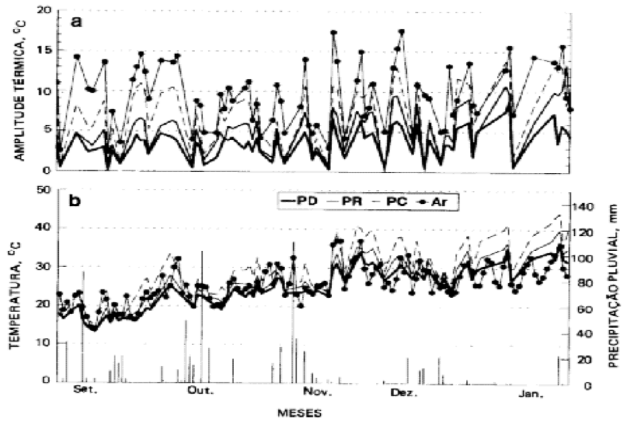
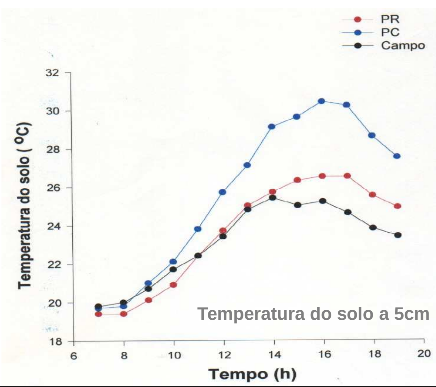
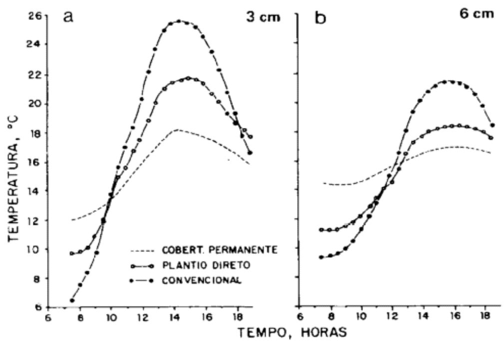


Figura 2. Temperatura máxima do ar (Ar); temperatura máxima do solo e ocorrência de chuvas (a); amplitude diária da temperatura do ar e do solo sob plantio direto (PD), preparo reduzido (PR), preparo convencional (PC) (b), em setembro de 1990-janeiro de 1991.

PERFIS DE TEMPERATURA DO SOLO



65



Influência do sistema de manejo do solo na sua temperatura, em intervalos de uma hora, a: a 3cm de profundidade e b: a 6 cm de profundidade (SIDIRAS & PAVAN, 1986.)

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EFEITO DA COBERTURA DO SOLO SOBRE A TEMPERATURA

Porquê? tº solo coberto < tº solo descoberto

O fluxo de calor que cruza a superfície é diminuído pela reflexão pelo resíduo de parte da energia incidente (coeficiente de reflexão)

Quanto a maior a percentagem da superfície do solo coberta por culturas ou seus resíduos, menores as temperaturas do solo e a sua oscilação diária

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A condutividade térmica da camada de resíduos é menor devido a presença de grande quantidade de ar (↓ transmissão de calor por convecção e condução)

Quanto maior a espessura da camada de resíduos, menores as temperaturas do solo

Influência da umidade

Coberturas claras vs escuras

- ✓ **Coeficiente de reflexão**
- ✓ **Coberturas claras > cobertura escuras**

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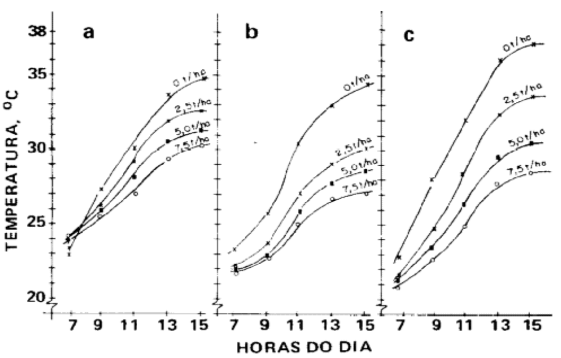
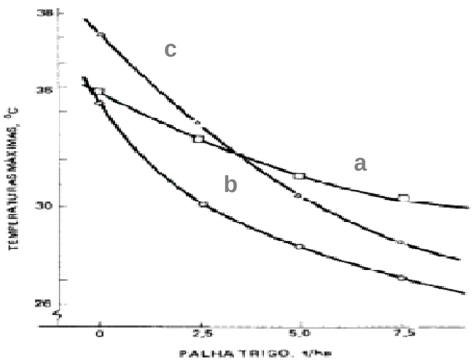


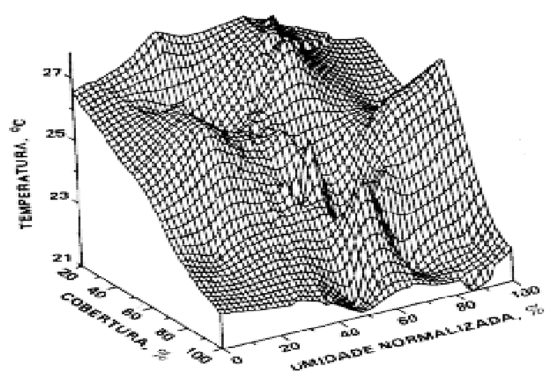
Variação diária da temperatura do solo a 5 cm de profundidade, em função de doses de palha de trigo, nos dias a, b e c. (BRAGAGNOLO & MIELNICZUK, 1990)

69



Relação entre temperaturas máximas do solo a 5cm de profundidade e doses de palha nos dias a,b e c. (BRAGAGNOLO & MIELNICZUK, 1990)

70



Representação gráfica tridimensional entre cobertura (%), umidade normalizada (%) e temperatura do solo (C) sob plantio direto (VIEIRA et al, 1991).

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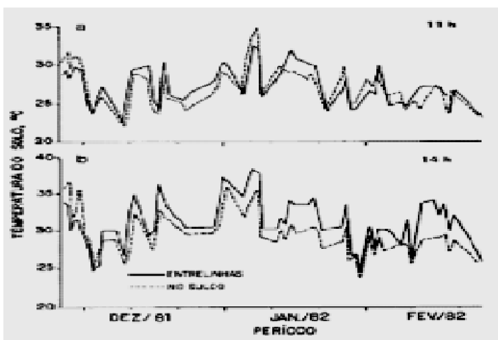

Variação da temperatura do solo registrada no sulco e nas entrelinhas durante o desenvolvimento da soja em plantio direto (PD) (SIDIRAS & PAVAN, 1986).

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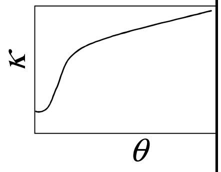
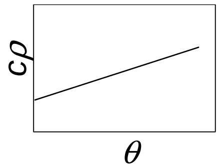
Measuring Thermal Properties in the Field

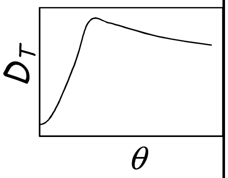
Thermal Conductivity





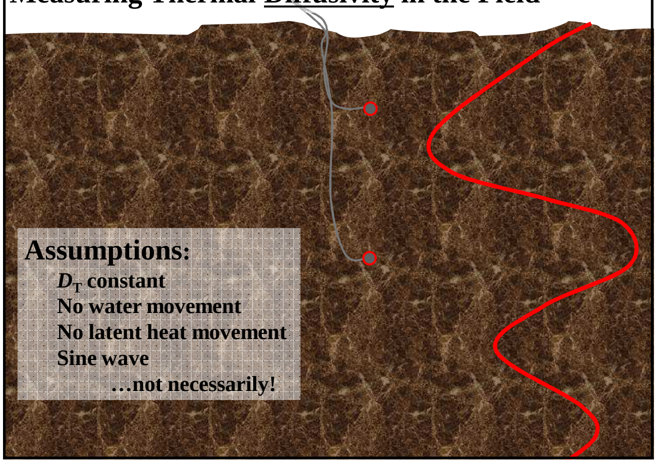
Volumetric Heat Capacity

Thermal Diffusivity



Inverse methods using many measurements at multiple depths and times?

Measuring Thermal Diffusivity in the Field



Assumptions:

- D_T constant
- No water movement
- No latent heat movement
- Sine wave

…not necessarily!

Measuring Thermal Diffusivity in the Field

?

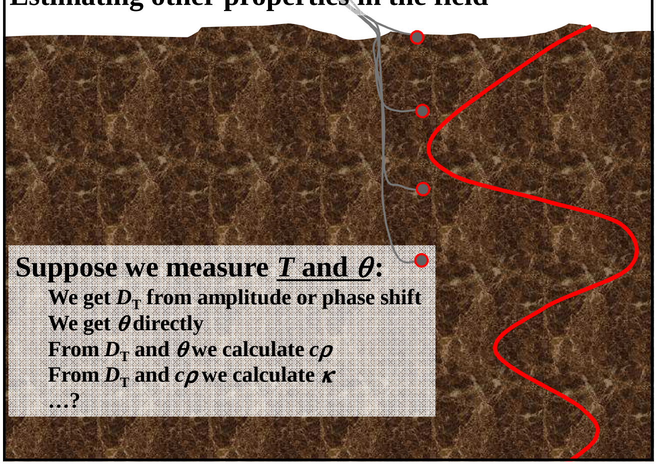
The phase change method: $$D_T = \frac{\omega(z_1 - z_2)^2}{2(\varphi_1 - \varphi_2)^2}$$

The amplitude method: $$D_T = \frac{\omega(z_1 - z_2)^2}{2\ln\left(\frac{A_1}{A_2}\right)^2}$$

Every sensor is a temperature sensor. But if you're clever, you can use it to measure something else as well.

-- Gaylon Campbell

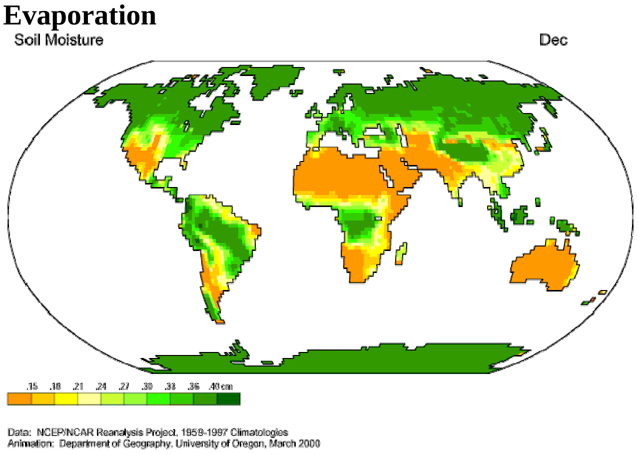
Estimating other properties in the field



Suppose we measure *T* and θ:

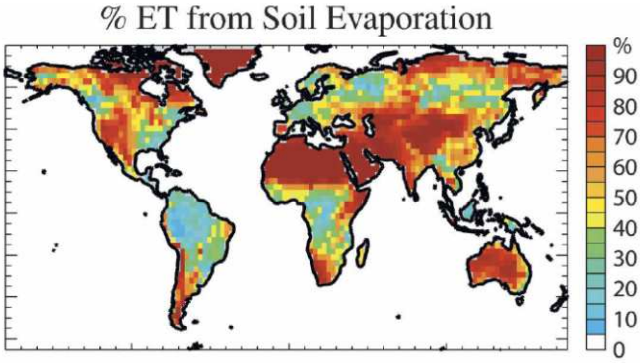
- We get D_T from amplitude or phase shift
- We get θ directly
- From D_T and θ we calculate $c\rho$
- From D_T and $c\rho$ we calculate κ
- …?

Evaporation



Evaporation

Lawrence et al., 2007

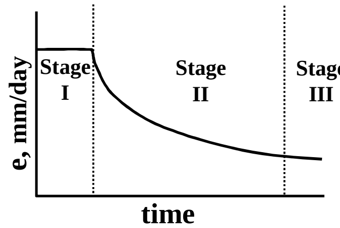


Evaporation from the soil can be an important part of the total water budget!

Evaporation

Evaporation may be limited by:

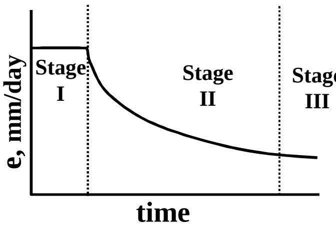
- Energy
- Water supply
- Vapor transport



Evaporation

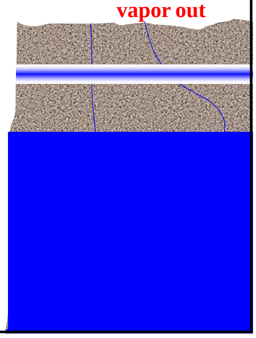
Evaporation may be limited by:

- Energy in
- Water in
- Vapor out



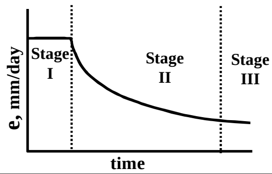
Water available; (mostly) energy-limited

Energy available; Transport limiting: water up vapor out



Main limitations on actual evaporation from soil

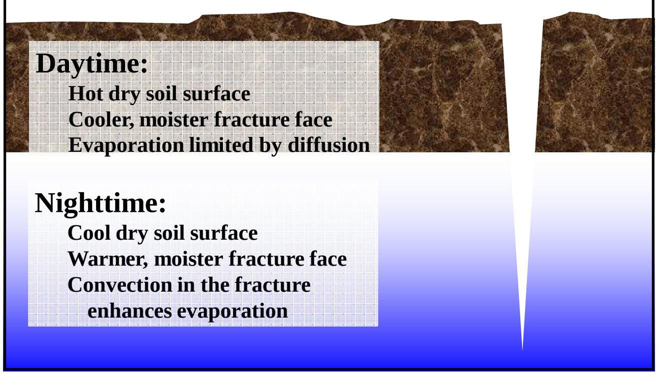
- Stage I: evaporation from the surface
  - Energy available at surface
  - Vapor pressure deficit in air near the surface
  - Transport of vapor away from the surface
- Stage II: evaporation from a retreating drying front
  - Flow of liquid water to the drying front
- Stage III: evaporation from a stationary drying front
  - Diffusion of water vapor from the drying front to air above the soil surface



Evaporation insights and innovations 1:

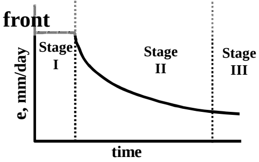
Maria Dragila:

Enhanced evaporation from fractures

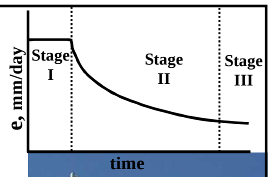


Main limitations on actual evaporation from soil

- Stage I: evaporation from the surface
  - Energy available at surface
  - Vapor pressure deficit in air near the surface
  - Transport of vapor away from the surface
- Stage II: evaporation from a retreating drying front
  - Flow of liquid water to the drying front
- Stage III: evaporation from a stationary drying front
  - Diffusion of water vapor from the drying front to air above the soil surface, which equals…
  - Flow of liquid water to the drying front



Measuring evapotranspiration



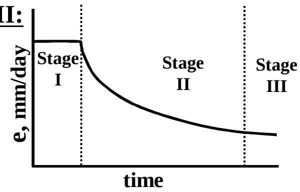
Meteorology magic:
Eddy Covariance

- Measure air mass fluxes in 3 orthogonal directions, many times per second.
- Simultaneously measure concentration(s) of gas(es) of interest, e.g. H_2O
- Make lots of assumptions and do some fancy math

Measuring Evaporation (from the soil)?

- Stage I: evaporation from the surface
  - Actual ≈ potential ≈ pan
- Stage II: evaporation from a retreating drying front
  - ?
- Stage III: evaporation from a stationary drying front
  - ?

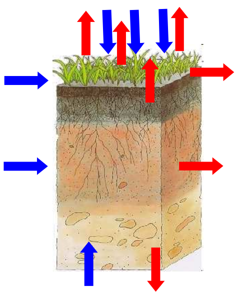
2 approaches to Stages II & III:
Conservation of mass
Conservation of energy



Conservation of Mass

Input - Output = Change in Storage

Input	Output	Change in Storage
Precipitation	Evaporation	θ over soil profile
Irrigation	Transpiration	~~Storage in plants~~
~~Condensation (dew)~~	~~Interception~~	
Water table rise	~~Abstraction~~	
~~Lateral flow~~	Water table fall	
~~Run-on~~	~~Lateral flow~~	
	~~Runoff~~	



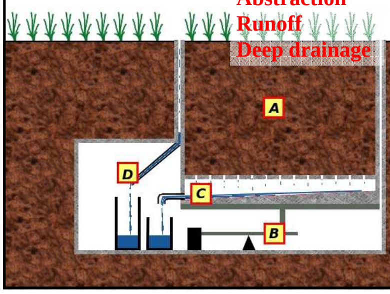
Too many variables
Errors are too big

E = ET – T
Precipitation
θ

Conservation of Mass: Lysimeter

Input - Output = Change in Storage

Input	Output	Change in Storage
Precipitation	Evaporation	θ over soil profile
Irrigation	Transpiration	Storage in plants
Condensation (dew)	Interception	
	Abstraction	
	Runoff	
	Deep drainage	



Lysimeters

Lysimeters

Conservation of Mass: Lysimeter

Lysimeter summary

Input - Output = Change in Storage

Input	Output	Change in Storage
Precipitation	Evaporation	θ over soil profile
Irrigation	Transpiration	Storage in plants
Condensation (dew)	Interception	
	Abstraction	
	Runoff	
	Deep drainage	

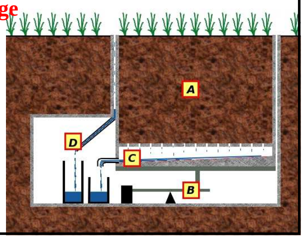
Really good for ET

For Evaporation only:

need 2 lysimeters?

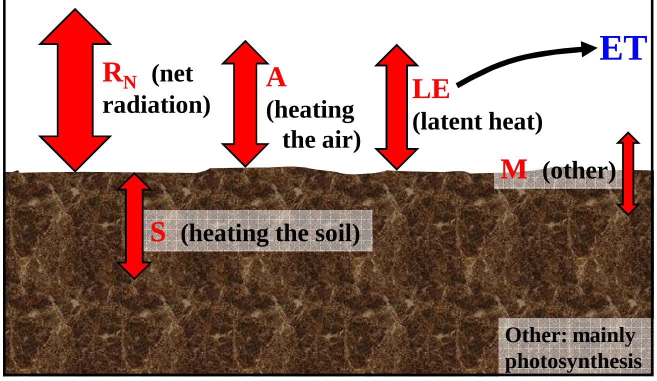
Cropped

Bare soil



2nd approach: Conservation of Energy

$$R_N = A + LE + S + M$$



How to measure S?

How much does the soil warm up (or cool off)?

Need to know temperature and heat capacity…

… or the sensible heat flux in and out

Heitman's soil E method

Key concept #1:
θ = 0.01 is small relative to measurement error, but LE for θ = 0.01 is big

Key concept #2:
LE in the soil is about E, not ET