Effect of Land-Use Management Systems on Coupled Hydraulic Mechanical Soil Processes Defining the Climate-Food-Energy-Water Nexus

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Abstract

Soils are the most critical life-supporting compartments of the biosphere. They provide numerous ecosystem services such as habitat for biodiversity, water and nutrients, as well as producing food, feed, fiber and energy. Soils undergo intense and irreversible changes due to a non-site adjusted land management and improper application of machinery and techniques in its broadest sense. In combination with the growing population (until 2050 we will have approx. 9 Billion people) the urgent need for a more reliable dataset of soil properties and soil functions gains in importance in order to even prepare more reliable models for various requests. The mechanical strength – the precompression stress - as the result of geo-, pedo- and anthropogenic long-term processes - can be defined as the basis for quantifying the rigidity boundary. It distinguishes between the recompression stress (i.e. elastic, rigid properties) and the virgin compression stress range where plastic deformation including irreversible changes of properties and functions occur. The changes in the hydraulic or pneumatic functions like hydraulic or air conductivity, the pore size distribution primarily all occur in the virgin compression stress range, The same is also true for redox reactions and the biological activity (respiration) in soils but also carbon sequestration potential is also linked with the precompression stress value. Thus, a more precise definition and following of site-specific functionality differences, which may exclude or concentrate certain land use or management forms are needed, in order to optimize yield, soil protection and a sustainable land use management considering the limited site specific resilience at the same moment.

Key words: stress/strain, stress distribution, precompression stress, coupled hydraulic and mechanical processes, ecological functions

Introduction

The properties of arable or forestry soils, or the substrate for horticulture, or landscape planning, are the basis for not only food production, filter and buffer for clean drinking water and sufficient groundwater recharge but they are also the basis for raw material, biological diversity as well as soils are archaeological documents. However, soils as three phase systems have only a limited resilience and exceeding these boundary conditions result in soil degradation, which is mostly irreversible. Very often, either soil classification is based on properties, which were defined from completely homogenized material, or capacity parameters are defined for both homogenized and aggregated soil samples. Well-known parameters are cation exchange capacity, air capacity, or plant available water. However, such data may not define or predict soil processes adequately because neither the accessibility of particle or pore wall surfaces nor the connectivity between pores within structured soils are considered. In the following, these interactions are discussed in order to define soil functions like redox reactions cation exchange intensity, or air permeability, hydraulic conductivity and actual soil strength. Furthermore, the coupling of physical, chemical and biological processes is mandatory in order to obtain a more complete picture of in situ conditions as the basis for the quantification of the boundary conditions for a sustainable land use management.

Stress strain and alterations of soil structure

According to the European Soil Framework Directive (2006) soil compaction is besides water and wind erosion one of the main physical reasons and threats of soil degradation. It is estimated, that 32% of the subsoils in Europe are highly degraded and 18% moderately vulnerable to compaction. The problem is not limited to cropland or forest areas (especially because of non-site adjusted harvesting machines) but it is also prevalent in rangelands and grassland, and even in natural non-disturbed systems. Wheeling during seedbed preparation or harvesting as well as animal trampling are main factors leading to soil degradation and biodiversity changes or losses. A decline of soil physical quality and changes in soil properties such as internal soil strength, precompression stress, infiltration rate, continuity of soil pores, air and hydraulic conductivity are considered as expressions of soil degradation (Horn, 1985, Krümmelbein 2007, Lei Gan 2012, Keller et al 2007, Keller et al. 2013, Berisso et al, 2012, Hartge and Horn 2016). In this context also the frequency of wheeling or trampling in combination with the actual matric potential and internal soil strength are examples of coupled processes and the outcome can either enhance the deterioration of existing soil structure by the formation of even stronger platy structure with more negative ecological properties. However, it can also result in complete structure deterioration due to shearing, puddling, and consecutive homogenization. Both processes can be classified as long-term irreversible and result not only in an increased sensitivity of such sites for consecutive water or wind erosion but also in an irreversible loss of soil properties or functions as well as crop yield or plant growth.

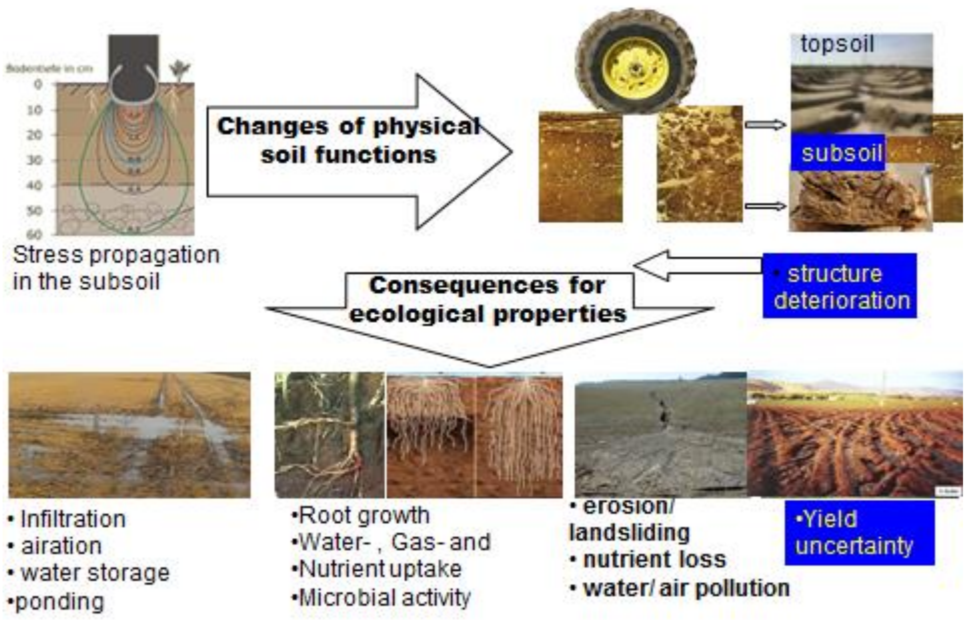


Figure. 1. *Soil degradation threats*

Figure 1 informs about some main soil degradation threats. Negative effects of soil mismanagement resulting in soil compaction, soil erosion including reduced filter and buffer processes and crop yield are well documented. However, the relation of sustainable soil properties to a well-defined parameter like soil rigidity as a link to interactions with chemical, physical and biological soil properties are still not completely understood as it seems to lack on a wider range of data.

Some information on mechanical properties and related dynamics

Soil compressibility defines the sensitivity of the pore system to mechanical stress application i.e. the susceptibility to soil compaction. One of the main parameters, commonly used to quantify soil strength is the precompression stress. It quantifies the stresses to which the soil was exposed in the past, irrespective of its origin. Pedogenic, anthropogenic or even geogenic processes or various hydraulic conditions and land management can cause altered soil strength even if its origin remains mostly unknown under in situ conditions – the direct link to any of these parameters fails under unknown in situ conditions (Fig.2). The precompression stress value can however be applied to quantify the overall strength range which is equivalent to the soil rigidity.

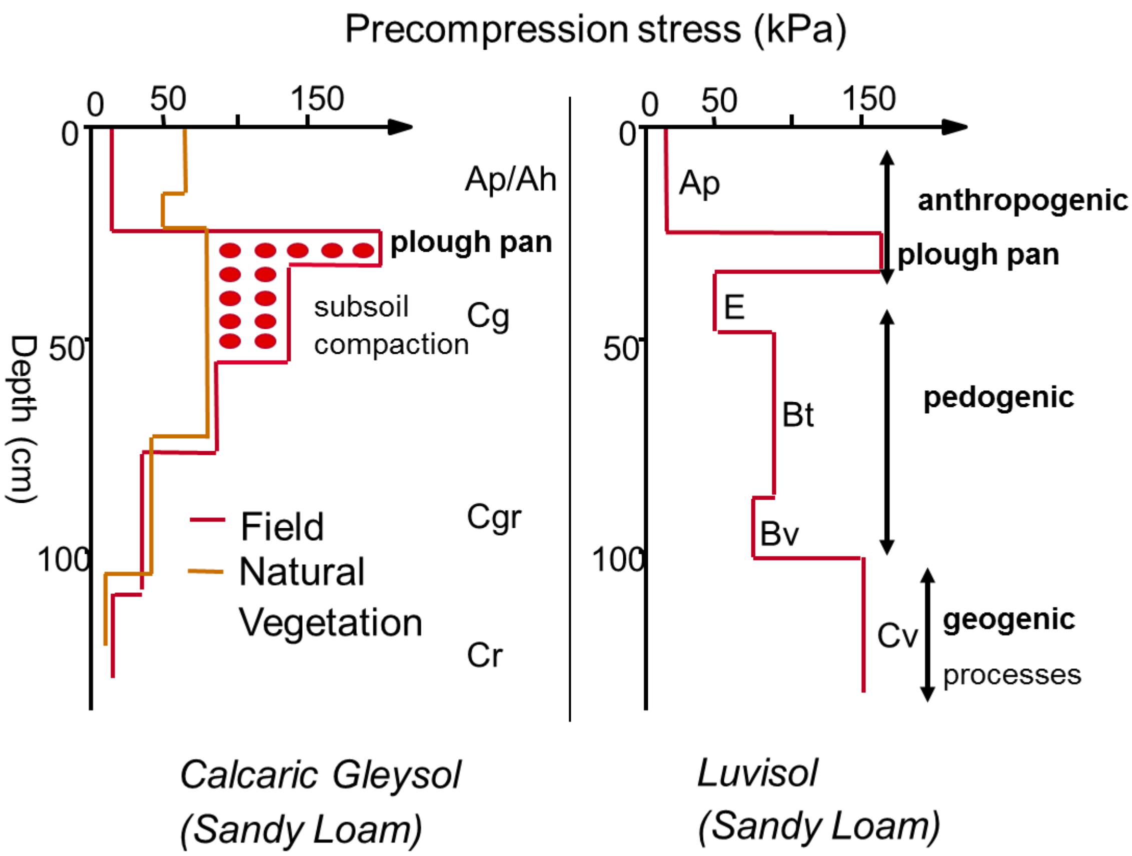


Figure 2. *Soil strength defined as precompression stress for a Calcaric Gleysol and a Luvisol.*

This direct relation between soil strength defined as precompression stress and soil rigidity also includes the dominant elastic behavior which results in permanent structure dependent soil functions (with a reversible deformation) if the actually applied stresses do not exceed the precompression stress value. Stresses higher than the precompression stress value result in a further plastic (irreversible) deformation (Horn 1981, Horn et al., 1995, Horn and Peth, 2011). This statement holds always true, if stresses are applied statically, while mostly dynamic stress application may cause a more intense soil deformation due to the rearrangement of particles, which then result in a new “dynamic equilibrium” under those conditions. In combination with altered hydraulic stresses it may even result in a complete puddling and weakening of soil structure (Krümmelbein et al. 2006, Bi et al.,1 2015).

The principles of aggregate formation and degradation based on swell /shrink but also its alteration due to mechanical stress application and the combination with hydraulic stresses are summed up in Fig. 3.

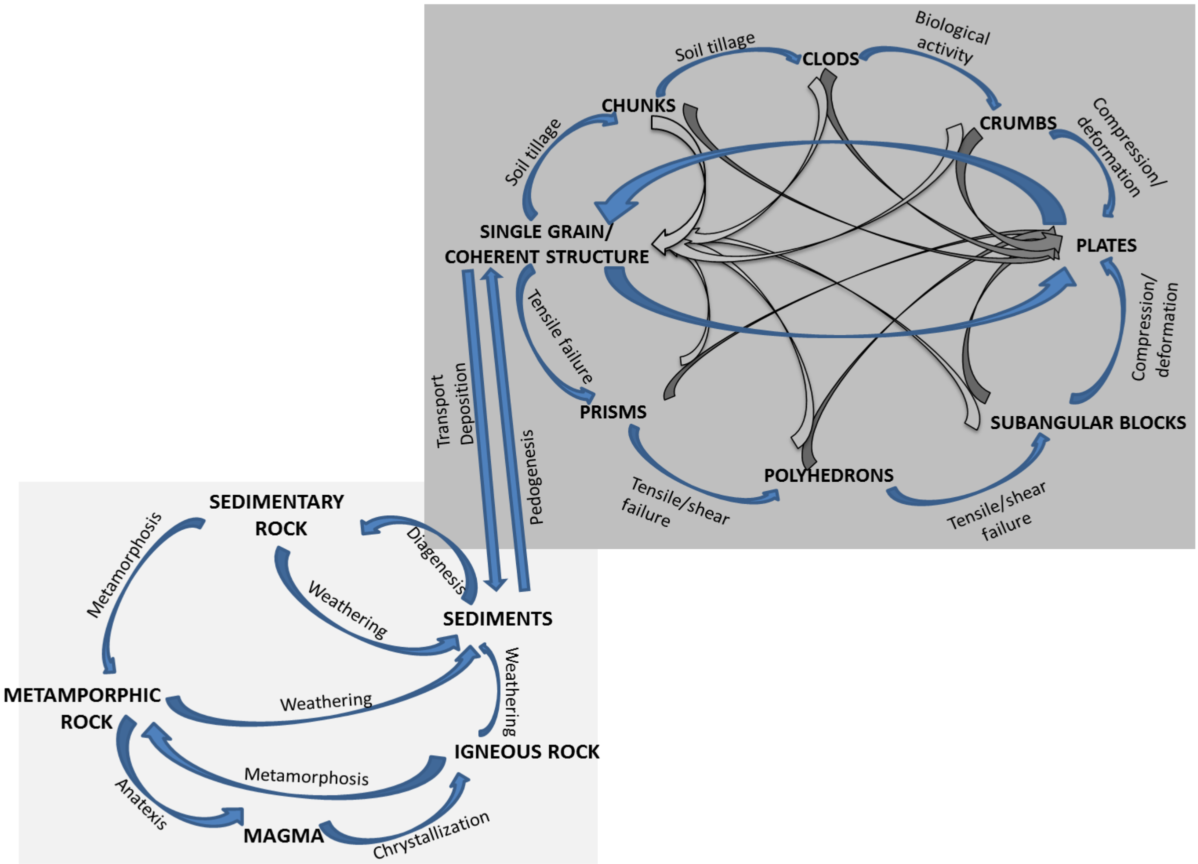


Figure 3. *Soil Structure Formation and Degradation (after Krümmelbein and Horn 2011)*

The initiation of aggregate formation due to shrinkage and swelling always causes tensile cracks and the formation of prismatic structure while after repeated wetting and drying a new dynamic equilibrium will be reached due to more pronounced shear failure processes (Fig.3). The typical aggregates: blocky or subangular blocky structures are defined by non-rectangular shapes and increased soil strength. Accumulation of organic matter and its decomposed constituents furthermore strengthen these aggregates. Crumbs as typical biologically formed aggregates are strong and often defined as macroscopic homogeneous. All aggregate types have however a limited internal strength as can be seen from the pattern of the Mohr Coulomb failure line (Fig.4) With more pronounced structure formation increase the cohesion and angle of internal friction values. However, as soon as mechanical stresses exceed these limits, will coarse pores in between aggregates be destroyed followed by intraaggregate pores. A shear .induced rearrangement of particles and the partial height change rectangular to the stress application finally forms a platy structure with an increased intraaggregate cohesion, but a reduced friction between the single particles (as a consequence of the rearrangement). Consequently, platy structure is defined by the highest cohesion but very small values for the angle of internal friction.

It must be furthermore stated that irrespective of whether the mechanical loading results from wheeling or from animal trampling, it can have an enormous effect on strain and consecutive homogenization processes if the hydraulic boundary conditions are still not equilibrated with the stress and kind of loading. If during the short term stress application the actual structure status coincides with pore deterioration and the pore water pressure cannot be equilibrated within short time even a complete weakening like during puddling or kneading occurs and may result in a complete homogenization of the former structural system (Krümmelbein et al., 2009). Aggregate formation also affects the internal flux processes and directions and alters the filter and buffer functions due to varying accessibility of pore surfaces or connectivity (Fig. 4). In this context we have to differentiate between the ecological effects of the whole soil profile with limited pore continuity and accessibility and the dominant flow directions with limited access to all surfaces or pores. Horizontal crack formations e.g. in plow pan layers, under ruts or in glacial till parent material creates dominant horizontal fluxes defined as horizontally anisotropic with restricted access of deeper soil layers for infiltrating water and a consistent increase in lateral soil erosion by water.

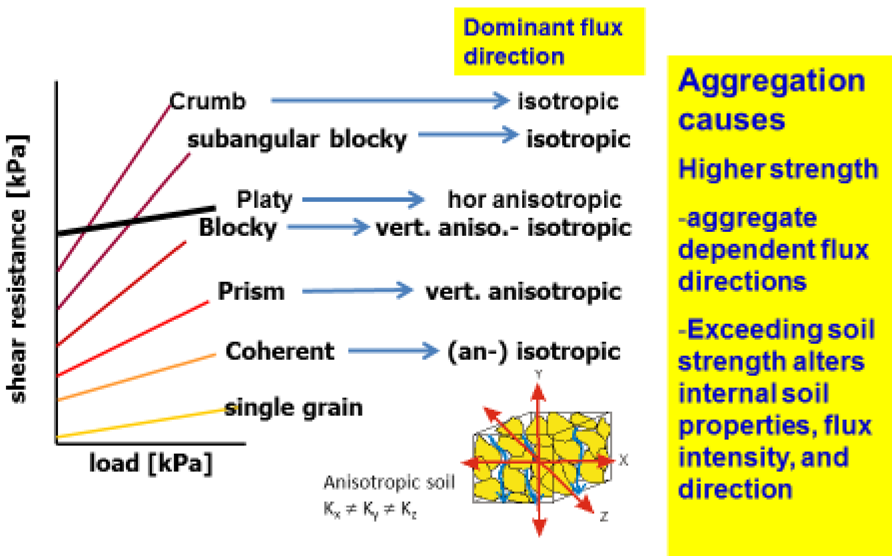


Figure 4. *Aggregate dependent pattern of the Mohr Coulomb failure lines and associated dominant flux directions.*

It is obvious, that structure dependent formation of interaggregate pore systems always affects pore continuity and directions and alters the values of the corresponding three-dimensional flux tensors or water, gas, heat, and ions.

Effect of stress application on changes in ecological soil functions

Capacity or intensity parameters

In soil sciences literature (e.g. Scheffer Schachtschabel, 2016, Huang et al., 2012, Brady and Weil, 2008) are primarily capacity parameters like cation exchange capacity, air capacity or plant available water (capacity) related to e.g. plant growth, yield or to environmental processes. This approach is certainly less straightforward then intensity parameters, which themselves are only valid in the rigidity ranges (Horn and Kutilek, 2009). However, such approach and the link to mechanical or hydraulic stresses amongst others improve the reliability of predictions for all kinds of hydraulic, mechanical, chemical or even climatic soil interaction processes.

Changes in soil functions like hydraulic conductivity, air permeability, redox potential, cation exchange intensity must be therefore related to parameters like precompression stress, aggregate strength, cohesion and angle of internal friction,. These strength parameters are appropriate to document the transition from elastic to plastic (= irreversible) changes in soil functions.

A quick approach to quantify stress induced changes of soil properties and consequences for ecological processes is the description of the rooting pattern, as it shows the effects of structure formation on plant growth, altered or even prevented accessibility of nutrients, water, air and the anchorage of the plant (Fig. 5).

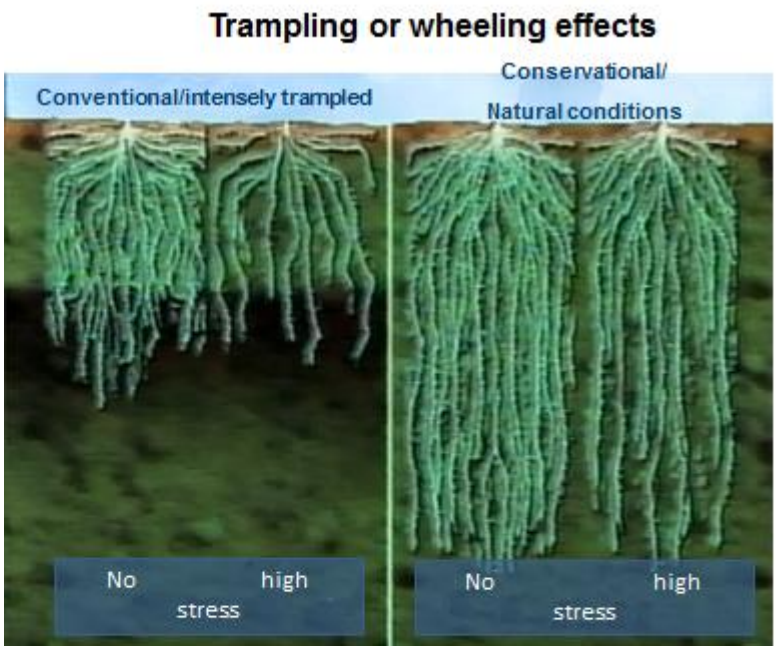


Figure 5. *Root growth and depth in soils: effects on availability and accessibility*

It is obvious, that deep rooting in soils is mostly prevented through a platy structure e.g. under conventional tillage or intensely trampled conditions and can be even furthermore reduced if more stress is applied. Conservation tillage or natural conditions with stronger aggregates and less dense conditions at the same time result in an even and deeper rooting, which guarantees a better plant growth with increased accessible particle or pore surfaces. The actual topic of carbon sequestration in soils to combat climate change effects is also linked with the accessibility and availability of particle or pore surfaces. However, it must be stated, that exceeding the internal soil strength i.e. the precompression stress results in a reduced rooting depth and intensity and less positive effects.

Furthermore, intensity parameters are mostly vectors and sensitive markers for soil properties changes in directions and time. Thus, pedogenic, geogenic or anthropogenic processes and their effects on flux processes or interrelated changes in biological, physical, and chemical functions including filtering and buffering, soil water erosion, or even the gas emission are direction dependent. They differ in quantity and quality at the given structure conditions and can be only quantified and extrapolated within the rigidity range of the pore system. Furthermore are the actually existing properties as the result of former management reference points for additional changes when exceeding the rigidity of pore functions.

Interaction between mechanical and hydraulic properties

Soil deformation due to applied mechanical stresses alters both pore volume and size distribution (Krümmelbein, 2007, Zhao et al., 2010, Horn and Peth, 2011), as well as it affects pore connectivity, with major impacts on water and air conductivity. (Fig.6)

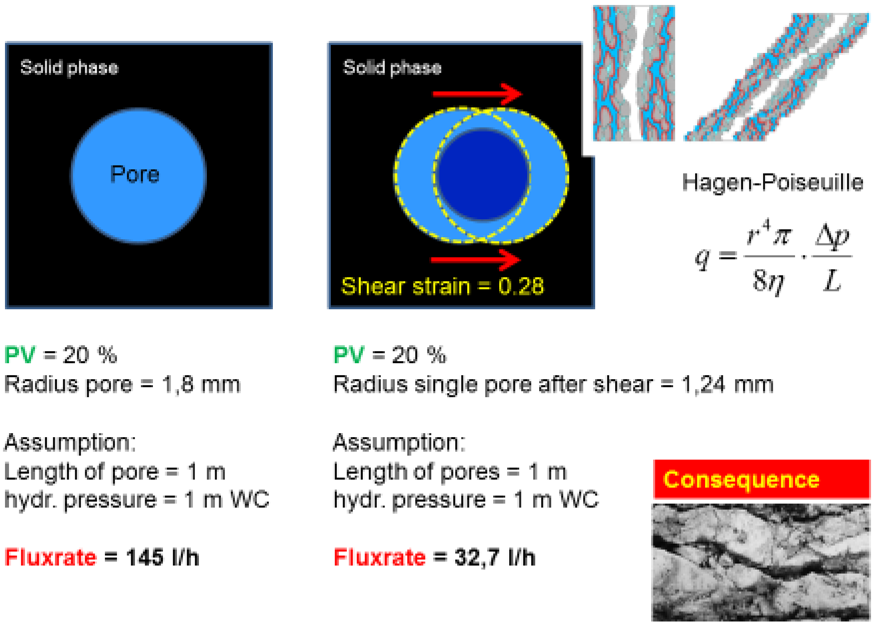


Figure 6. *Effect of shear deformation on pore space dynamics and water flux*

Reszkowska et al. (2011) proofed that even depending on the trampling intensity not only a drastic and mostly irreversible reduction of the hydraulic conductivity occured especially in the topsoil but the direction dependent changes in the fluxes serve as indicator for the preservation of soil sustainability (Fig. 7).

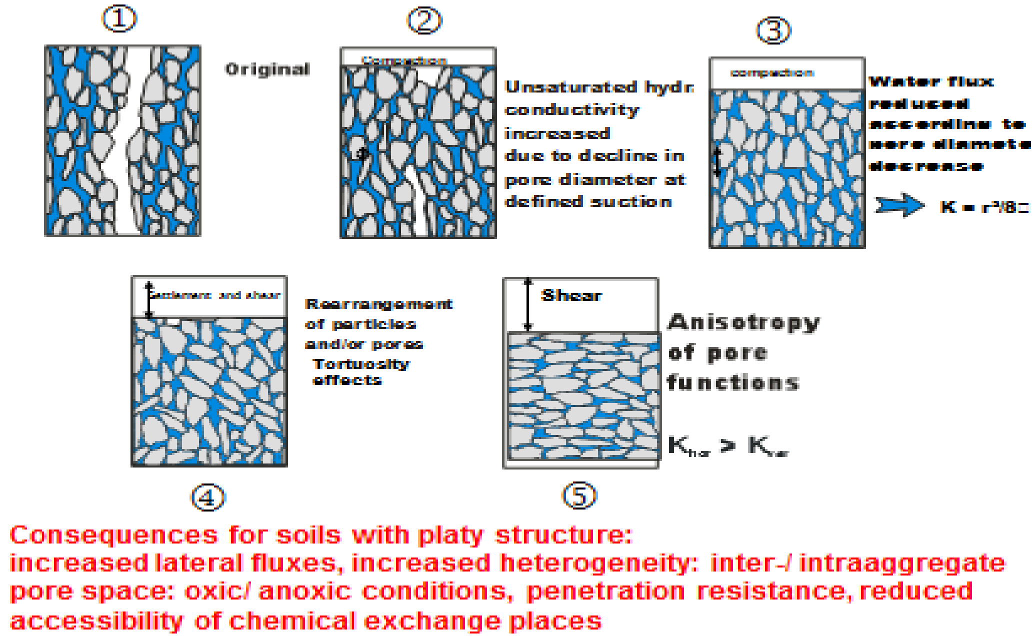


Figure 7. *Stress and strain effects on hydraulic properties*

Within the recompression stress range the pore size distribution and the hydraulic conductivity both remain constant as it was proved by uncounted measurements summed up in DVWK (1995,1997) directives. In the virgin compression load range, however, decreases the total pore volume, air capacity, and the saturated hydraulic conductivity even if the plant available water content partially increases at low stress application. In total are the pore system as well as the functions unstable and react flexible in this stress range.

3.3. Coupling of physical, chemical and biological processes

Soil structure properties and functions are interlinked with mechanical stresses (Fig. 8)

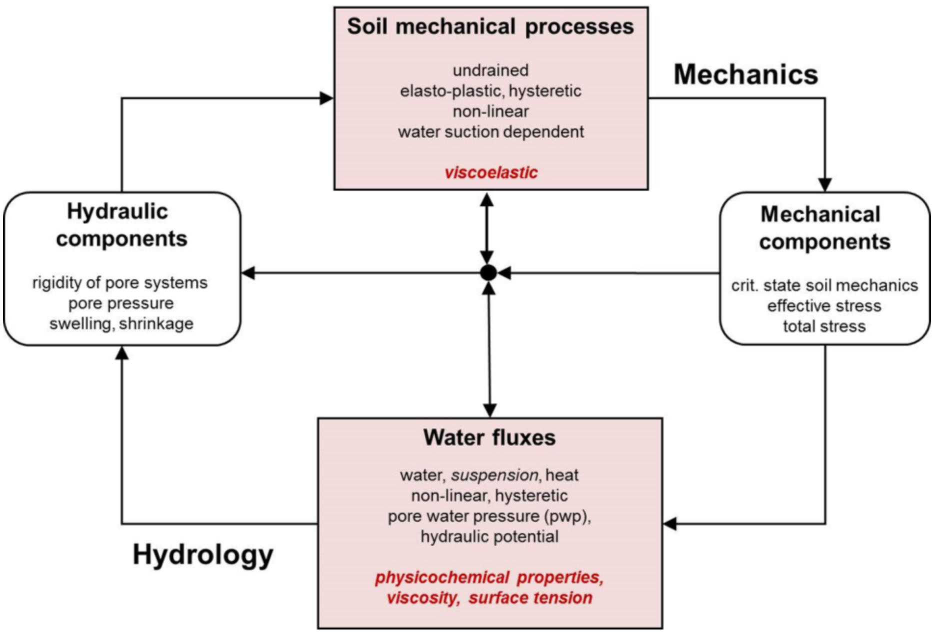
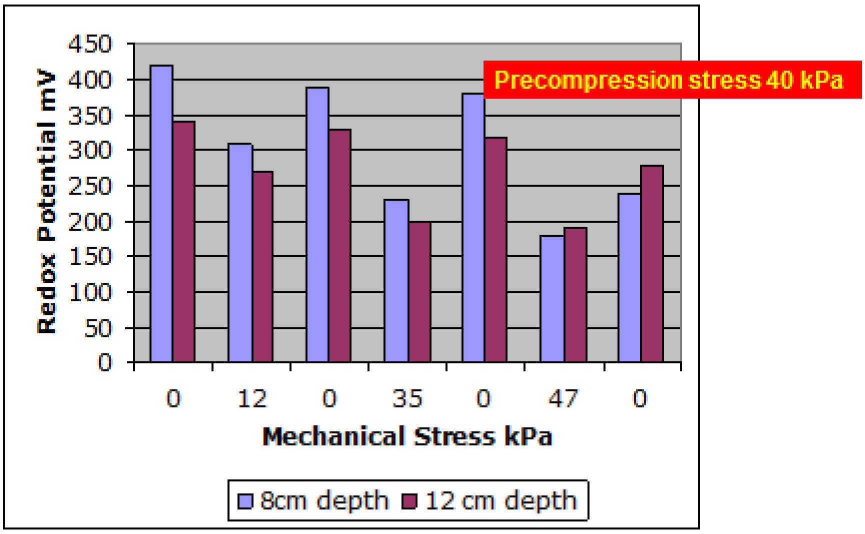


Figure 8. *Coupled mechanical and hydraulic properties and processes (modified after Richards et al., 2001)*

How intense these interactions also coincide with microbiological behaviour if stressed mechanically can be derived from the sink source changes of CO_2 or CH_4 emission under stress (Fig. 9). As long as the internal soil strength is not exceeded, the stress-induced decline in redox potential regains the former values after stress release, while after exceeding the rigidity of the soil structure results in a continuous and permanent decrease of the redox potential values. The strong interactions between stress application and changes in biological activity can be also derived from the changes in CO_2 emission and even in the formation and release of methane because of completely anoxic conditions in soils (Horn, 1985; Horn et al., 2009). Exceeding the precompression stress therefore also separates microbial species from their origins, which again underlines the necessity to quantify and to separate the internal strength and related permanent properties from unpredictable soil properties and behaviour in the virgin compression load range.



Cambisol Ah horizon, pH: 5.2, -60 hPa, alpine forehill pasture land, cattle herds

Data taken from Horn 1985

Figure 9. *Redox Potential values as function of applied mechanical stress.*

In the same context can be discussed the gas exchange with the atmosphere, the aeration of the rhizosphere and the composition of the microorganisms (oxic/anoxic) (Horn and Smucker 2005, Uteau et al., 2014, Krümmelbein et al., 2013). Doerner and Horn (2006), documented the increasing effect of stress and shear affected horizontal anisotropy on the hydraulic and gas permeability, which coincides with a retarded gas exchange and an increased proportion of e.g. CO_2 or even CH_4 in soil pores and hinders the normal population growth. If the internal soil strength is exceeded the microbial composition and activity is converted to anoxia and results even in the emission of CH_4 (Haas et al., 2016). Additionally an aggregate dependent carbon sequestration is enhanced and depends on its previous soil management or history (Wiesmeier et al., 2012). Thus, the rigidity quantified as precompression stress separates the beneficial storage and increased accessibility from the non-rigid conditions and a complete alteration of the physicochemical properties and processes and affects not only the internal soil processes but also even the atmospheric composition.

Limitations for modelling approaches

These strong interactions and sensitive changes of soil properties and functions in relation to the amongst others mechanical, hydraulic history of soils or even soil horizons require a more general classification of such rigidity interactions also with respect to modelling approaches. Table 1 sums up the effects of soil structure in various soil horizons on properties, and options to model physical processes. Weak aggregates are very sensitive to stresses and alter the properties very intensely already at low stresses, while more advanced aggregates are more rigid and maintain their properties over a larger stress range. Consequently, the accessibility of surfaces e.g. for cation exchange processes is limited in weak aggregates and the pore system is not very rigid and can therefore not be reliably used for modelling. Very rigid soil horizons like those with polyhedral or sub angular blocks allow more reliable model predictions.

These difficulties also prevent a reliable modelling of coupled processes because these input data still is mostly unknown and require a more advanced research for process based modelling of transport processes in the Soil Plant Atmosphere continuum.

Table 1. *Effect of soil structure in various soil horizons on properties, and options to model physical processes. (Horn and Smucker, 2005)*

	property	property	property	time dependence of functions	time dependence of functions	time dependence of processes	modelling
	typical horizons	typical structure	rigidity of pore system	pore system	hydraulic properties	pore water pressure (due to compaction)	application of (existing) models
ploughed horizon	Ap	coherent	small	very high	extreme	extreme	impossible
plough pan	App	platy	extremely high	small	small	high	++
subsoil	Al (clay depletion)	coherent	small	high	high	medium	- -
	Ae (eluviation)	coherent	small	medium	high		-
	Bt (clay accumulation)	subangular blocky - prism	very high-medium	small-medium	small-medium		++
		coherent, cementation	small	small	medium		+
	Bhs (illuviation of organic compounds, sesquioxides)	prismatic-polyhedral	medium-high	medium	high		-
	Bv (weathering, oxidation)	coherent	small - high (glacial till	high small	very high medium	small	- -
	C (parent material)	solid (rock)	extremely high	extremely small	very small		+ (++)

Conclusions

Soil structure formation results in increased mechanical strength, which can be quantified both by the precompression stress or the parameters of the Mohr Coulomb failure line. The higher the internal soil strength the more pronounced is the rigidity of the pore system and the more elastic react soils within the recompression load range.

The elasticity is replaced by plastic irreversible soil deformation within the virgin compression load range and causes additional changes in soil functions.

Physical, chemical, and biological properties show an identical pattern with mostly constant values within the recompression load range and alterations beyond the precompression stress value. Thus, within the recompression load range behave the soils primarily elastic, while in the virgin compression load range (beyond the precompression stress) react soils with a plastic deformation and a corresponding intense change in physical, chemical and biological properties and functions.

All corresponding modelling attempts are therefore limited to this recompression stress range, where the rigidity assumption still holds true. As long as the soil structure remains rigid, all soil functions remain and can guarantee corresponding ecological functions and even maintain an extended biodiversity.

The main parameters and functions of the hydraulic, gas, or heat flux under given potential gradients must be added by the rigidity information in order to finally obtain in future work also a more complete insight in the effect of Land-use Management Systems on Coupled Hydraulic Mechanical Soil Processes Defining the Climate-Food-Energy-Water Nexus"

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