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# Soil compaction



## Soil Compaction (general info)

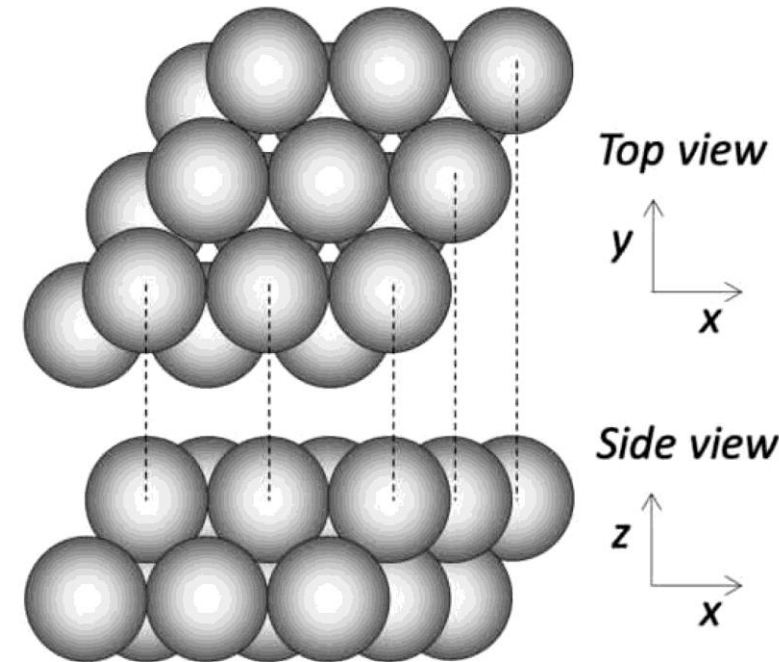
- definition: an increase in soil bulk density due to **dense packing of particles**
- however, soil compaction may be caused by formation of secondary minerals or aggregates due to precipitation / crystallization of solid species from soil solution
- often it is a result of (re)arrangement / translocation of soil particles to decrease void space and bring them into closer contact with one another → **increase of bulk density** → **decrease of porosity**
- there are also other soil properties that are important in this regard (besides bulk density and porosity), such as **penetration resistance** (for plant roots) or **permeability** for air and water
- similarly to other processes that we discussed previously (acidification, erosion,..), soil compaction is **partially natural** (it is a consequence of natural soil genesis) → there are many soils (not significantly affected by humans) that show high bulk density and penetration resistance values (especially in dry conditions)

## Soil Compaction (general principle)

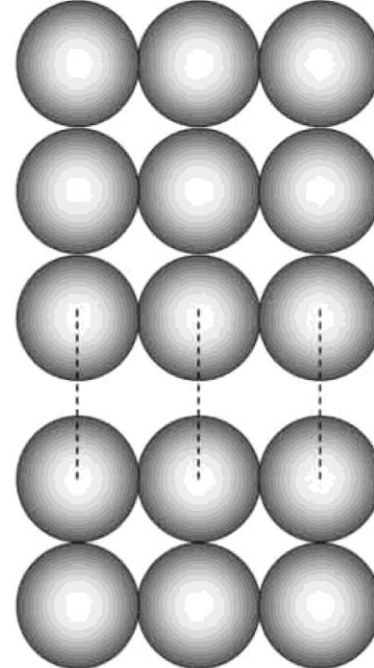
- simplified scenario: spheric particles with identical diameter
- example: two types of arrangement
  1. rhombohedral (dense) and 2. cubic (loose)approximately 26 % vs. 48 % porosity
- even the arrangement of spherical particles can be little bit tricky:

[https://en.wikipedia.org/wiki/Close-packing\\_of\\_equal\\_spheres](https://en.wikipedia.org/wiki/Close-packing_of_equal_spheres)

Rhombohedral packing

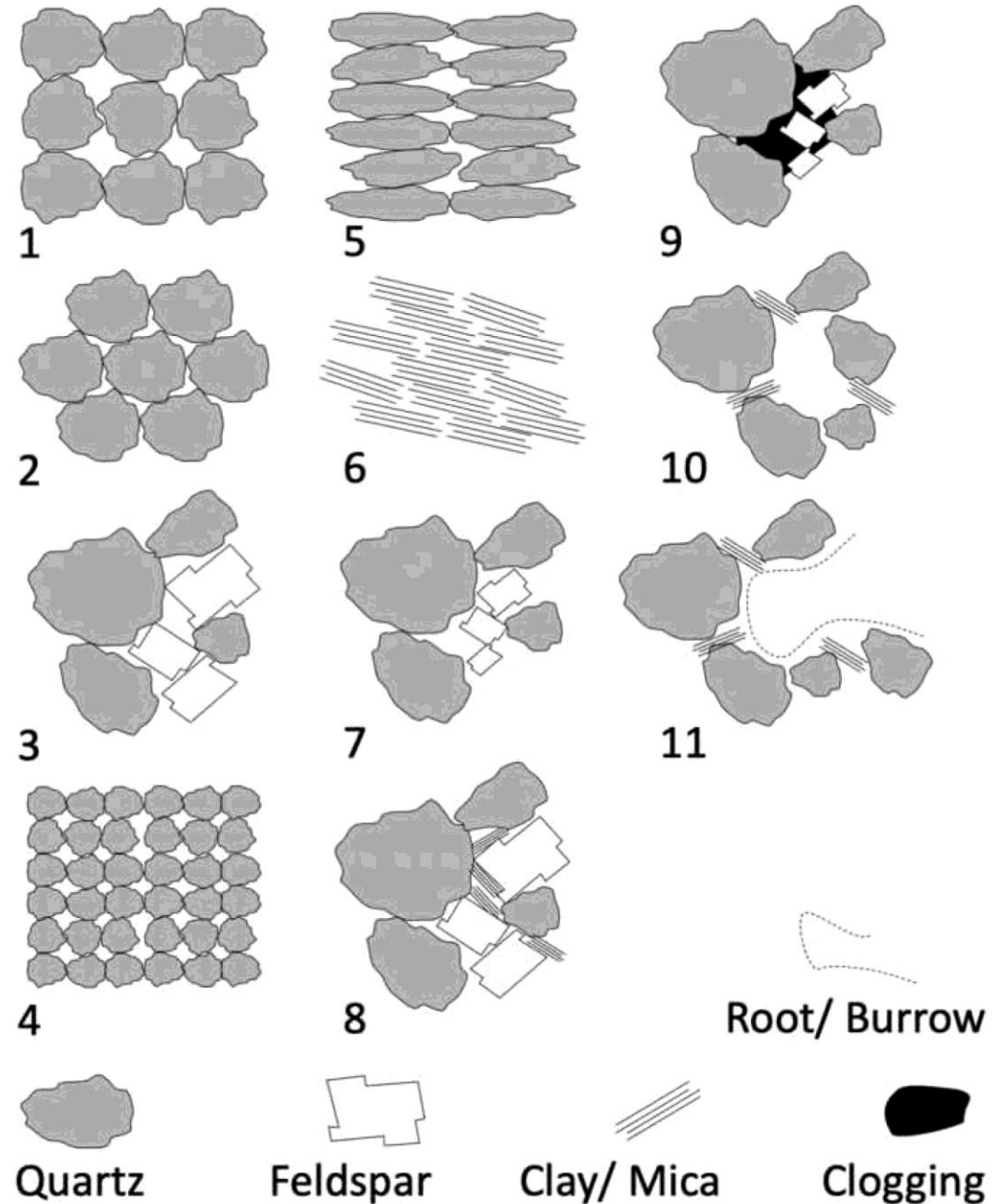


Cubic packing



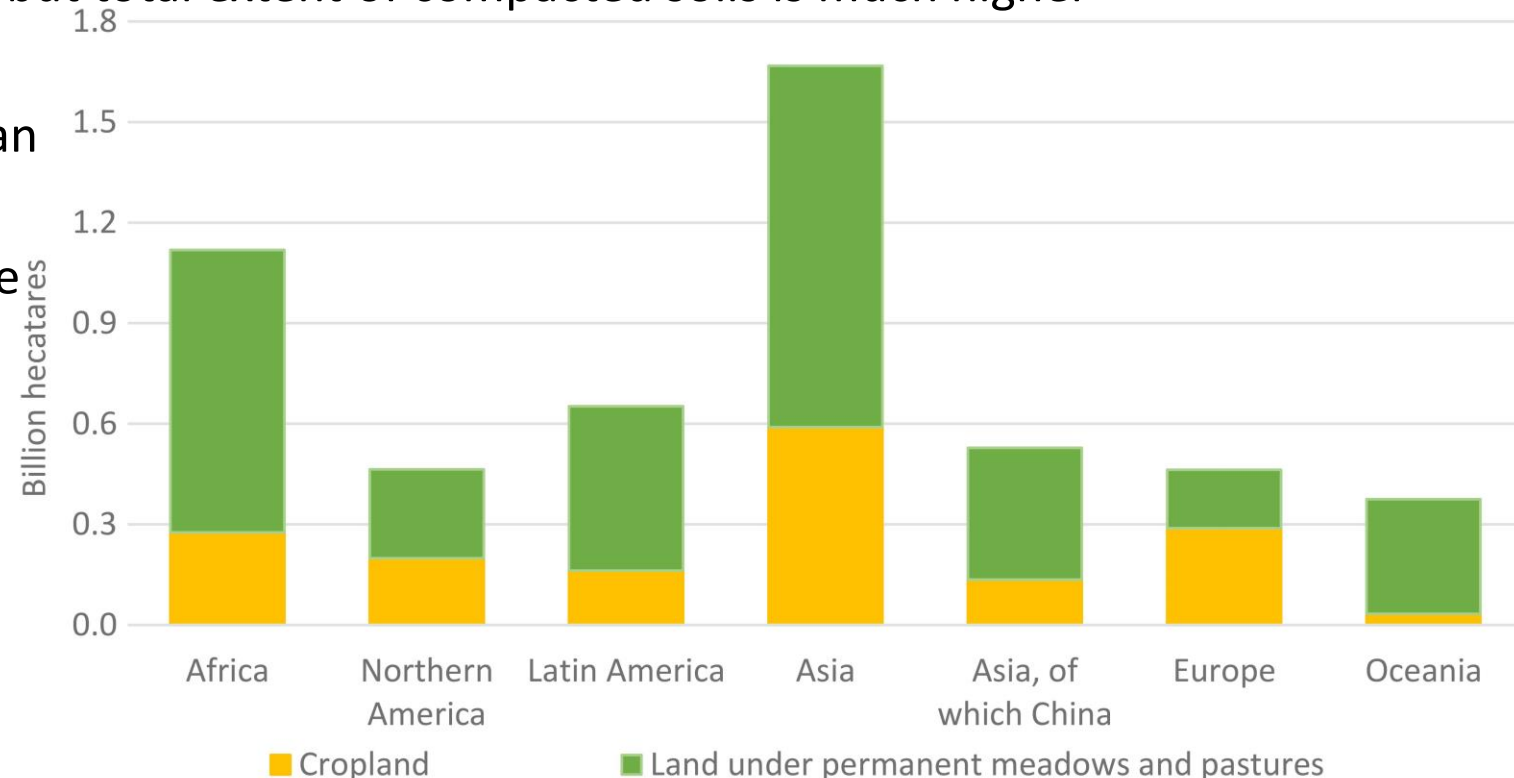
## Soil Compaction (general info)

- **soil particles are not spheric**, but the approximation with spheric shape is reasonable in certain cases, for example in particle size analysis
- soil particles show variable sizes and shapes



## Soil Compaction (occurrence)

- Although exact data on soil compaction distribution in the world are lacking, there are number of indices showing that soil compaction is a wide-spread phenomenon limiting land and ecosystem productivity
- The extent of compacted soils is estimated worldwide at 68 million hectares of land (Afghanistan  $\approx$  65 mil ha) from vehicular traffic alone, but total extent of compacted soils is much higher
- Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe
- about 4 million ha are degraded due to compaction in the wheat belt of Western Australia
- other countries that reported land degradation due to compaction include Azerbaijan, Japan, Russia, France, China, Ethiopia or New Zealand.



## Soil Compaction (measured parameters)

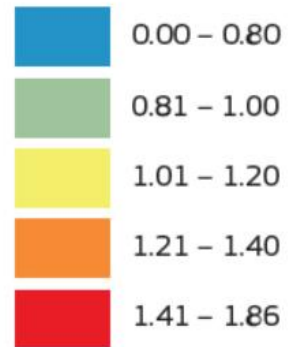
- **bulk density (BD)** – direct measure of soil compaction: soil mass per volume unit ( $\text{g cm}^{-3}$ ); in certain cases, however, the BD values may be affected by presence of gravel in given soil volume, the sample shows higher BD but not because of compaction, but due to the rocks present in soil; additional parameter, packing density (PD) expresses BD and clay content at the same time ( $\text{PD} = \text{BD} + 0.009 \text{ clay}$ )
- **penetration resistance** (given usually in pressure units, MPa): force acting upon an object penetrating through a soil; it can be tip of plant root or tip of penetrometer

## Bulk density map:

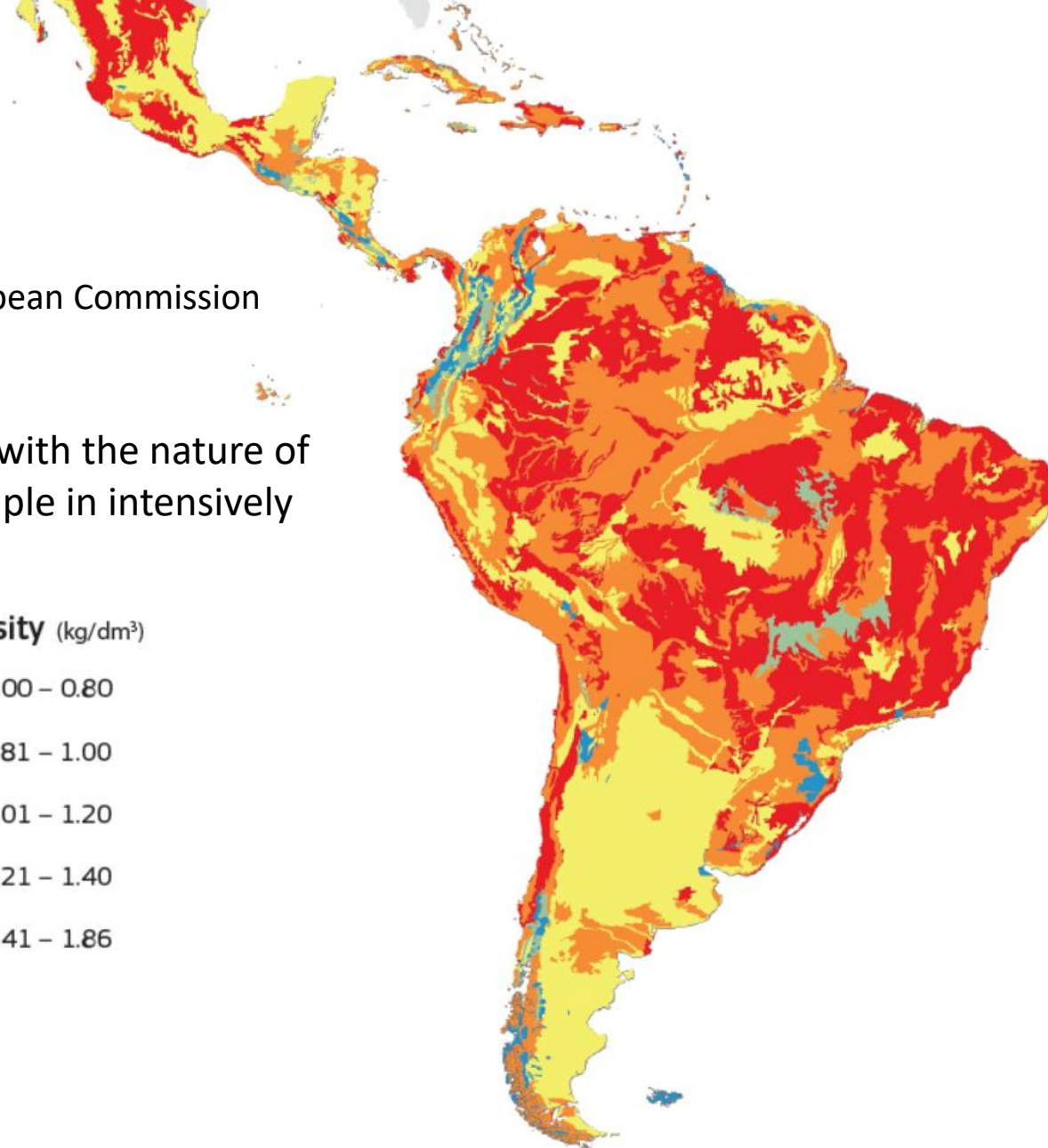
Soil Atlas of Latin America and the Caribbean, European Commission

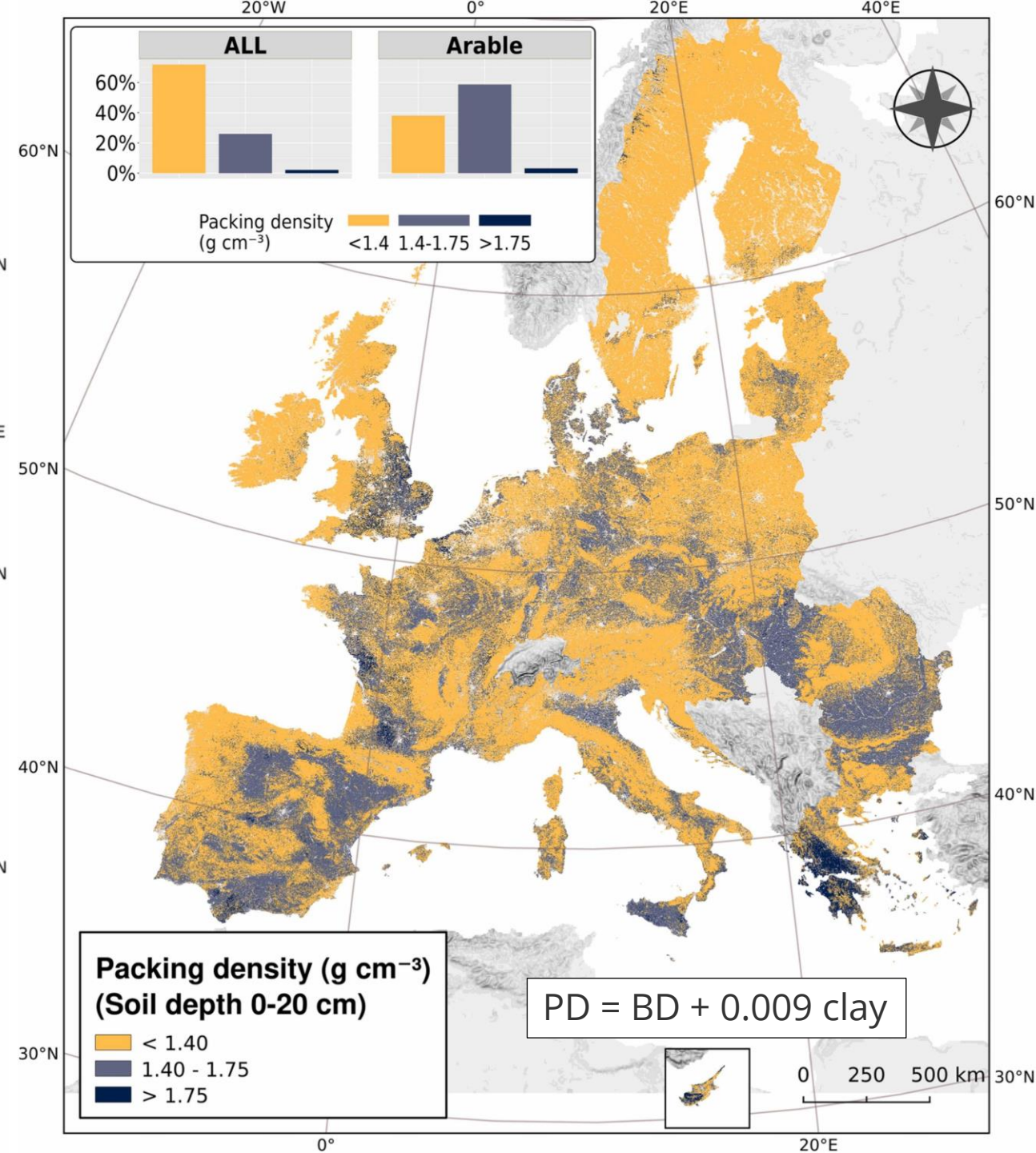
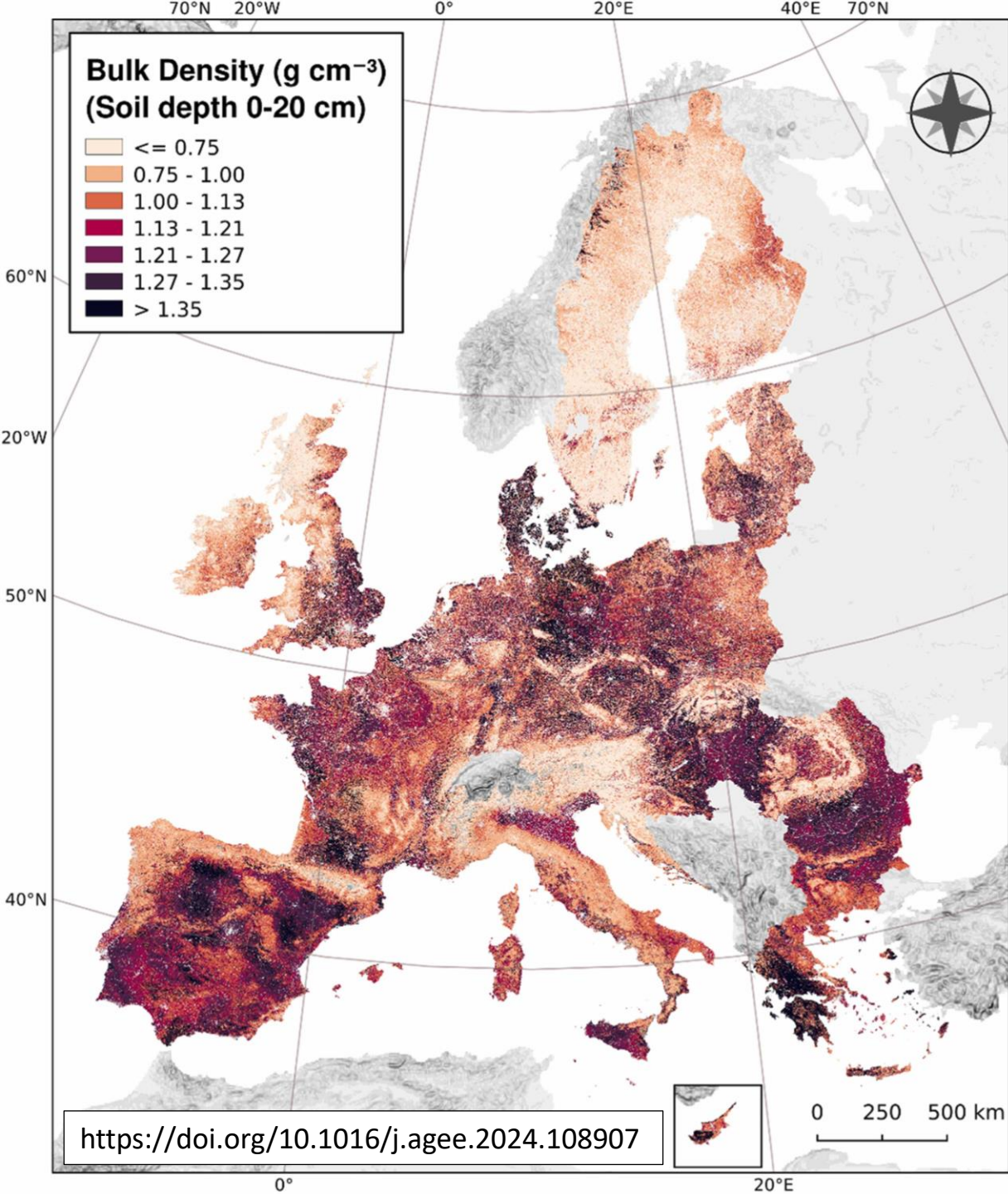
Soil compaction in tropics is often associated with the nature of soil parent material and soil genesis (for example in intensively weathered tropical soils)

### Bulk density (kg/dm<sup>3</sup>)

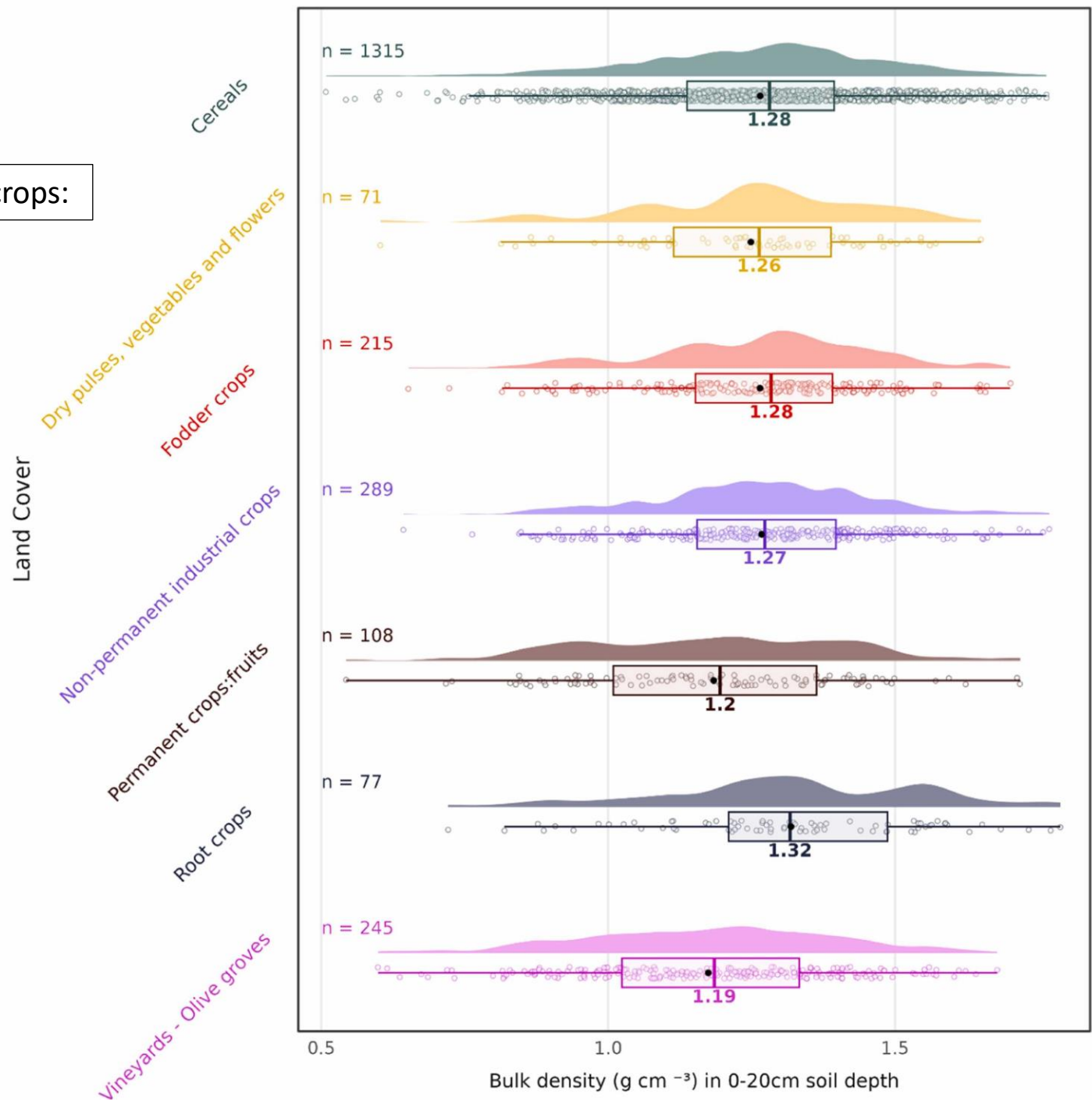


Bulk density is a measure of the soil's weight per unit volume (e.g., kg/cm<sup>3</sup>). Variations in this soil parameter depend on the degree of compaction, a property directly related to porosity. Most mineral soils have between 1 and 2 kg/cm<sup>3</sup> bulk density, while soils rich in organic matter can have a bulk density of well below 1.

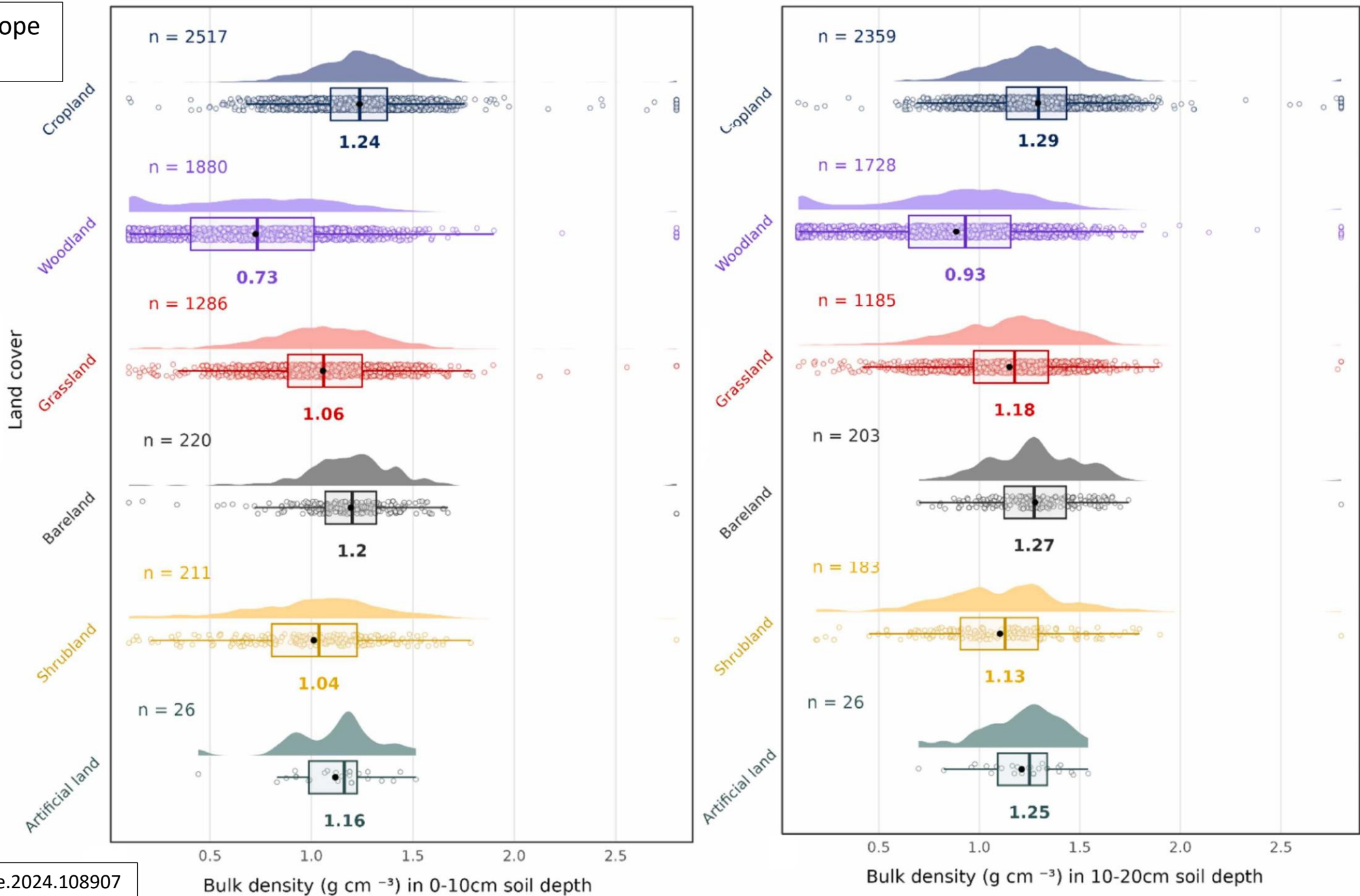




Soil bulk density in Europe for different agricultural crops:



Soil bulk density in Europe  
for different land uses:



## Soil Compaction – the causes (natural)

- soil particles are held together by biological and/or chemical cementing agents → soil structure (aggregates) formation → higher penetrometer resistance
- hydrous oxides of iron and aluminum, silicate clay minerals (kaolinite, illite, montmorillonite, chlorite), organic compounds and dissolved species in soil solution (ions) interact with each other in a complex manner (hydration/dehydration) to form soil aggregates → mechanically stable aggregates show higher penetration resistance
- many soils show higher degree of compaction in dry state or when frozen (fine- as well as coarse-textured), especially if they are depleted in organic matter (carbon)
- general trend: soil moisture decreases → soil penetration resistance increases (and vice versa), this obviously does not pertain to soil freezing

## Soil Compaction – susceptibility of agricultural crops

- although in many cases there are no significant differences between individual plants species used in agriculture in terms of their susceptibility to soil compaction, certain examples may be pointed out
- less susceptible: Alfalfa (*Medicago sativa*), Clover (*Trifolium* spp.), Wheat (*Triticum aestivum*), Rye (*Secale cereale*), Barley (*Hordeum vulgare*), Peas (*Pisum sativum*)
- more susceptible: Tomatoes (*Solanum lycopersicum*), Lettuce (*Lactuca sativa*), Carrots (*Daucus carota*), Cabbage (*Brassica oleracea*), Onions (*Allium cepa*), Spinach (*Spinacia oleracea*)
- roots of some tree species have significant ability to penetrate through compacted soil

## Examples of natural soil compaction

Plinthosols, South America:



In some cases, when plinthite is exposed to repeated wetting and drying cycles, it forms petroplinthite (irreversibly hardened plinthite, also known as laterite). (See photo below, on this page). (CG)

## Examples of natural soil compaction

Durisols, South Africa:



A duric horizon from South Africa containing rounded or sub-angular durinodes. These indurated accumulations of silicon dioxide are hard and brittle. (EM)

## Examples of natural soil compaction (partially natural, partially anthropogenic)

Luvisol, Slovakia:



## Examples of natural soil compaction

Vertisol, Slovakia:

many soils containing higher portion of silt or clay particles show significant compaction when dry

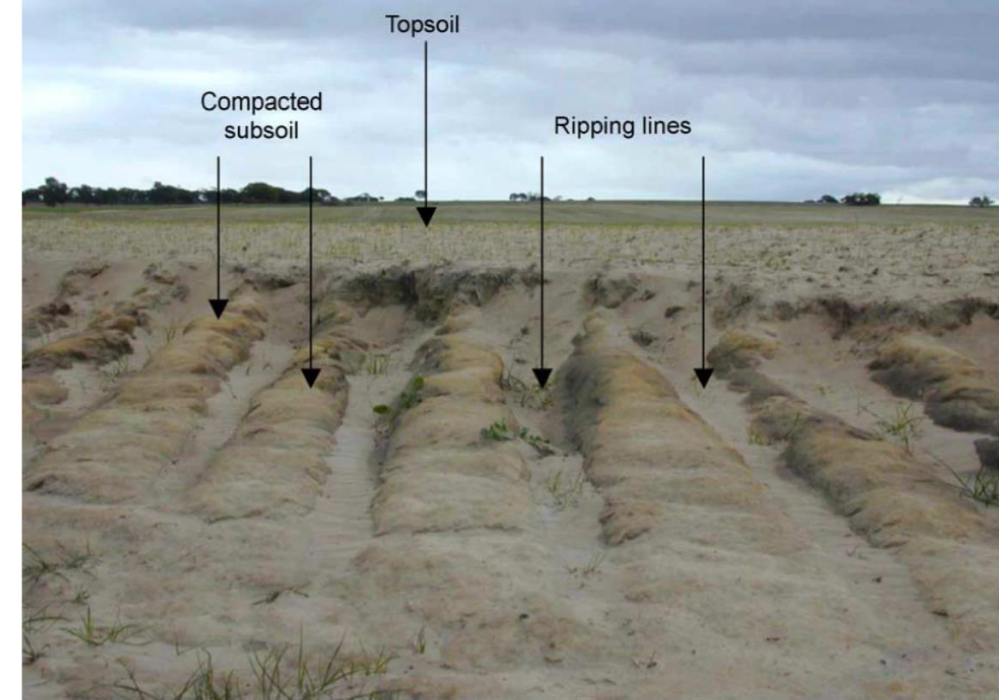
there are however also sandy soils that show significant compaction; for example, formation of secondary iron minerals may contribute to compaction of coarse textured soils



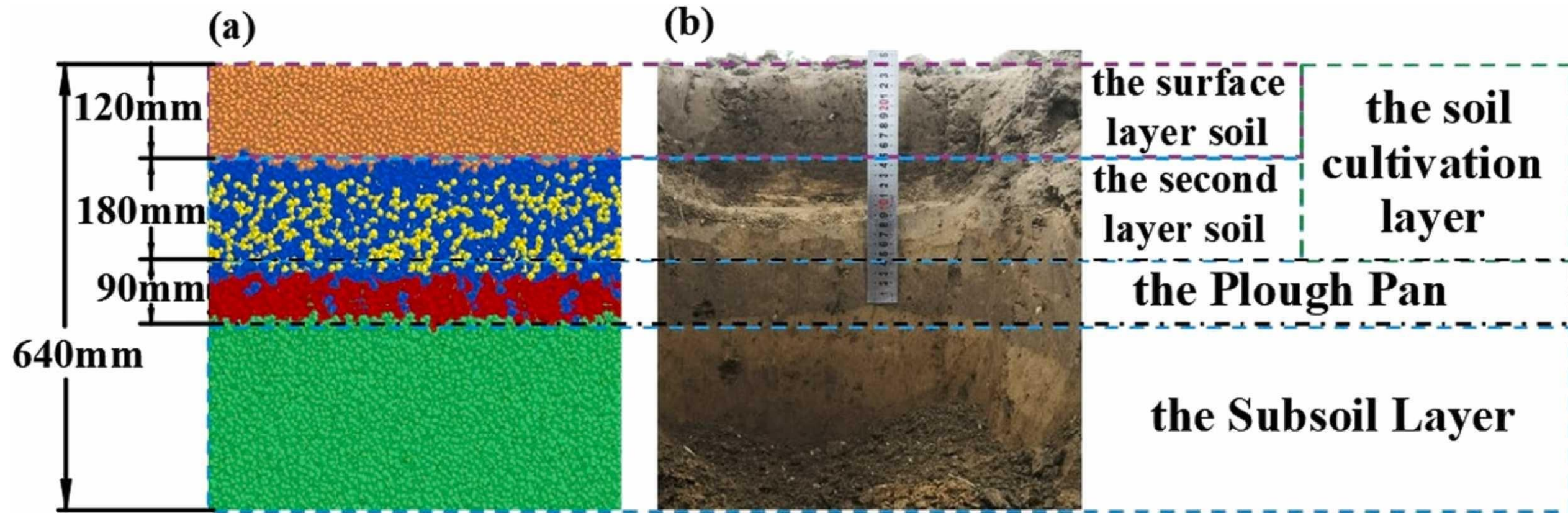
## Soil Compaction – the causes (anthropogenic)

- The intensification of modern food production → traffic and weight of agricultural vehicles → chronic/severe soil compaction
- Ploughing → repeated (periodic) mechanical disturbance of topsoil → vertical movement of fine particles and their accumulation in the subsurface → “plough pan” formation
- excessive animal trampling on grazing lands

## Soil Compaction – anthropogenic (examples):



Soil Compaction – anthropogenic (examples):

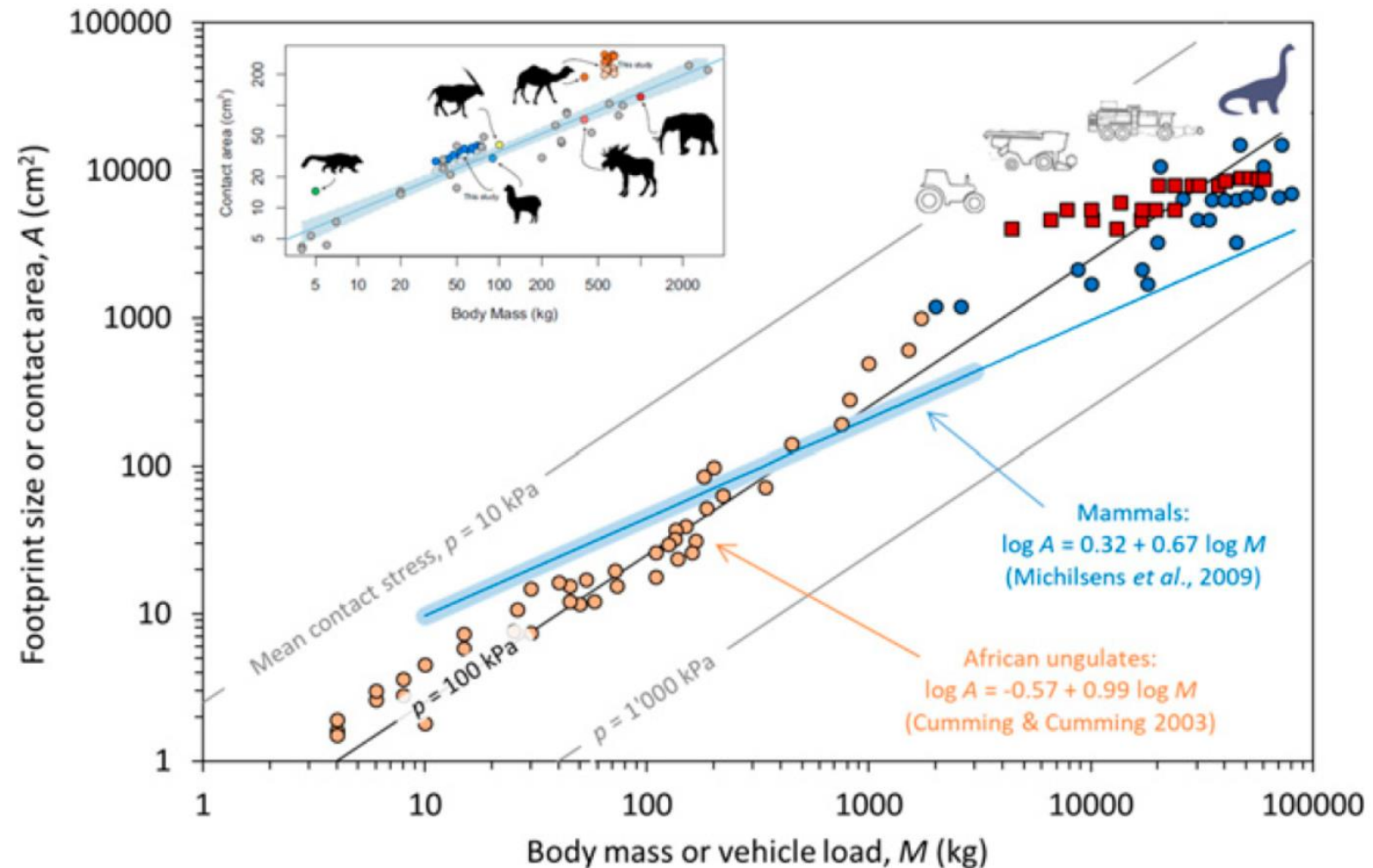


Song et al. (2022) Increasing the width of disturbance of plough pan with bionic inspired subsoilers.  
Soil and Tillage Research 220.

## Soil Compaction – fun fact:

the total weight of modern harvesters used in agriculture is now approaching that of the largest animals that walked Earth, the **sauropods**!

source: Keller, T., Or, D., 2022.  
Farm vehicles approaching  
weights of sauropods exceed safe  
mechanical limits for soil  
functioning. PNAS 119 (21),  
e2117699119.  
<https://doi.org/10.1073/pnas.2117699119>

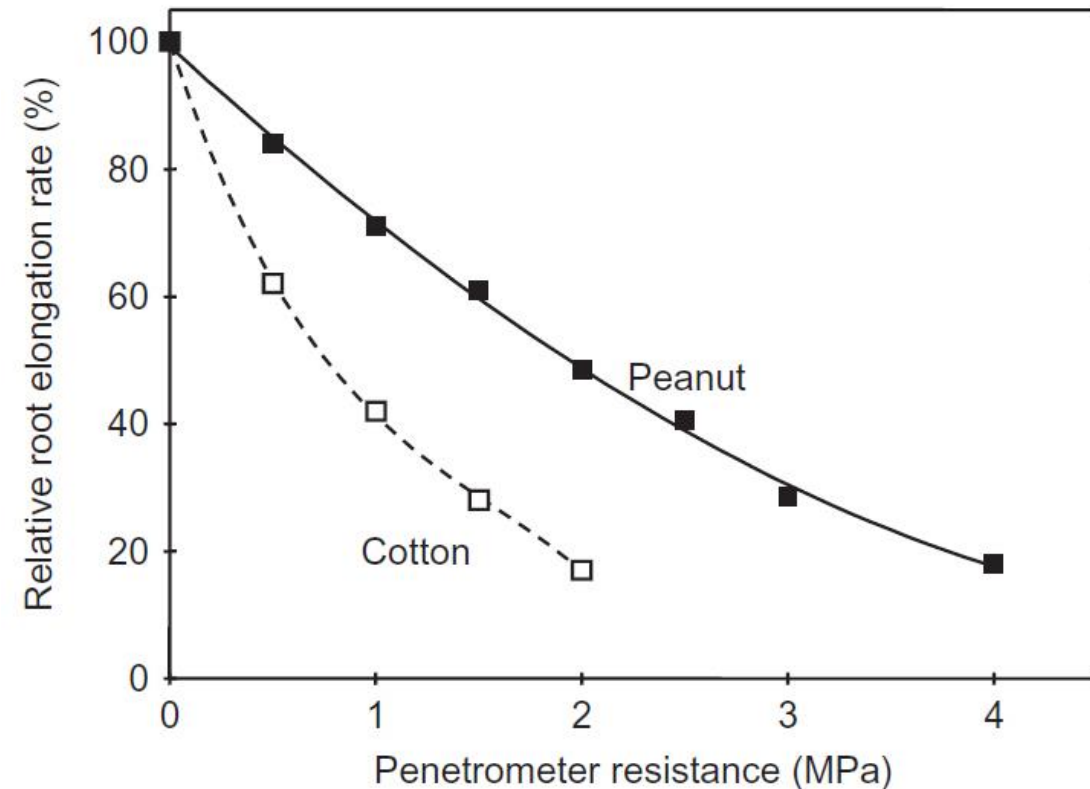


## Soil Compaction – consequences

- reduces/limits long-term productivity of soils, biological activity, porosity, infiltration rate and nutrient uptake; it not only limits (vertical) water movement, but it also creates barrier for soil aeration
- plough pan → **contributes to water erosion** in agricultural areas located on slopes, due to limited permeability of subsurface layer, formed usually around 30 cm beneath the surface
- limited root growth due to mechanical impedance
- higher soil compaction is detrimental to all soil organisms, not only plants, but also (in)vertebrate, and microorganisms
- increase in bulk density and decrease in porosity (mainly loss of large pores) results in low levels of oxygen (hypoxia / anoxia), reduced water movement and nutrient supply

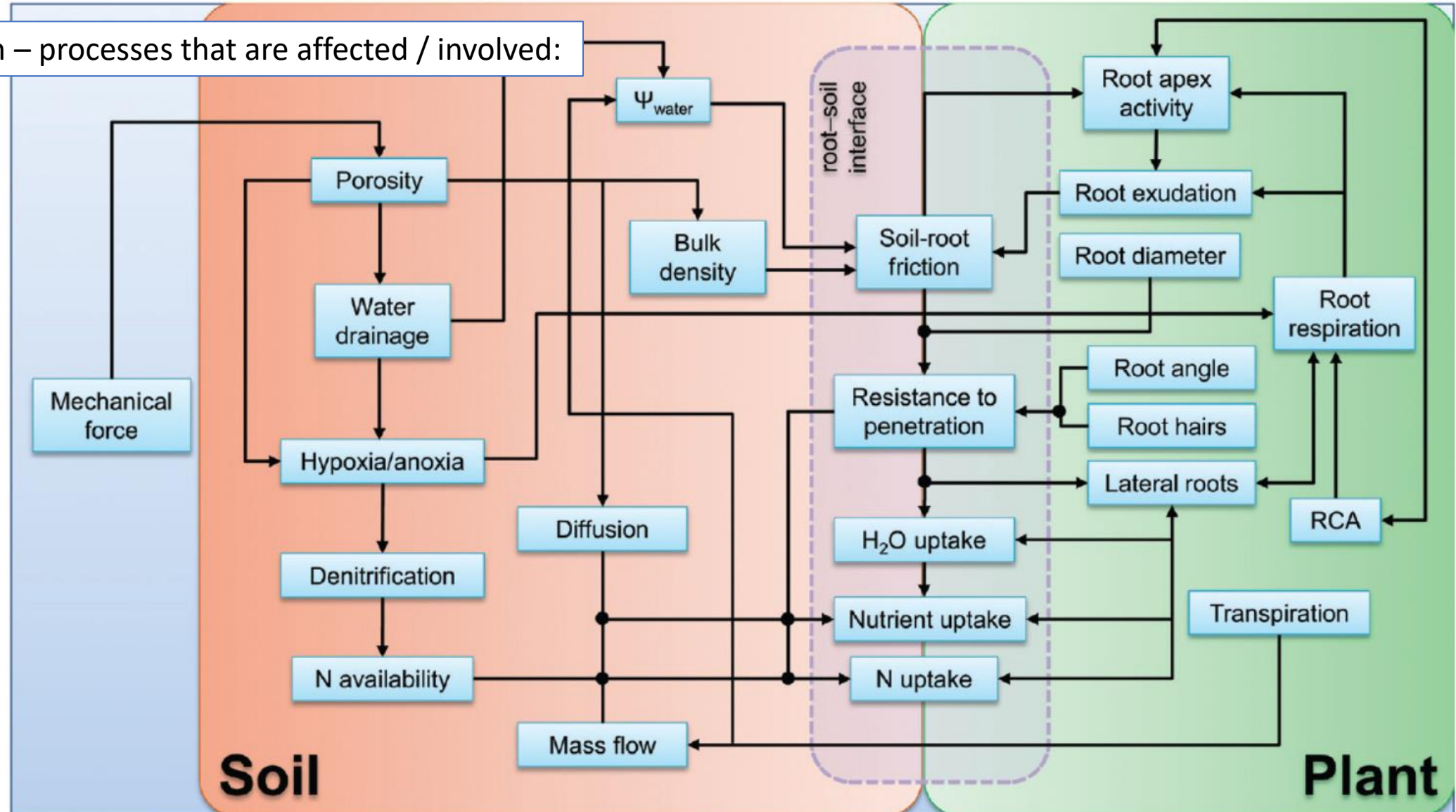
## Soil Compaction (effect on plant roots)

- root elongation is driven by cell turgor in the elongation zone. This turgor must overcome the impedance of the soil as well as frictional forces along the outside of the root.
- some plant may show negative symptoms when  $PR > 2$
- different plants may show differing susceptibility to soil compaction



Root elongation rates of peanut and cotton as a function of soil strength (measured as penetrometer resistance). *From Taylor and Ratcliff (1969).*

Soil compaction – processes that are affected / involved:



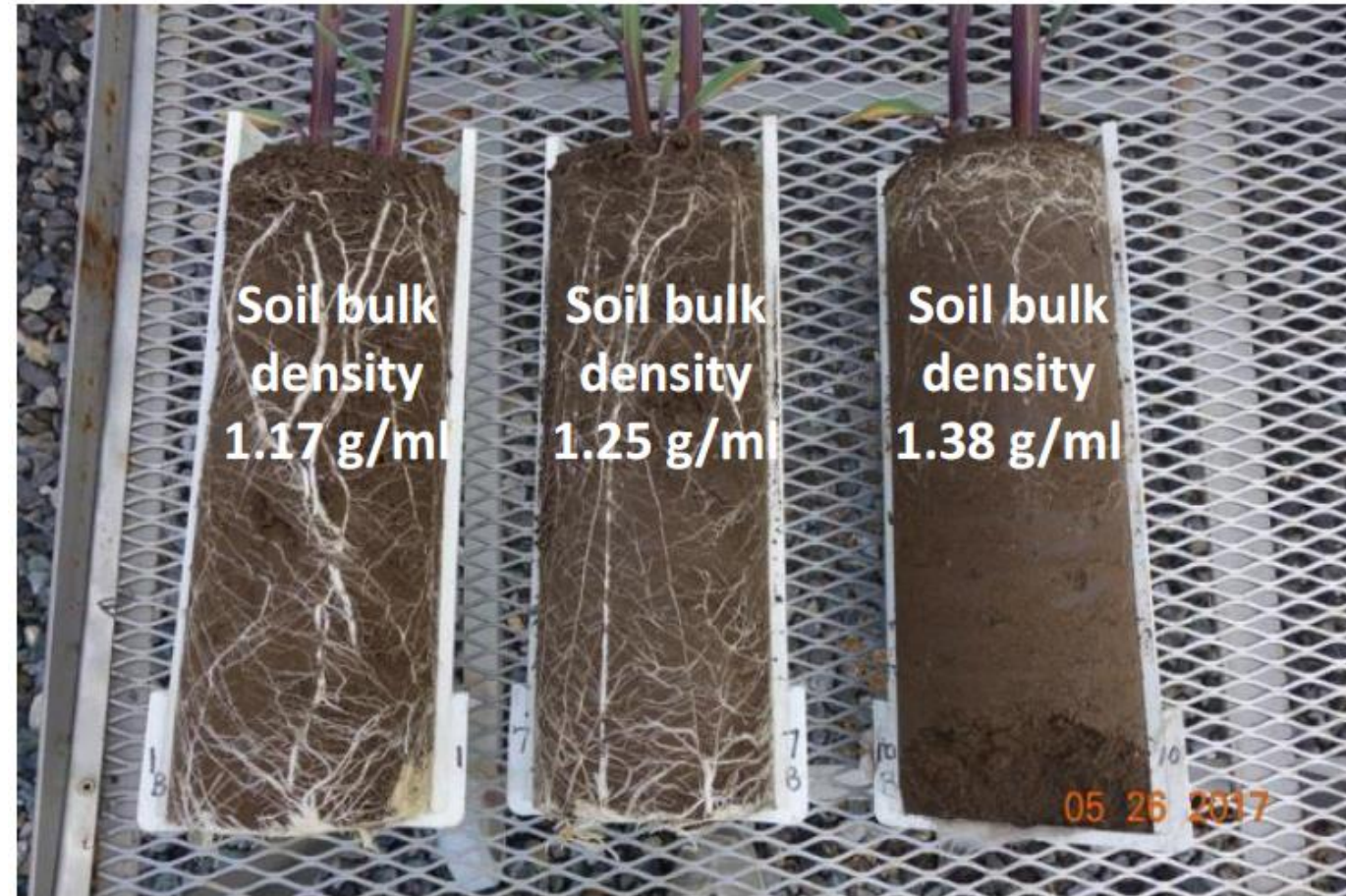
Relational diagram of the main interactions among soil physicochemical properties and root function and structure observed under conditions of soil compaction.  $\Psi_{\text{water}}$ , water potential; RCA, root cortical aerenchyma. The arrow ( $\rightarrow$ ) indicates the influence of one property on another whose interaction can be of synergistic or antagonistic nature; a two-way arrow ( $\leftrightarrow$ ) indicates a reciprocal influence between two properties; a black bullet ( $\bullet$ ) indicates converging influence between two or more properties on the following property; if two or more arrows have a point of intersection without a bullet, no direct interaction between them is indicated.

<https://doi.org/10.1093/jxb/erz383>

## Soil Compaction (effect on plant roots)

General relationship of soil bulk density to root growth based on soil texture (USDA-NRCS, 2008).

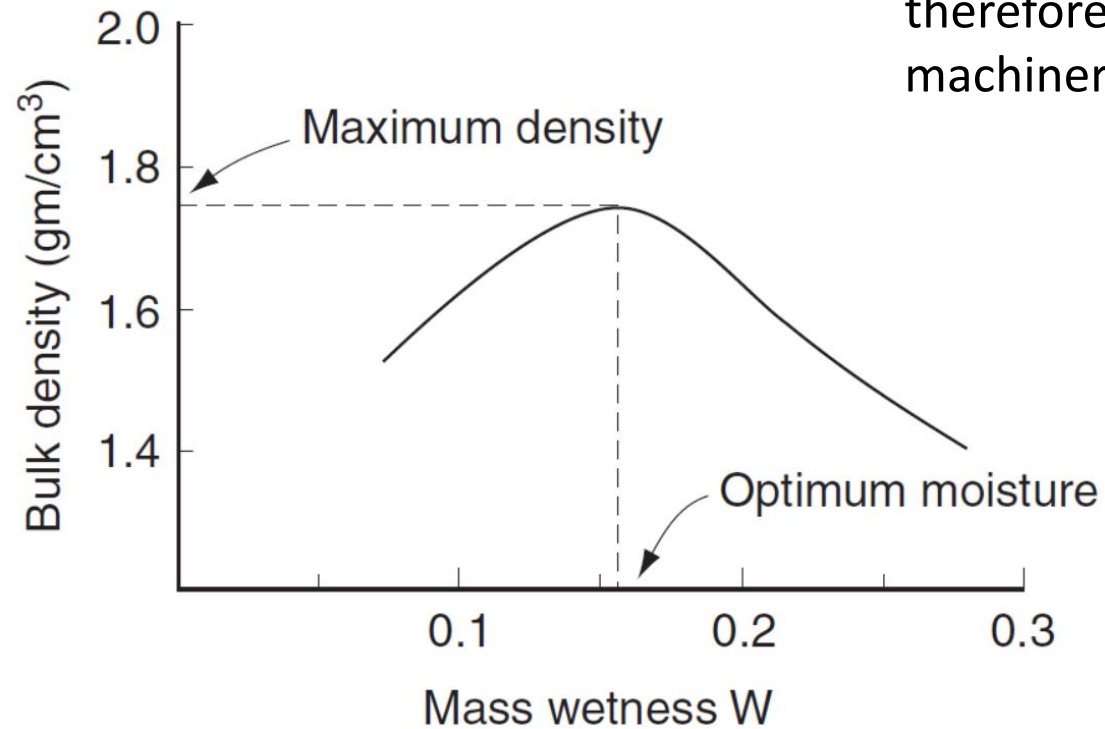
| Soil Texture | Ideal Bulk Density for Plant Growth | Bulk Density that Restricts Root Growth |
|--------------|-------------------------------------|-----------------------------------------|
|              | g/cm <sup>3</sup>                   | g/cm <sup>3</sup>                       |
| Sandy        | < 1.60                              | > 1.80                                  |
| Silty        | < 1.40                              | > 1.65                                  |
| Clayey       | < 1.10                              | > 1.47                                  |



Root growth of corn plants (V5 growth stage) growing in soil compacted to different bulk densities before corn seeds were planted (Strachan and Jeschke 2017).

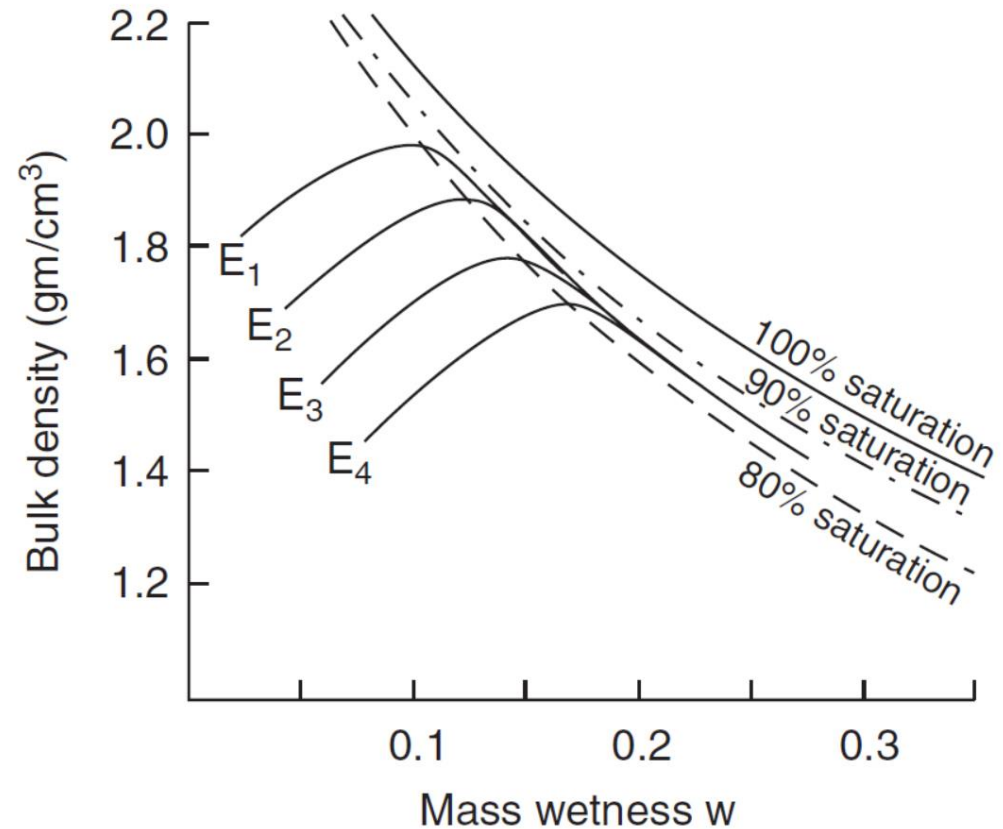
## Soil Compaction – how it “works”?

In general, wet soils are more susceptible to compaction compared to drier conditions → therefore, it is more convenient to use heavy machinery when soil moisture is lower.



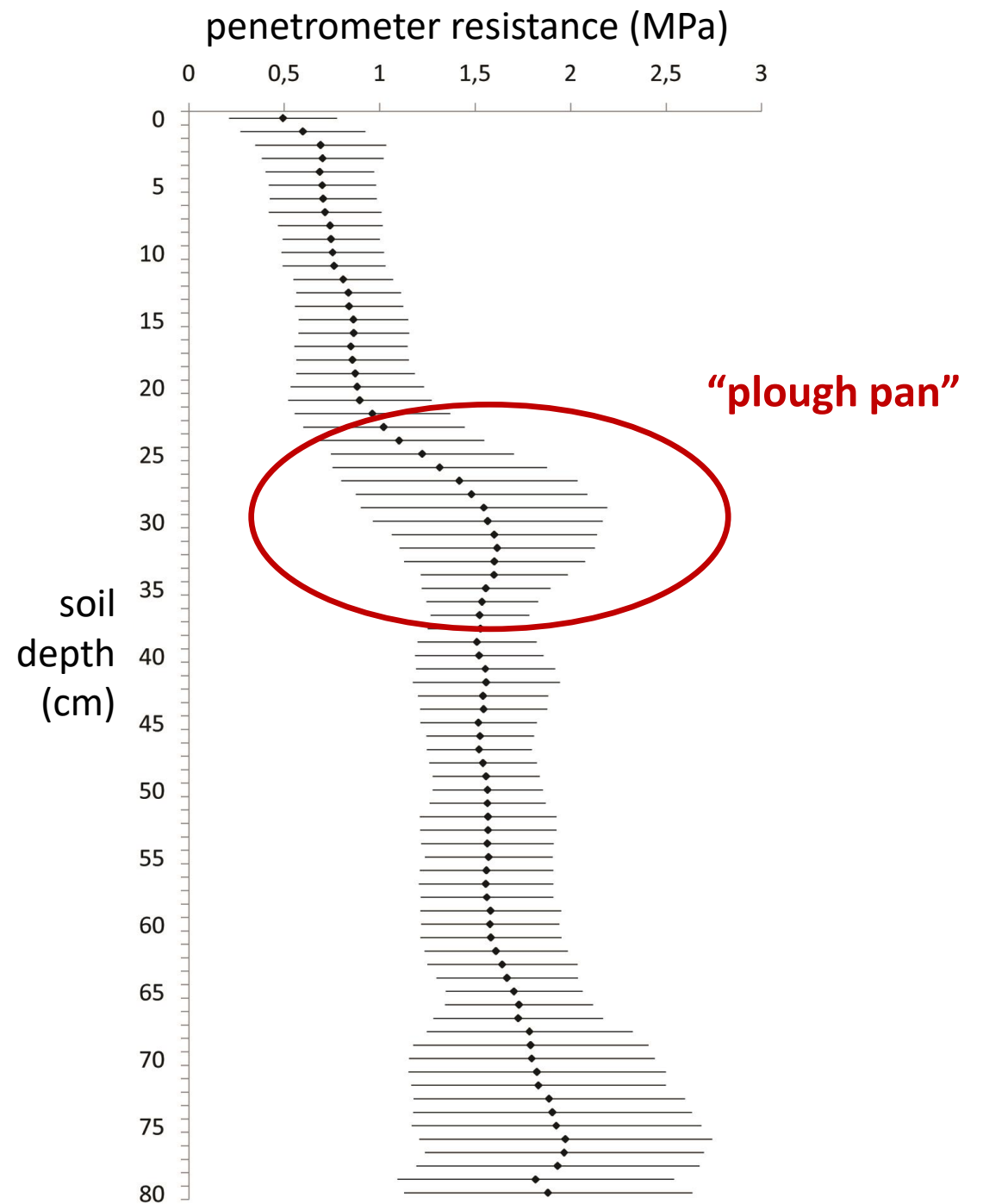
Typical moisture–density curve for a medium-textured soil, indicating the maximum density obtainable with a given compactive effort.

## Soil Compaction – how it “works”?



Family of moisture-density curves for different compactive efforts ( $E_1 > E_2 > E_3 > E_4$ ). Note that the 100% saturation line, representing zero air-filled porosity, was calculated assuming a particle density value of  $2.63 \text{ g.cm}^3$ .

Soil Compaction – measurement:

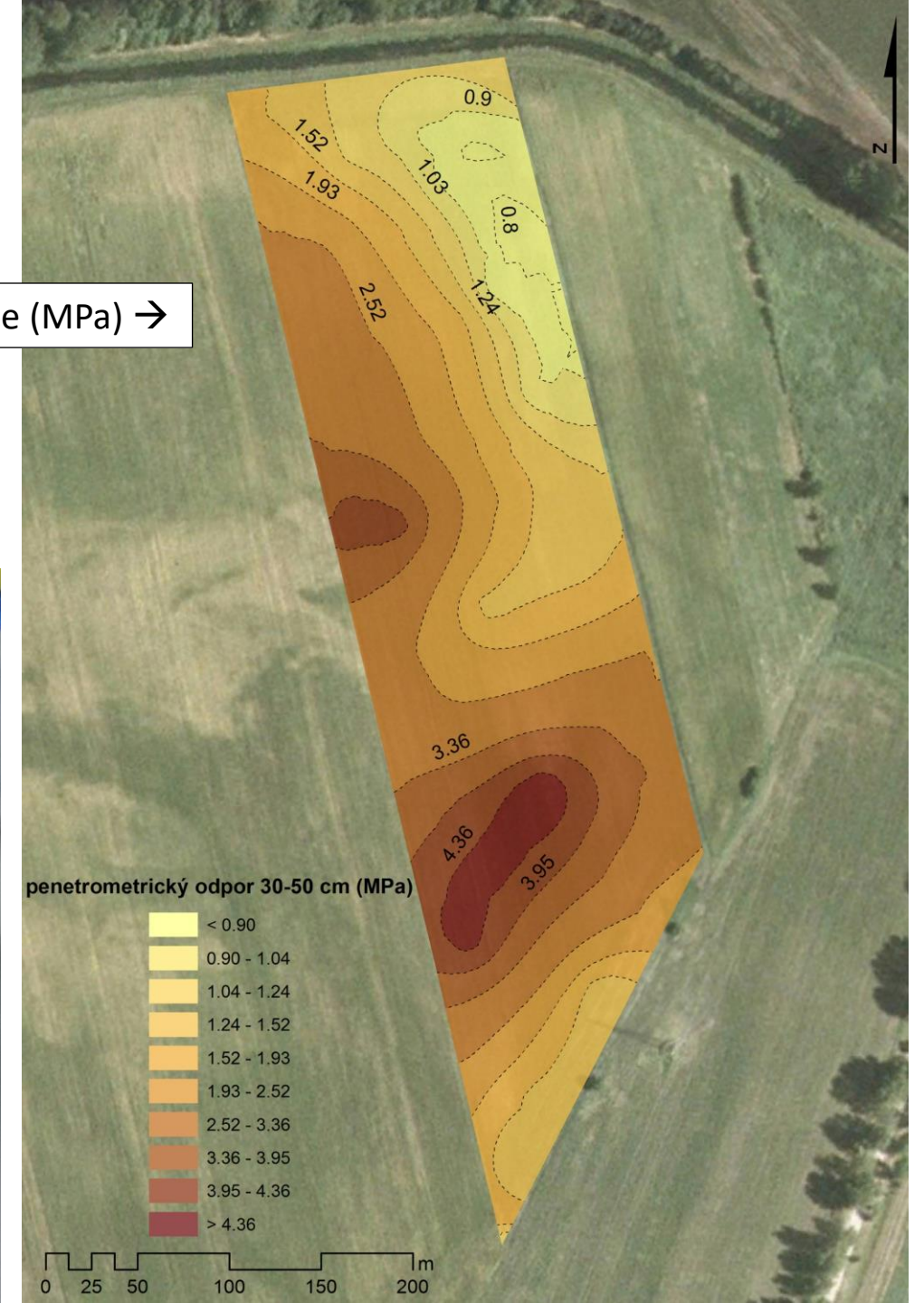
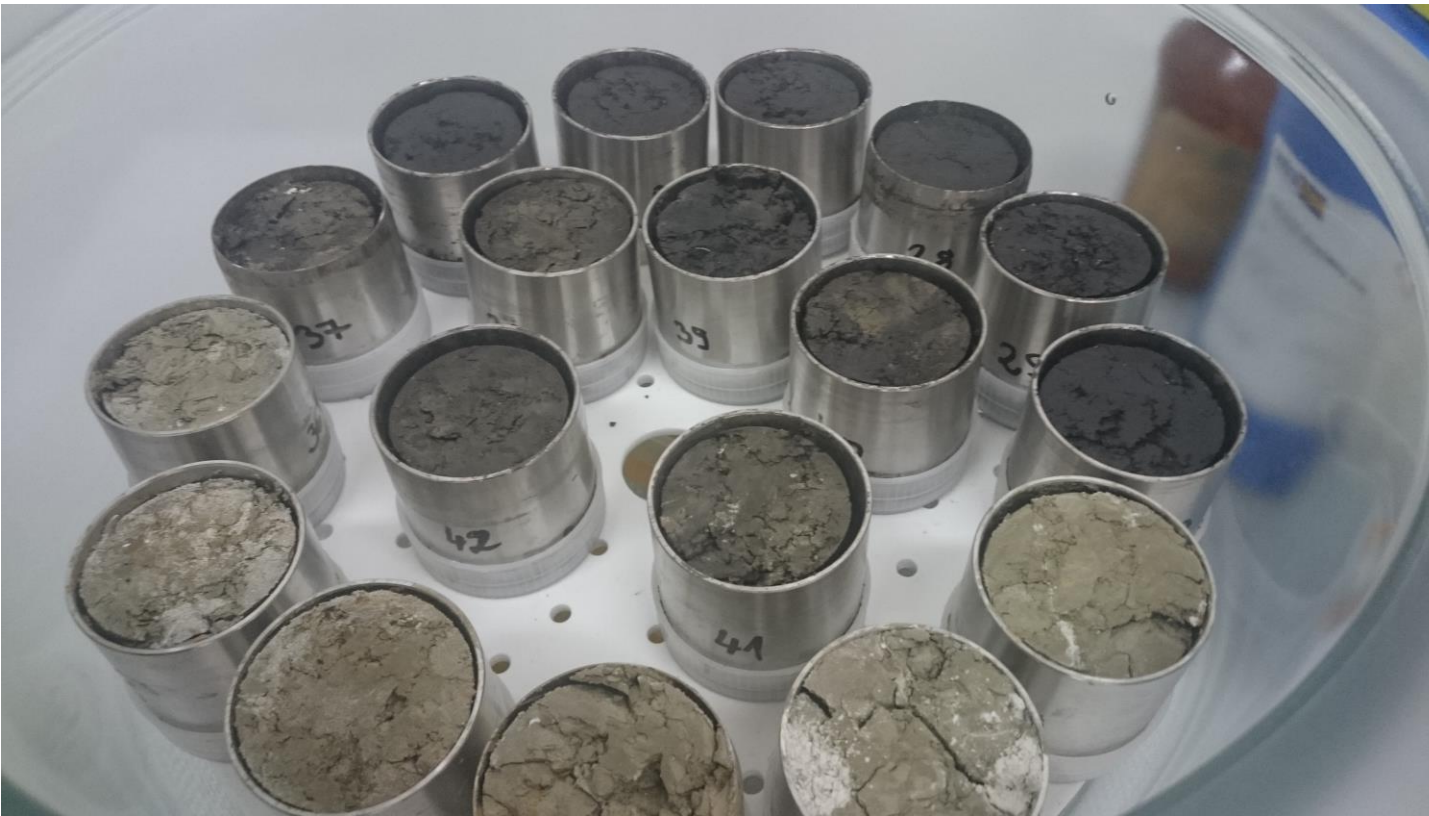


# Soil Compaction – measurement

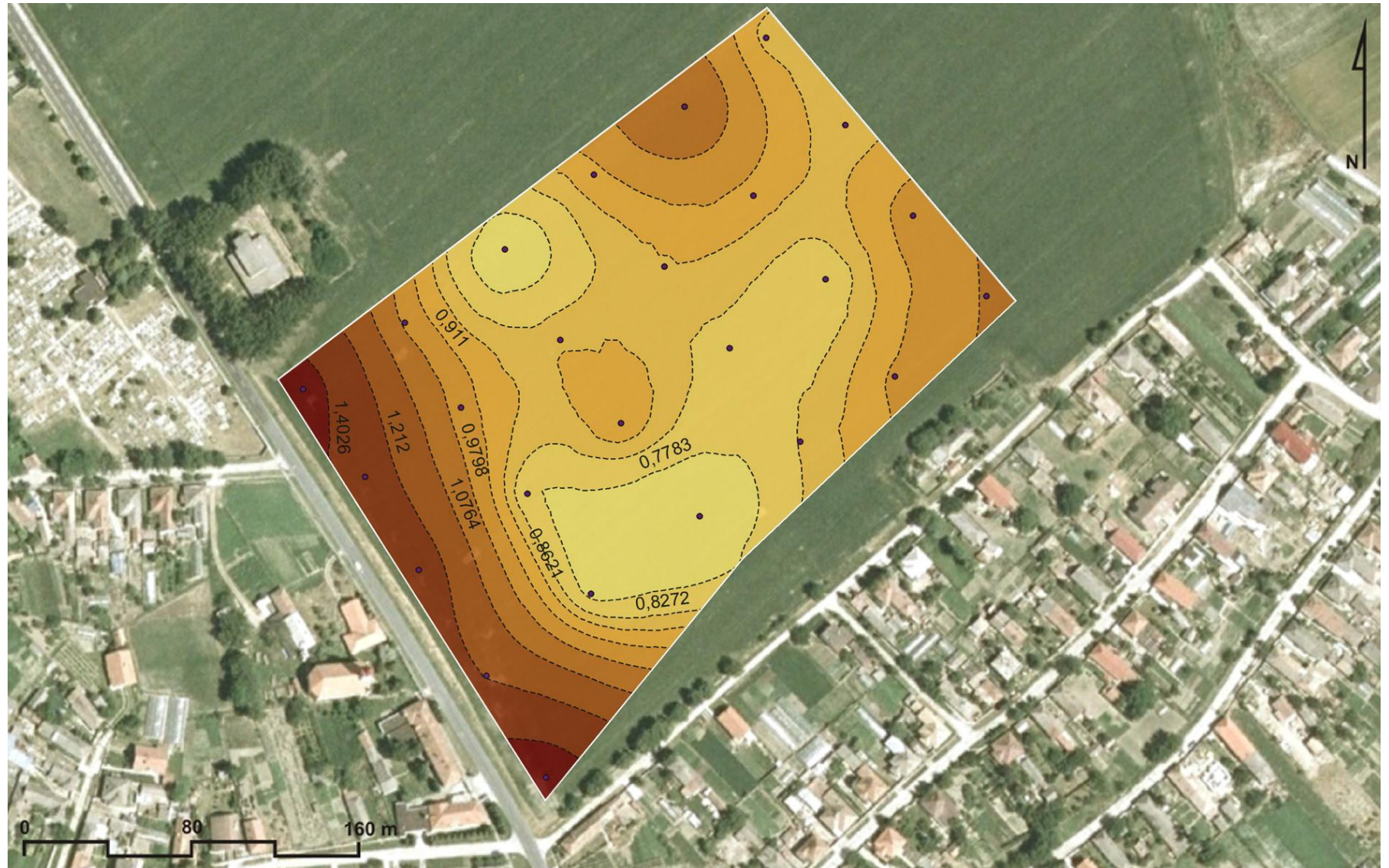
## Danubian Lowland

penetration resistance (MPa) →

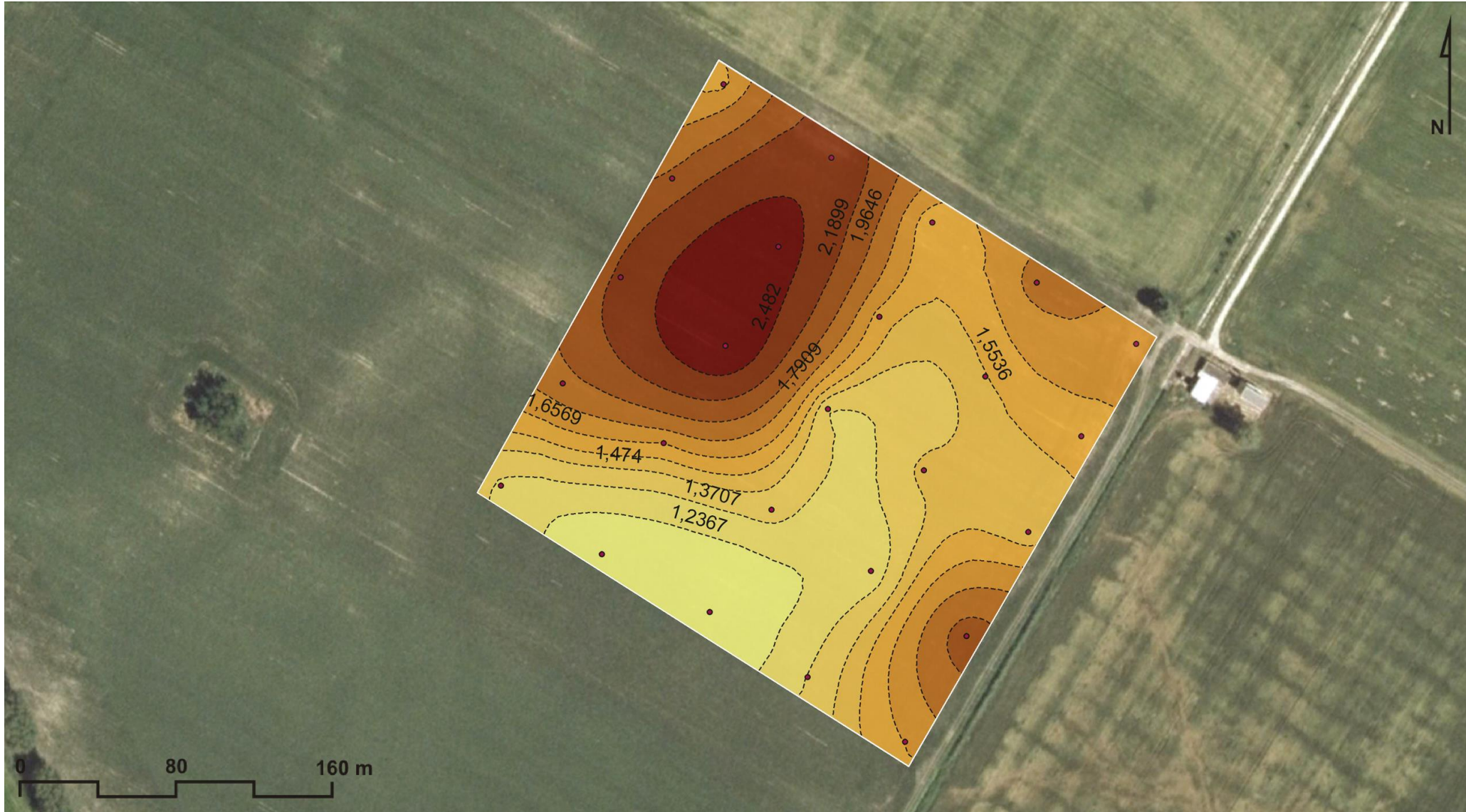
“intact” soil cores (bellow) enabling soil bulk density quantification  
(the soils shrank because of drying – it is caused by smectite minerals; they expand upon wetting and shrink upon drying)



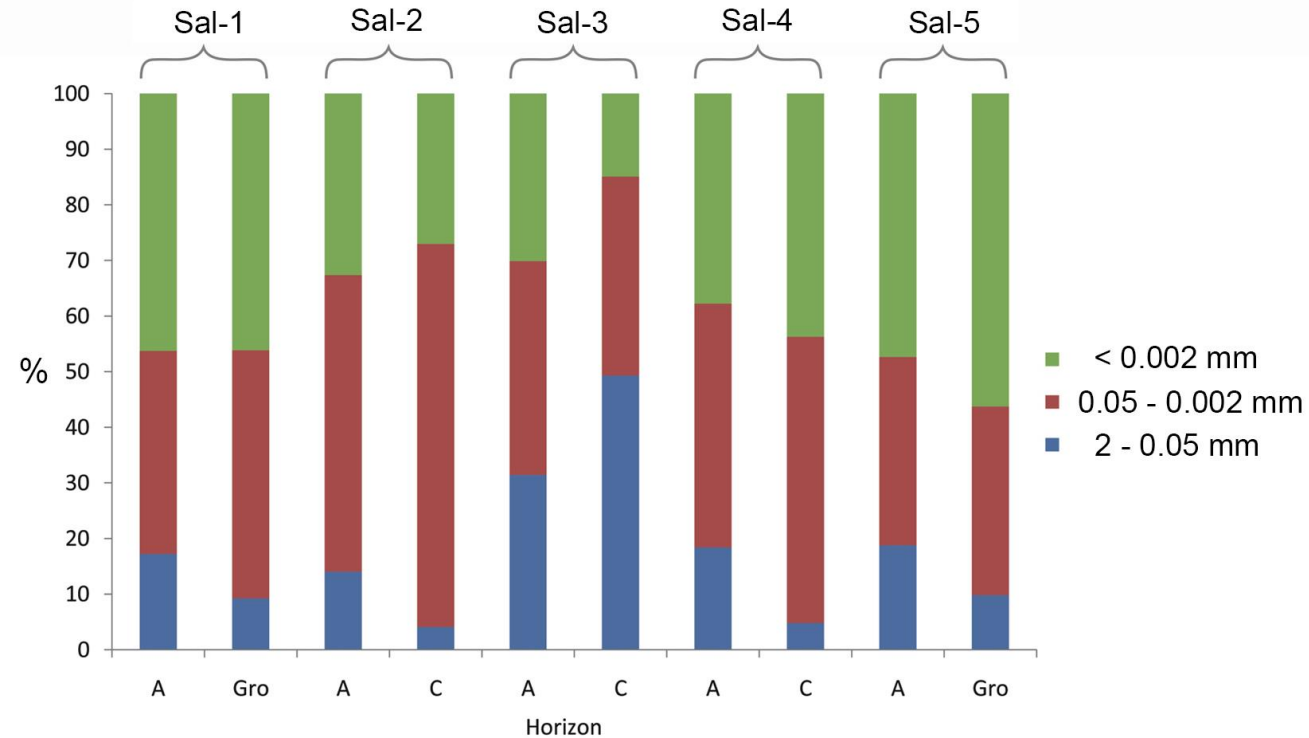
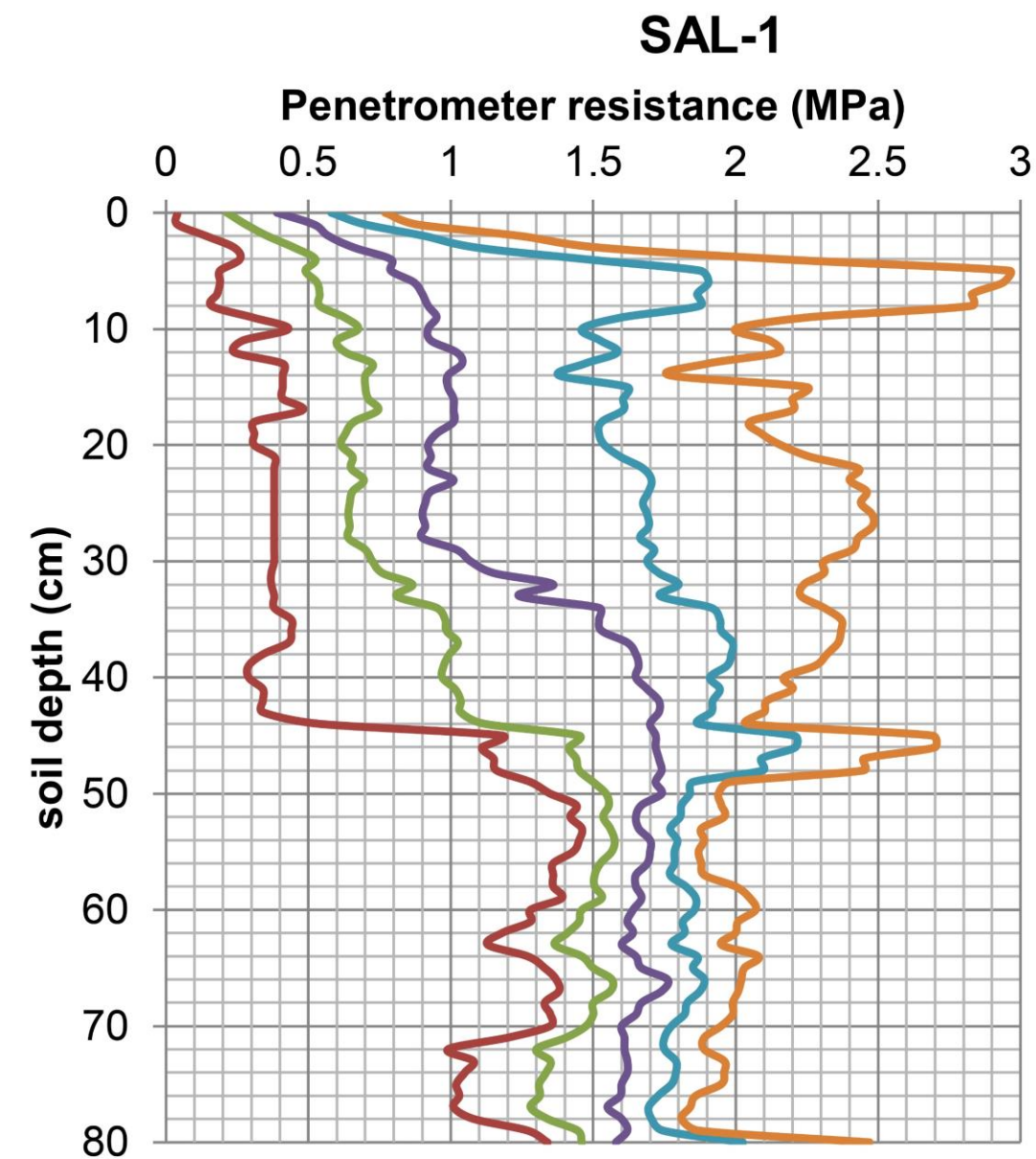
## Soil Compaction – measurement (Danubian Lowland)



## Soil Compaction – measurement (Danubian Lowland)

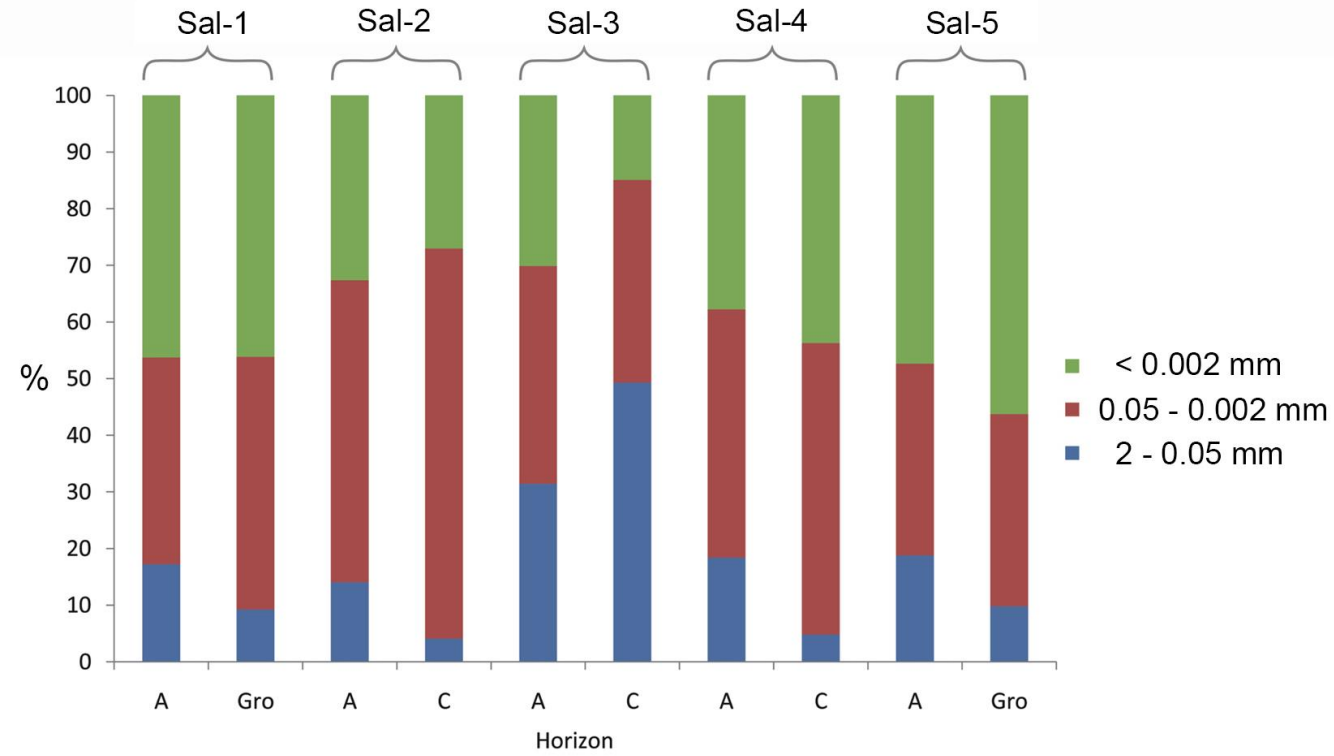
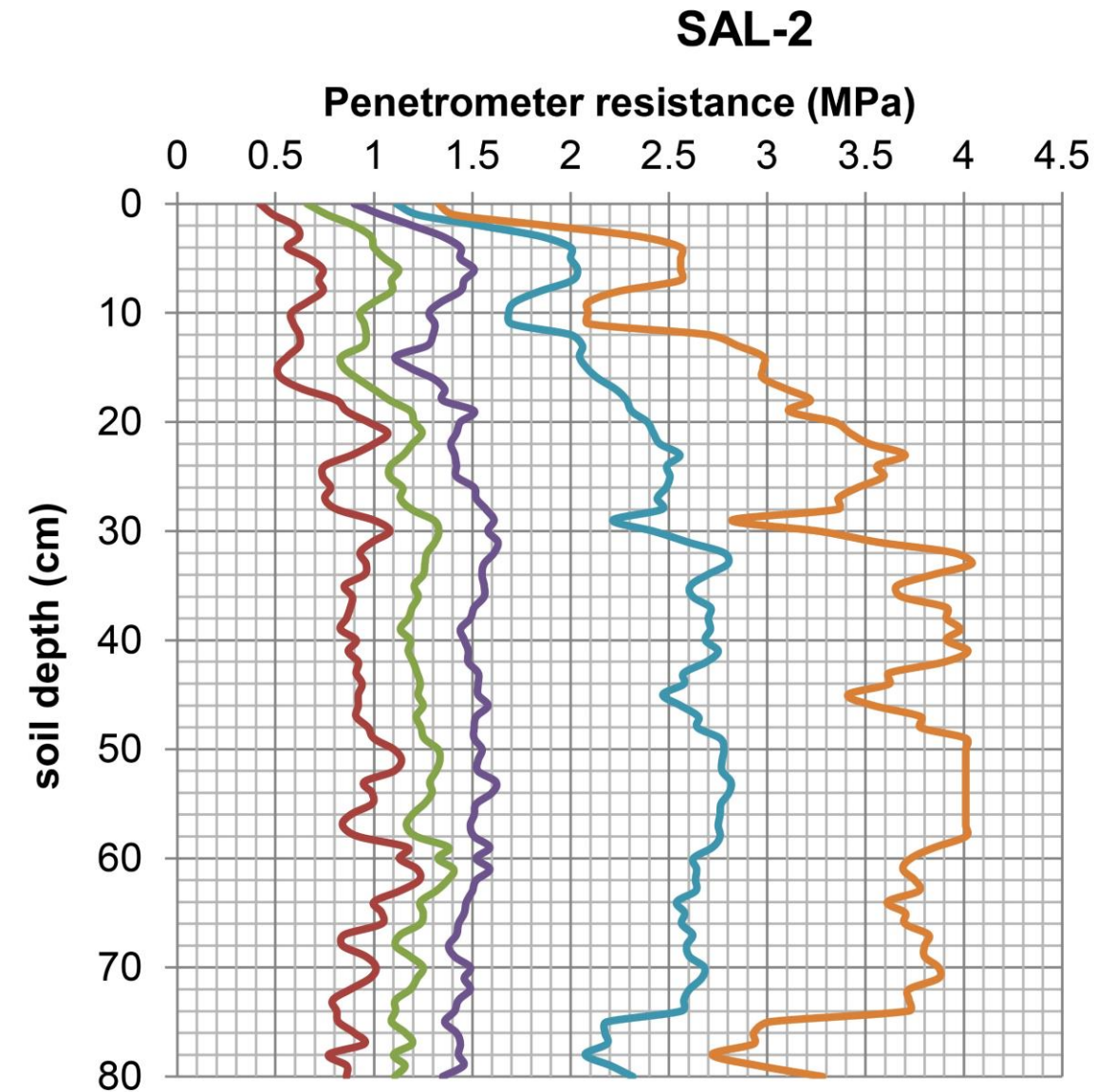


25 measurements were taken per site (Sal-1, 2, 3, 4, 5)



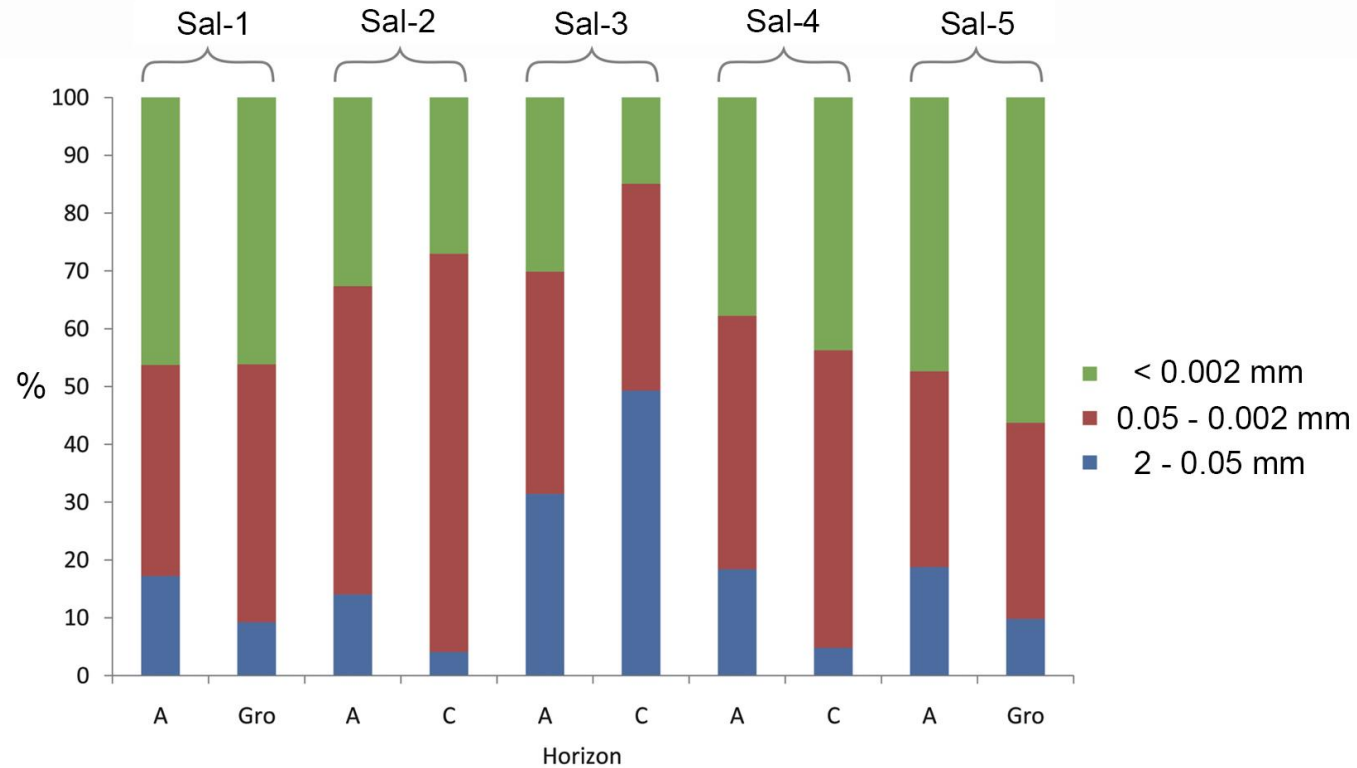
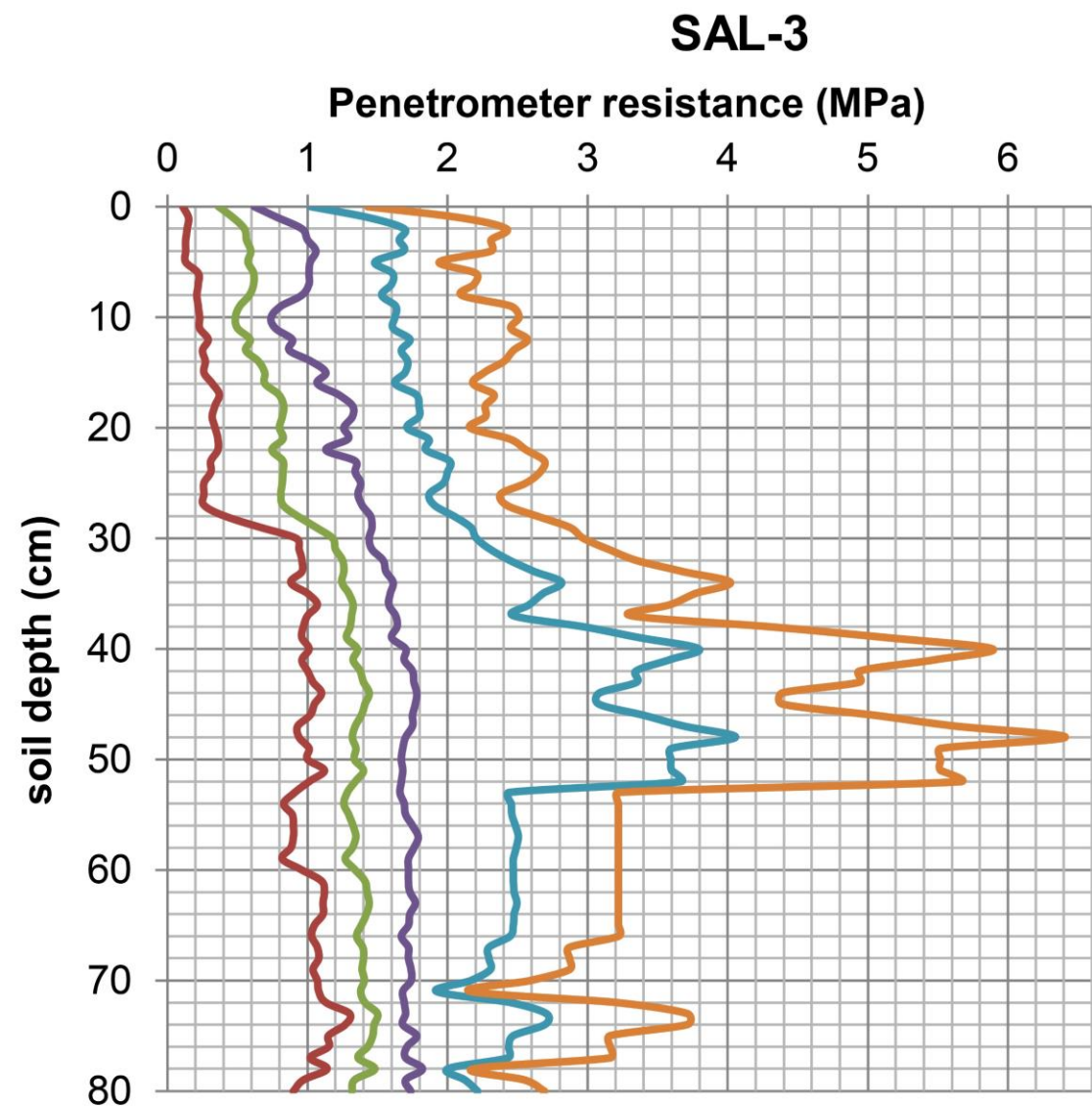
↑  
particle size distribution

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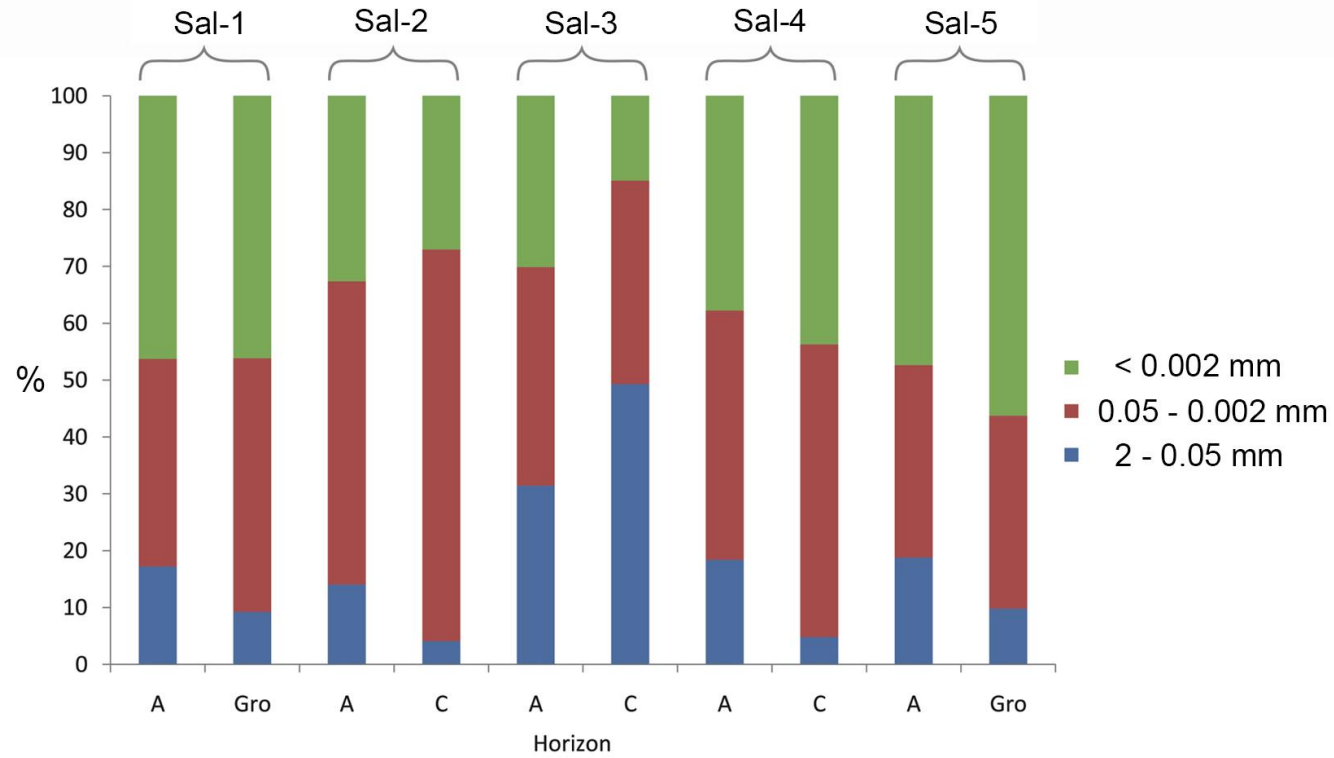
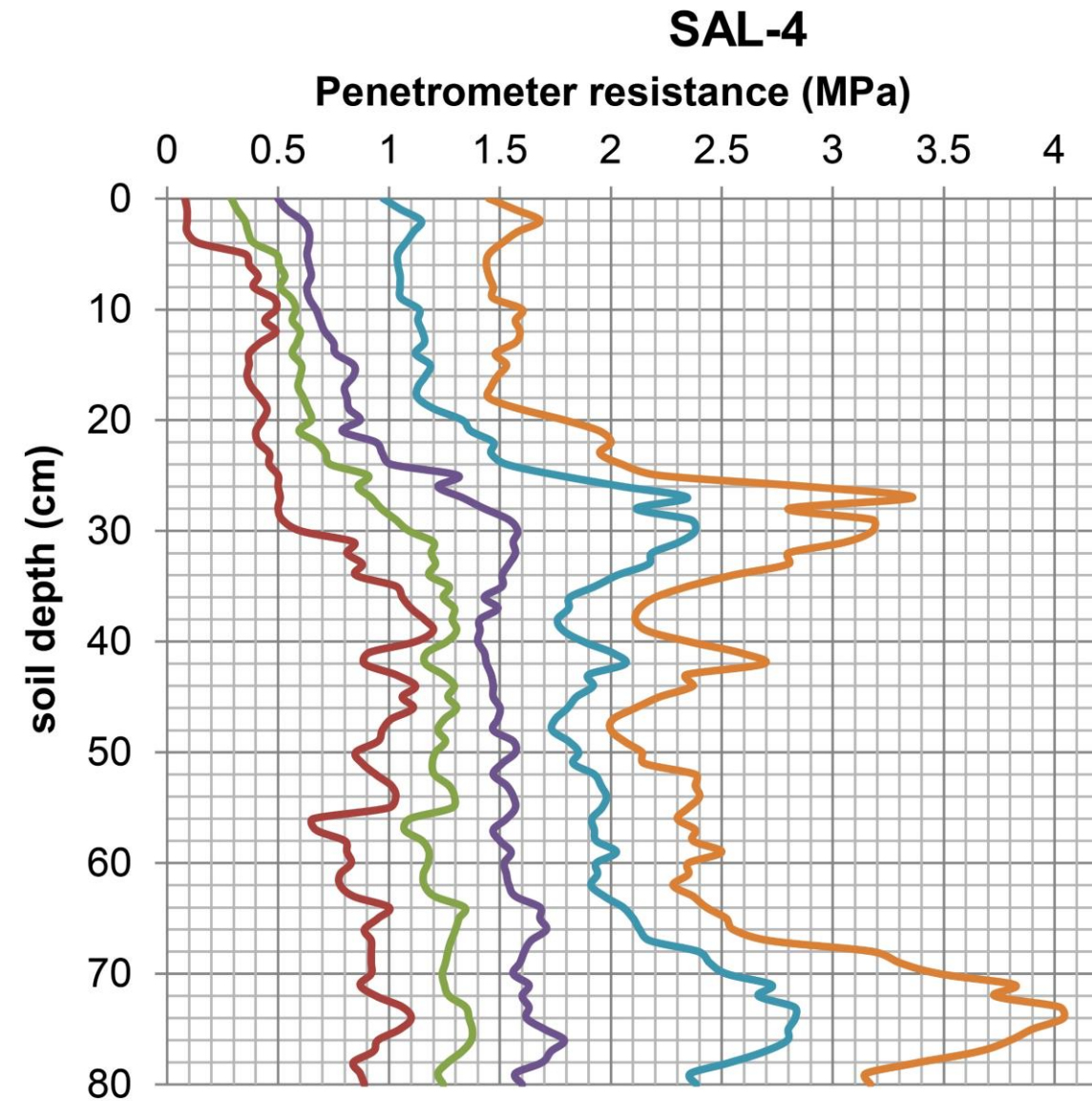
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particle size distribution

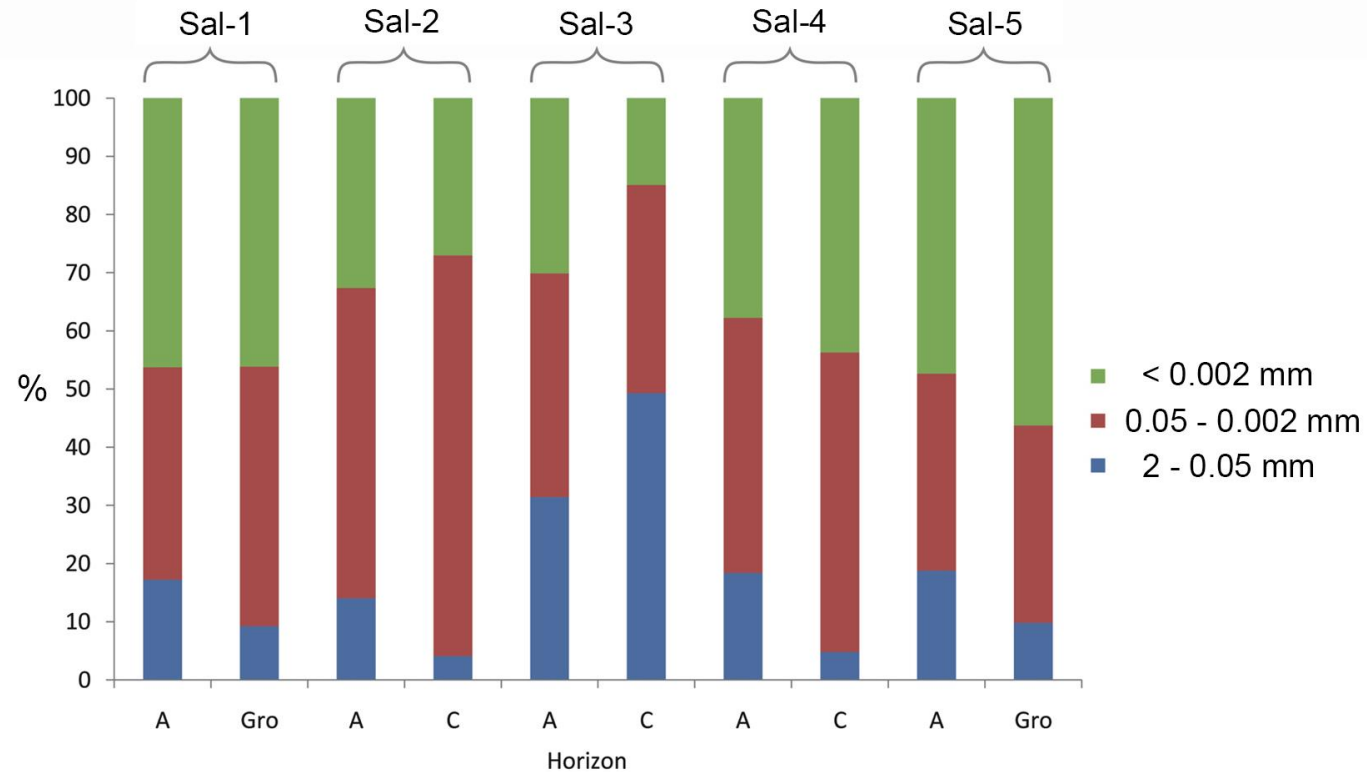
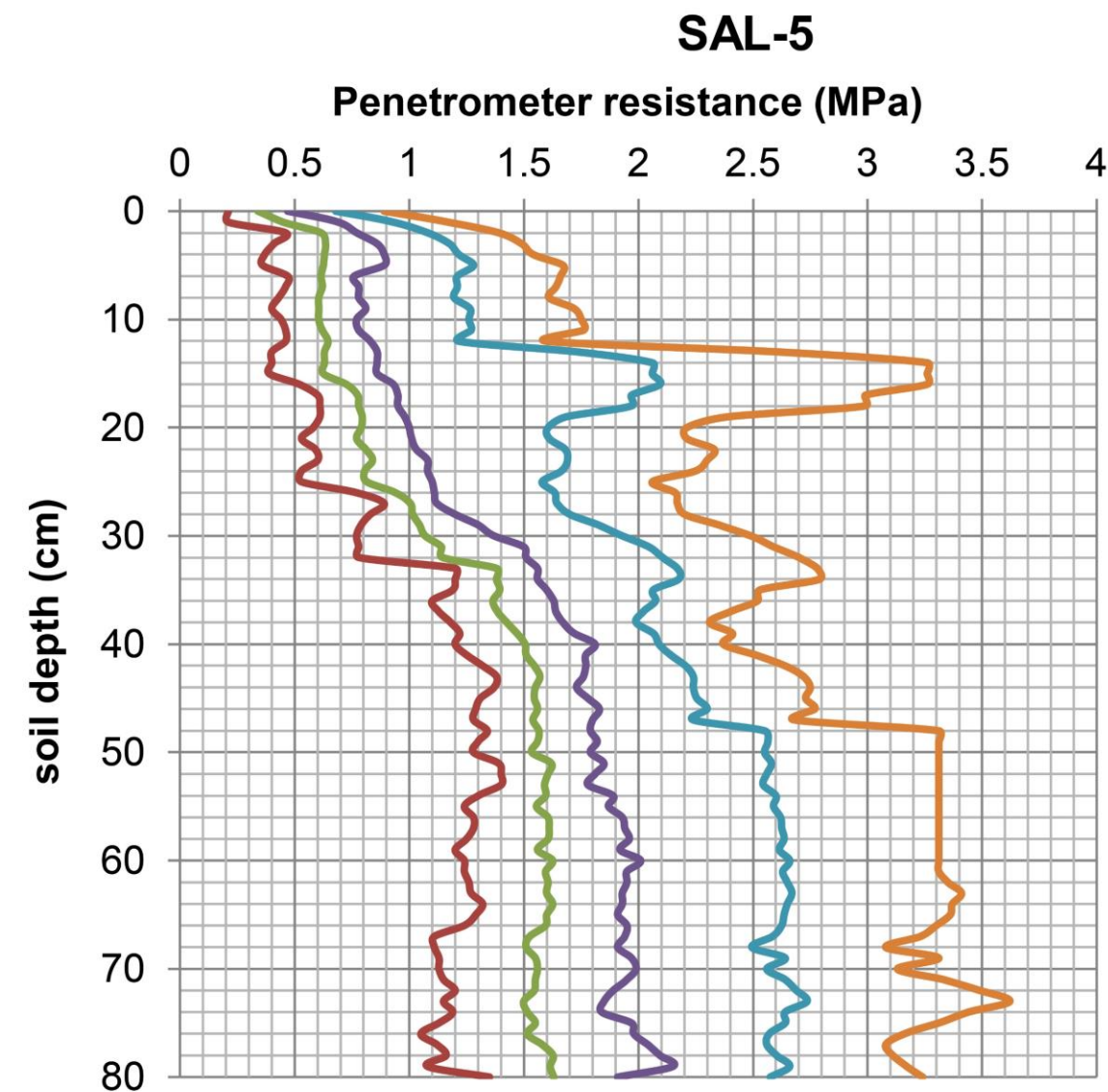
25 measurements were taken per site (Sal-1, 2, 3, 4, 5)



Minimum  
25 percentile  
Median  
75 percentile  
Maximum

particle size distribution

25 measurements were taken per site (Sal-1, 2, 3, 4, 5)



↑  
particle size distribution

## Soil Compaction (prevention, treatment and alleviation)

- on soils containing more clay and/or silt → do not use heavy machinery when soil is too wet
- there are attempts to change the design of ploughing devices to alleviate negative impact of tillage → ploughs that cut subsoil, without creating rills and turning topsoil upside-down → less disturbance
- use of dual tires or broader tires on agricultural machines to impose less pressure per area unit of soil
- avoid ploughing repeatedly (regularly) to same depth
- adding fresh organic matter (plant biomass residues) into the soil is beneficial, as soils rich in organic matter are usually less susceptible to compaction
- subsoiling: mechanical disruption of compacted layer using special ploughs that disintegrate deeper parts of a soil profile
- although subsoiling may help to loosen compacted soil temporary, it may contribute to further erosion and compacted layer may be reappear after reestablishing of conventional tillage
- the example of effective measure would be to perform subsoiling and then limit tillage as much as possible (use some less invasive cultivation method)

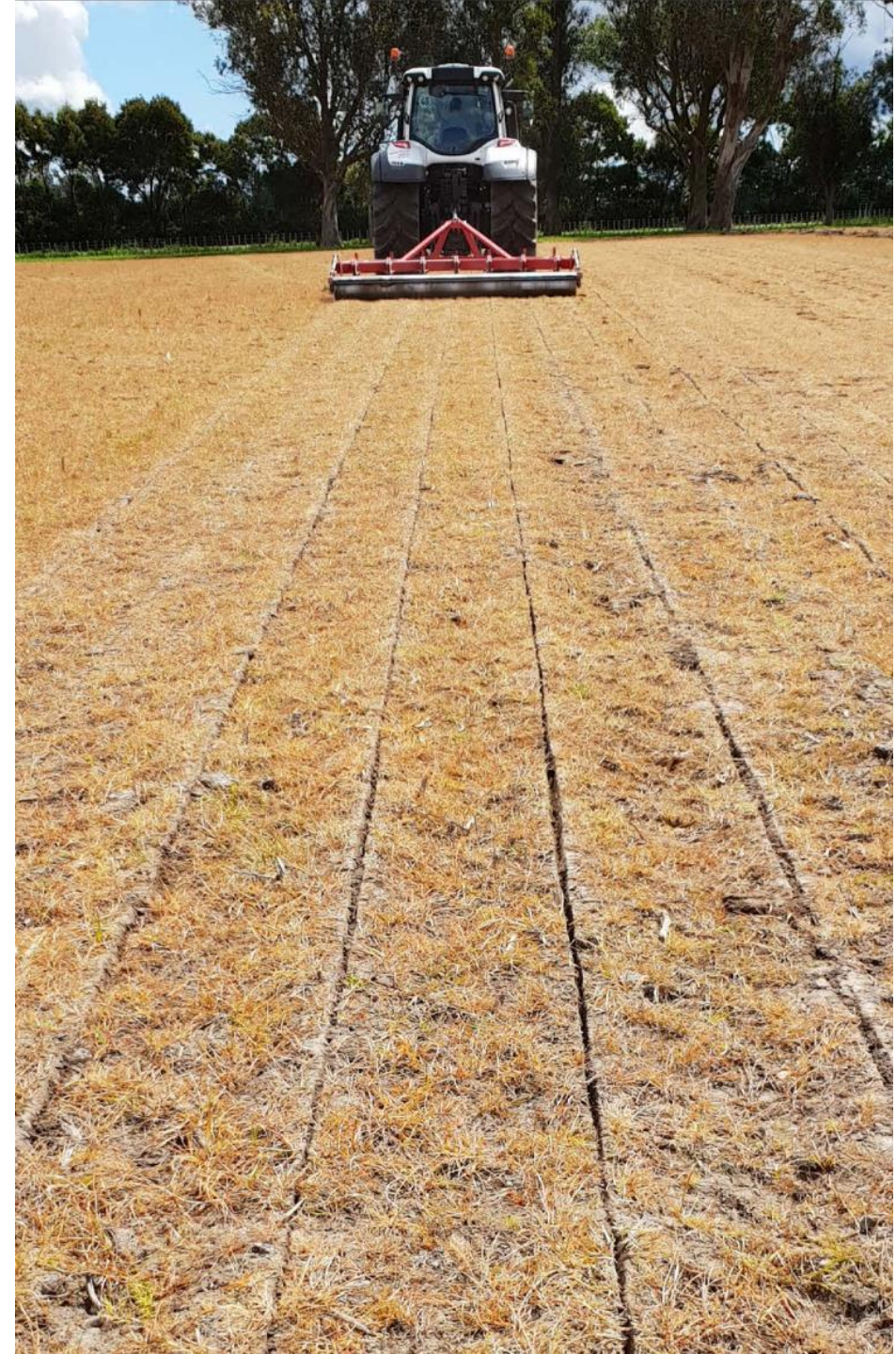
## Soil Compaction (prevention, treatment and alleviation)

ploughing to different depths:



# Soil Compaction (prevention, treatment and alleviation)

cutting compacted layers:



## Soil Compaction (prevention, treatment and alleviation)

use of dual tires on agricultural machines to impose less pressure per area unit of soil:



## Soil Compaction (prevention, treatment and alleviation)



“subsoilers” designed to “break down” (loosen) compacted layer located in deeper parts of soil profile