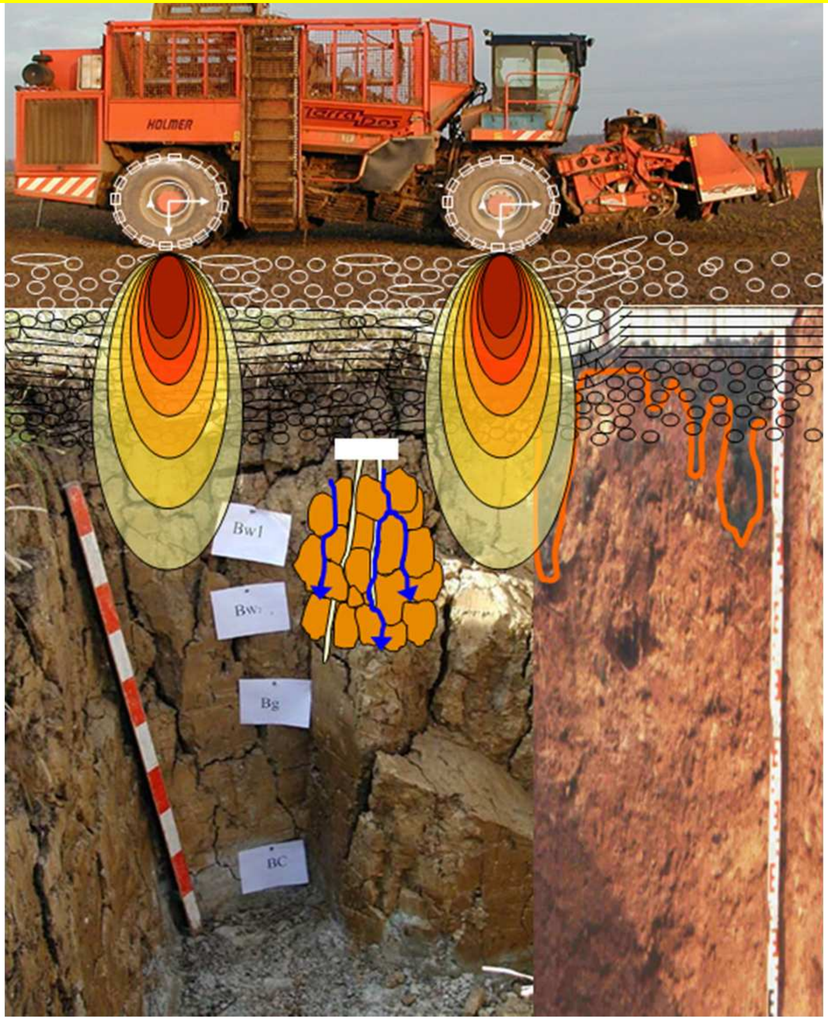
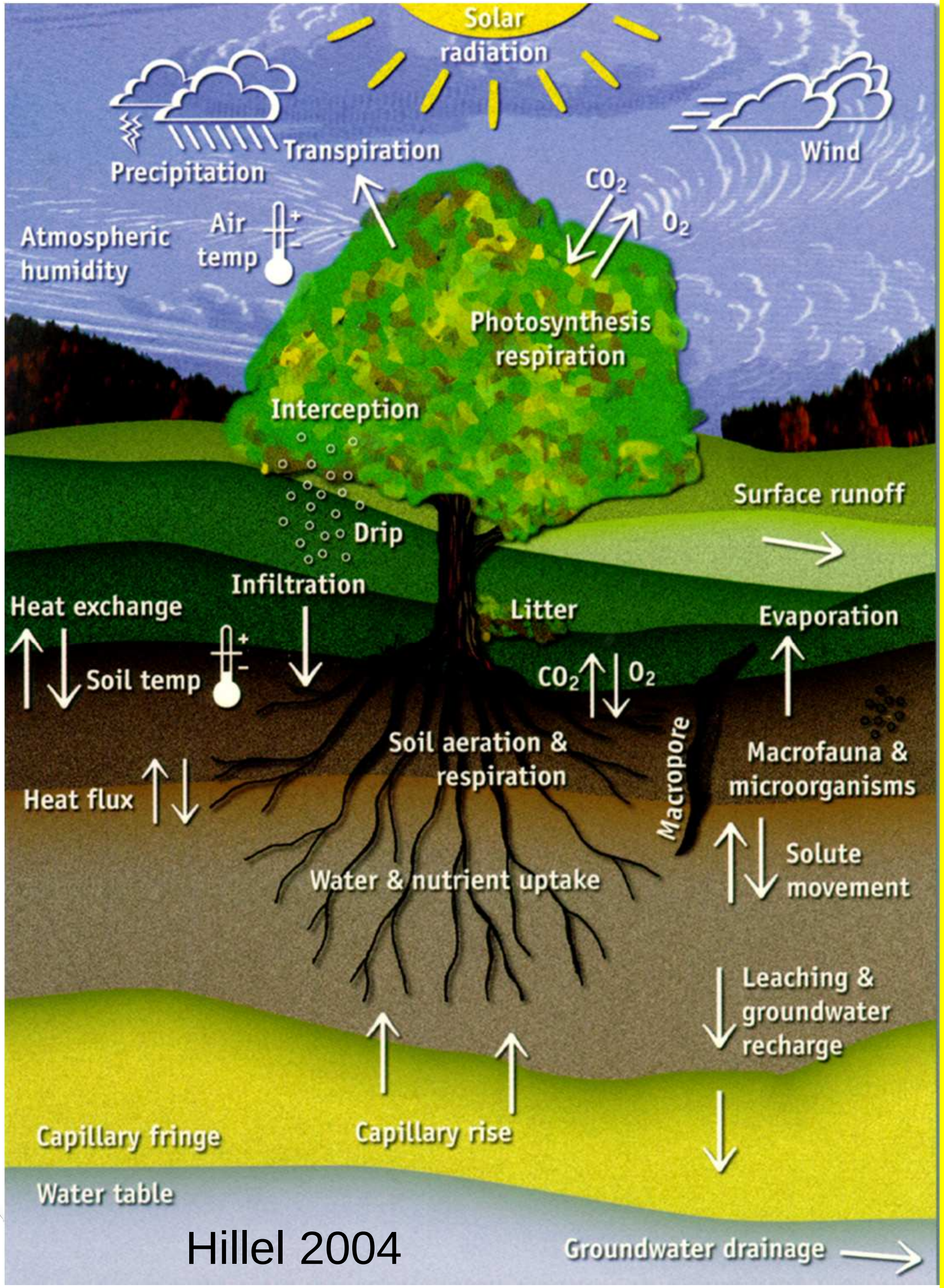
# SOILS ARE SENSITIVE REACTORS – DO WE NEED A PARADIGM CHANGE TOWARDS A MORE SUSTAINABLE SOIL USE?





**Prof. Dr. R. Horn**
**CAU Kiel/ Germany**
**Soil Science**

# Soils are reactors




Hillel 2004

**Soils are needed not only for food production, but**

- **9 Billion people 2050**
- **>1 Billion people are starving already today**
- **+70 % food /2050**
- **More than 2.5 Billion ha are already lost worldwide**
- **+ 100 ha/ day are irreversibly lost even only in Germany – worldwide?????**
- **Global change aspects include soil deterioration e.g. due to high flooding**

- INTRODUCTION
- Bearing capacity
- Some detailed insights on various scales
- Stress dependent changes in soil functions
- Predictability of soil strength and soil resilience or: Heavy Soil Loading - how much is too much?
- Conclusions

**Soils as non renewable and sensitive goods have functions,** but they are exposed to…

… soil deformation and degradation like changes in hydraulic functions, biological activity, gas composition, mass transport, C-storage, altered pesticide application need, remediation etc.

(Thin section: Pagliai et al.)

# Bearing Capacity of Soils

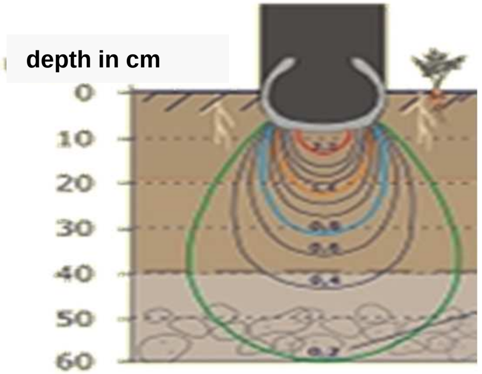
## also an ecological perspective

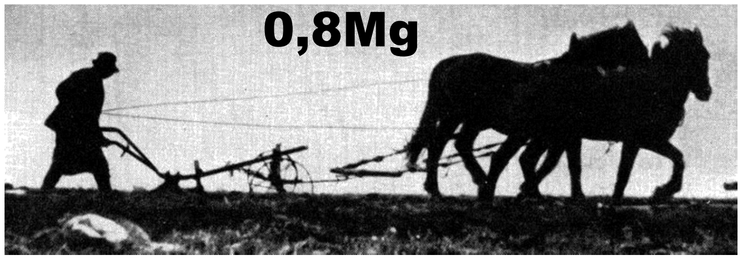
# Development of the mechanical stress input in agriculture and forestry - anthropogenic effects

C | A | U

Increased area requires more powerful machinery

Enhanced stress intake and depth distribution




around 1900

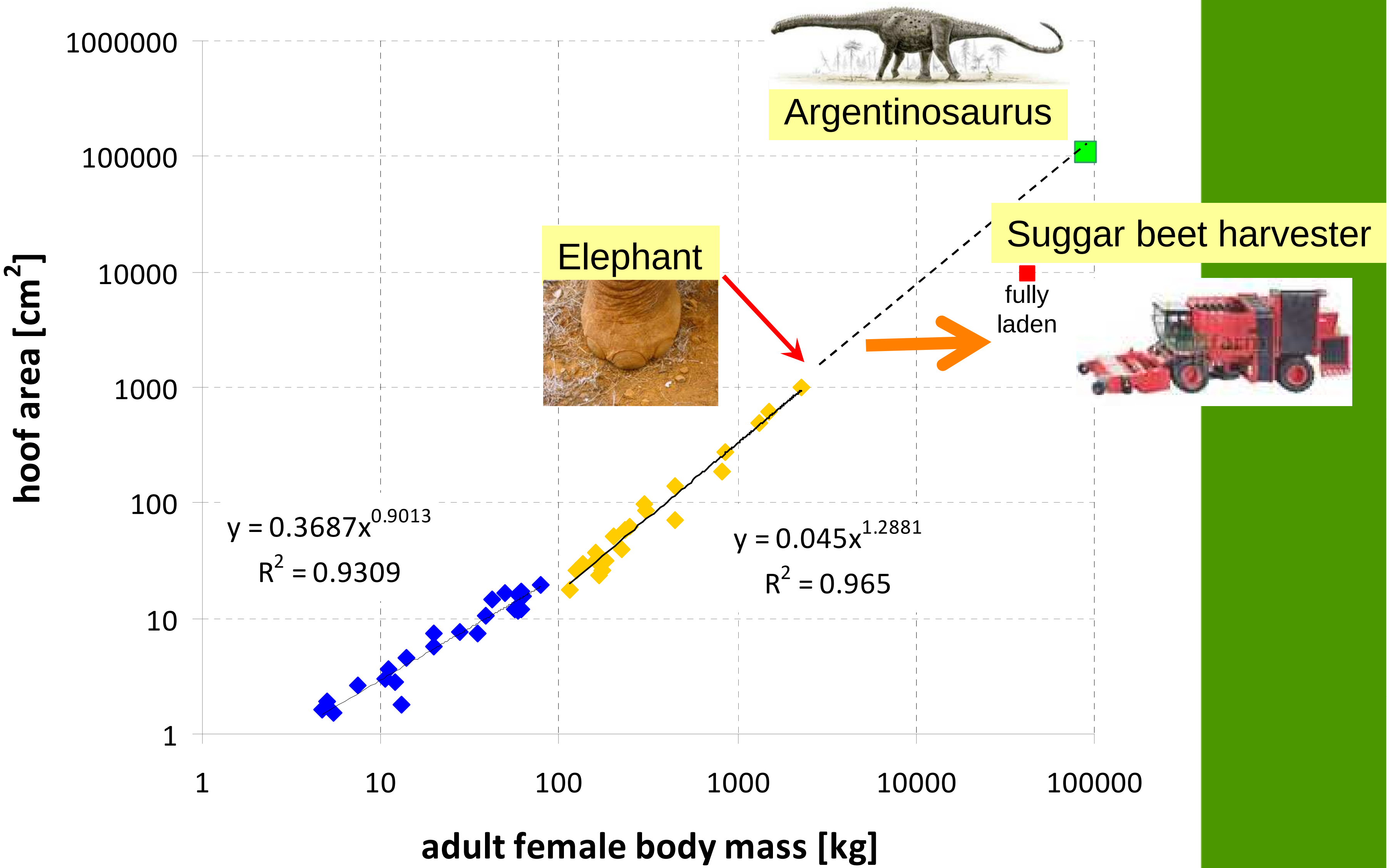
3,5Mg


about 1960



today

# Is there an ecological principle in „sustainable“ ground pressure?

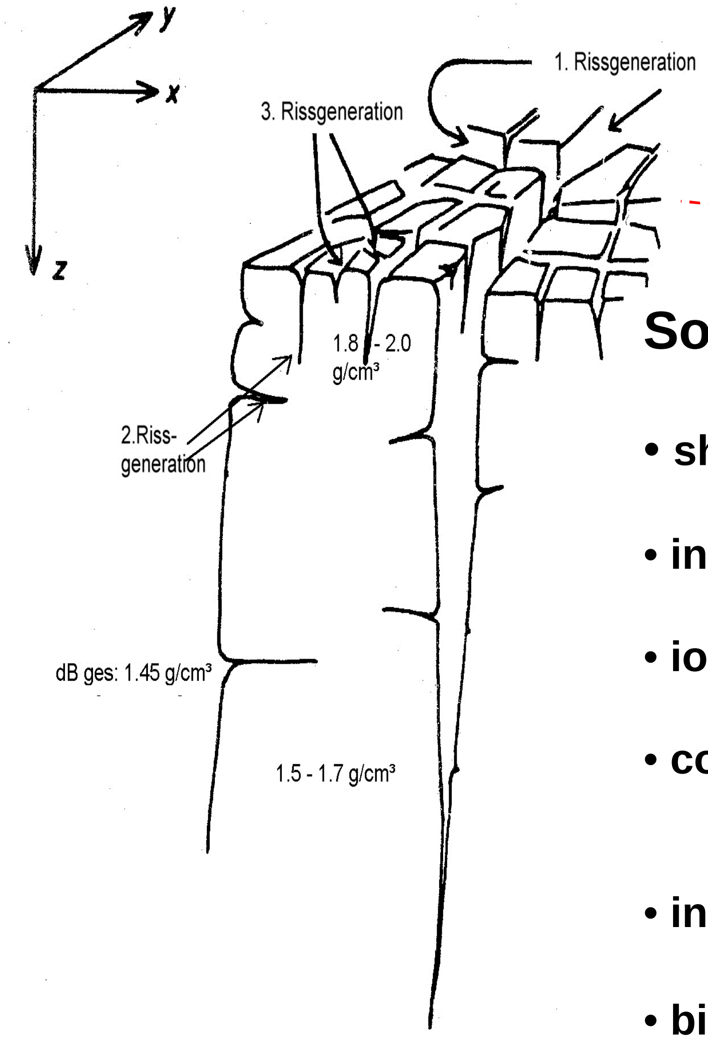



Cumming & Cumming (2003)

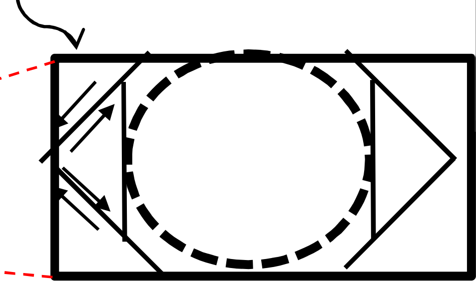
picture: Peth 2009

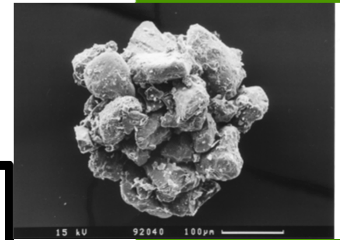
# Natural Effects of Soil Strengthening

1) Tensile failure




2) Shear failure

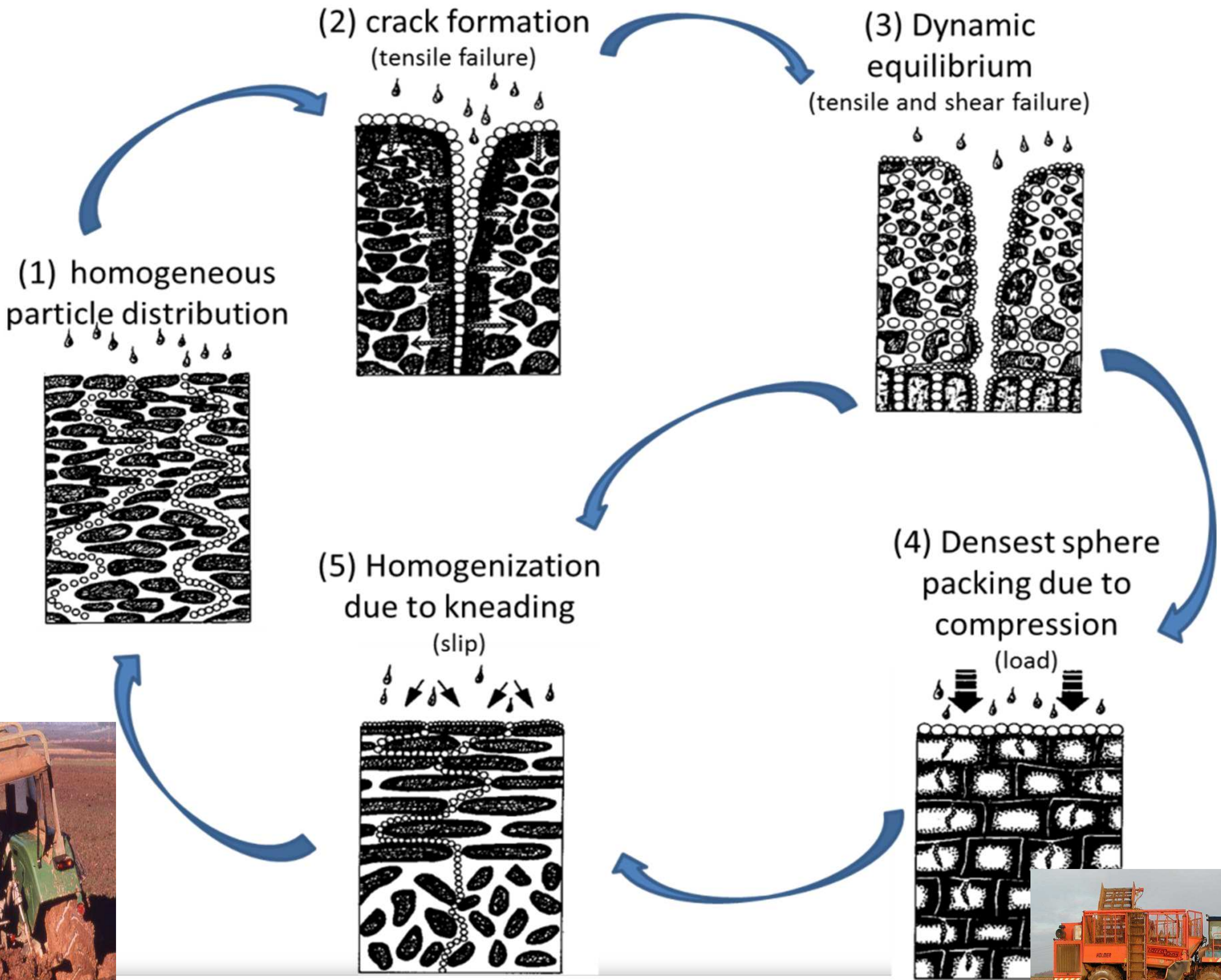




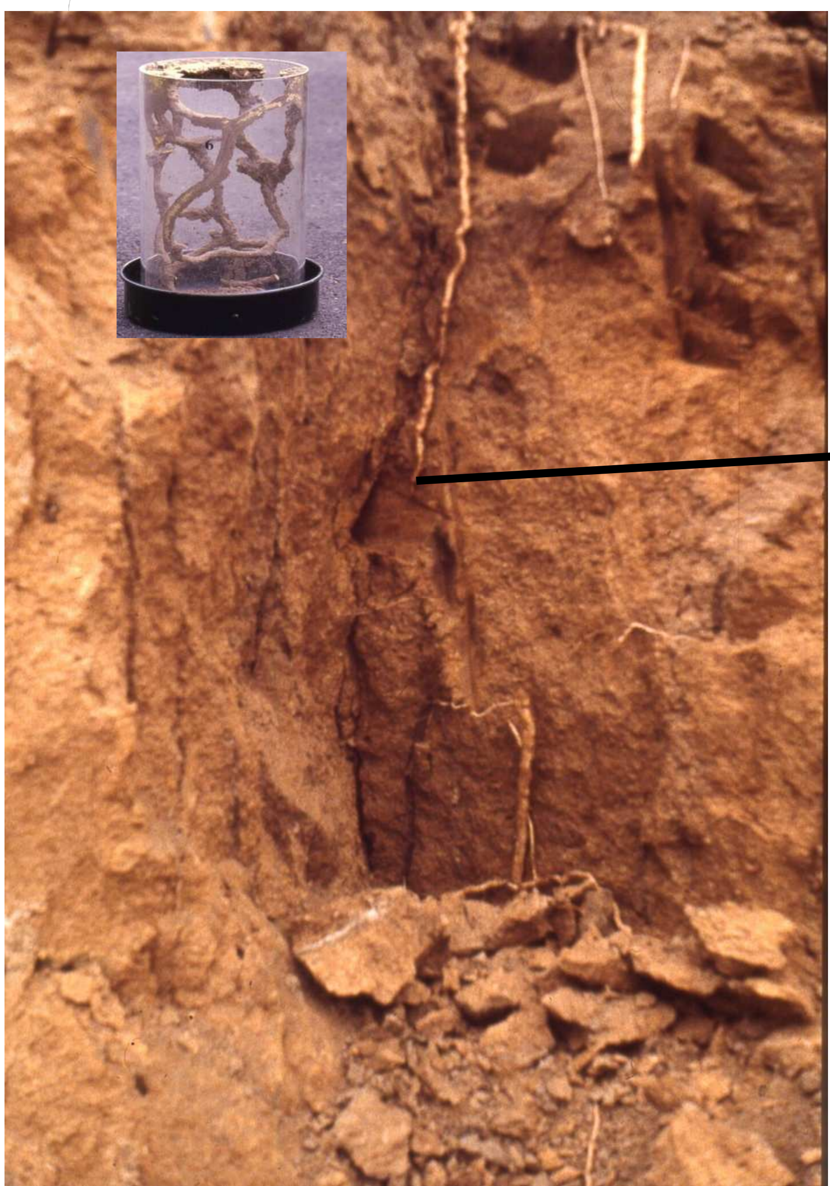
## Soil structure formation will be enhanced by:

- **shrinkage intensity and frequency**
- **increasing salt concentration of the soil solution**
- **ionic valency and strength of the soil solution**
- **content and type of clay minerals**
  - **(e.g. Smectit, Vermiculit)**
- **increasing org. carbon content and composition**
- **biological aspects.**

# Soil Structure Formation and Degradation

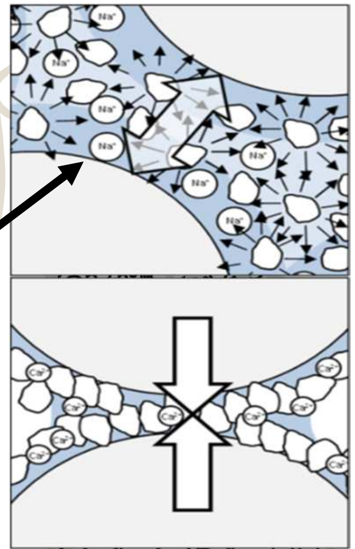



# Accessibility of water, gas, and nutrients - scale effects



colloidal scale

<1μm



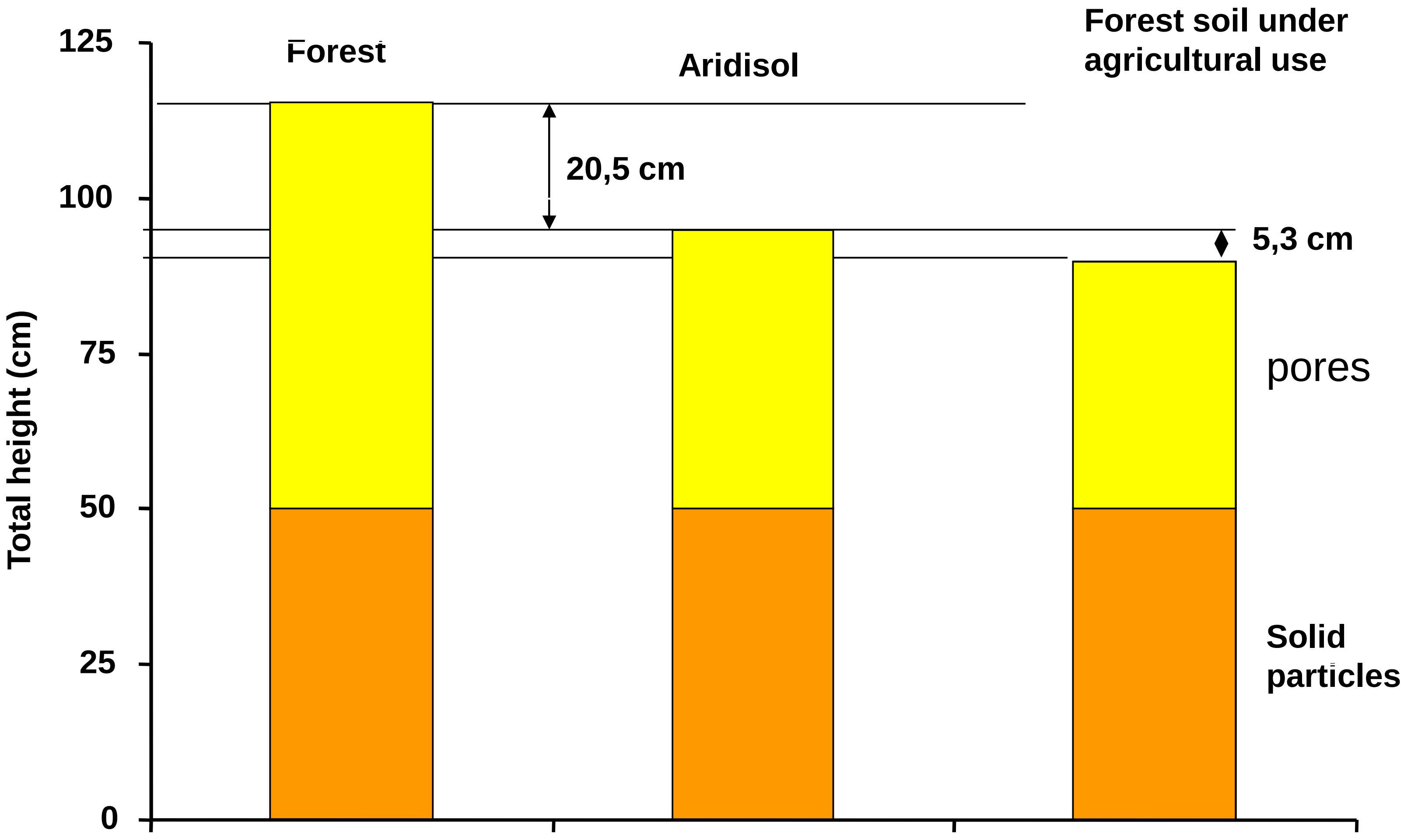
zeta potential ζ

What kind of physical soil degradation processes are essential?

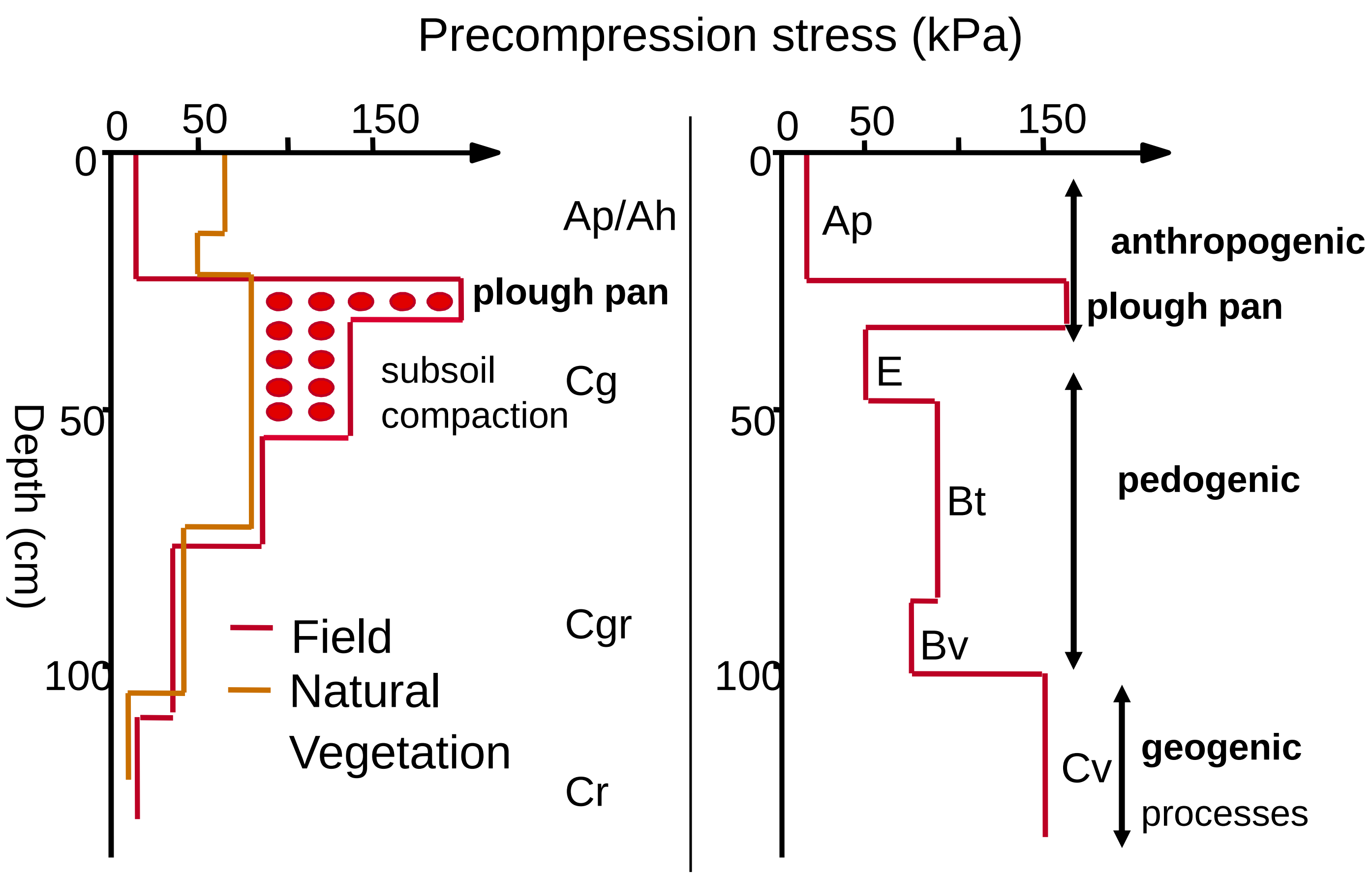
What do we have to evaluate?

# 1) Loss of air and water filled pores

Insight in soils as 3 phase systems under various landuse



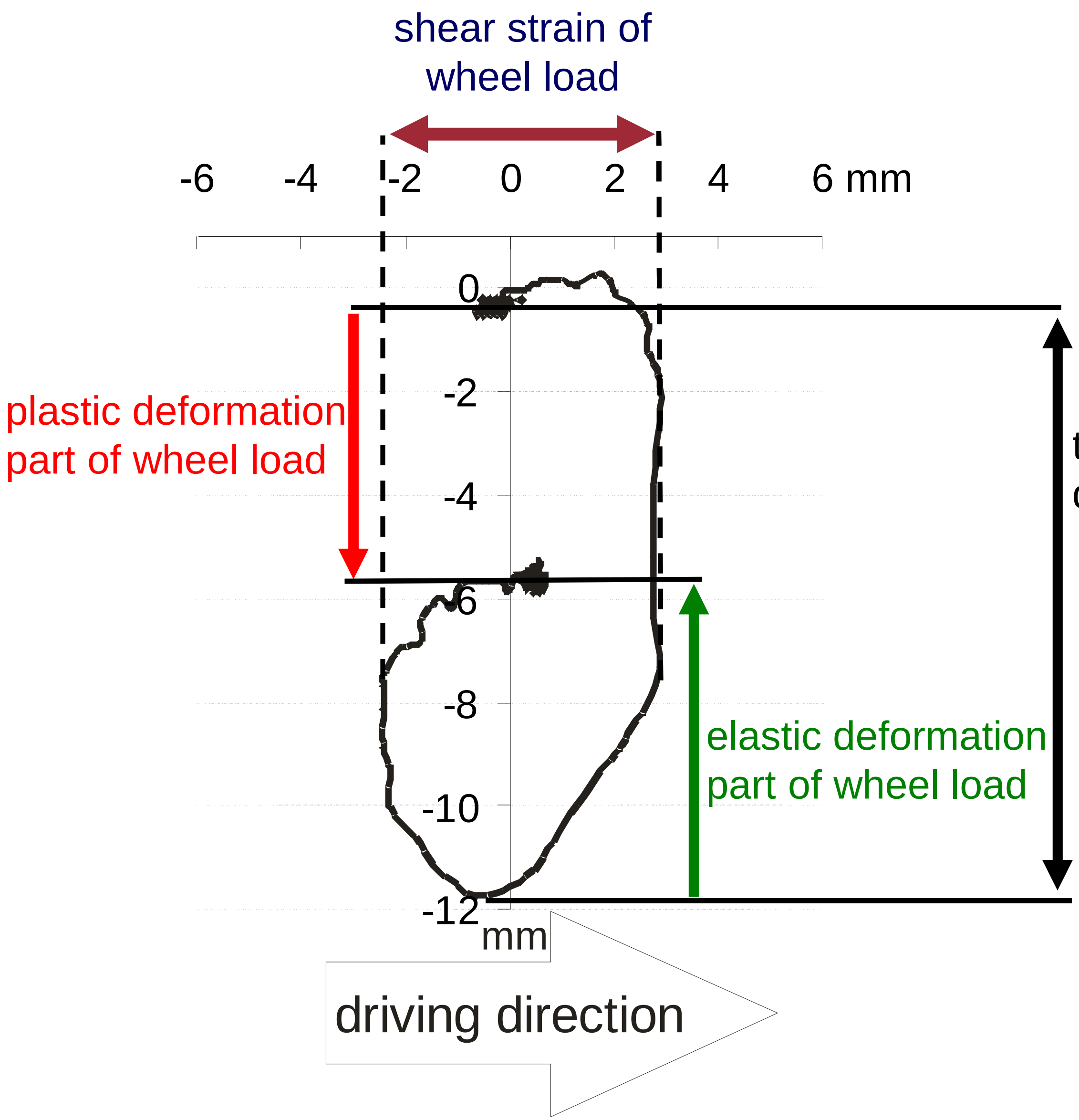
# 2) Soil strength defined as Precompression stress
(structural and pore rigidity in marsh and moraine soils, pF 1.8)

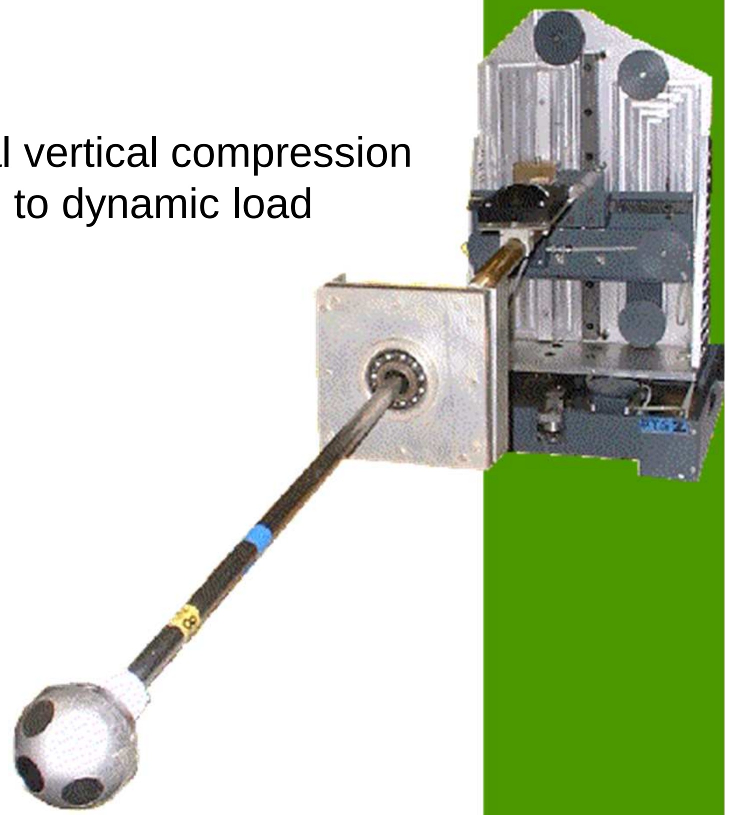



*Calcaric Gleysol*
*(Sandy Loam)*

*Luvisol*
*(Sandy Loam)*

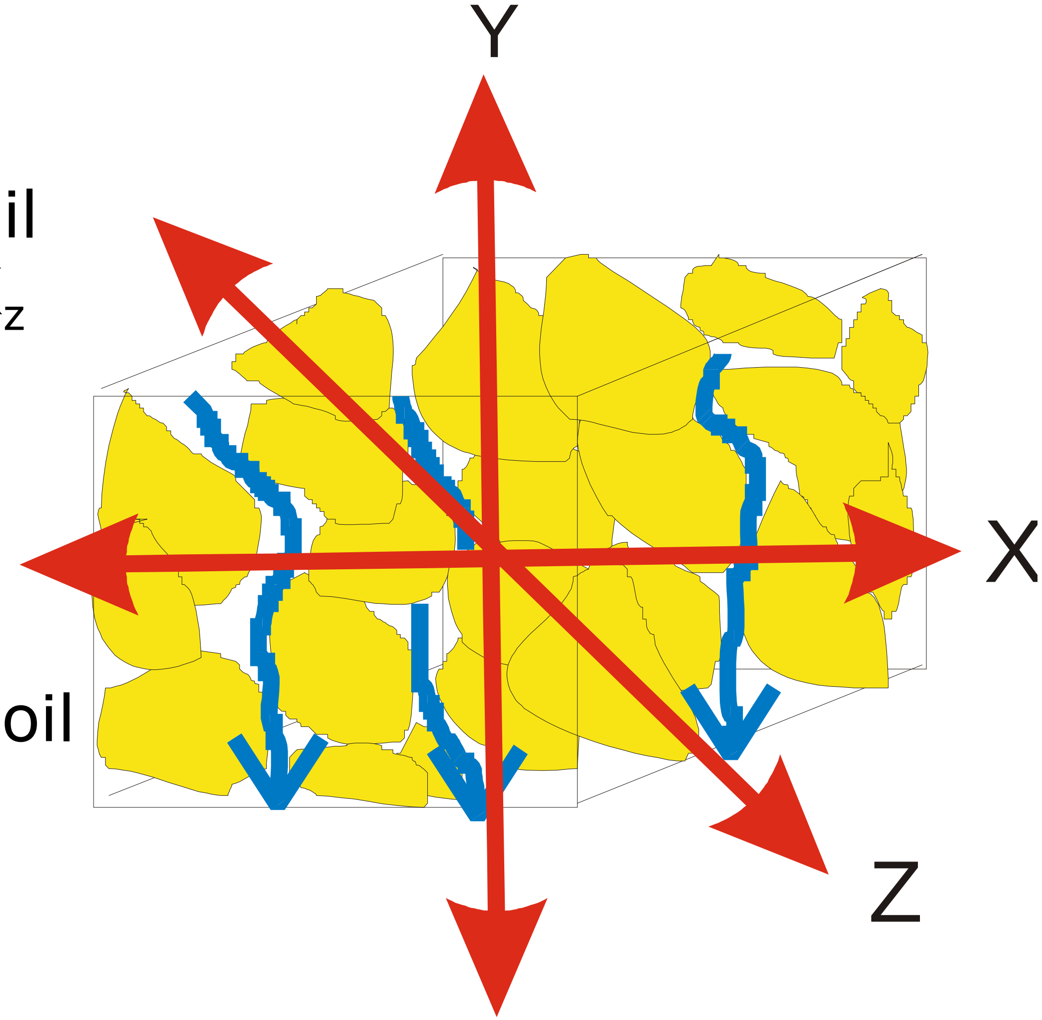
# 3) Change in position: altered pore functions due to shear effects and induced soil weakening



# 4) Change in direction and functions

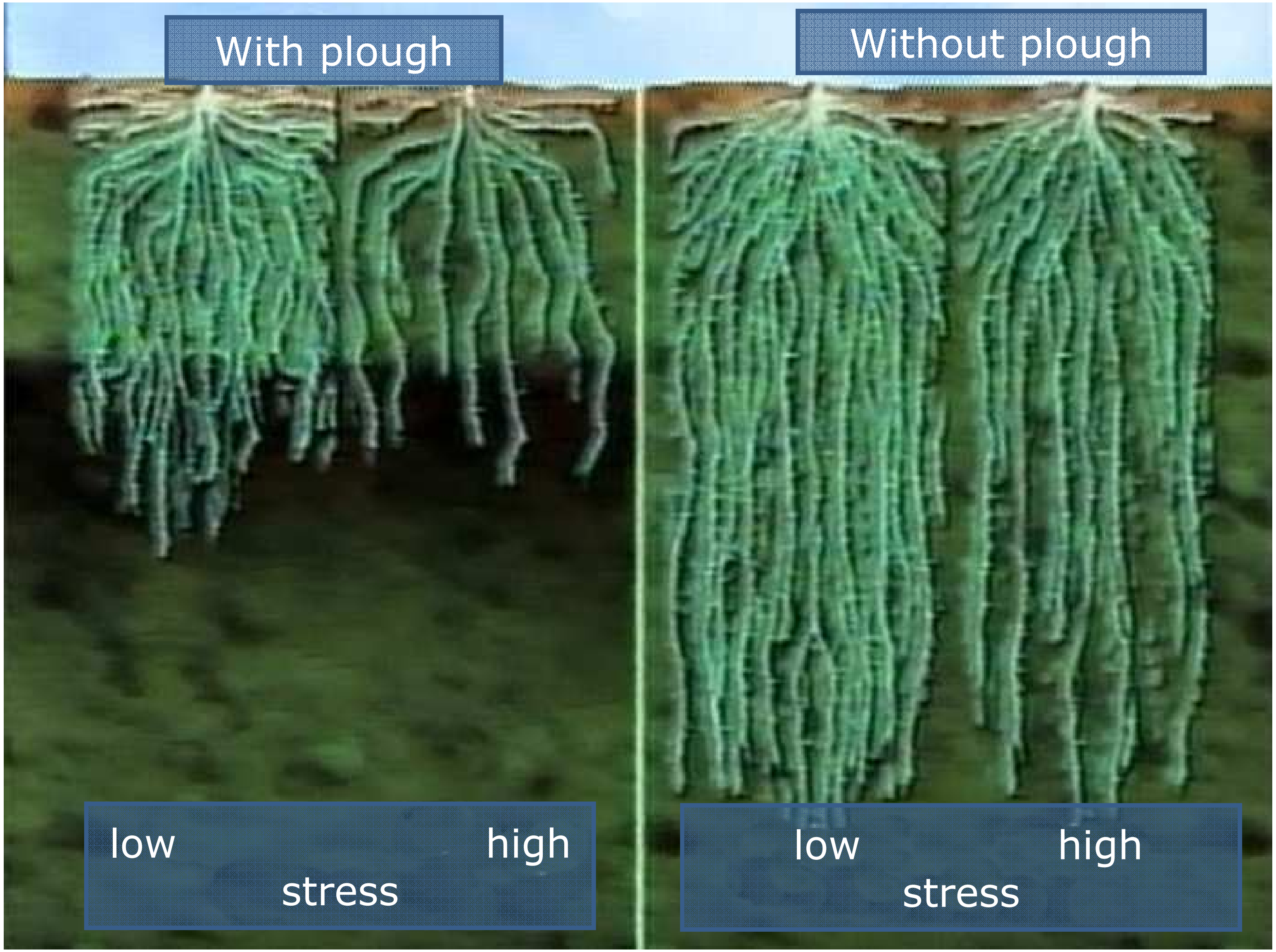
Isotropic soil
$K_x = K_y = K_z$




Anisotropic soil
$K_x \neq K_y \neq K_z$

# 5) Availability and Accessibility
# e.g. root growth and rooting depth in soils and corresponding nutrient uptake

**conventional** **conservation**



# 6) What parameters are needed?
# How to define soil functions and basic soil properties

C | A | U

Soil parameters

Capacity

- Bulk density
- Pore size distribution
- Cation exchange capacity
- Texture

?

Intensity

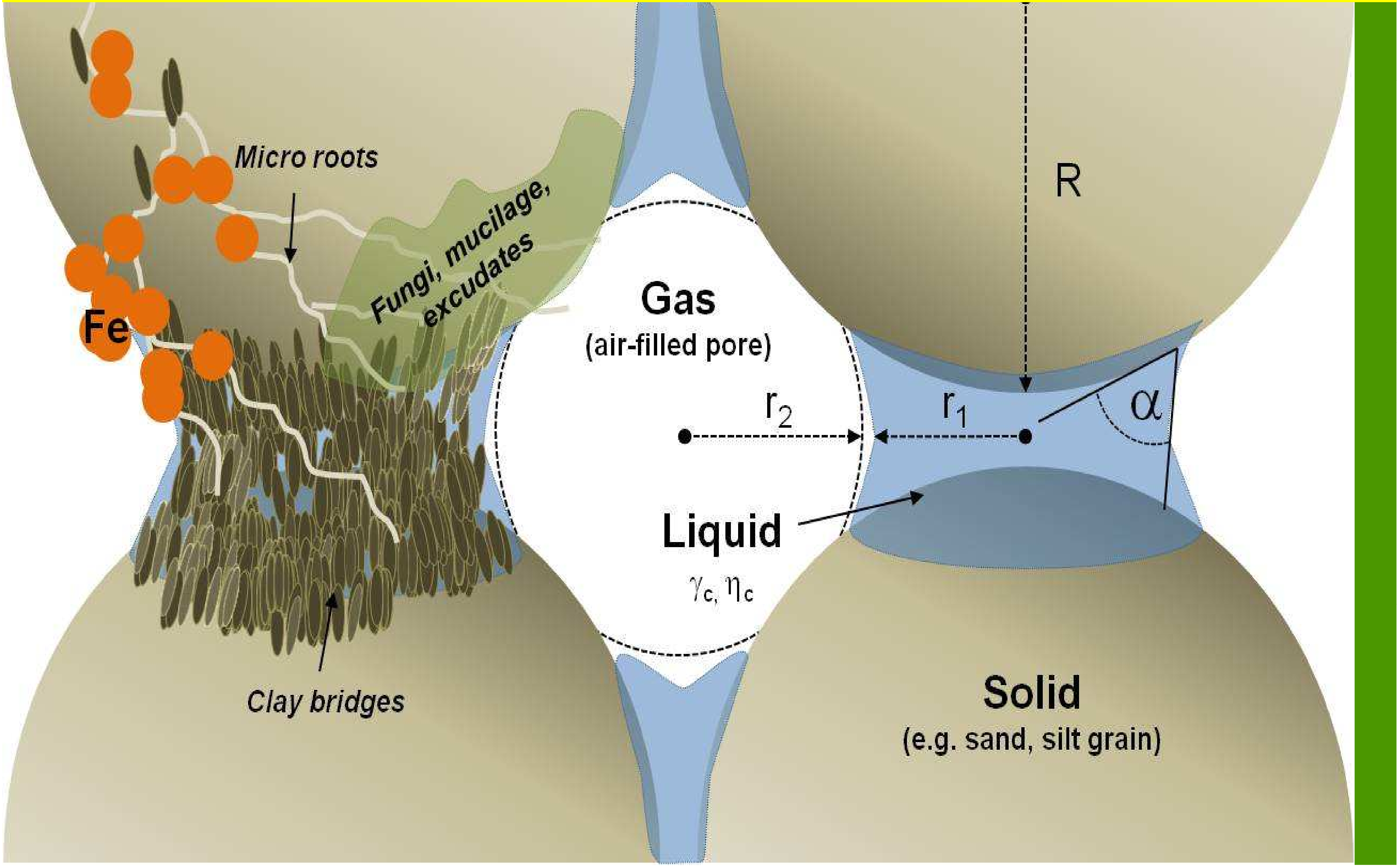
- Hydraulic conductivity
- Aggregate strength
- Air permeability
- Diffusive processes
- Redox potential
- cation exchange intensity

Arrangement, Organization,
and Functioning of Soil Structure

Horn & Kutilek. 2009.

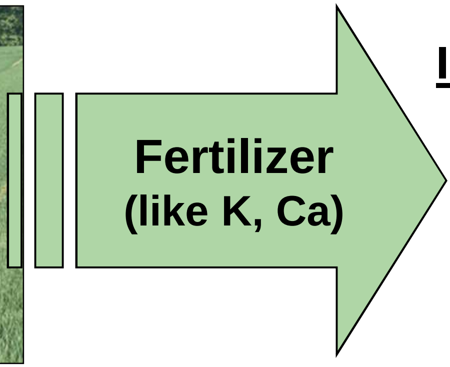
# Some detailed insights on the microscale – a rheological approach

## Three phase system soil with interfaces, solid-liquid, liquid-vapor, and solid-vapor, physicochemical interparticle bonding and capillary forces



# Influence of fertilization on aggregation and shear strength

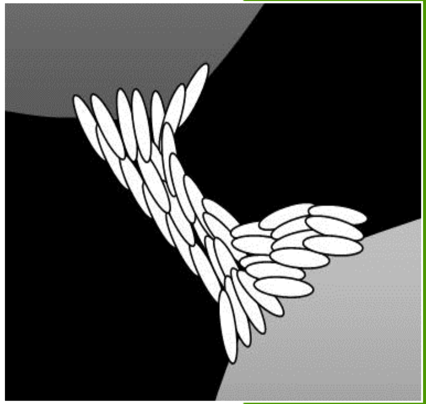
Holthusen et al. 2010




**Improvement of structure**

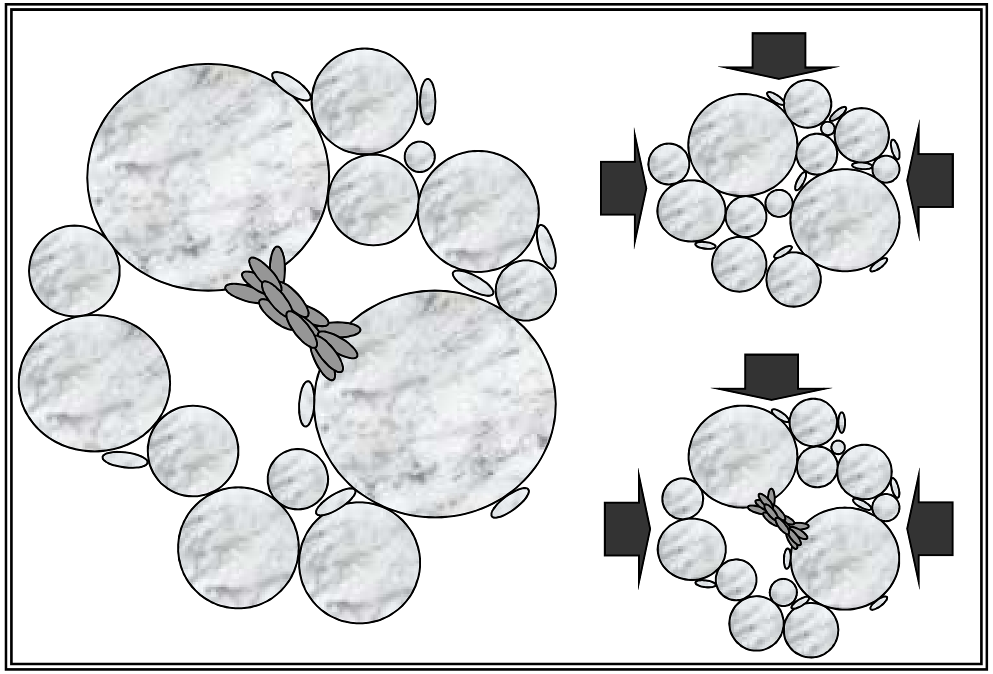
**direct**
by salts

**indirect**
by plant growth

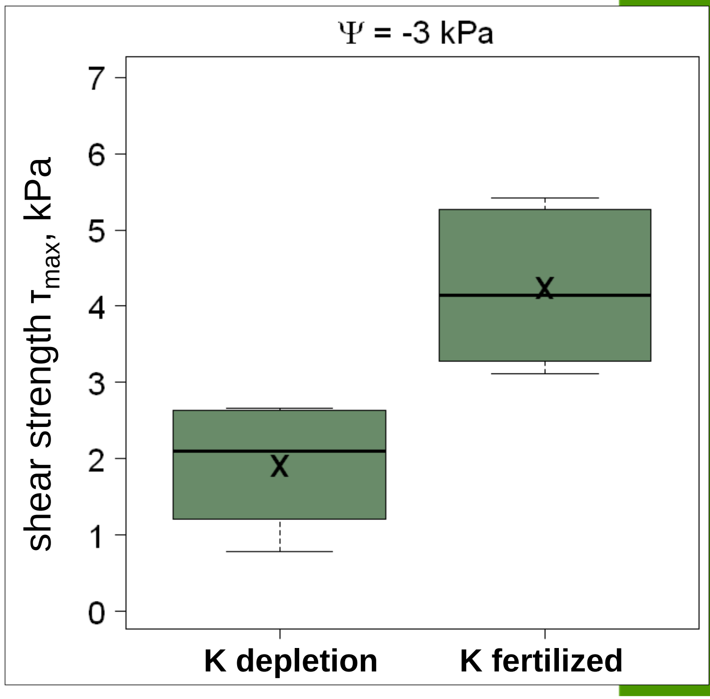


schematic drawing
(according to Feeser et al. 2001)

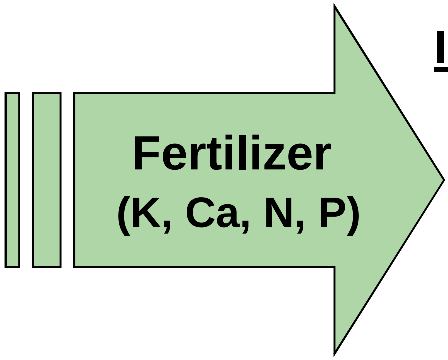
## 2. Shear strength



## Example potassium



# Effect of fertilizer application on plant available water

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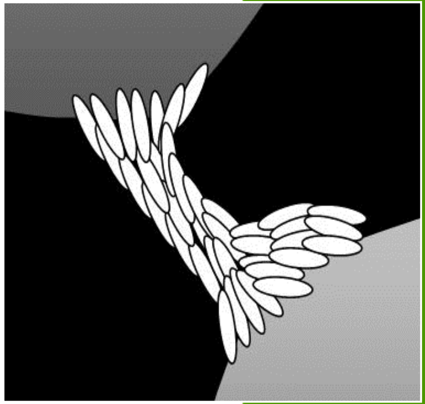
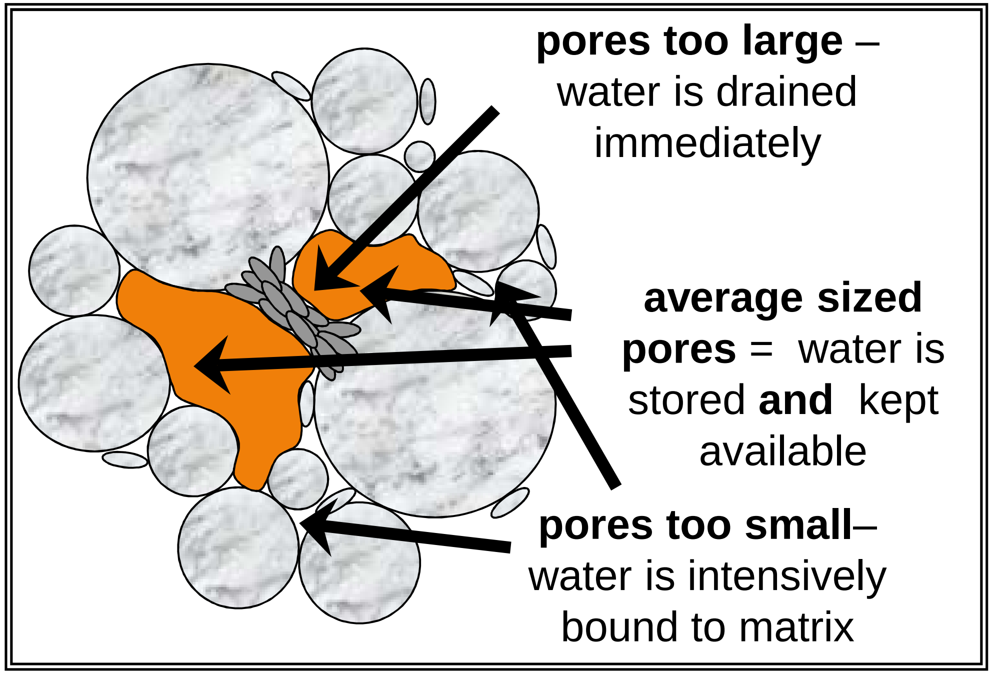


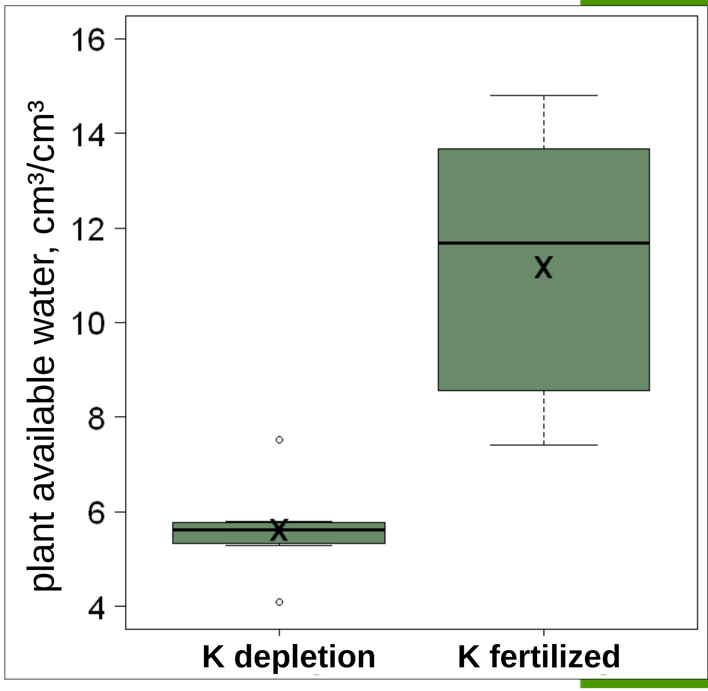
schematic drawing
(according to Feeser et al. 2001)

**Water storage –explanation**

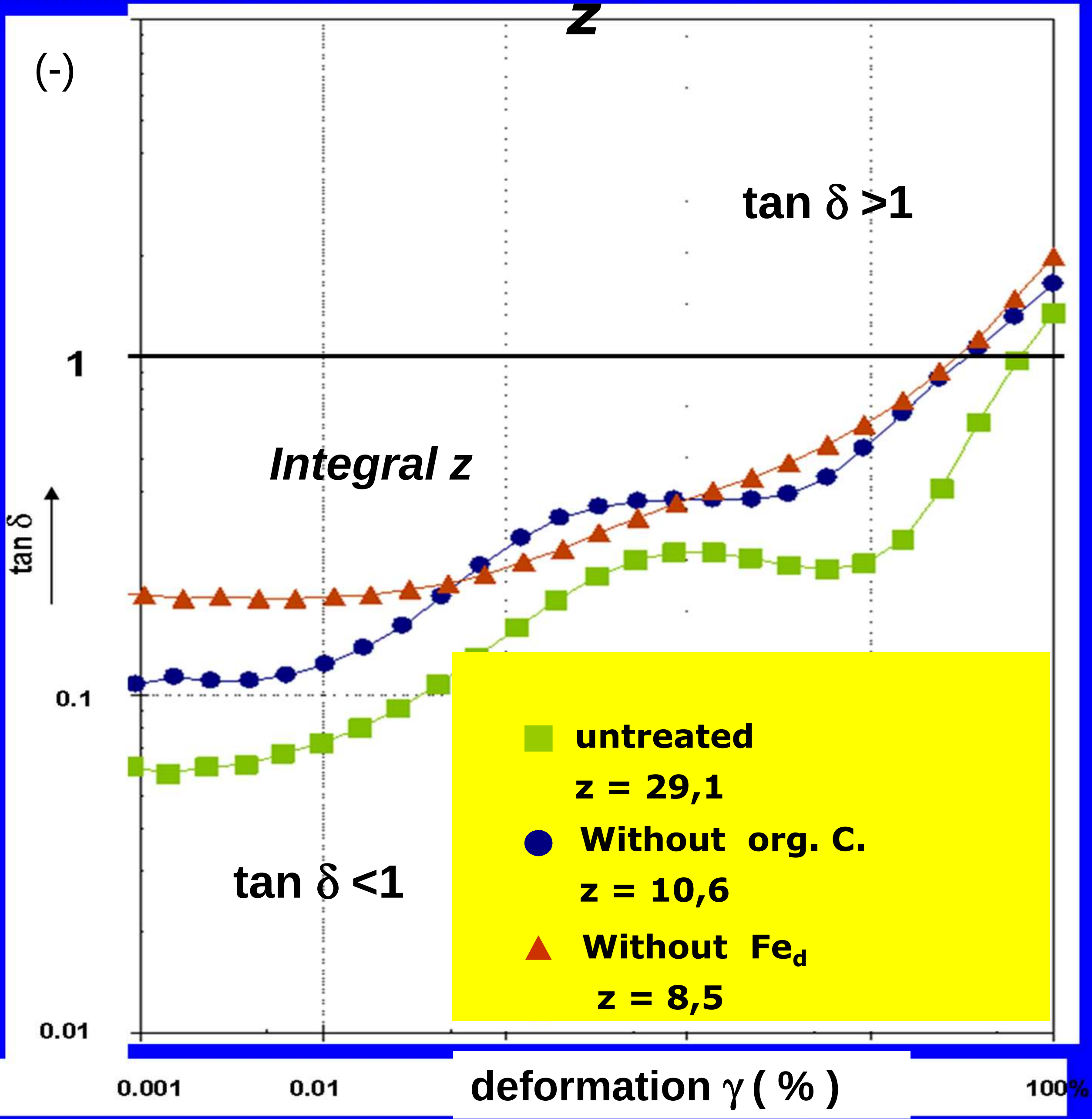


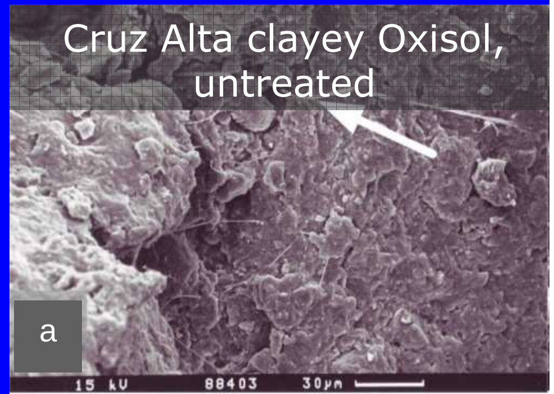

Holthusen et al. 2011

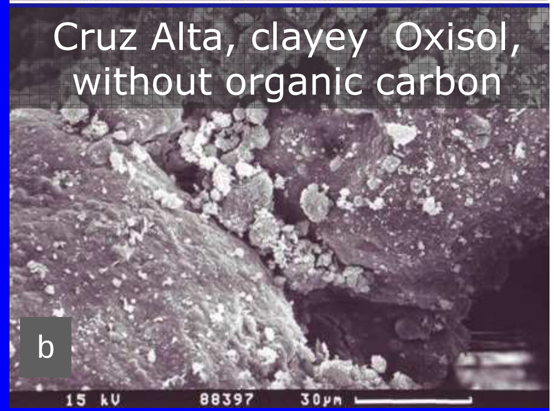
**Example potassium**

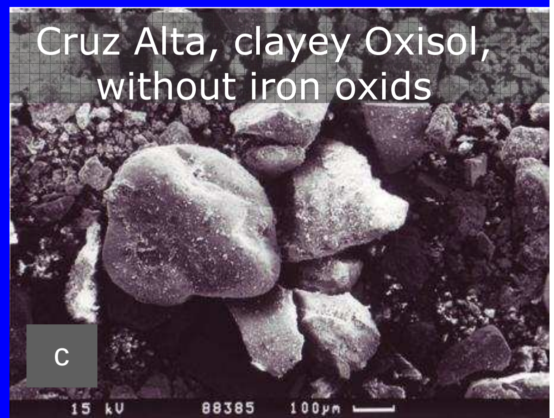


# Strength value: *tan δ; Integral z*



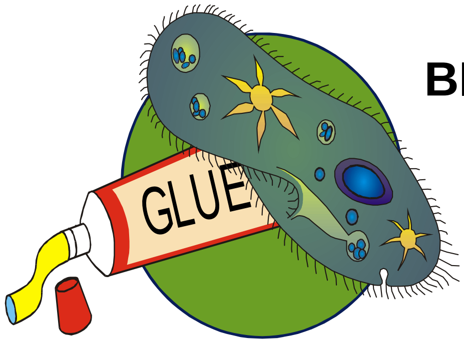



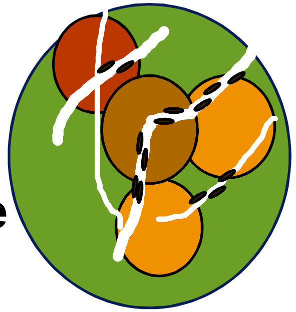

Markgraf and Horn, SSSAJ (2006)

# Engineering of soil structure by plants and microbes



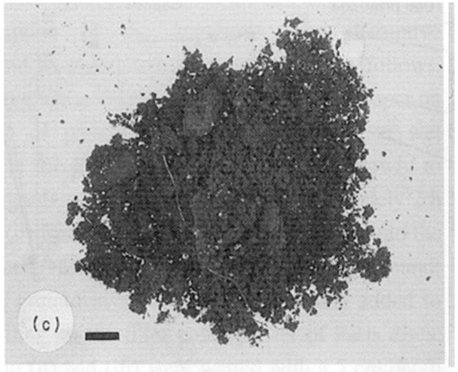

**BIOLOGICAL GLUES**

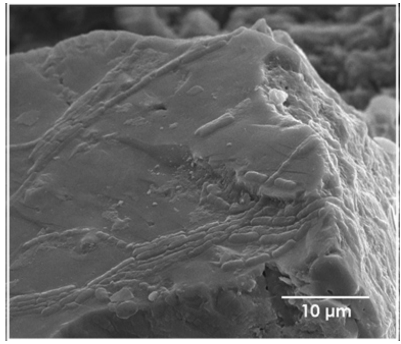
**Higher interparticle strength**



**BINDING BY FUNGI AND ROOTS**

**Stringy bag concept.**
**Biological pile groups.**





**LUBRICANTS, GELS**

**Root exudates, border cells**
**Humic acids**

**HYDROPHOBIC EXUDATES**

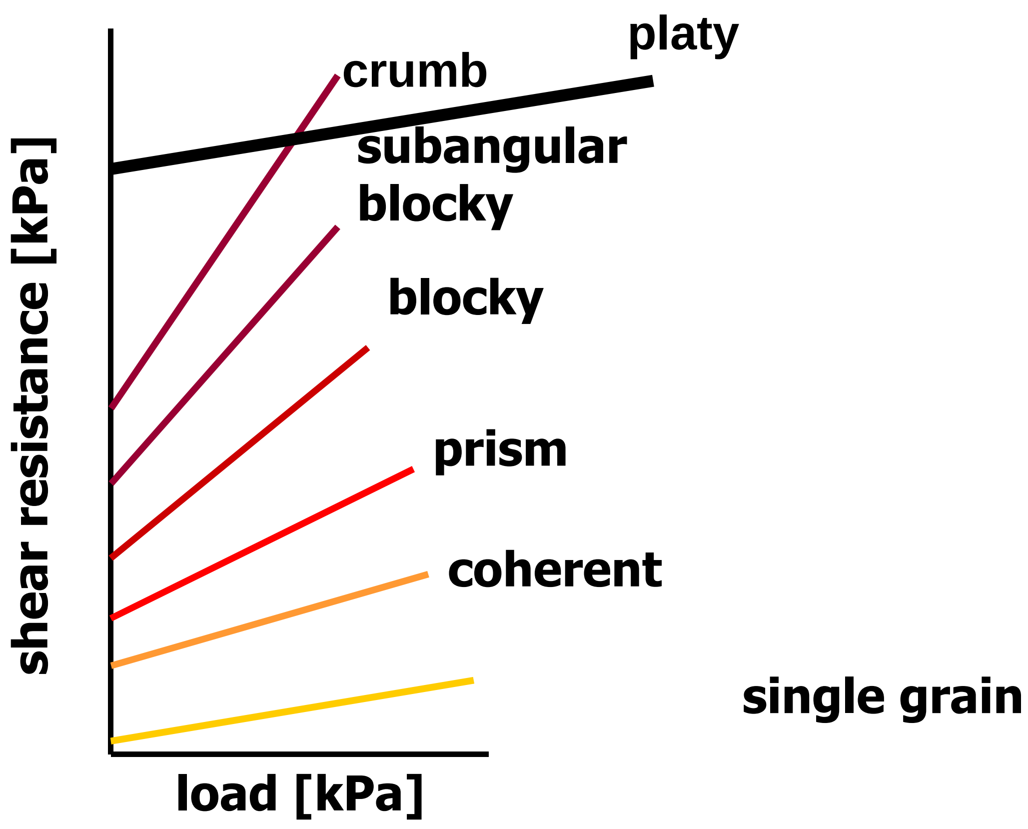
**Contact angles**
**Surface tension**
**Hydrophobicity**

Hallett et al. 2011

# The Mesoscale

# Aggregate dependent shear strength

# (Mohr Coulomb failure line)





Aggregation results in

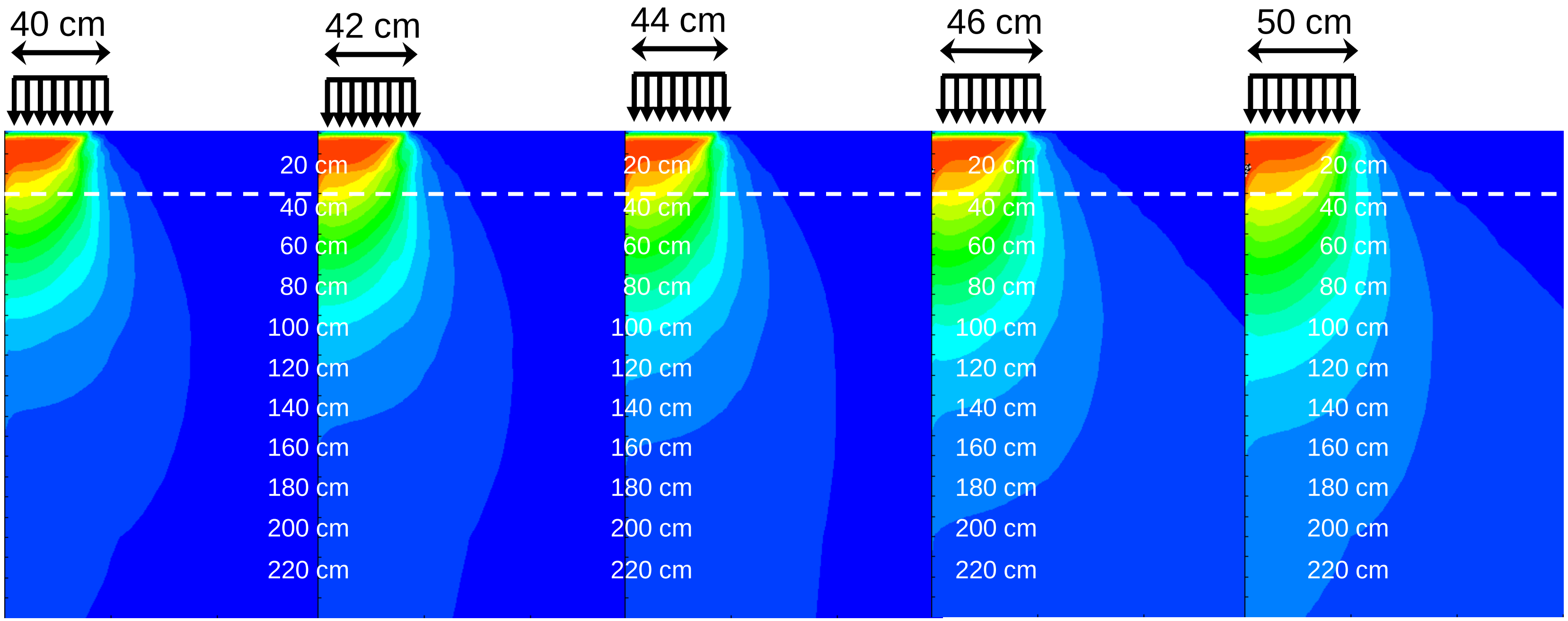
-Higher strength

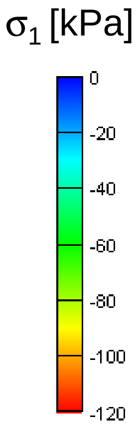
-Strength change after exceeding internal resistance

-Better aeration and water flux

# The Macroscale

# Effects of tyre size and contact area pressure on stress distribution



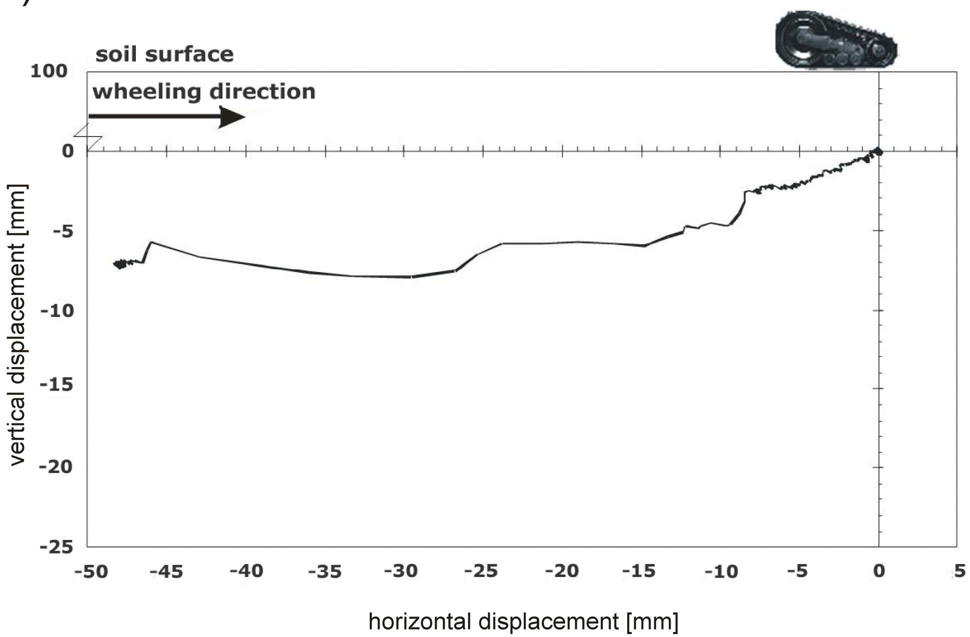




stress = 100 kPa

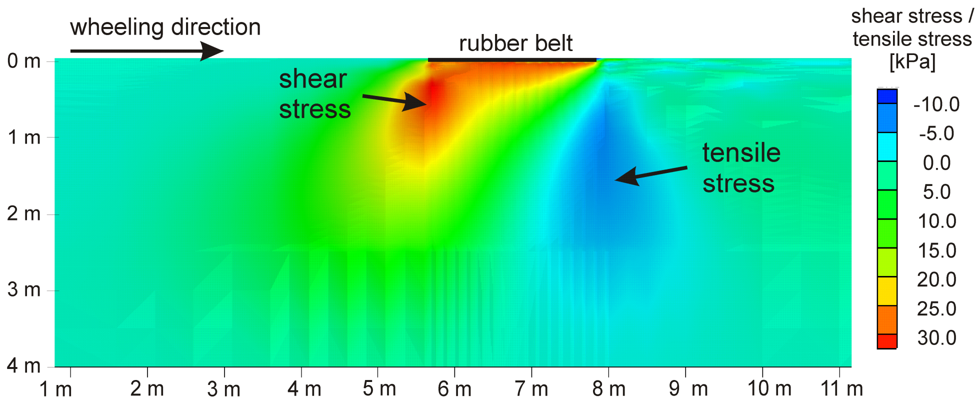
Consequence: stress distribution is the deeper, the greater the contact area at a given applied stress

# Effect of shear deformation on stress and strain

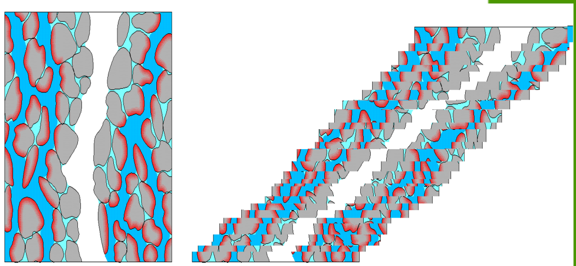
a)




b)



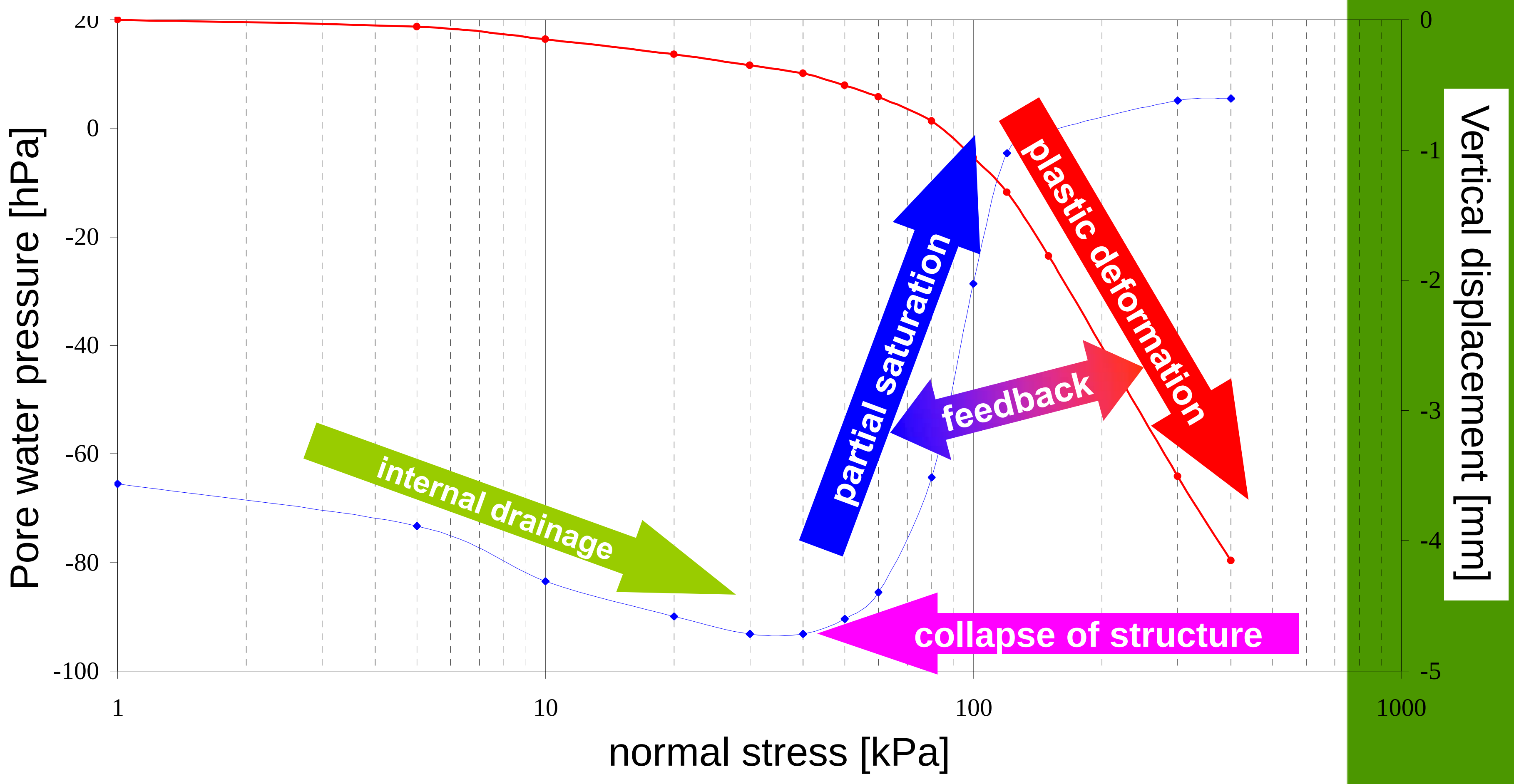

Consequence for pore functioning on meso and microscale



**Shear effects cause a more severe structure deterioration, soil weakening, rearrangement of pores and accessible surfaces than vertical soil compaction**

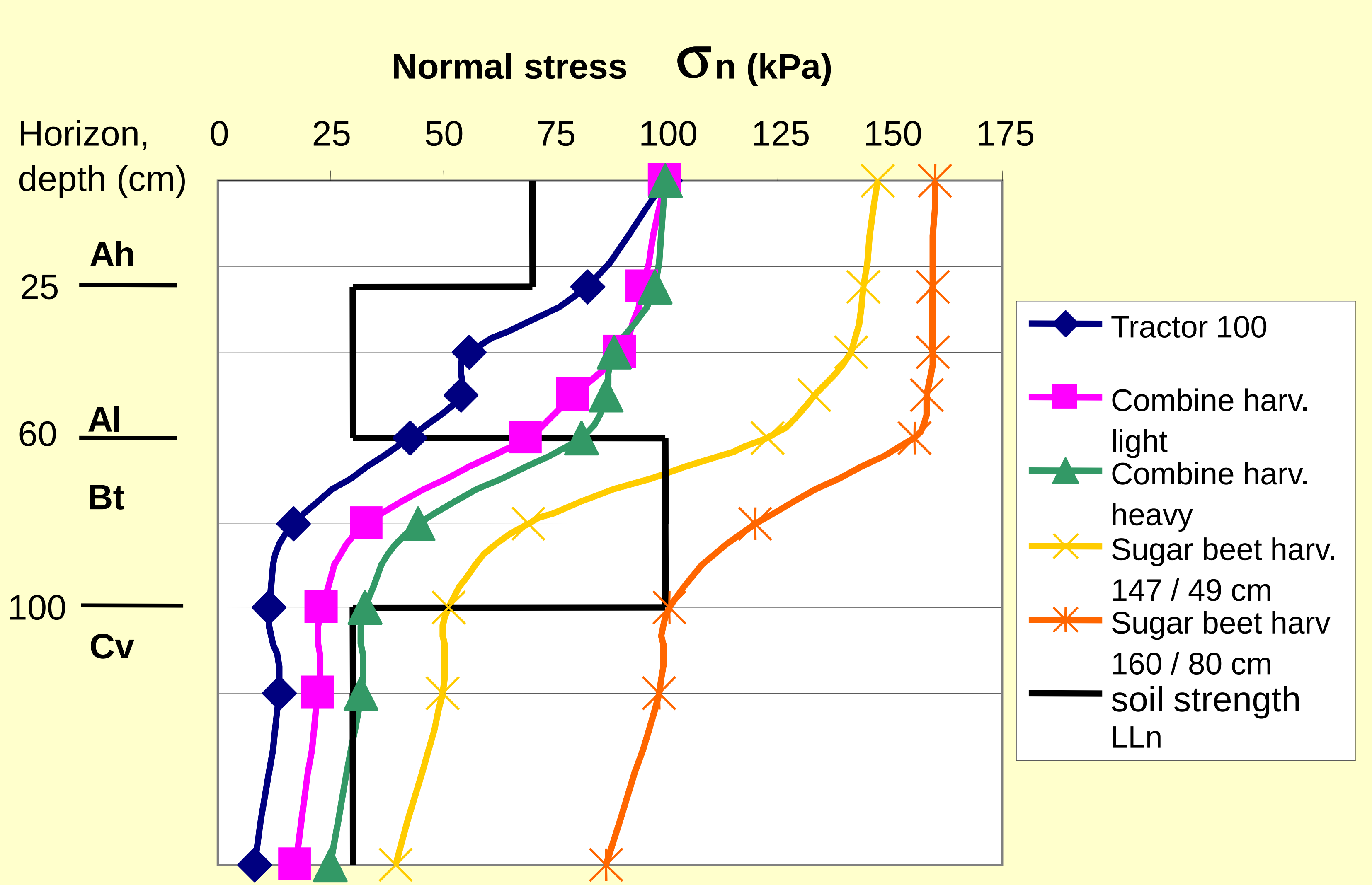
# What are the detailed processes during such mechanical deformation?

Interaction of stress strain and pore water pressure changes



# How can we quantify changes in soil properties and soil functions

# Interaction Between External Stresses And Internal Soil Strength




**The intensity of changes depends on soil strength and management**

# Consequences for…

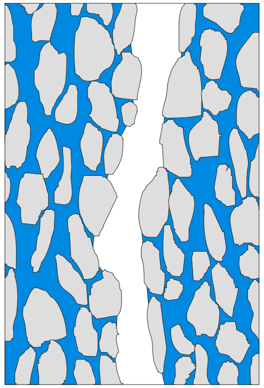
**Soil structure, Soil strength,**

**Gas fluxes and Cation Exchange Processes**

**- the question of availability and accessibility-**

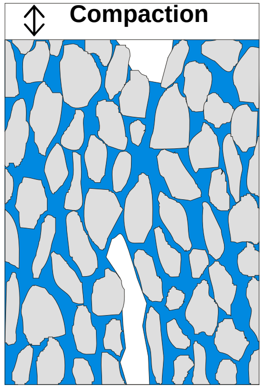
# Stress And Strain Effects On Hydraulic Properties

①



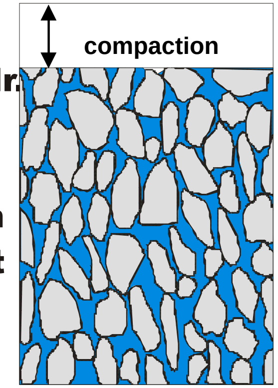
Original

②



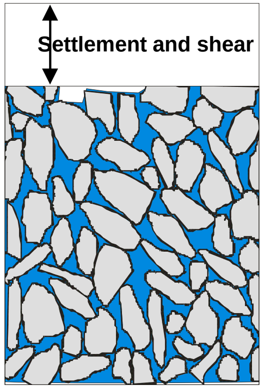

Unsaturated hydr
conductivity
increased
due to decline in
pore diameter at
defined suction

③



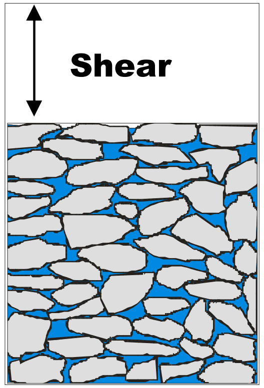

Water flux
reduced
according to
pore diamete
decrease

$K = r^2/8$




④

Rearrangement
of particles
and/or pores
Tortuosity
effects




⑤

Anisotropy
of pore
functions

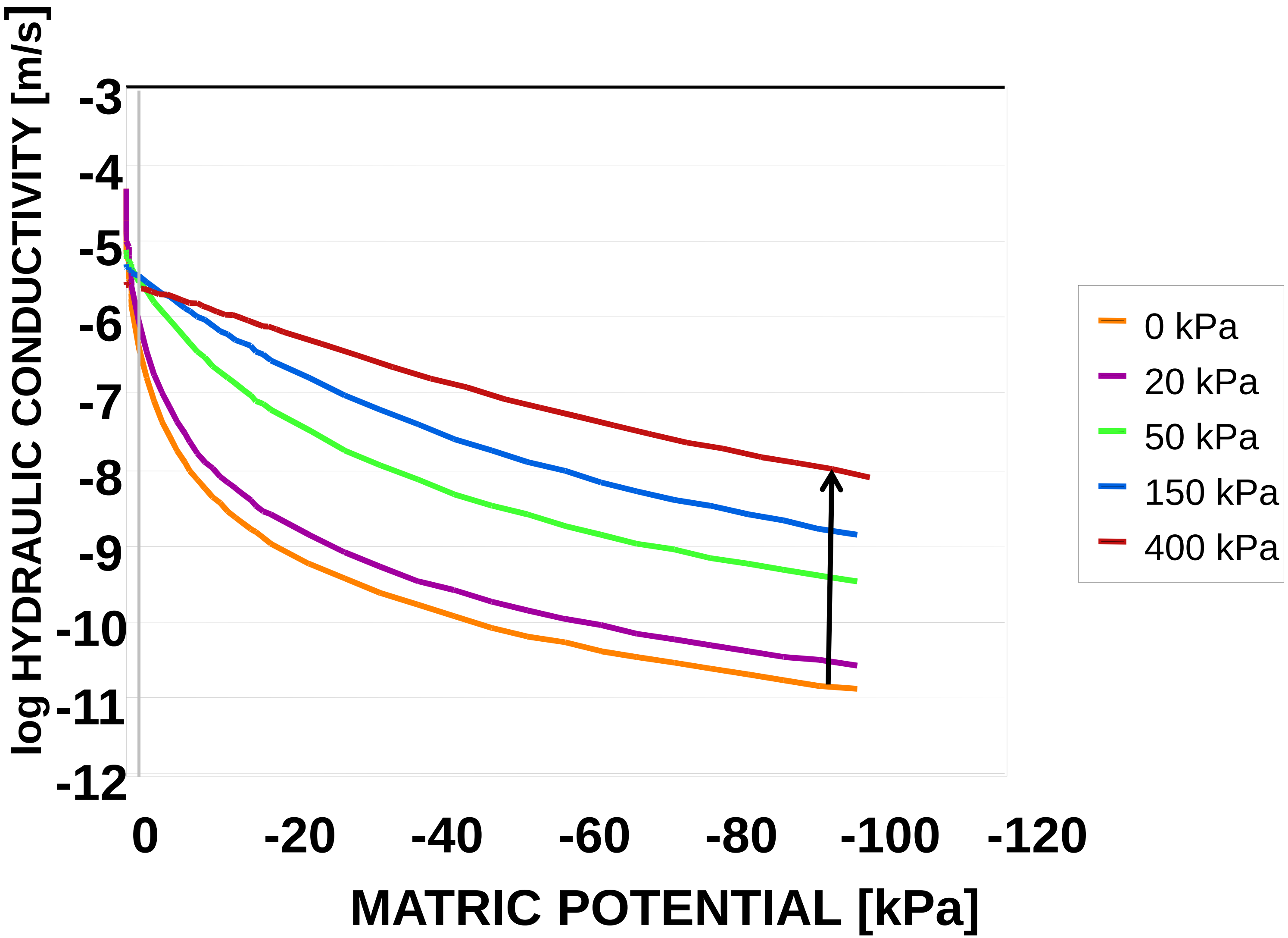
$K_{hor} > K_{ver}$

Enhanced lateral flow and run off, reduced filtering and buffering

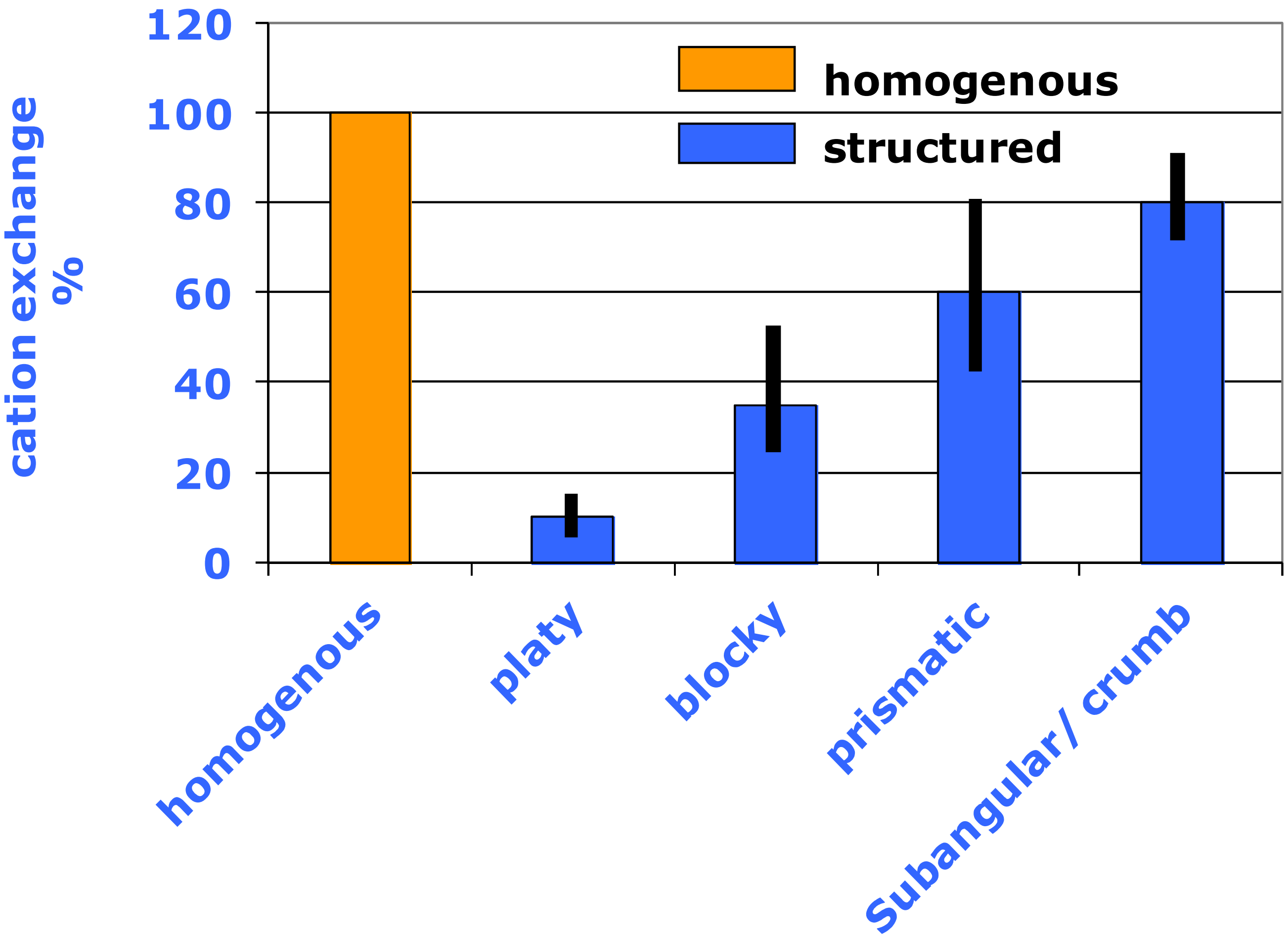
# Stress Effects On Hydraulic Conductivity

C | A | U

**Soils remain wetter and colder especially in spring**

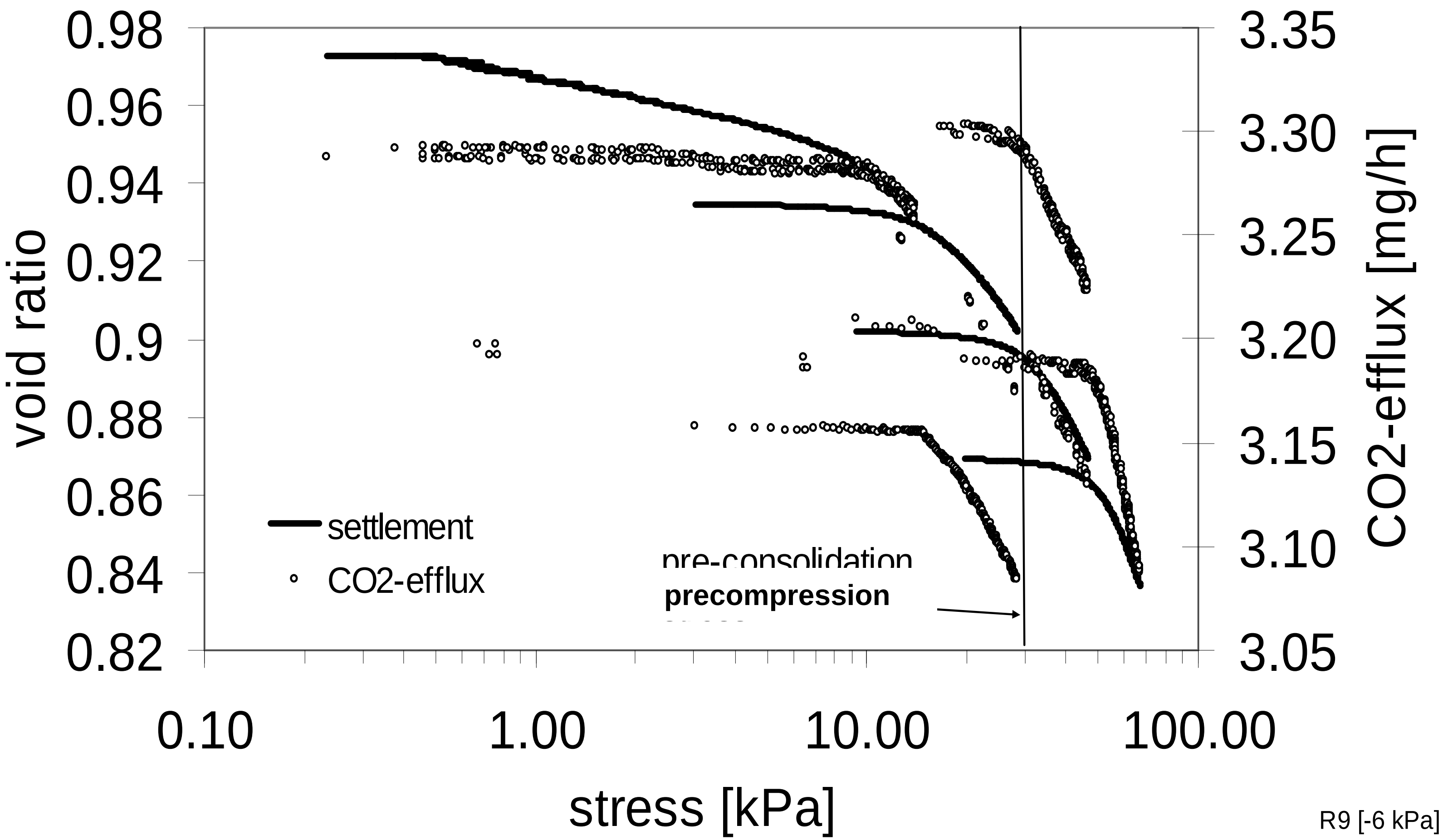


# Effect Of Structure Formation And Stress Application On The Accessibility Of Chemical Cation Exchange Places




**Shearing and smearing result in enhanced accessibility but reduced advective and diffusive fluxes**

# Interaction between mechanical strength and microbial activity




**A stress induced decline of $CO_2$ may be followed by an increased $CH_4$ concentration**

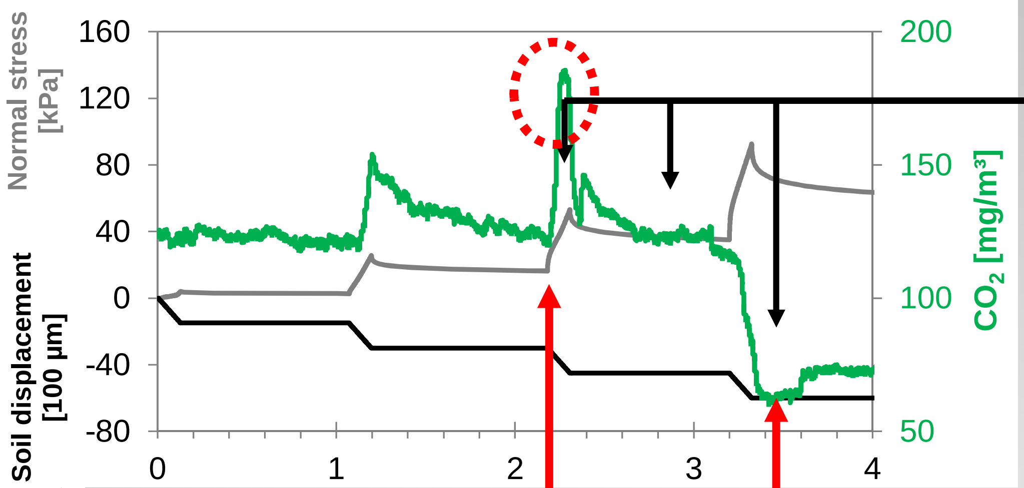
From Jasinska et al. 2006

# Dynamic $CO_2$ Effluxes

GaFloCod

**15 cm**

**Fescue**




$CO_2$-Peaks not directly related to physical changes

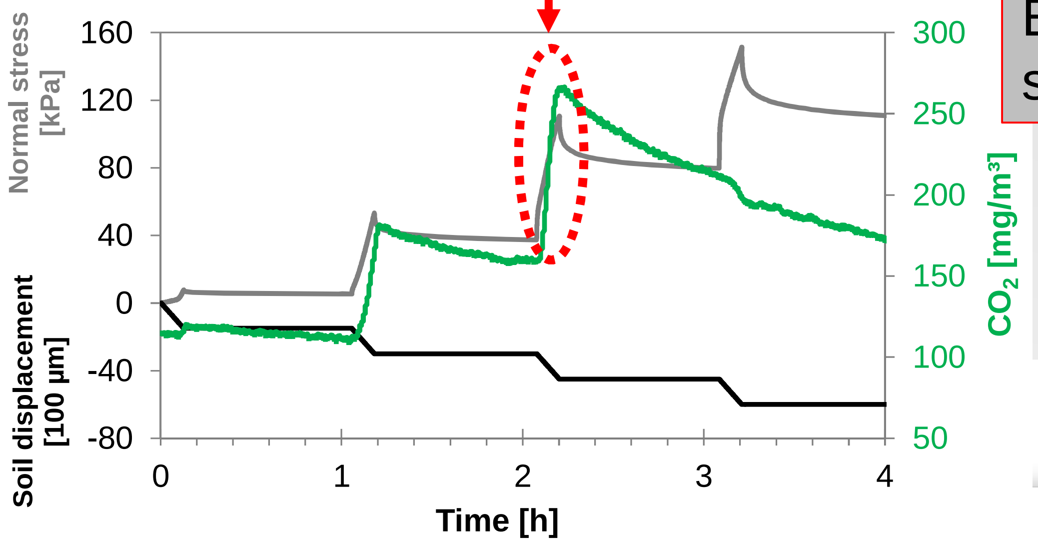
Microbial effects?

Degradation of pore continuity

Extreme $CO_2$-Peaks related to pore system changes (Δ 100 mg $m^{-3}$)

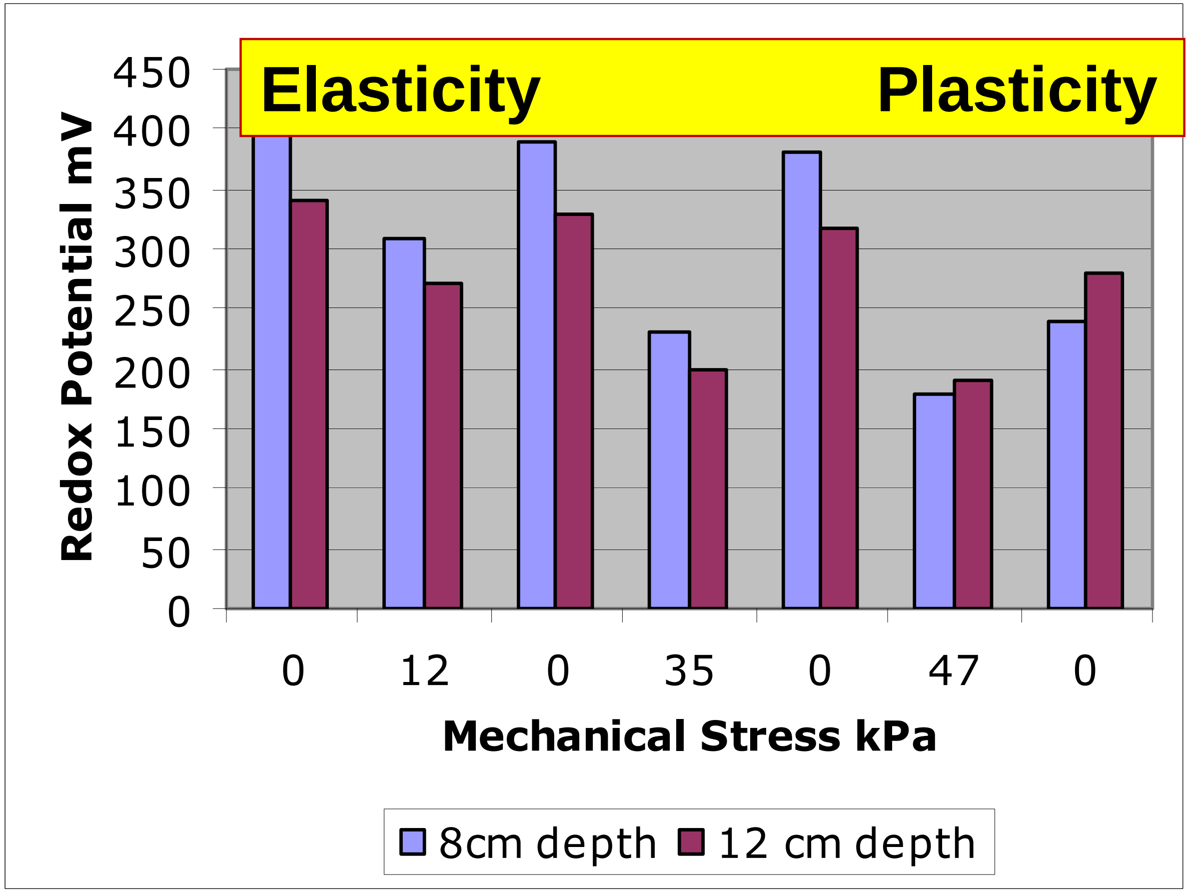
**40 cm**

**Fescue**



# Redox Potential as a function of applied mechanical stress






**Cambisol Ah horizon, pH: 5.2, -60 hPa**

Data taken from Horn 1985

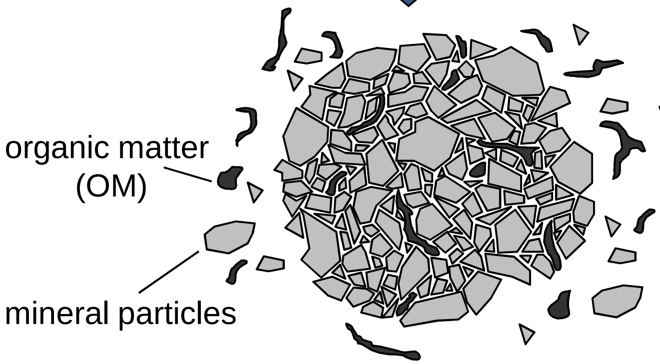
# Stabilization/mineralization of SOC – an effect for global processes

C | A | U

**CG**
repeated mechanical stress
low OM input

**UG79**
no mechanical stress
high OM input

**mechanical stress ≤ precompression stress**

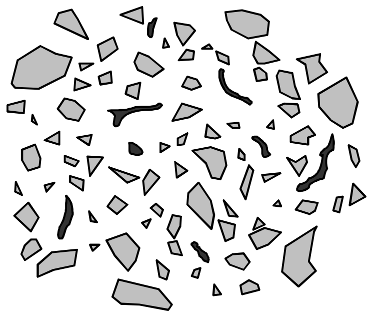



OM
mineralization


mechanically compacted „clods“
high tensile strength
low extent of physical OM protection

OM-induced aggregate hierarchy
low tensile strength
high extent of physical OM protection

**mechanical stress > precompression stress**



**low release of OM** → **OM mineralization** ← **high release of OM**

Wiesmeier et al. 2010

# Heavy Soil Loading

## how much is too much?

## What kind of changes are required?

# How heavy is too heavy?

## 1st. conclusions

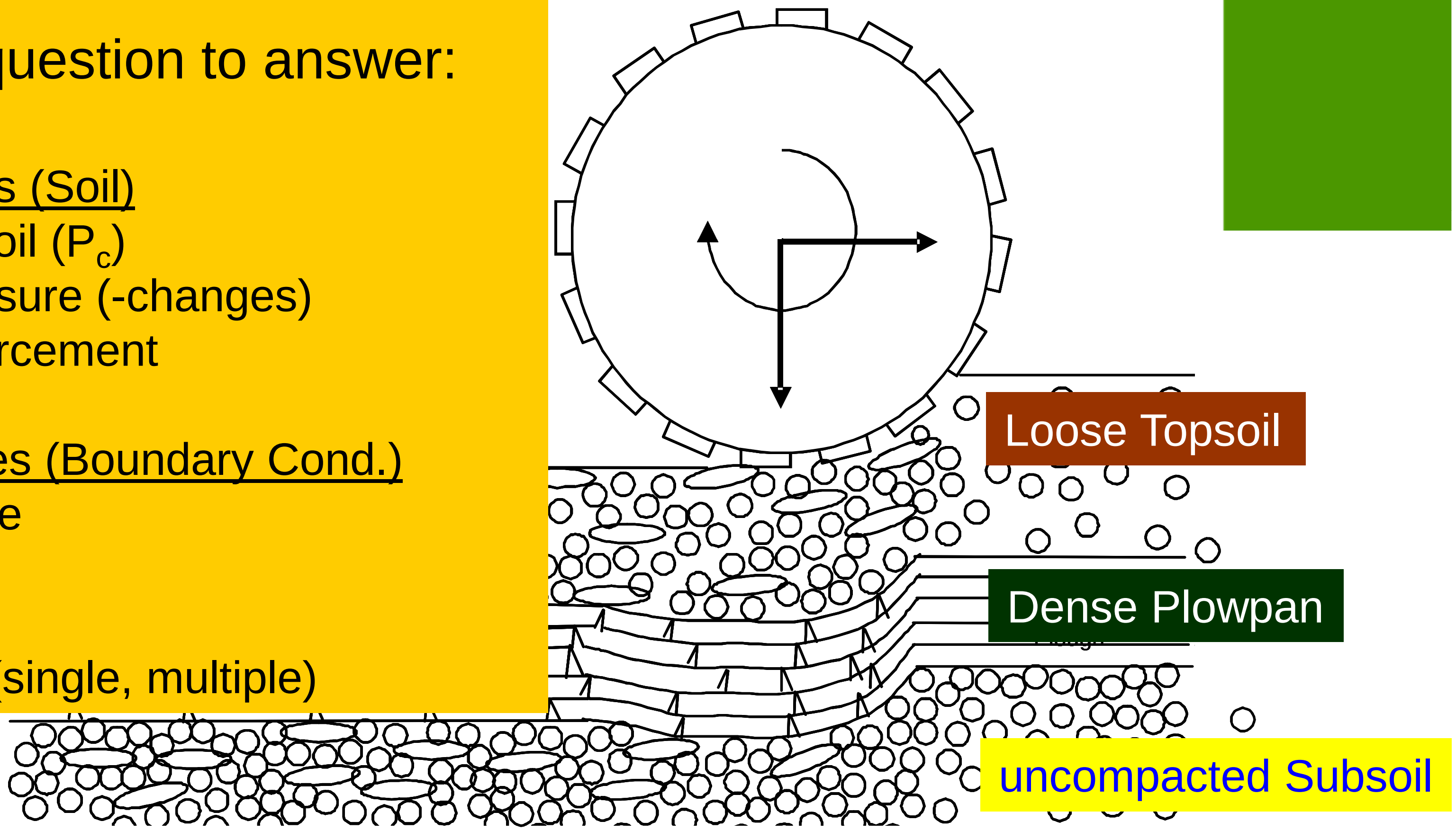
Not a simple question to answer:

<u>Internal properties (Soil)</u>

- stability of the soil ($P_c$)
- pore water pressure (-changes)
- biological reinforcement

<u>External properties (Boundary Cond.)</u>

- weather / climate
- management
- shear forces
- type of loading (single, multiple)

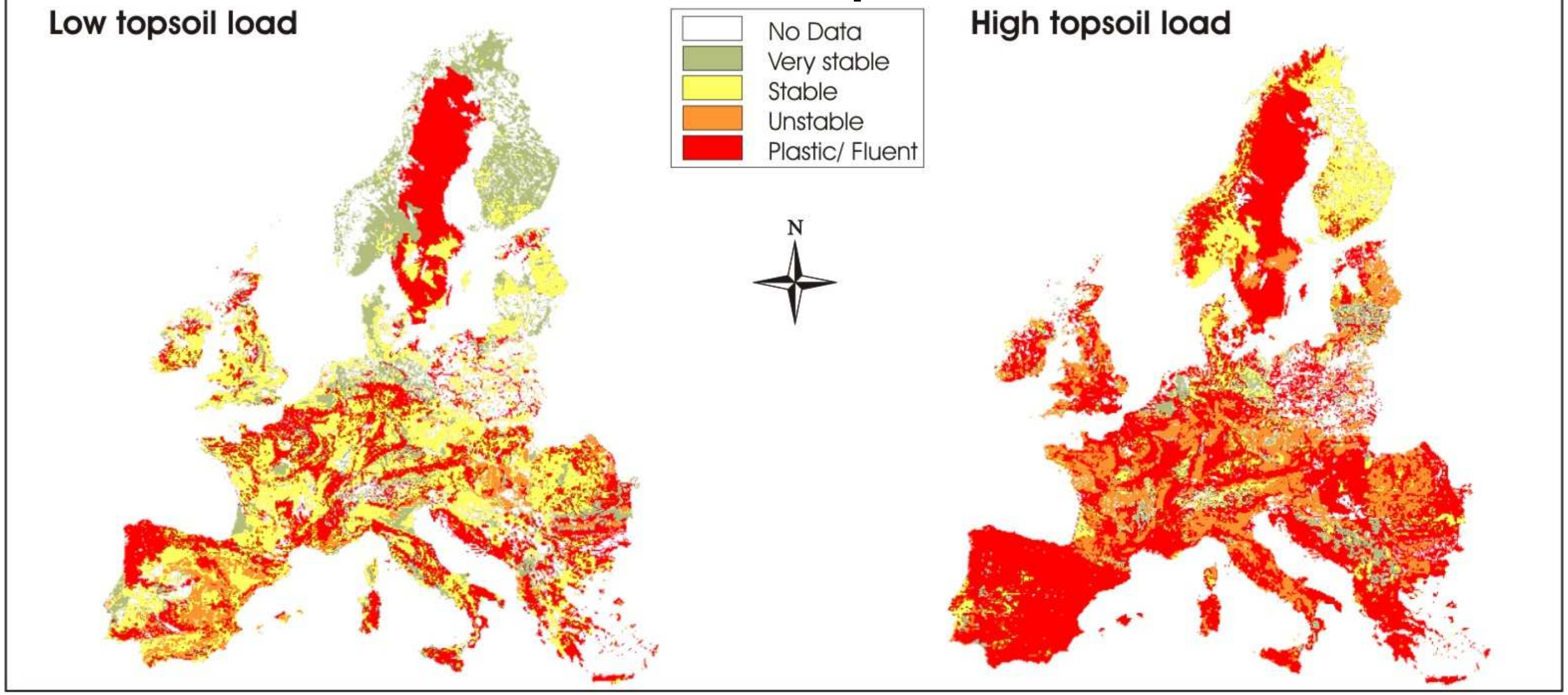



Wheel loads / mechanical stresses must be adapted to the specific (soil) environment with the focus not only on trafficability but mainly on the preservation of soil functions!

# Use soils according to their soil strength !

C|A|U

**Small scale info 1:1.000.000 data based on the database: EU-subsoil compaction**




Precompression stress at a given pore water pressure pF 1.8 for topsoils of Europe in relation to a given low topsoil load (tyre inflation pressure: 60 kPa), high topsoil stress: 200 kPa)

Classification of the effective soil strength by the relationship of precompression stress to soil pressure: >1.5 very stable, elastic deformation, 1.5-1.2 stable, 1.2-0.8 labile, >0.8 unstable, additional plastic deformation.

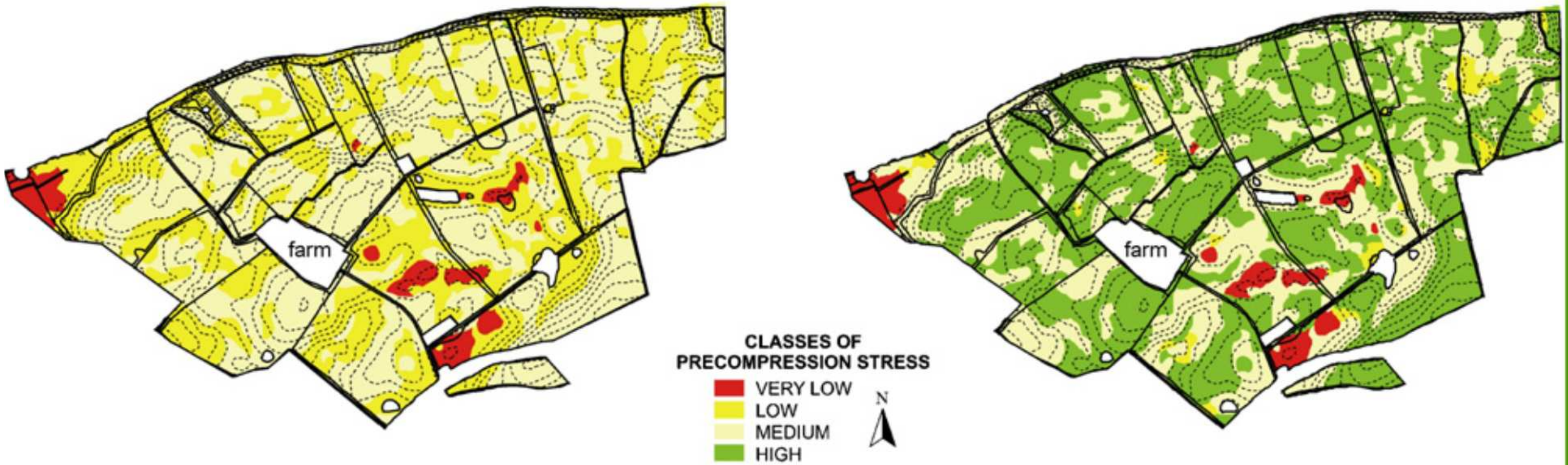
# Identification of compaction sensitive areas

C|A|U

## farm scale 1:5000

Moist: pF 1.8

drier: pF 2.5




**parent material: glacial till**

**(Horn & Fleige (2009)**

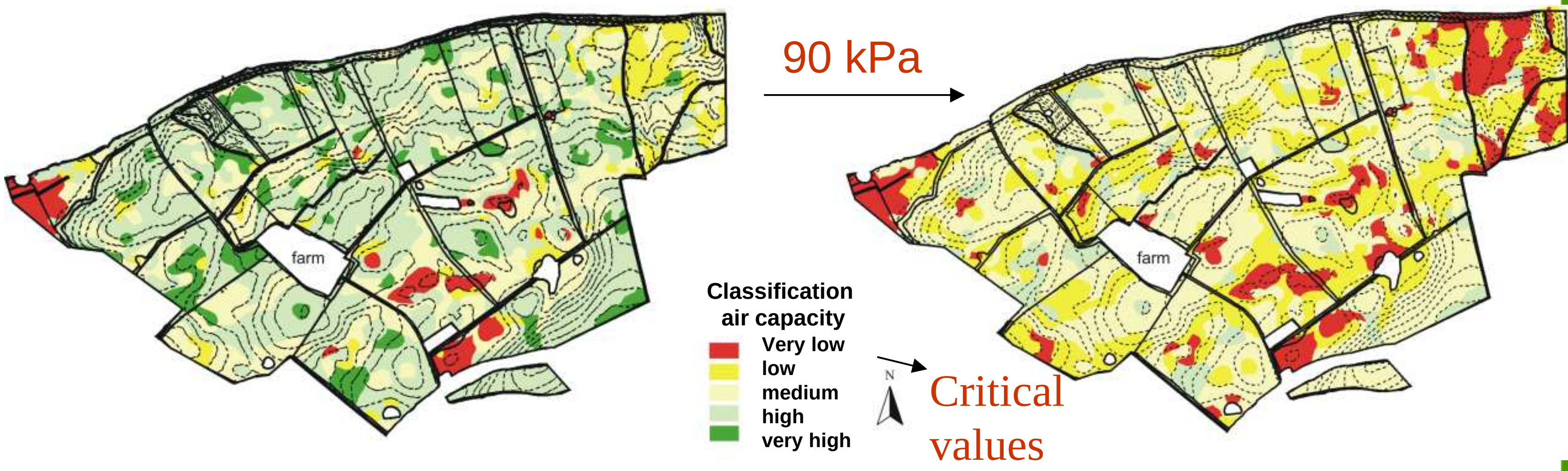
# Critical value: air capacity

**Farm scale, 140 ha, subsoil: > 40 cm, pF 1.8**

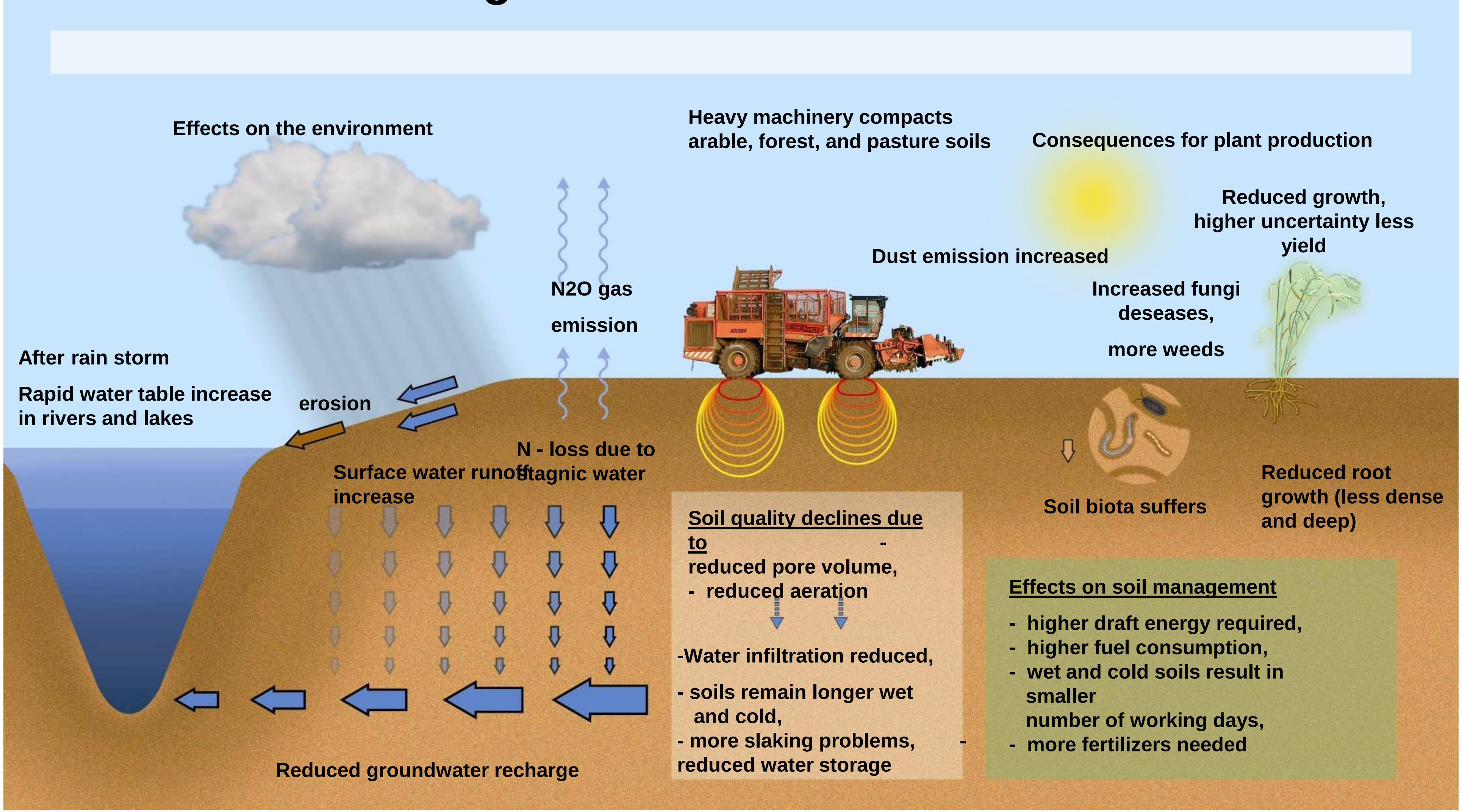
**Actual stress impact: 90 kPa**

Changes in air capacity (including the effect of areas with stagnic water (right) in comparison with the original conditions (left).

*classification (Vol.-%): very low: <2, low: 2-<5, medium: 5-<13, high: >13*



# Concluding remarks

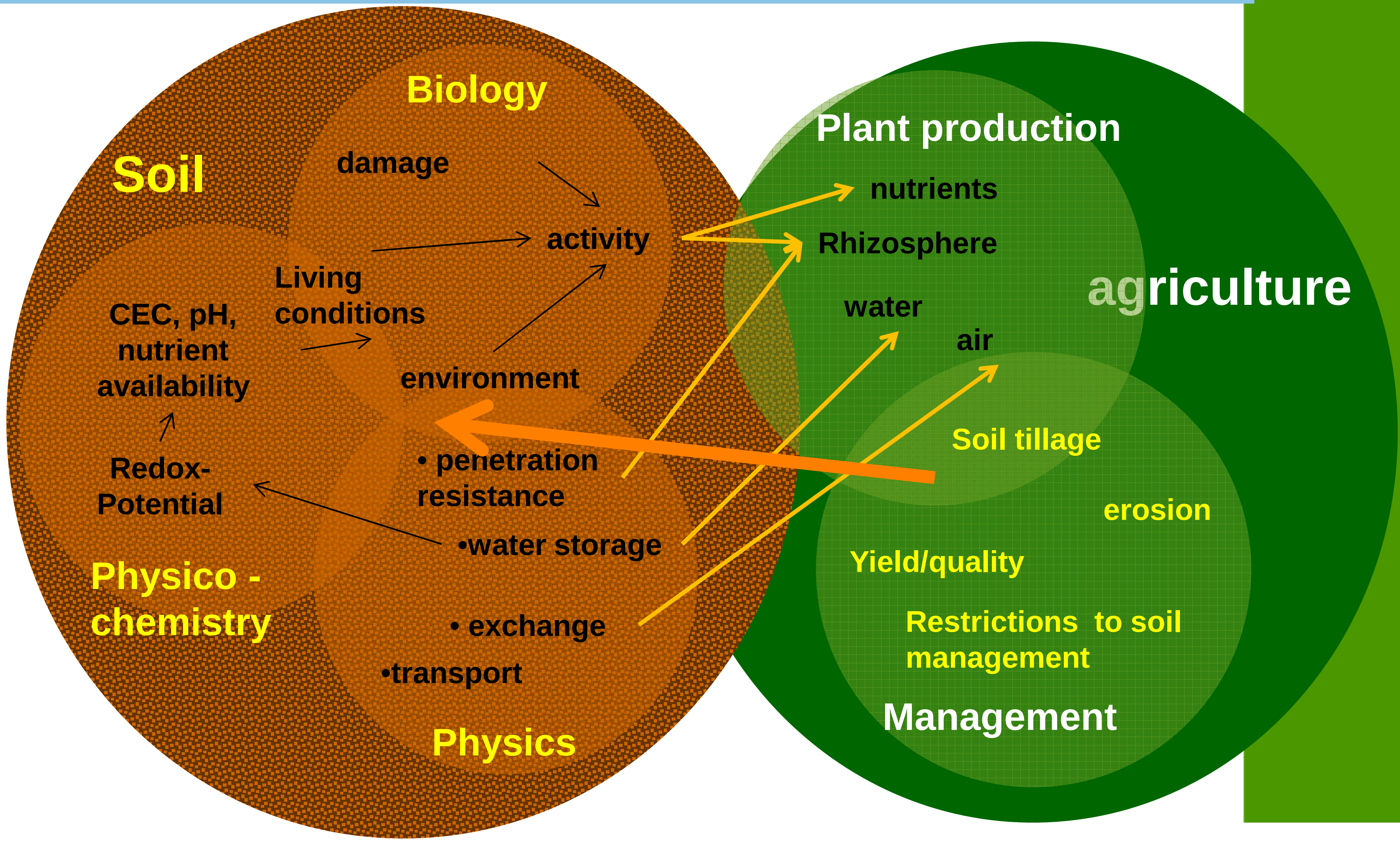


# Conclusions

C | A | U

- **1) Soil degradation processes occur at all scales, are mostly irreversible especially at deeper depth**
- **2) Soil protection and landuse are not conflicting each other, there are boundaries – soil degradation can be prevented but not reameliorated!**
- **3) Soil use must be adjusted to its rigidity and resilience conditions;**
- **4) we need a paradigm change towards a more sustainable land management system for a reliable future**

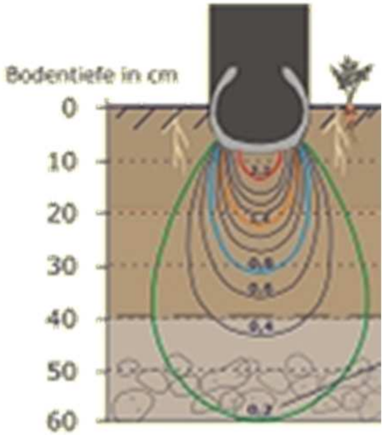
# Many thanks for your attention




**muito obrigado**

Modified after Weißkopf 2010

# Physical Soil degradation threat




Stress propagation in the subsoil

**Changes of physical soil functions**


subsoil

- structure deterioration

**Consequences for ecological properties**

- Infiltration
- airation
- water storage
- ponding

- root growth
- Water- , gas- and
- Nutrient uptake
- microbial activity

- erosion/ landsliding
- nutrient loss
- water pollution


- Yield uncertainty
- Wind/water erosion

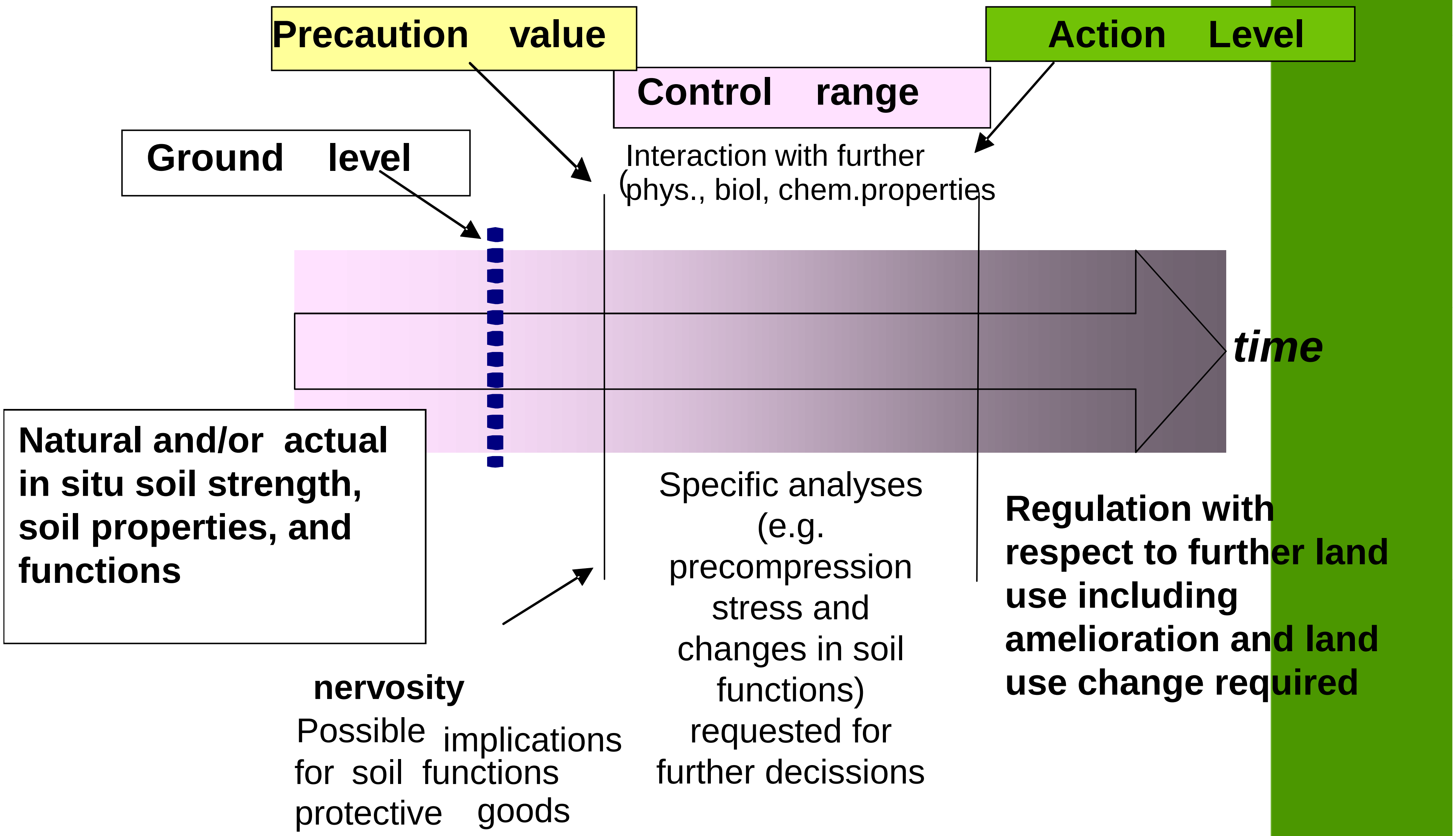
## Final consequences: Is there a chance to develop a world wide soil protection manual/law based on agrophysical research and site specific properties?

C|A|U

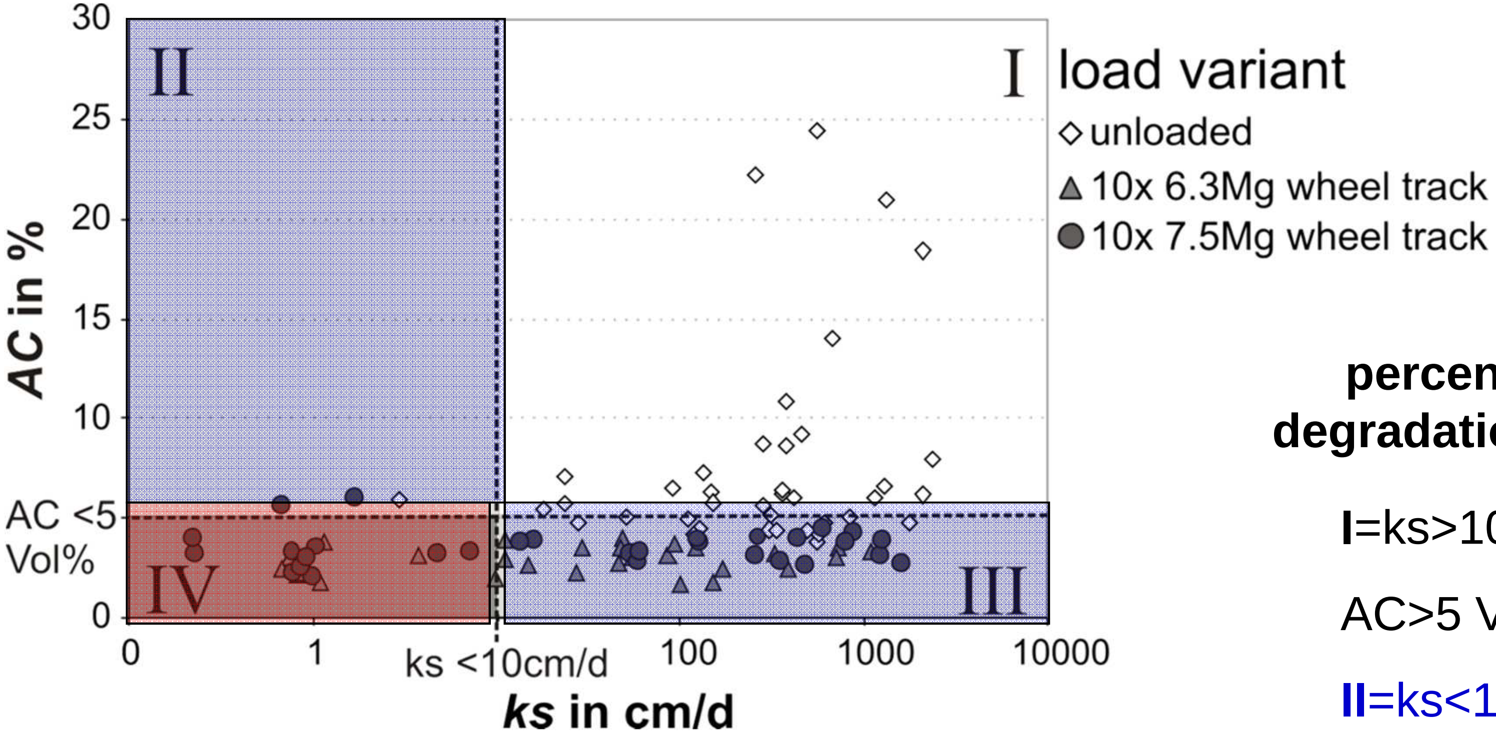
| Precaution | Action Value |
| --- | --- |
| **Max mass: < 5-6 Mg/wheel** | **Max mass >7-8 Mg/wheel** |
| **Stress/strength:<0.7** | **Stress/strength >1.2** |
| Sat. Hydraulic Conductivity: $>10^{-4}$ cm/s site specific variation; Anisotropy hor/vert <=1 | Sat. Hydr. Cond.: $<10^{-5}$ cm/s; Anisotropy: > 3 (if in 0-50 cm); Anisotropy >2 (if > 50 cm depth) |
| Air permeability: $>10^{-6}$ cm² | Air permeability: $< 10^{-7}$ cm² |
| ODR: 70 | ODR < 35 |
| Penetration resistance: <2MPa | Penetration resistance: > 2 MPa |
| Redox Resistance: >5 days 300mV | Redox Resistance: < 3 days 300 mV |
| CEC/CEI >1.0 | CEC/CEI >3 |
| Plant available water and minimal air capacity /effective rooting depth: Sand: 60 mm /15 Vol %; Silt: 200-240 mm/ 10 Vol %; Clay:150 mm/10 Vol % | Plant available water and minimal air capacity/effective rooting depth: Sand: - /10 Vol %; Silt: 150mm / 4-6 Vol %; Clay: 200 mm/ 4-6 Vol % |

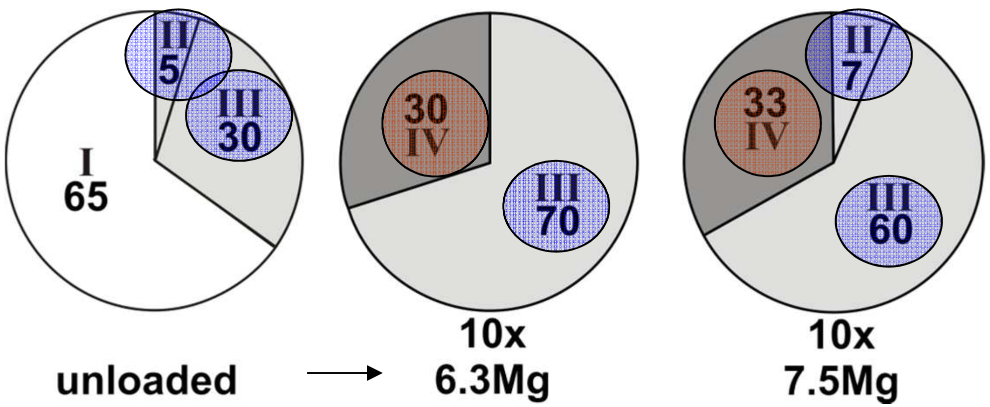
# Values for a sustainable landuse planning – can we apply our knowledge also for regulations and formulation of laws

Modified according to the German Soil Protection Law (1998)



## *Critical value concept* to verify a damaging (sub-)soil compaction /multiple passes, n=100)




**percentage of degradation classes**

**I**=ks>10 cm/d

AC>5 Vol%

**II**=ks<10cm/d

AC>5 Vol%

**III**=ks>10cm/d

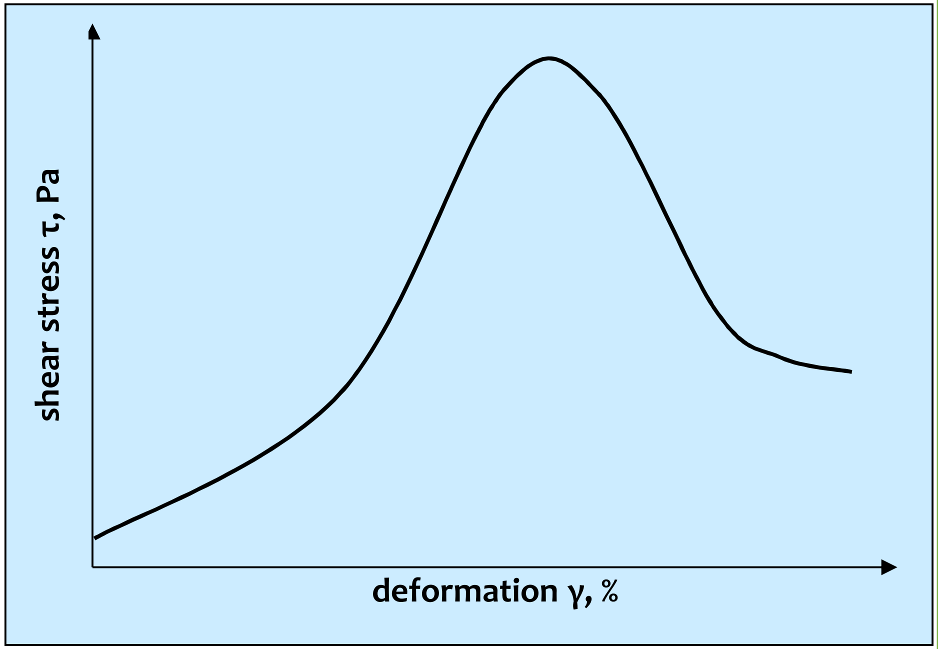
AC<5Vol%

**IV**= ks<10cm/d

AC<5Vol%

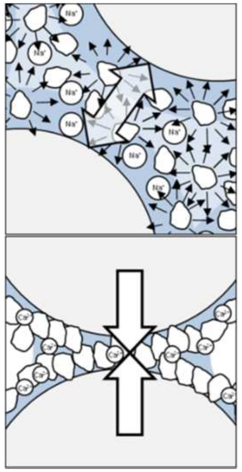
Subsoil compaction

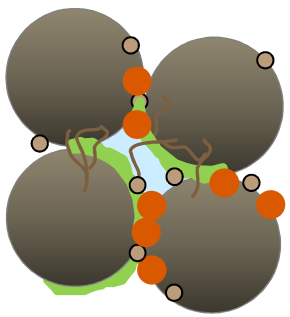
# Some detailed insights on the microscale – a rheological approach

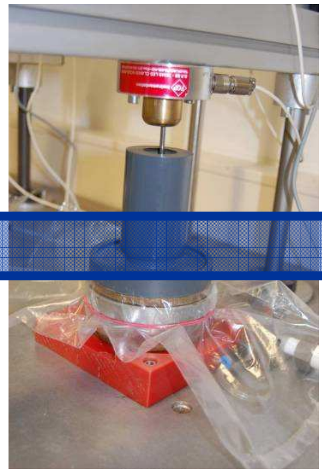


## Sensitive Soil Parameters at Various Scales

| PCD | Rheometry | Dynamic loading | Geophysics |
| --- | --- | --- | --- |
| colloidal scale | particle-to-particle scale | aggregate to field scale | field scale landscape |
| <1µm(-5µm) | <250µm | >250µm | |







zeta

G', G'', tan δ, z,

cyclic compressibility index c

shear

**At all scales we need to include the chemical, physico chemical, physical and biological processes and functions in order to understand, to explain and to define the elasticity and resilience limits of soils.**

*agglomeration behaviour*

*stiffness degradation*

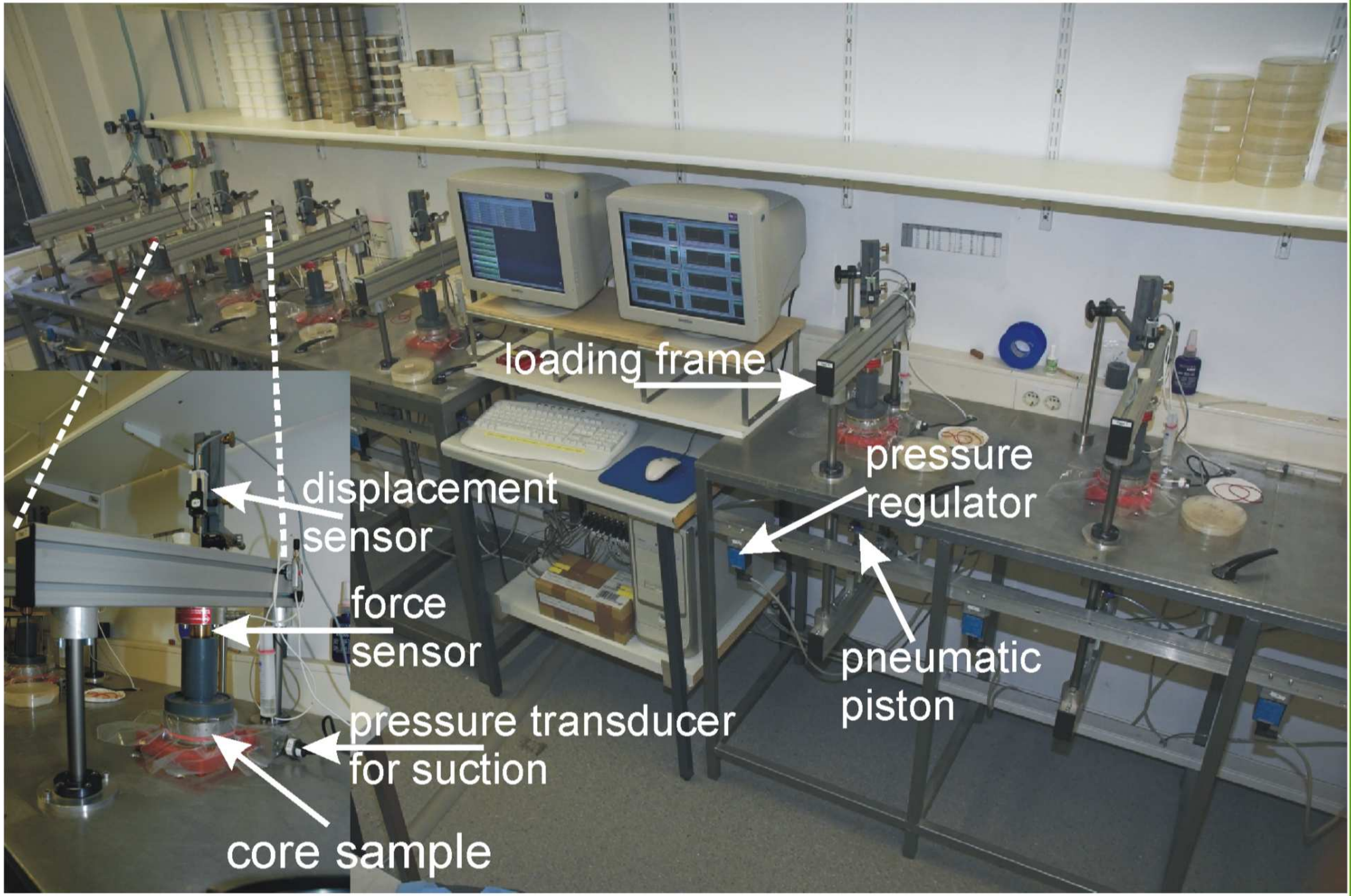
*shear behaviour*

*direct shear: c; Φ*

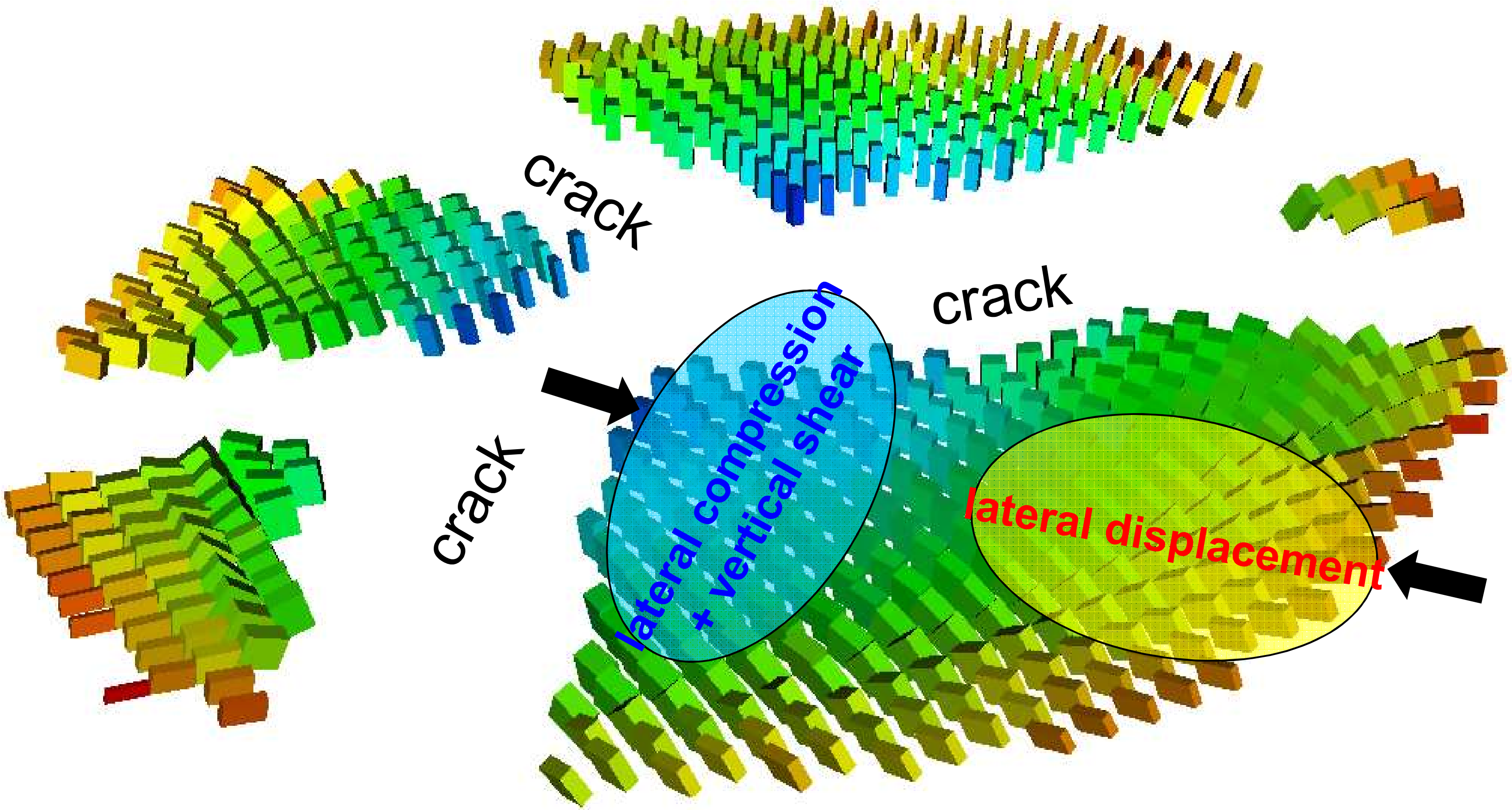
*liquefaction*

**Markgraf (2011)**

# Programmable Multistep Oedometer (PMO)



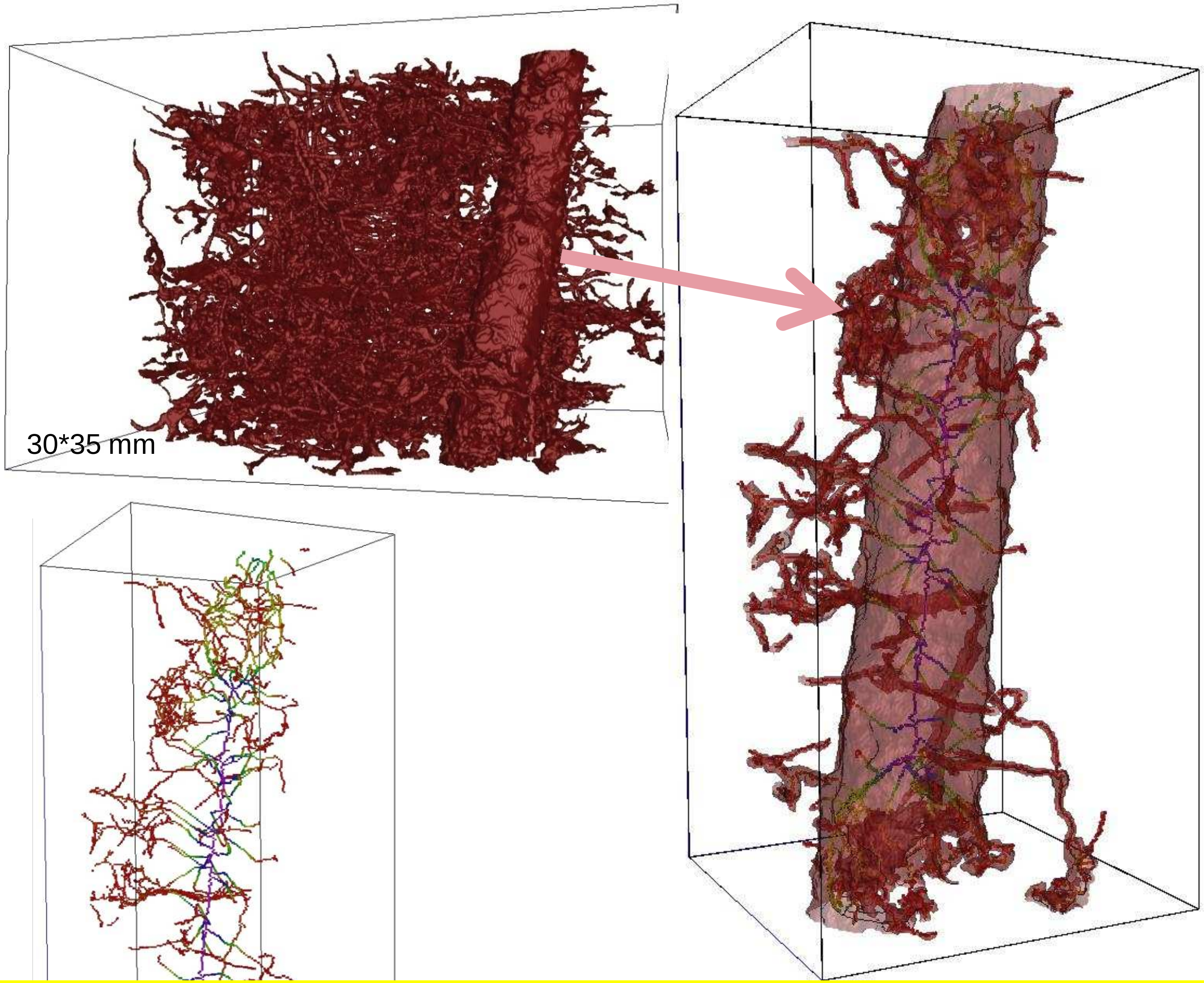
# Wetting and drying induced changes in particle arrangement



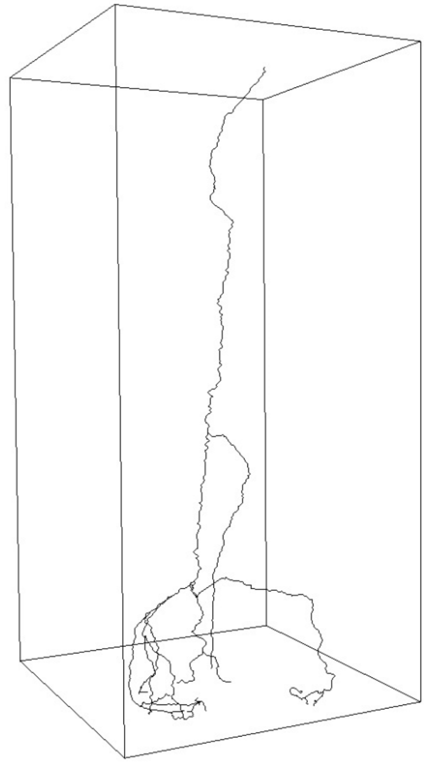

Peth et al. 2010

**Consequences: changed tortuosity, altered accessibility for nutrients, gas, and water**

# Wie sieht es eigentlich in einem Bodenblock aus?



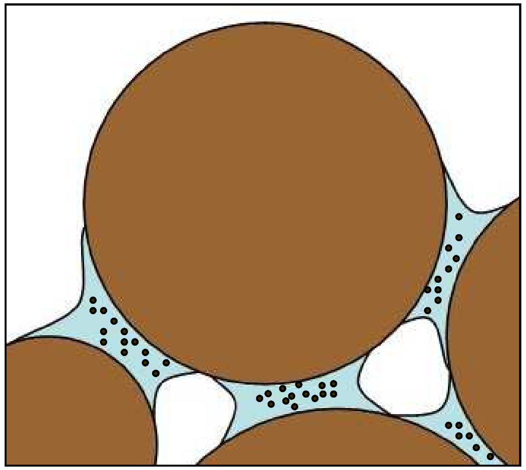

Verbindung von oben bis unten!

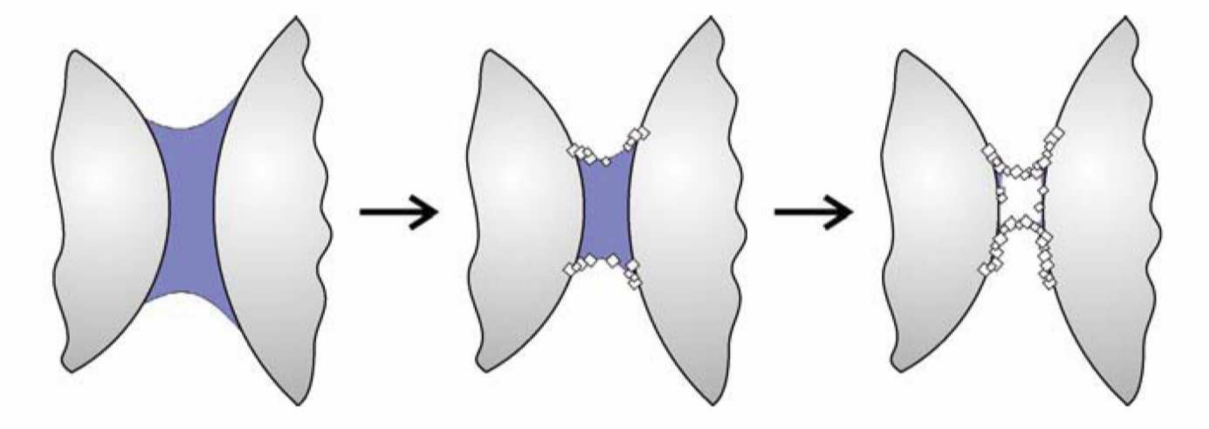


Pagenkemper et al. 2011

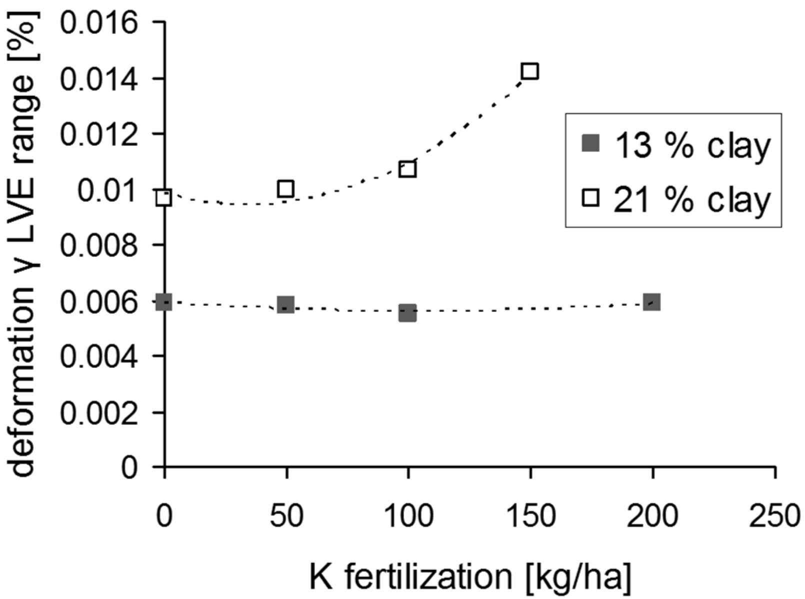
**Fazit: Nicht alle Hohlräume, sondern nur die verbundenen Volumina entscheiden über den Austausch (Wasser, Gas, Wärme, sowie die insgesamt tatsächlich speicherbaren und für die Wurzeln etc erreichbaren Nähr- und Schadstoffe**

# Salts for aggregate strengthening





Soulié et al. 2007 Powder Technol



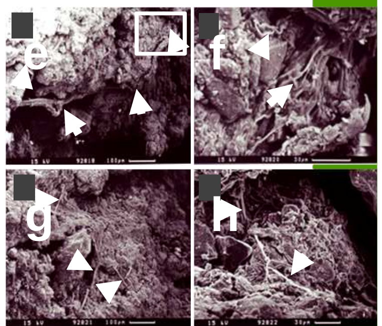

D. Holthusen et al. 2011

**A higher deformation γ value indicates a higher stability**

# semi-quantifying stiffness: *integral z*

| Plot | Treatments | saturated | pre-drained | |
|---|---|---|---|---|
| | | 0 kPa | -6 kPa | -15 kPa |
| **3** | NIL | 24.99 | 31.67 | 63.47 |
| **2.1** | $FYM+N_2$ | 30.09 | 64.19 | 66.05 |
| **2.2** | FYM | 33.71 | 63.30 | 62.01 |
| **6** | $N_1PK(Na)Mg$ | 30.64 | 55.42 | 65.36 |
| **7** | $N_2PK(Na)Mg$ | 30.01 | 55.27 | 65.27 |
| **9** | $N_4PK(Na)Mg$ | 34.93 | 59.35 | 65.96 |
| **16** | $N_6PK(Na)Mg$ | 32.98 | 58.69 | 65.66 |
| **W2** | Wilderness (grass) | 38.36 | 62.82 | 63.03 |
| **PF** | Bare fallow (Highfield) | 31.37 | 51.91 | 63.27 |

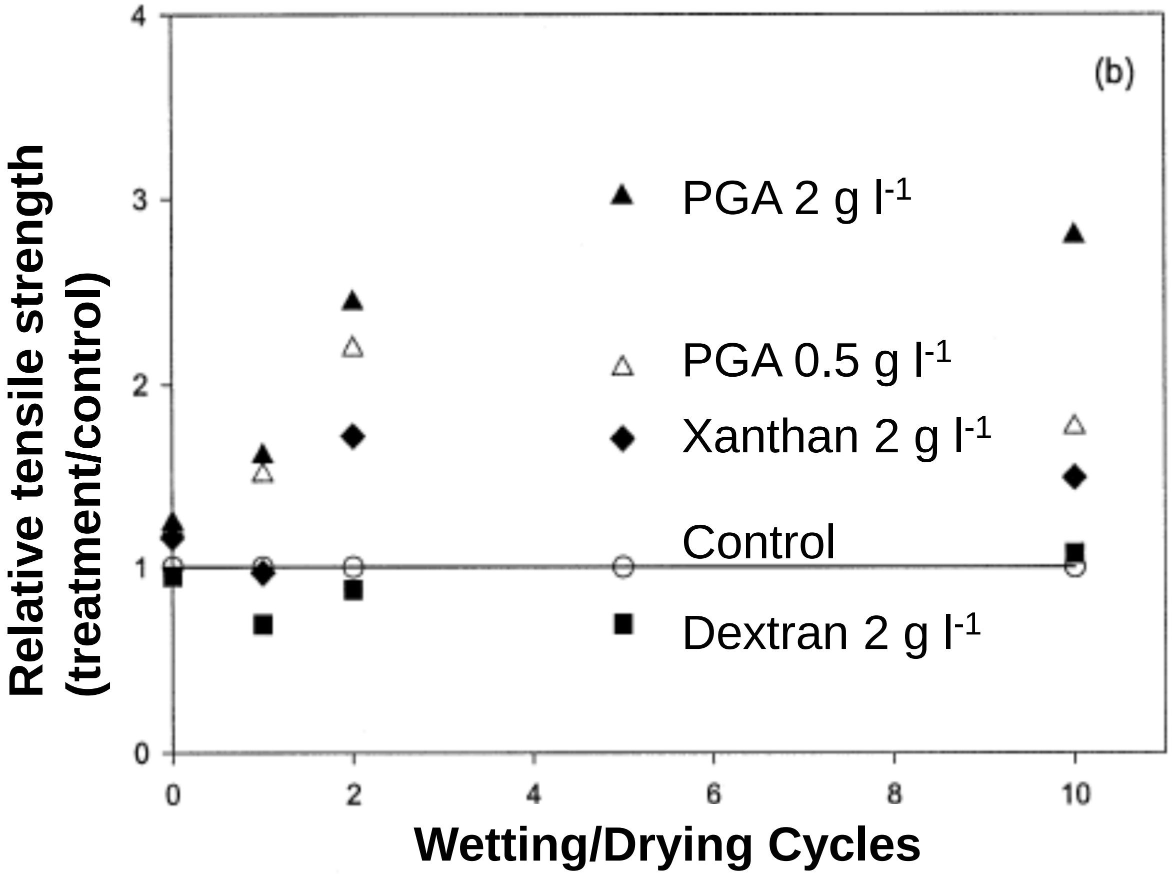
Plot 3; PF << 6; 7 < 9; 16 < 2.2; 2.1 < W2




**no fertilizer << mineral N< organic N< wilderness (grass)**

no fertilizer << $Ca^{2+}$ (lime) < $Ca^{2+}$ (lime) with fungal hyphae < micro roots and fungal hyphae

# Biological exudates influence the strength of dry soil



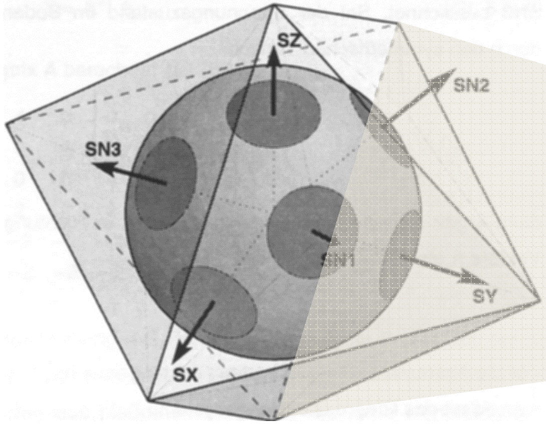

Polygalacturonic acid - Model root exudate

Bacterial Exopolysaccharide

Bacterial Exopolysaccharide

Czarnes, Hallett, Bengough & Young. 2000. European Journal of Soil Science, 51, 435-443

# Stress propagation in situ

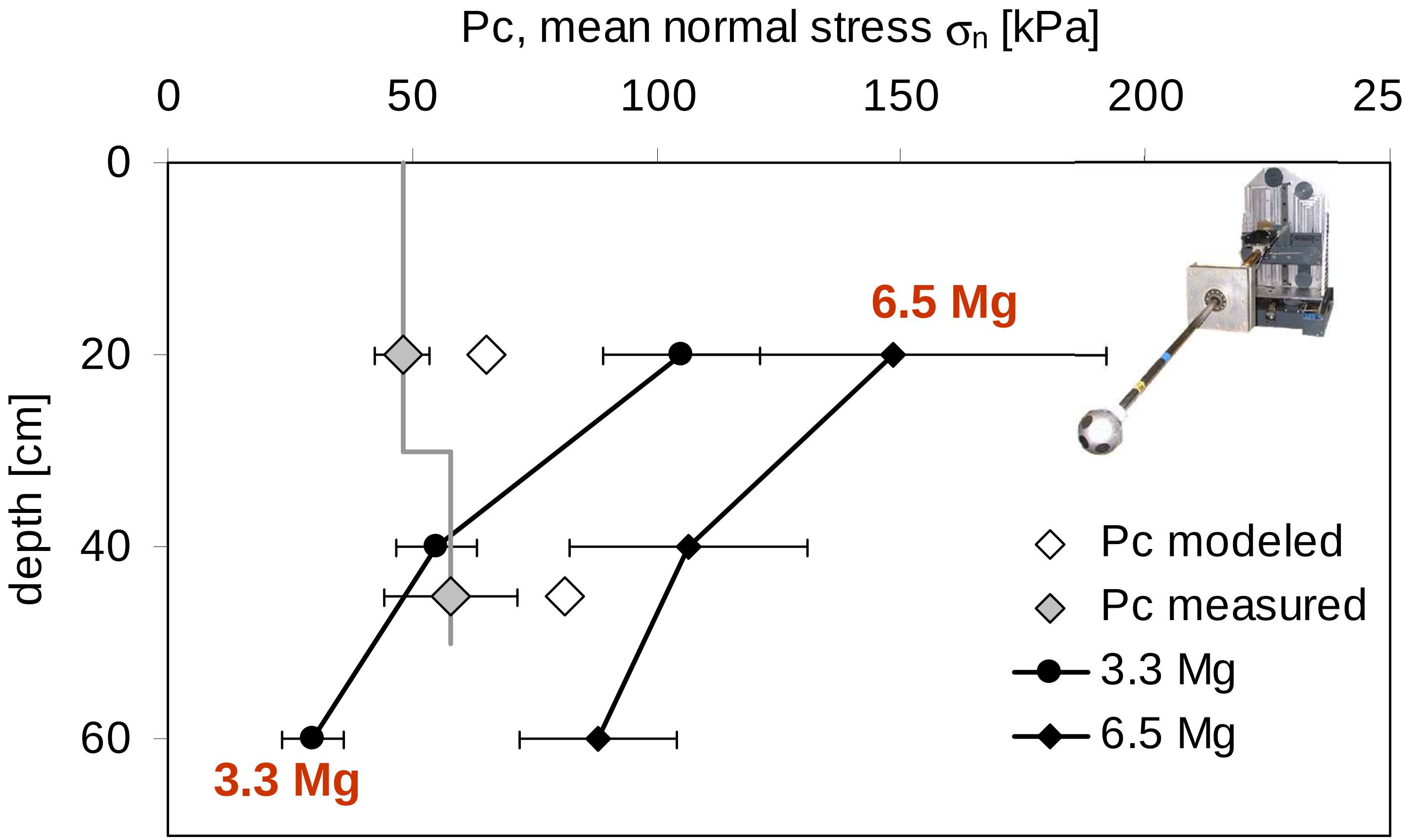



Stress tensor

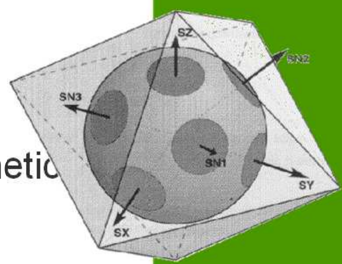
$$\begin{pmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{pmatrix}$$


BMVEL 03HS003

# Pc versus stress (modelled/measured)

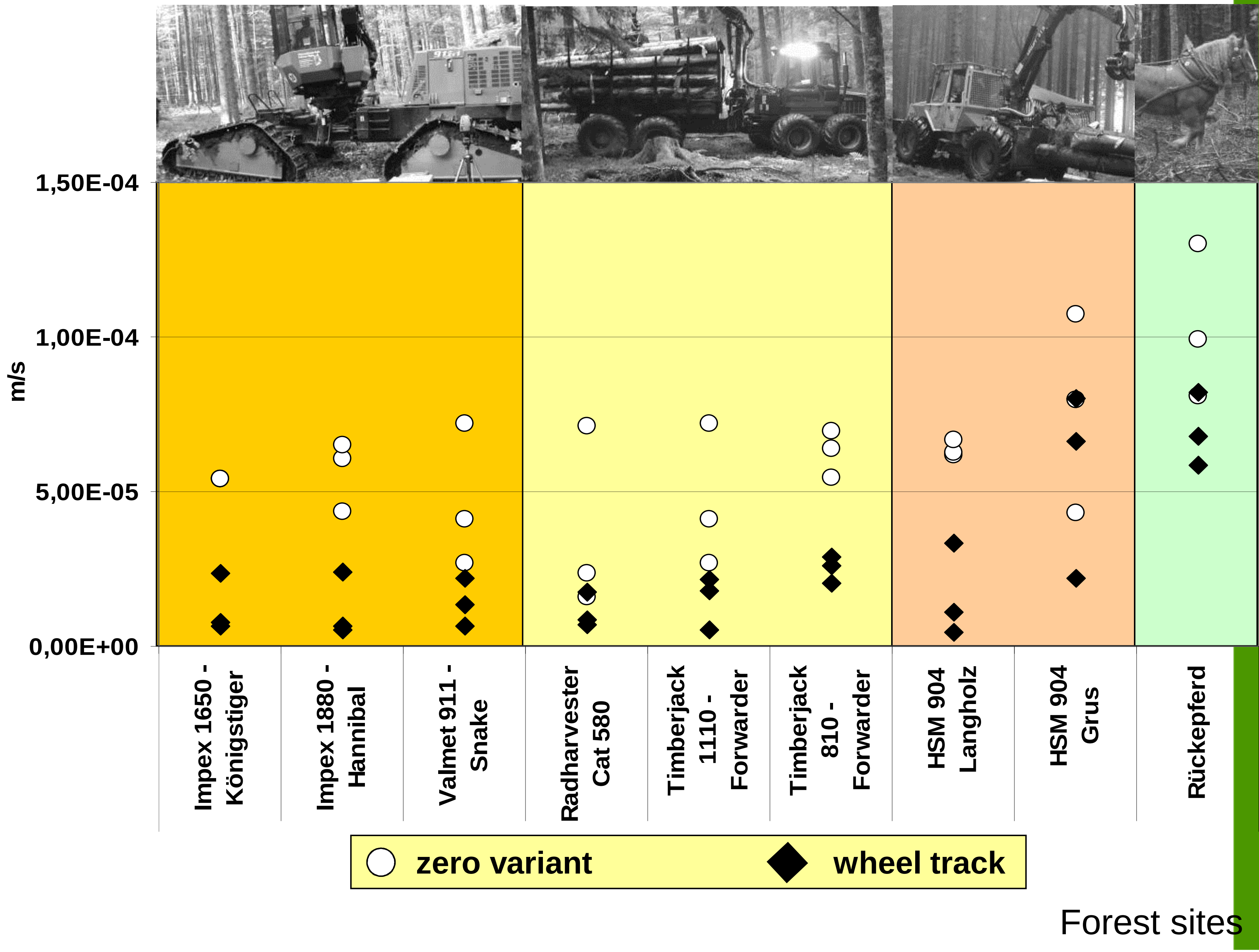



Stagnic Luvisol, glacial till, conventional tillage

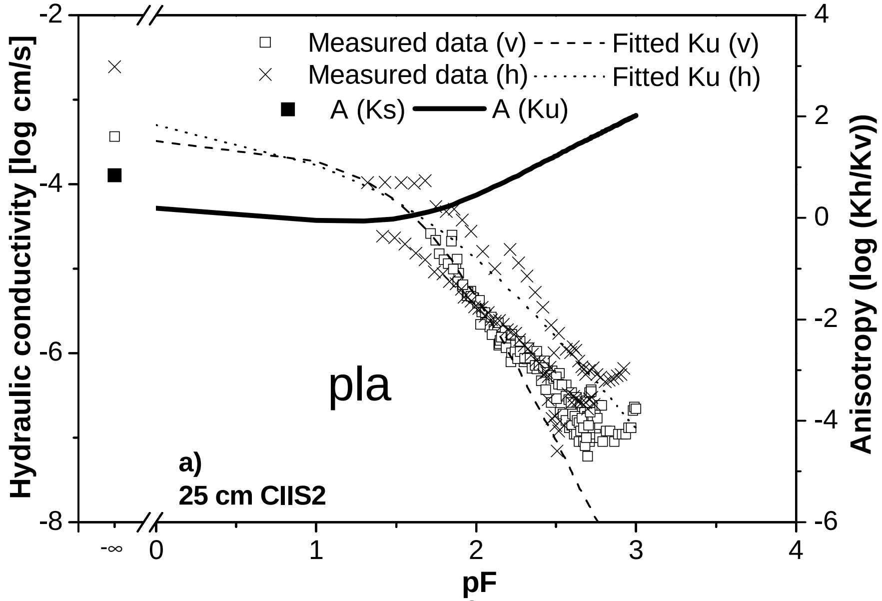


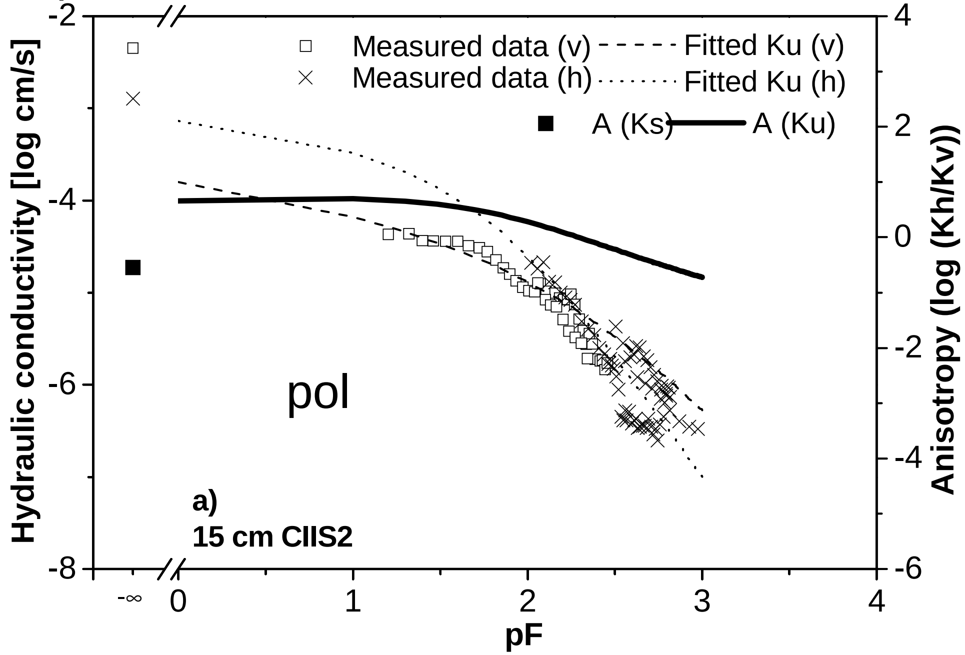

Comparison of measured Pc (pF. 1.8, n=6, arithmetic mean and standard deviation) and modeled Pc by using pedotransfer functions and in situ soil stresses (3 replicates, arithmetic mean) using the SST-sensor system

# Changes in air permeability



# Structure effects on the saturated hydraulic conductivity and anisotropy

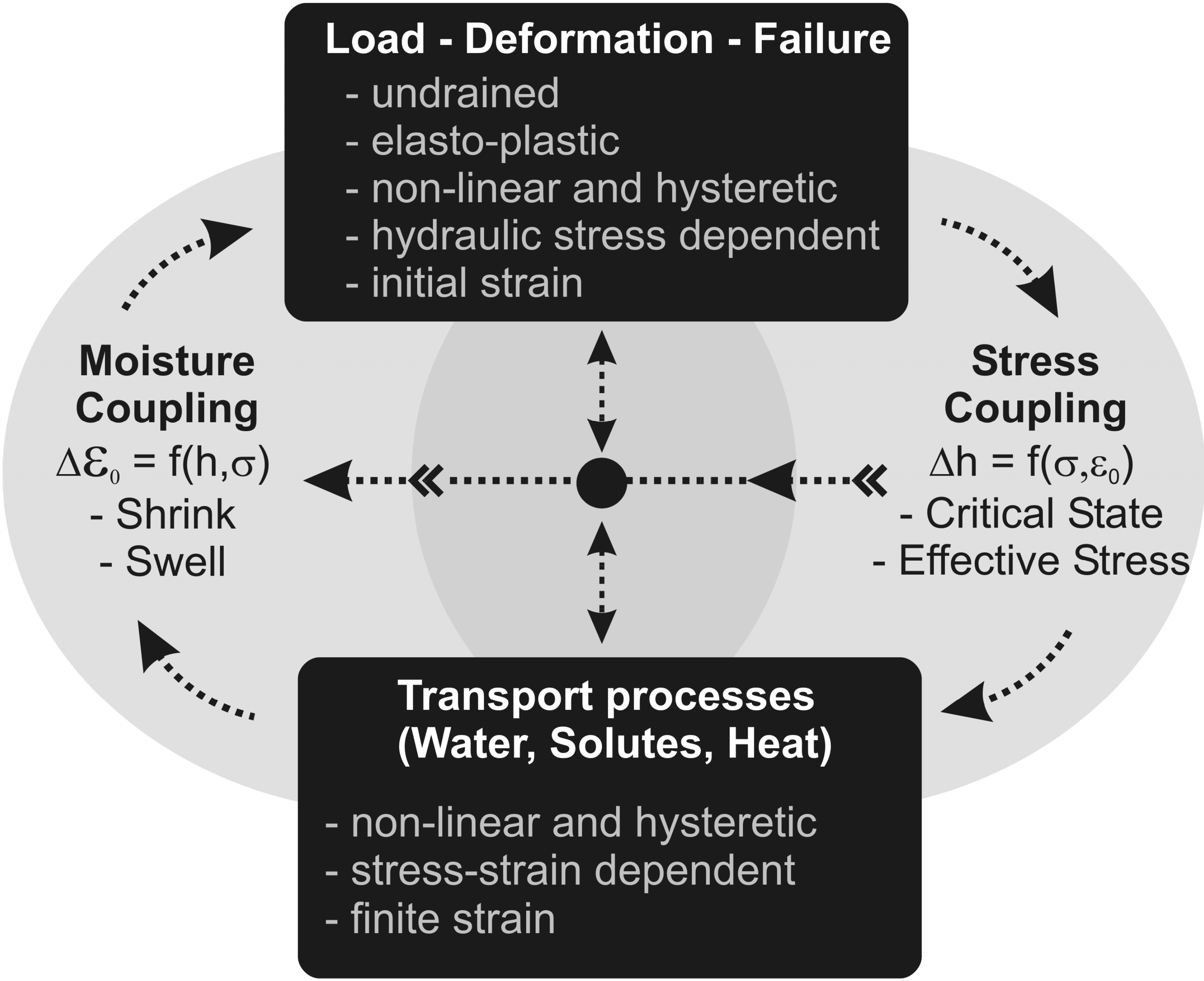



Doerner 2005

**Consequences for soils with platy structure: increased**
**-lateral fluxes**
**-anoxic conditions**
**-Penetration resistance**

**Reduced accessibility**


Load - Deformation - Failure
- undrained
- elasto-plastic
- non-linear and hysteretic
- hydraulic stress dependent
- initial strain
Moisture Coupling
$\Delta\varepsilon_0 = f(h,\sigma)$
- Shrink
- Swell
Stress Coupling
$\Delta h = f(\sigma,\varepsilon_0)$
- Critical State
- Effective Stress
Transport processes (Water, Solutes, Heat)
- non-linear and hysteretic
- stress-strain dependent
- finite strain

## Root growth  a key factor for

- Mechanical strength
- Water, ion, gas transport
- Nutrient uptake and release
- Root growth
- Microbial activity

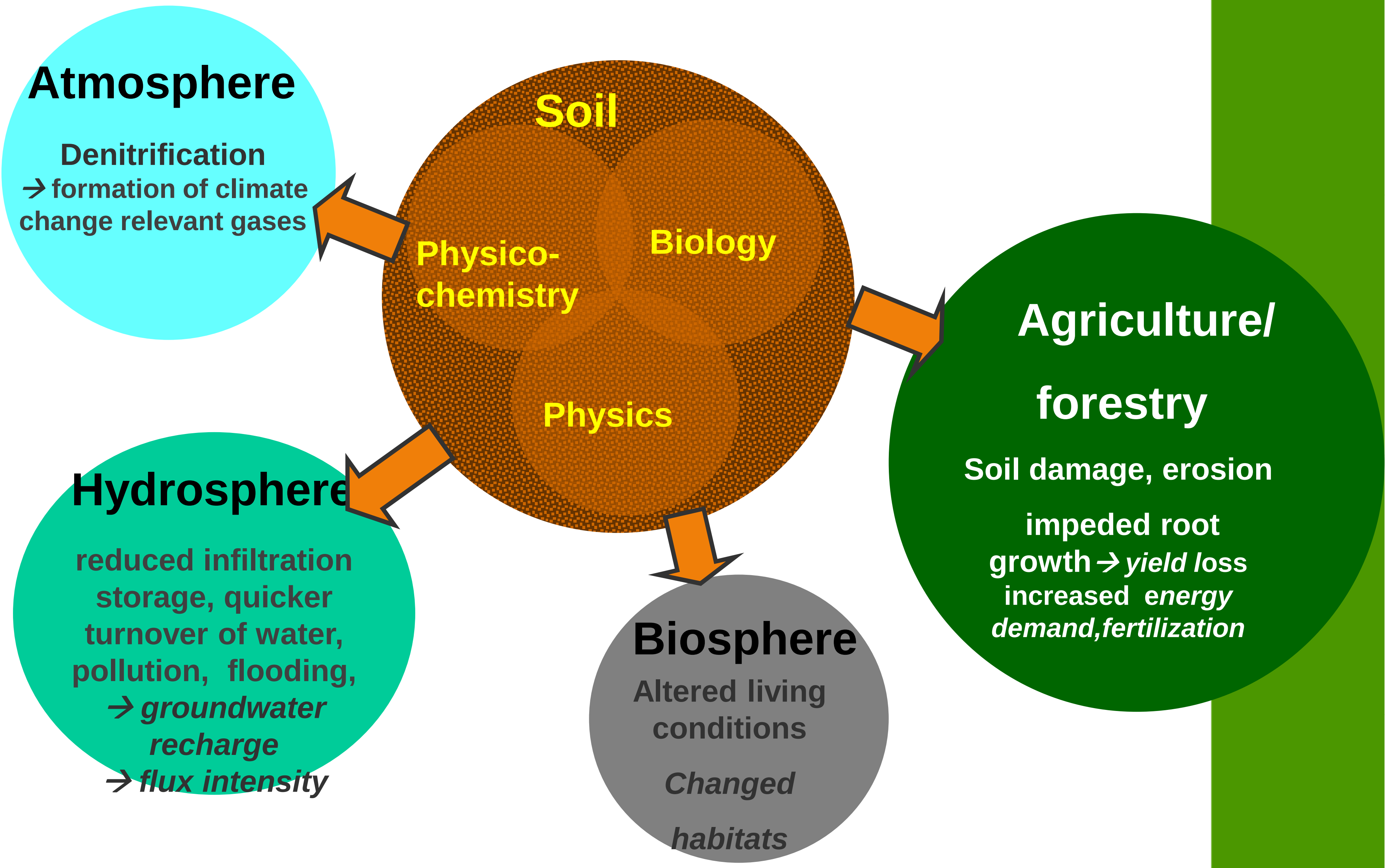
Physical

Chemical

Biological

Physico-chemical

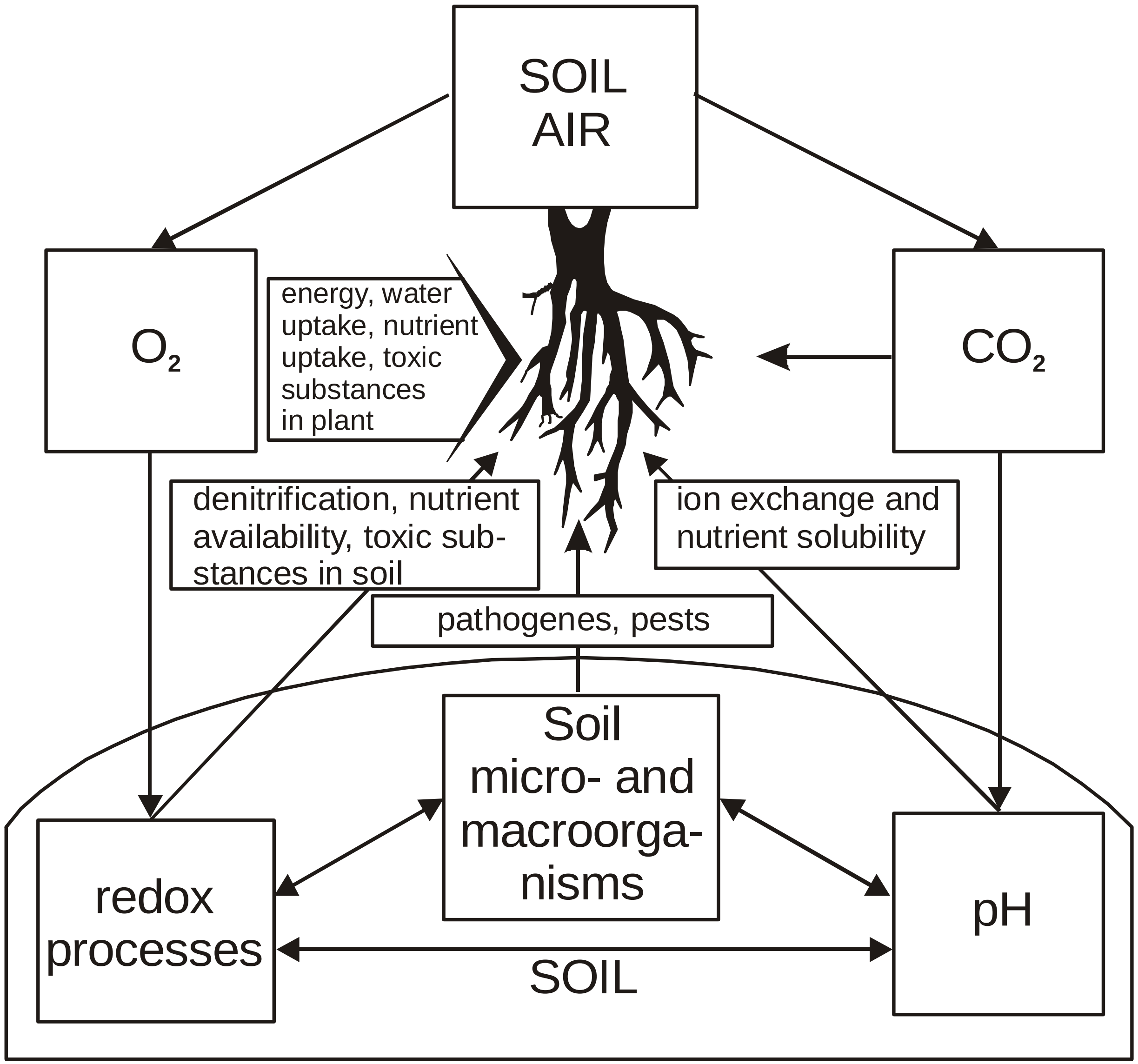
# Interaction between soil properties and the environment




**What is the critical resilience of soil properties?**

ntly modified from Weißkopf 2010

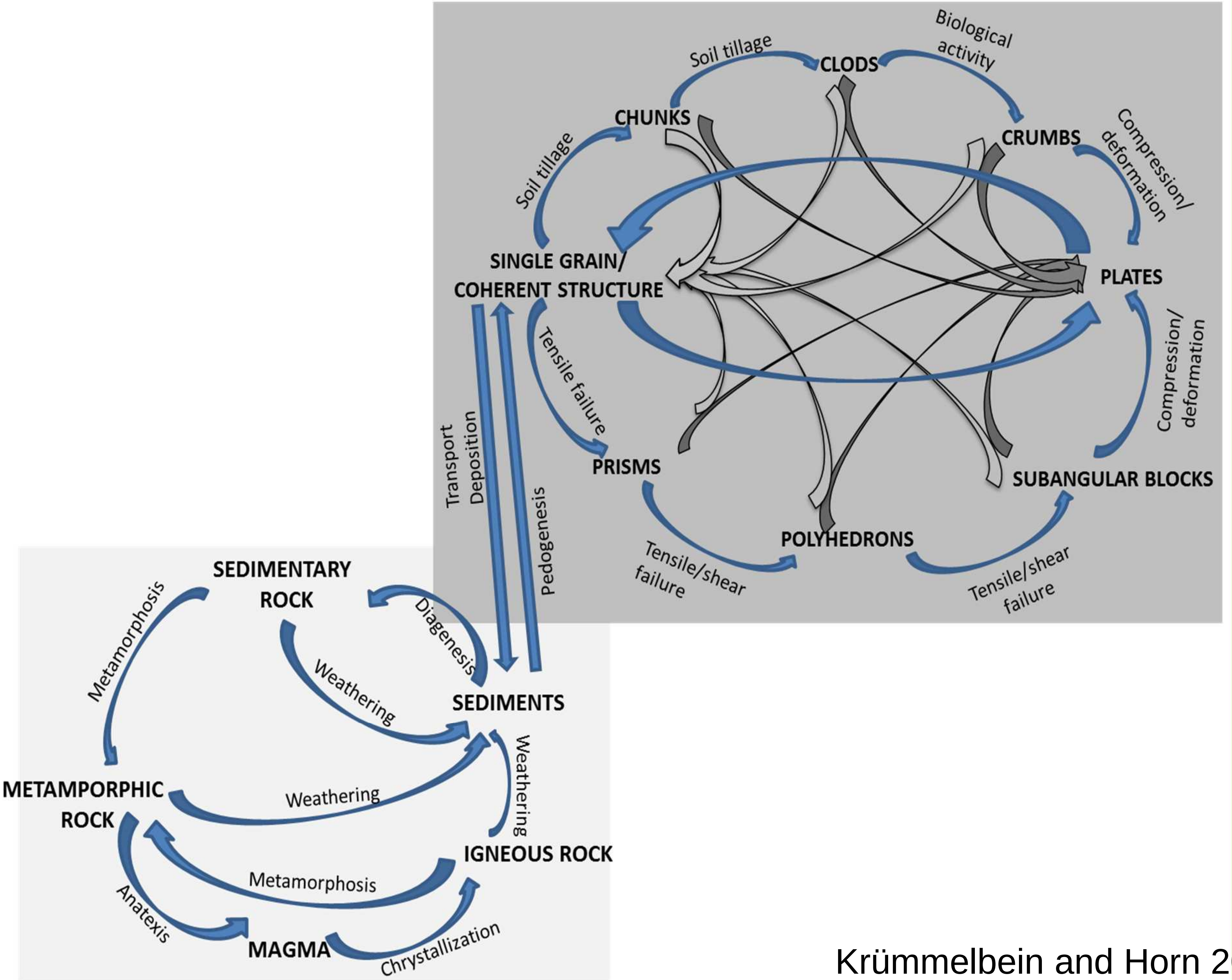
# A Scheme Of Direct And Indirect Effects Of Soil Oxygen On Plants




(After Gliński and Stępniewski, 1985)

# The cycle of rocks complemented by the cycle of soil

C | A | U




Krümmelbein and Horn 2013