Photo: R. Ketler, UBC

10 Soil thermal properties

Learning objectives

- Provide examples of why processes in the ground are of interest to climatologists.
- Know what are the key properties that describe the thermal behaviour of the soil / substrate in the climate system.
- Explain how the key properties relate to the process of heat conduction in soils.

Photo: J. Verfaillie

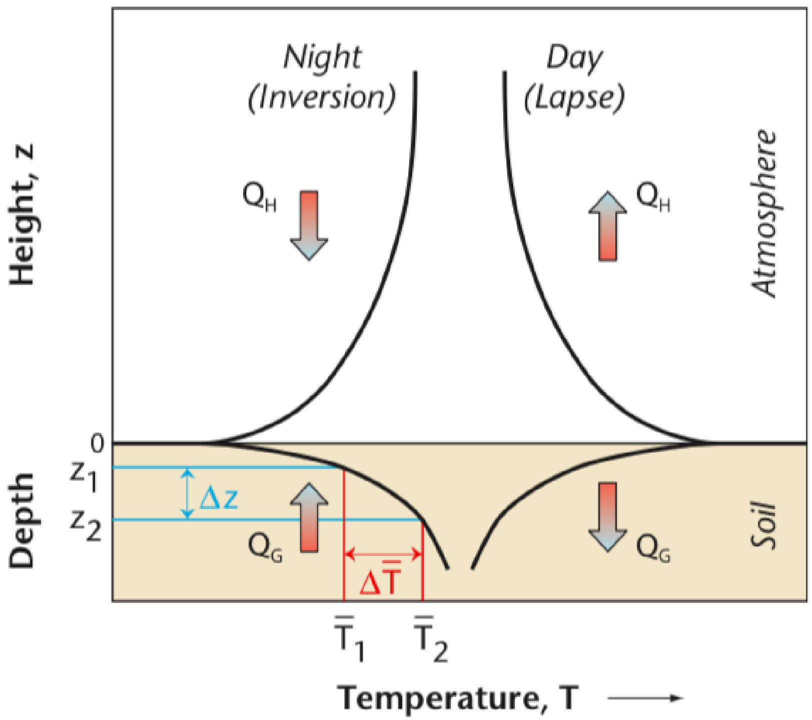
Why might climatologists be interested in studying soil thermal properties and subsurface processes?

Permafrost thawing on Ellesmere Island / Photo: A. Cassidy, UBC Geography


Graduate student in Geography / Photo: T. Lenkowich

Tonzi Ranch, California. Photo: J. Verfaillie

The role of the soil in the climate system



The influence of the **active surface** extends down into a relatively shallow layer of the substrate.

Nevertheless the properties of the shallow substrate layer make it a **significant volume of storage ΔQ_S** of sensible heat and water over diurnal and annual scales.

Soils act as 'batteries' of energy forms and mass relevant in the atmosphere.

Heat capacity and specific heat

Heat capacity *C* is the quantity of heat required to raise the temperature of a **unit volume** of a material through 1 K.

$J\ K^{-1}\ m^{-3}$

Specific heat *c* is the quantity of heat required to raise the temperature of a **unit mass** of a material through 1 K.

$J\ K^{-1}\ kg^{-1}$

Heat capacity and specific heat of soil materials

Material	Heat capacity C ($MJ\ m^{-3}\ K^{-1}$)	Specific heat c ($kJ\ kg^{-1}\ K^{-1}$)	Density ρ ($Mg\ m^{-3}$)
Air	0.0012	1.01	0.0012
Water (liquid)	4.18	4.18	1
Ice	1.9	2.1	0.9
Soil mineral	2.1	0.8	2.65
Soil organic matter	2.5	1.9	1.3
Rock	2	0.8	2.7

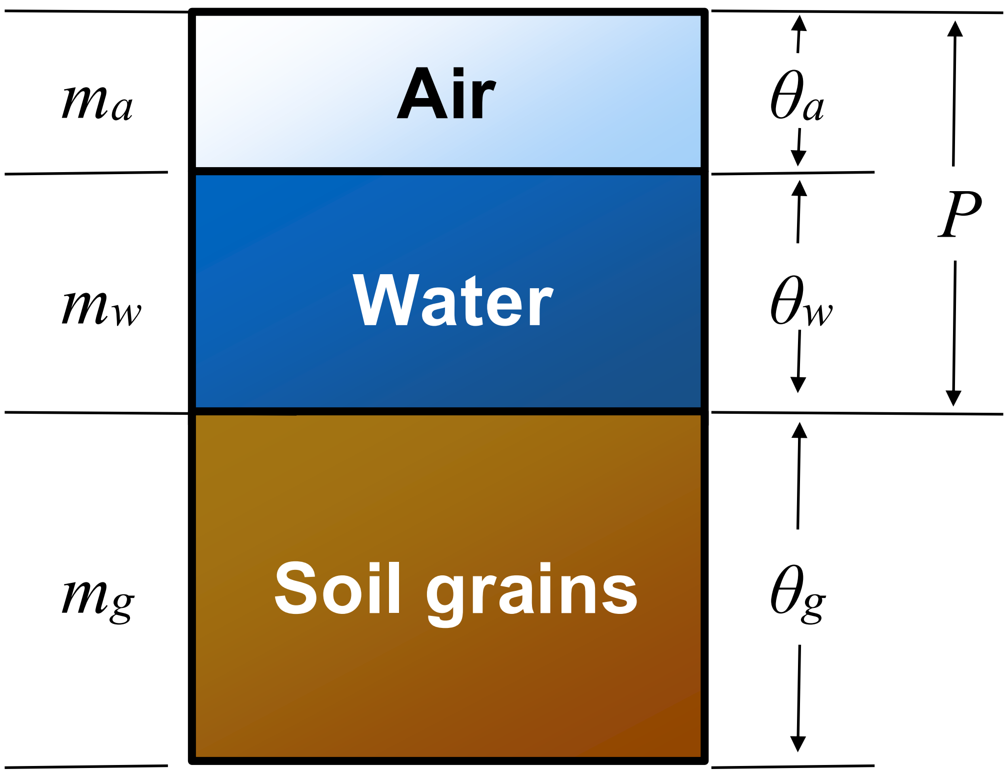
Porosity, volume fractions and mass

Mass

Expressed in mass (kg) of a sample

$$m_a + m_w + m_g = m_s$$

m_s = total mass of soil



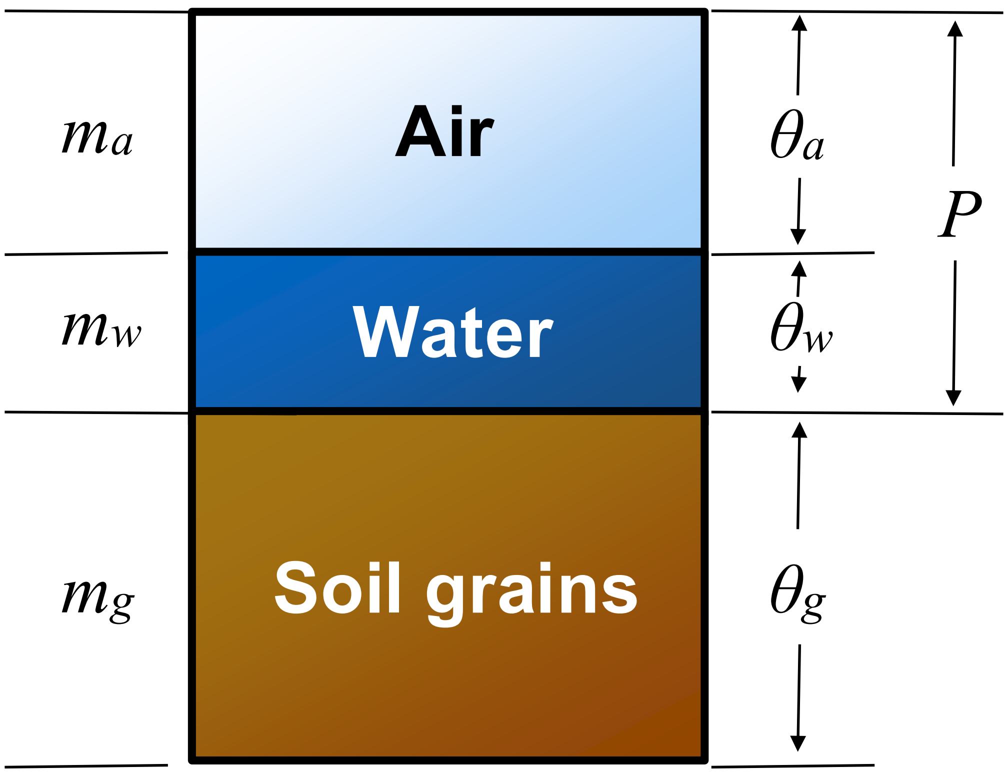
Volume

Expressed as volume fractions (m^3 m^{-3})

$$P = \theta_a + \theta_w = 1 - \theta_g$$

$$\theta_a + \theta_w + \theta_g = 1$$

Porosity, volume fractions and mass



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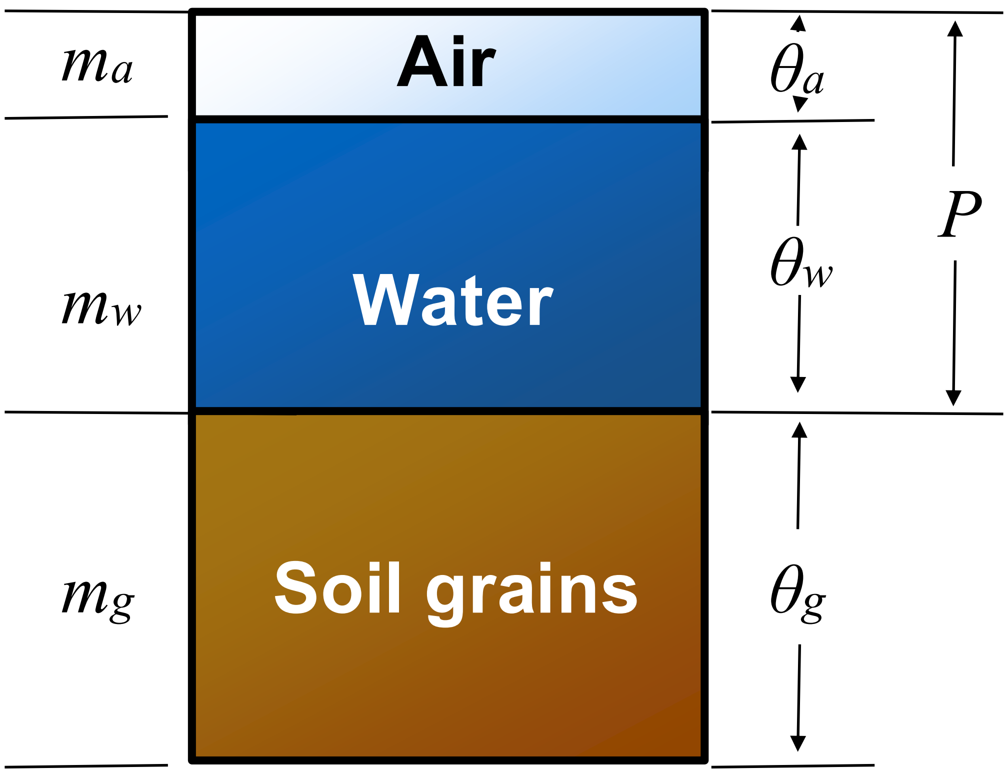


Volume

Expressed as volume fractions ($m^3\ m^{-3}$)

$$P = \theta_a + \theta_w = 1 - \theta_g$$

$$\theta_a + \theta_w + \theta_g = 1$$

Heat capacity of compound substances

The **heat capacity of a mixture** of substances such as soil can be calculated if the heat capacity and volume fraction of each component are known. In the case of soil, C_s is calculated using:

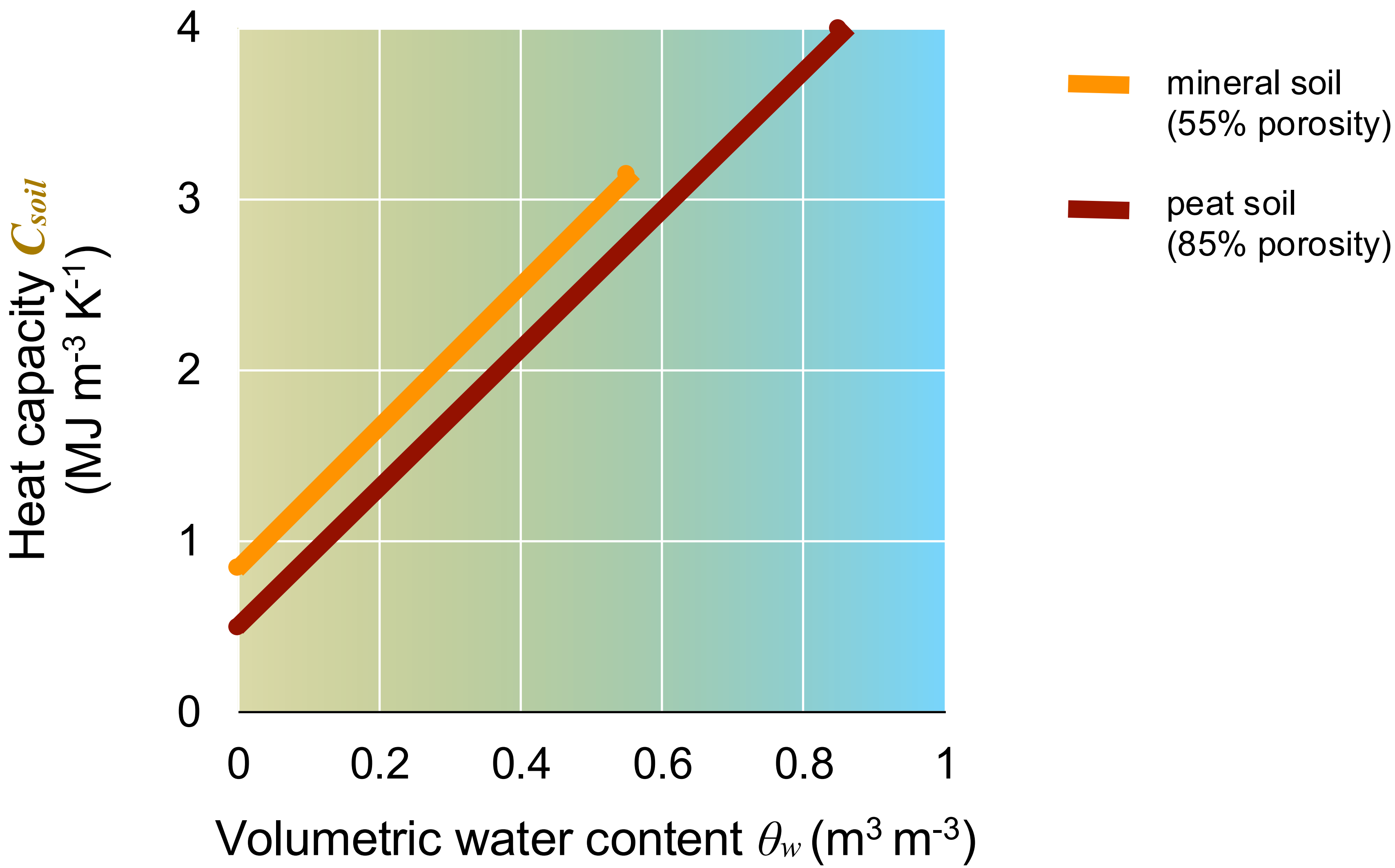
$$C_s = C_m\theta_m + C_o\theta_o + C_w\theta_w + C_a\theta_a \quad \star$$

where θ is the volume fraction occupied by mineral (m), organic matter (o), water (w) and air (a).

C_a is very small relative to the other values of C, so it can be neglected.


Photo: R. Ketler

Heat capacity and soil water content



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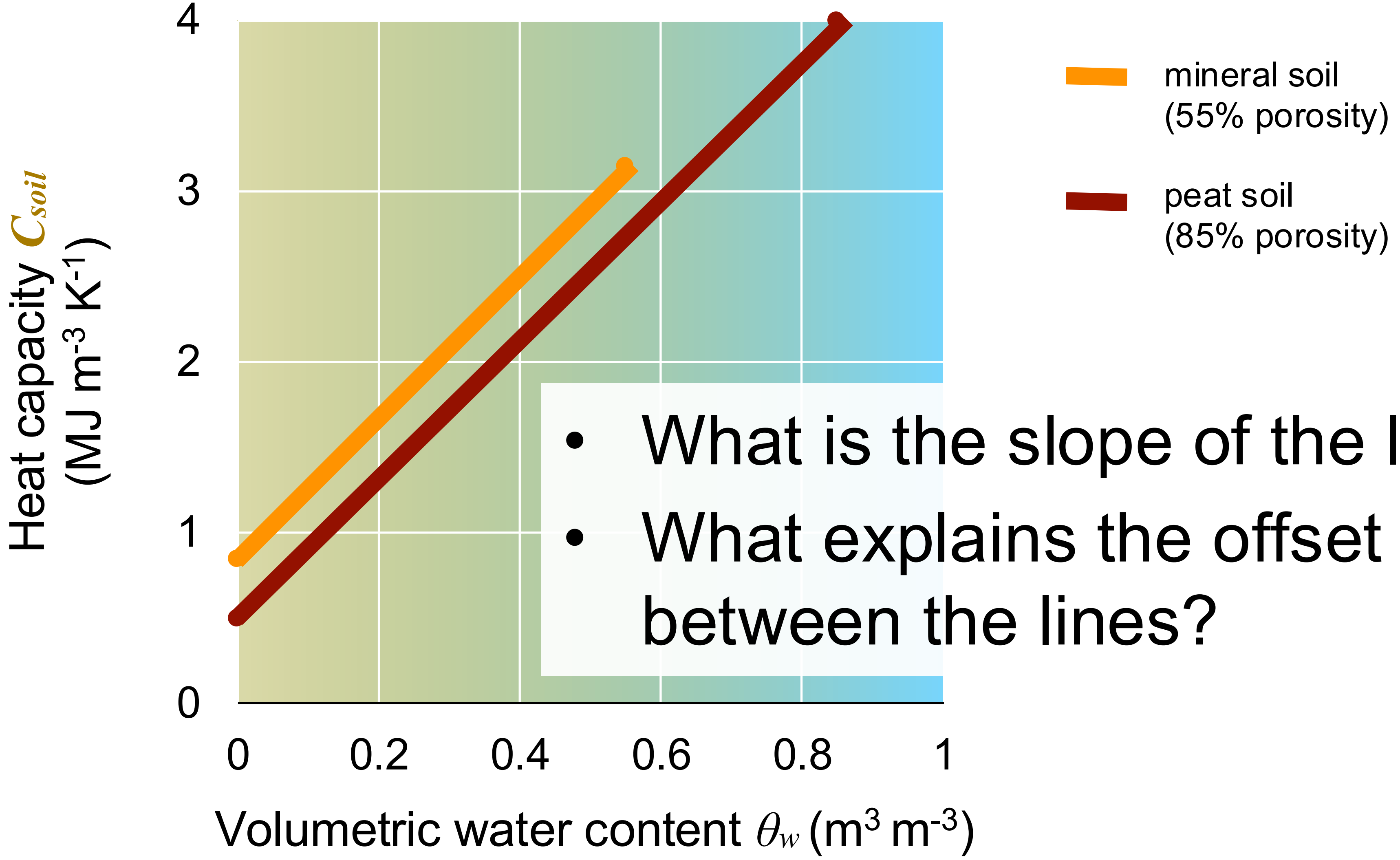
Heat capacity and soil water content



- What is the slope of the line?
- What explains the offset between the lines?

Warming / cooling of a soil

Relating the **change of soil heat flux with depth** (the divergence of Q_G, i.e. $\partial Q_G / \partial z$) to the **rate of temperature change** ($\partial T / \partial t$) due to the **heat capacity** of the layer:

Heat capacity
in J m^{-3} K^{-1}

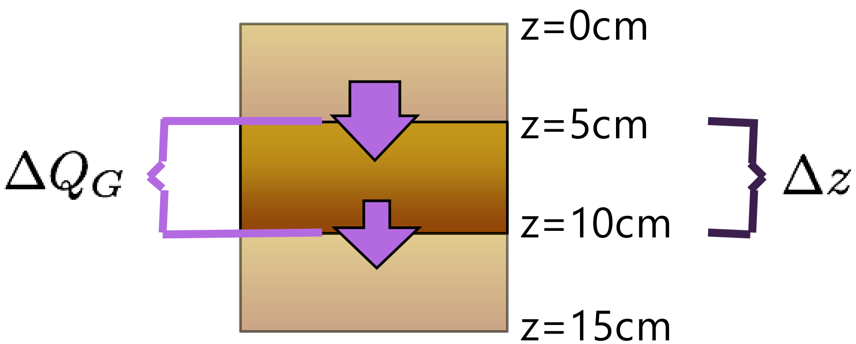
$$\frac{\partial Q_G}{\partial z} = C_s \frac{\partial T}{\partial t} \qquad \text{(Eq 1)}$$

Heat flux divergence with depth
in W m^{-2} m^{-1} = W m^{-3}

Temperature change with time
in K s^{-1}

Warming / cooling of a soil

Re-arranging and writing in finite form gives the **rate of temperature change** in an actual layer of thickness Δz as:



Change of heat flux (i.e. input - output) in W m^{-2} m^{-1}

$$\frac{\Delta T}{\Delta t} = \frac{1}{C_s}\frac{\Delta Q_G}{\Delta z}$$

Change of temperature over time in layer (i.e. warming or cooling rate) in K s^{-1}

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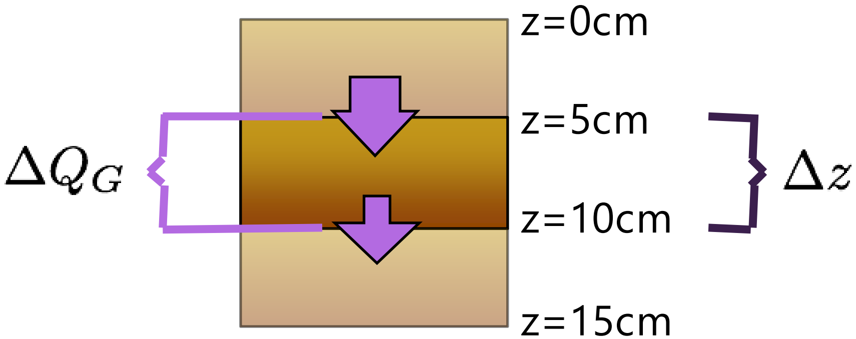
If the soil has a high heat capacity, the rate of warming or cooling will be:

A) Higher

B) Lower



Change of heat flux (i.e. input - output) in W m^{-2} m^{-1}

$$\frac{\Delta T}{\Delta t} = \frac{1}{C_s}\frac{\Delta Q_G}{\Delta z}$$

Change of temperature over time in layer (i.e. warming or cooling rate) in K s^{-1}

Fourier's law

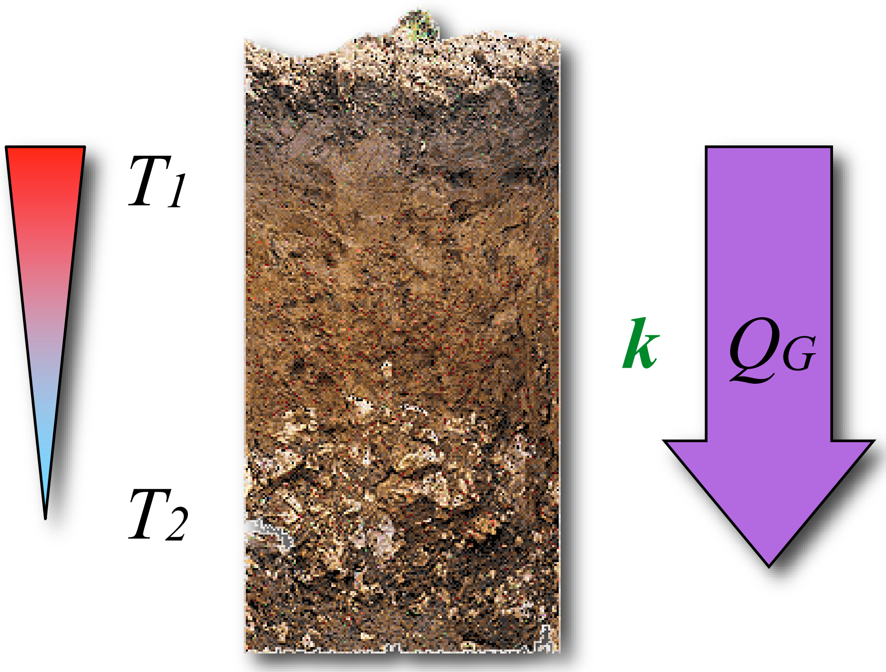
Fourier's law describes that the **flux density of heat conducted** Q_G is proportional to the **temperature gradient**:

Soil heat flux at a given depth in W m^{-2}

Temperature gradient with depth in K m^{-1}

$$Q_G = -k \frac{\partial T}{\partial z} \quad \star \quad \text{(Eq 2)}$$

Constant of proportionality *k* is the thermal conductivity (a property of the material) in W m^{-1} K^{-1}



Thermal conductivity *k* of various materials

Material	*k* (W m^{-1} K^{-1})
Air	0.025
Water (liquid)	0.59
Ice	2.1
Quartz	8.8
Clay minerals	2.9
Organic matter	0.25
Stainless steel	21
Copper	380

Mineral matter is a good conductor

Water is intermediate

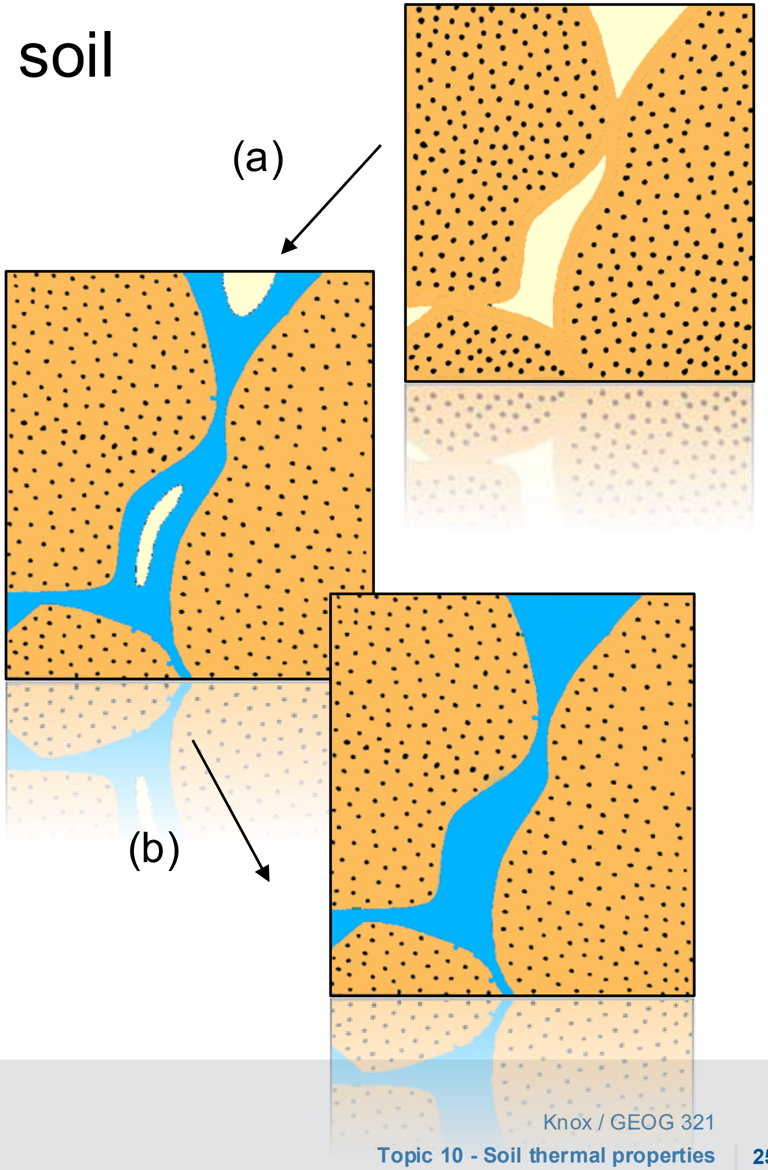
Air is very poor

Thermal conductivity k and water content

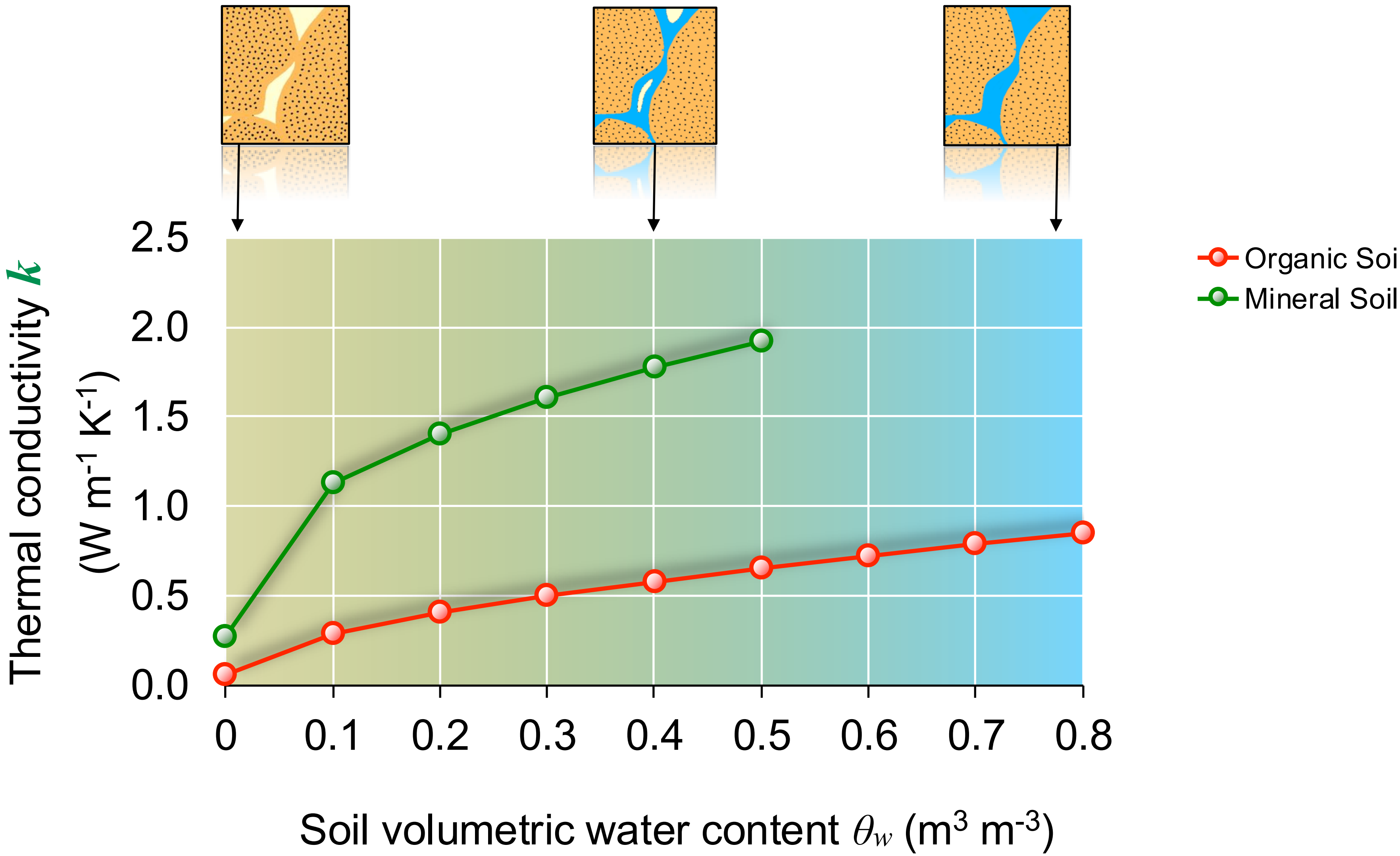
A non-linear relation exists between k and soil water content (θ_w)

- Adding water to dry soil (a) initially causes k to increase rapidly – rapid increase in area of contacts between soil particles resulting from water film.

- As more water (b) is added, k increases less rapidly – area of contacts increases more slowly per unit of water added (i.e. diminishing returns).

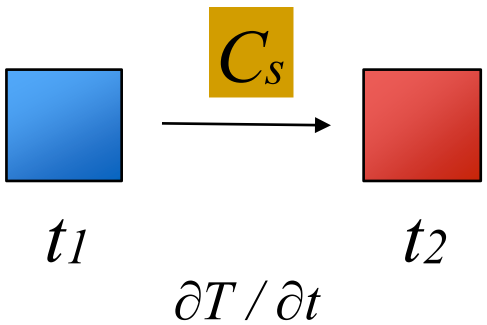


Soil water content and thermal conductivity *k*

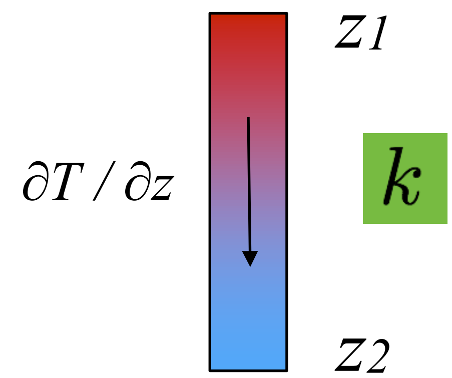


Combining thermal properties

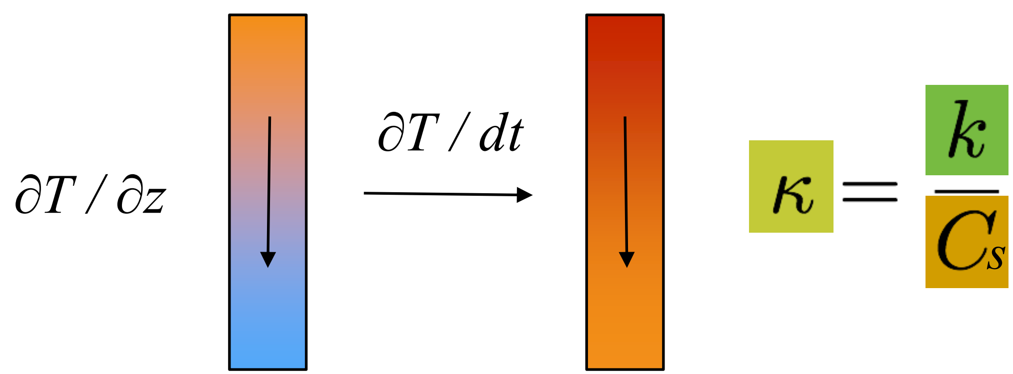
How rapidly does a volume warm when a certain amount of energy is supplied?



How well does heat conduct from one depth to another for a given temperature gradient?



How rapidly does a soil warm at depth if energy is available at the surface?



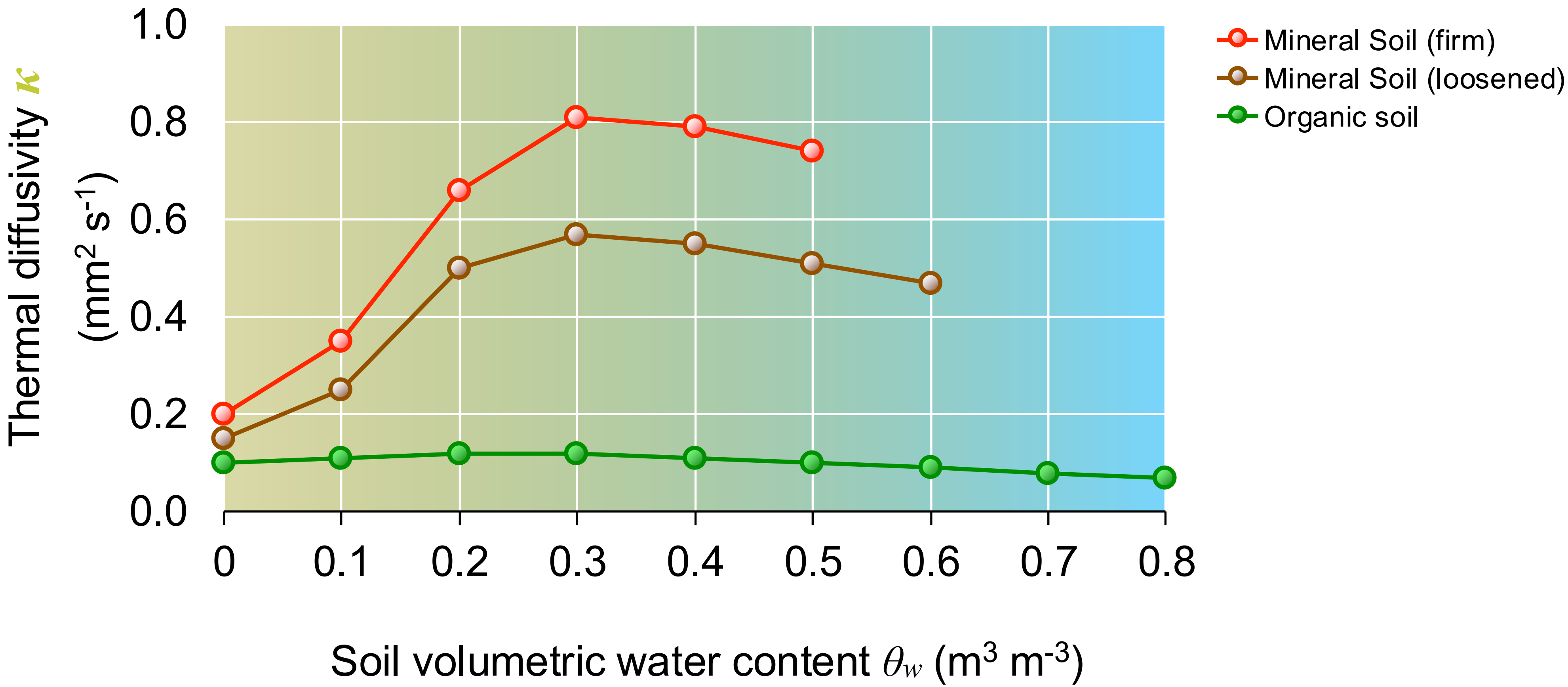
Thermal diffusivity

Thermal diffusivity κ *(greek 'kappa' - not 'K')* – indicates how quickly soil at depth will warm or cool in response to heating or cooling at the surface. It tells us how fast a temperature wave will diffuse or travel downward into a soil. It is defined:

$$\kappa = \frac{k}{C} \quad \star$$

Units: $m^2\ s^{-1}$

Soil water content and thermal diffusivity



Why the curious shape?

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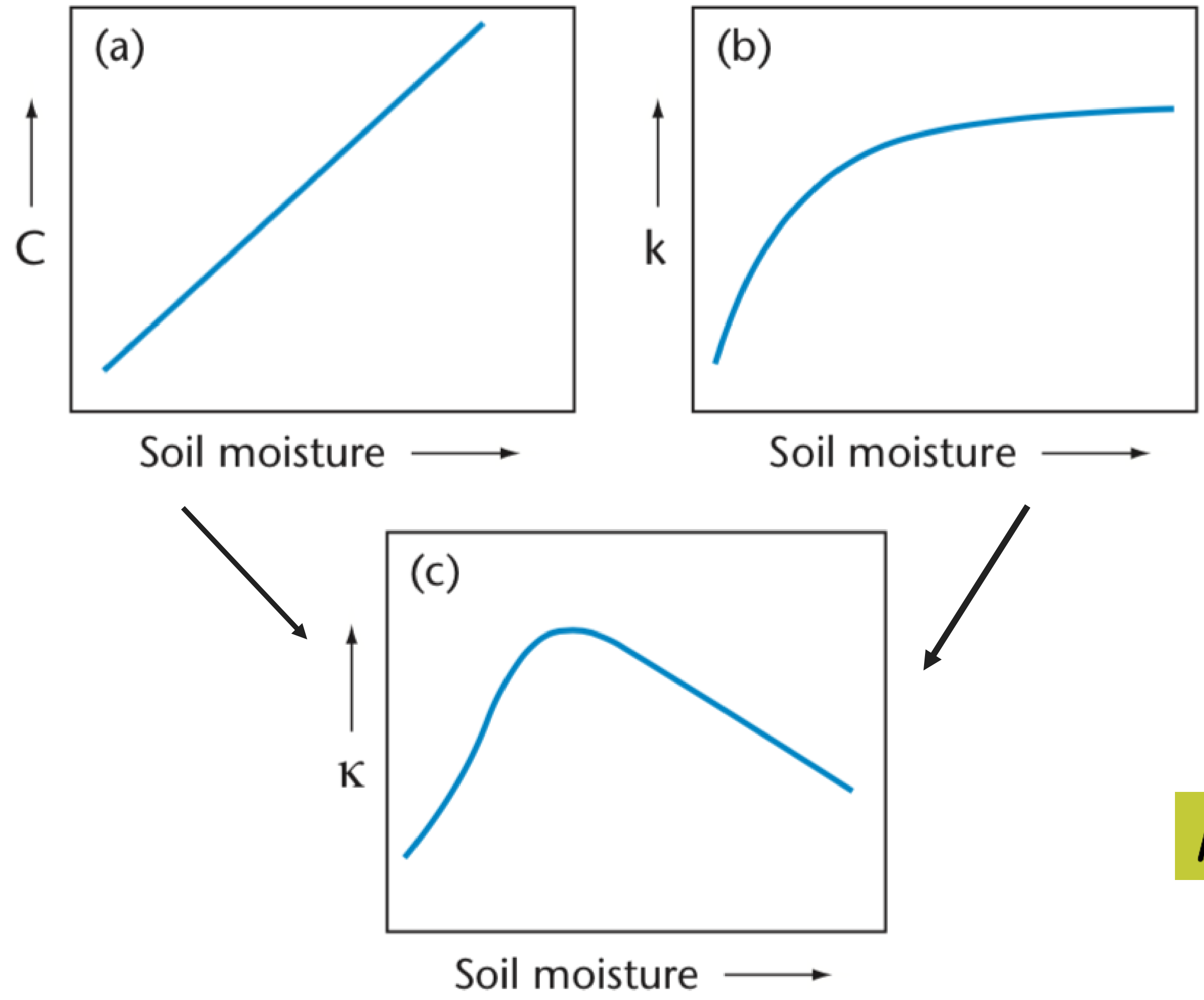

$$\kappa = \frac{k}{C}$$ ★

Take home points

- Soils are important for **storage of heat and water** in the climate system.
- Two basic thermal properties regulate the exchange - **Heat capacity** C_s and **thermal conductivity** k. From those we can derive **thermal diffusivity** $\kappa = k / C_s$.
- The **water content** of the soil is significantly altering both C (linearly) and k (non-linearly).