

Soil Structure Formation and Management Effects on Gas Emission

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Abstract: The aim of this paper is to clarify the effect of soil management and thus also of soil aggregation on physical and chemical properties of structured soils both on a bulk soil scale, for single aggregates, as well as for homogenized material. Aggregate formation and aggregate strength depend on swelling and shrinkage processes and on biological activity and kinds of organic exudates as well as on the intensity, number and time of swelling and drying events. Thus, soil management like conventional or conservation tillage alter not only the mechanical strength but also the pore continuity and the hydraulic, gas and heat fluxes, and also alter the accessibility of exchange places for nutrients and for carbon storage (global change aspects). Based on the present state of knowledge, aggregates are in the beginning denser than the bulk soil. The intra-aggregate pore distribution consists not only of finer pores but these are also more tortuous. Therefore, water and gas fluxes in aggregated soils are mostly multidimensional and the corresponding water fluxes in the intra-aggregate pore system are much smaller. Furthermore, gas diffusion fluxes, as well as the composition depend intensely on the pore continuity. Depending on the kind and intensity of aggregation, the intra-aggregate pores can be completely anoxic, while the inter-aggregate pores are already completely aerated. Thus, soil management effects can be also derived from the gas composition in the soils. The same effect can be also proofed for the ion transport both by mass flow and diffusion which are delayed if the accessibility of exchange places is reduced due to compressive forces or repeated soil disturbance. The main effects can be summarized by an altered length of the flow path in such tortuous finer pores which further retards chemical exchange processes. The rearrangement of particles by aggregate formation also induces an increased apparent thermal diffusivity as compared with the homogenized material. The possibility to predict physical properties on these various scales depends on the rigidity of the pore system. In general this rigidity depends on the above-mentioned physical and chemical processes both with respect to intensity and frequency which again are linked to the soil management systems.

Key words: Aeration; Aggregate formation; Anoxia; Biomass; Carbon; Carbonates; Dissolved organic carbon; Hydraulic properties, Intra-aggregate pores; Modelling; Plant residues; Respiration; Root Exudates; Swelling; Shrinkage;

PROCESSES OF AGGREGATE FORMATION AND PERSISTENCE

Soils containing more than 12% clay (particle size < 2 μm) or even pure sandy soils with some salts tend to form aggregates. Usually the process occurs when soils dry and swell, and it is further enhanced by biological activity. Aggregates may show great variation in size from crumbs (diameter < 2mm) to polyhedre or subangular blocks of 0.005-0.02 m, or even to prisms or columns of more than 0.1 m. During the first period of shrinkage, mineral particles are pulled together by capillary forces which increase the number of points of contact and result in a higher

bulk density. The initial aggregates always have rectangular-shaped edges because, under these conditions, stress release would occur perpendicular to the initial crack and stress would remain parallel to the crack (strain-induced fracturing). However, due to the increased mechanical strength the particle mobility declines and results in the formation of nonrectangular shear plains as the following crack generation. They are created after repeated swelling and shrinking processes and result in fractures in which the value of the angle of internal friction determines the deviation from 90° (Or and Ghezzehei. 2002). In newly-formed aggregates, the number of contact points depends on the range of water

potential and on the distribution of particle sizes as well as on their mobility (i.e., state of dispersion, flocculation, and cementation). Soil shrinkage, including crack formation, increases bulk density of aggregates. The increase in bulk density with the initial wetting and drying of the soil permits the aggregates to withstand structural collapse. The increase of the strength of single aggregates is further enhanced by a particle rearrangement, if the soil is nearly saturated with water increasing the mobility of clay particles due to dispersion and greater menisci forces of water. (Horn and Dexter, 1989). Following drying causes enhanced adhesion by capillary forces which lead to greater cohesion as mineral particles are brought into contact following the evaporatory losses of the capillary water. Thus, the strength of the bigger i.e. initial aggregates is increased due to a particle mobilization and results both in smaller and stronger aggregates with even a smaller aggregate bulk density. The strongest aggregate type under this aspect is the spherical shape which has reached the stage of the smallest free entropy. Therefore, aggregate strength depends on (i) capillary forces, (ii) intensity of shrinkage (normal/residual), (iii) number of swelling and shrinkage cycles, i.e. the shrinkage/swelling history, (iv) mineral particle mobility (i.e., rearrangement of particles to achieve arrangements of lowest free energy), and (v) bonding energy between particles in/or between aggregates or in the bulk soil. Generally, aggregates persist As long as the soil strength (defined by the failure line of Mohr-Coulomb) is higher than the given load or shrinkage forces (Horn et al., 1994). Fig. 1 informs about the general aggregate type dependent Mohr Coulomb failure line as well as Horn et al. (2005) summarized based on numerous measurements structure dependent values for the angle of internal friction and cohesion as a function of texture and predrying intensity.

If however, additional kinetic energy (which even is more efficient in combination with accessible water) is applied, aggregate deterioration and homogenization occurs. Thus, a complete homogenization of the soil structure due to shearing and/or puddling takes place if kneading (expressed as octahedral shear stresses and mean normal stresses) exceeds the aggregate and structure strength. After a mostly complete homogenization normal shrinkage

processes start again (Horn et al., 1994). Consequently, a weaker soil structure and finally a pasty structure can be defined by very small cohesion and angle of internal friction values (Horn, 1976, Janssen et al. 2006). Thus, the determination of soil and/or aggregate strength has always to be subdivided into (1) mechanically, hydraulically or chemically prestressed and (2) virgin conditions, which also ultimately affect the predictability of physical properties. These general ideas have been described in greater detail by Hartge (1965), Toll (1995), Baumgartl and Horn (1999), Groenevelt and Grant (2002), Grant et al. (2002).

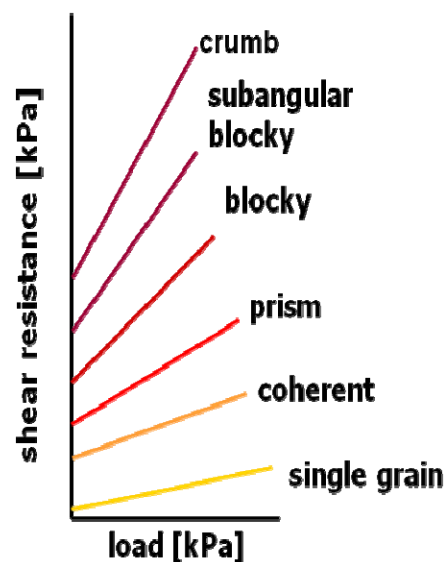


Fig. 1. Mohr Coulomb failure line for various aggregate elements (generalization)

In conclusion, it has to be stated, that aggregate formations as well as changes in aggregate strength are directly related also to tillage systems. Conventional tillage especially of the A-horizon annually includes plowing, chiseling and the seedbed preparation apart from multiple wheeling events depending on the crop management requirements which ends in mostly homogenized structure conditions annually. Thus, a more complete aggregate formation will not take place. Conservational tillage systems on the other hand causes less disturbance and allow a more complete rearrangement of particles and strengthening of the structure system if preserved throughout several years.

SOIL AERATION

In general, soil aeration is governed by two processes, namely (a) transport of 21% oxygen from the atmosphere into the soil and (b) consumption of oxygen by biological respiration or by chemical reactions. Enhancement of gas transport in the soil occurs both as mass flow along a pressure gradient and as diffusional flow with a concentration gradient in air-filled pores. As for water, gas transport phenomena in soils also include the problem of pore size distribution, pore continuity and water saturation. Gas transport in soil profiles will occur preferentially through this inter-aggregate pore system formed by macropores. Additionally, net oxygen diffusion to sinks (respiration by soil microorganisms) in the intra-aggregate pores is induced by the concentration gradient. Besides diffusion, diurnal pressure and temperature changes allow an exchange of soil macropore air by mass flow processes. However, the transported gas volume is rather small and exchanged gas volumes are mainly in the top 20 cm of the soil (Glinski and Stepniewski, 1985). Oxygen diffusion to soil microbial respiration sinks takes place in the interaggregate pores and is controlled by the concentration gradients resulting from respiration. When oxygen demands, within soil aggregates, are high and O₂ diffusion is limited by partial or complete water saturation and low pore continuity, anoxic sites develop even if the interaggregate pore space contains sufficient oxygen. These anoxic conditions occur frequently at oxygen sink microsites (eg., rhizospheres, decomposition hot spots, etc. within the soil profile (Fig.2).

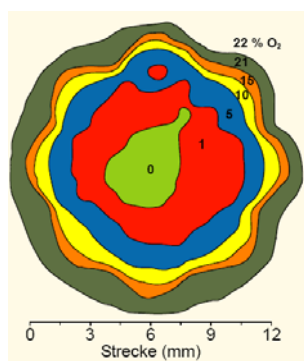


Fig.2. Oxygen distribution within single aggregates

It was also found that the intensity of anoxia and the diameter of anoxic centres would be controlled

not only by microbial and chemical oxygen demand but also by parameters such as aggregate hydraulic conductivity and pore size distribution. A mathematical description of oxygen fluxes to plant roots was given by Simojoki (2001). In addition it has to be pointed out that the air entry value is reached only at more negative matric potential values the denser and more developed they are. In prisms of sandy-loamy texture the increase in O₂ partial pressure occurred at a soil water potential of about -15 kPa while polyhedrons with loamy-clay became aerated at more negative water potentials of < -60 kPa (Zausig et al., 1990). (Fig.3)

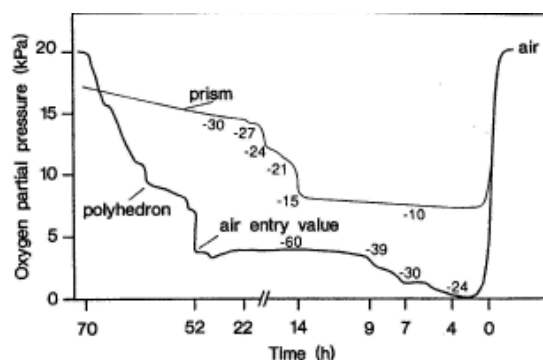


Fig.3. Oxygen partial pressure as a function of soil water potential - Changes inside a prism (loamy sand) and in a polyhedron (loamy clay) (taken from Zausig et al. 1990)

If the depth depletion of the air filled porosity and of the relative gas diffusivity (i.e. the ratio of the gas diffusion in soil to that in air) for a Luvisol derived from loess (site Goettingen) is plotted as a function of a mechanical stress applied due to wheeling, both values decrease. If we furthermore compare the change of the initial values in the arable soil (6% air filled pores and 0.02 for the relative gas diffusivity-classified as very low) with those after the first time stressing with a 6 row sugar beet harvester in autumn 2003 (35Mg mass) a further decrease below these accepted minimum values was proofed (Stepniewski et al. 1994, Simojoki et al. 2008, Wiermann and Horn 2000). Thus, it became obvious that even only a single wheeling with such too heavy machine resulted in a further value decrease for both parameters which explain and proofed the tremendous negative effect of such machines on soil structure: i.e. aeration, water infiltration and physicochemical processes if the internal soil strength is too low (Fig.4).

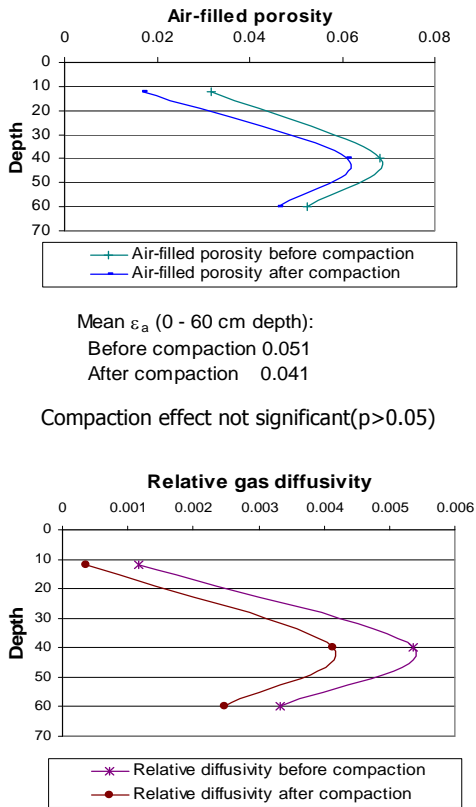


Fig.4. Stress induced changes in gas diffusion and air filled porosity in a silty luvisol derived from loess

EFFECT OF SOIL MANAGEMENT ON GAS COMPOSITION

Each reduction in conducting coarse pores also result not only in a prevented CO₂ exchange to the atmosphere and a prevented O₂ flux in the soil but it will also lead to anoxic conditions in the soil which will also affect the quality and quantity of the emitted gas.

Aeration and gas exchange in soils always depend on the microbial composition and activity, which depending on the pH value and water saturation can lead to an enormous alteration of the gas composition, microbial activity and composition, and redox potential values. As an example of possible stress effects on redox potential changes in dependence of the internal soil strength (expressed as precompression stress) Fig.5 informs about stress dependent Eh value changes in an Ah horizon of a Cambisol. It can be seen that stressing with up to 35 kPa followed by a stress release (0kPa) at both depths always resulted in a complete recovery. If exceeding the internal soil strength of approximately

42 kPa by a further increase to 47 kPa a significant and irreversible decline was detected with no recovery after stress release.

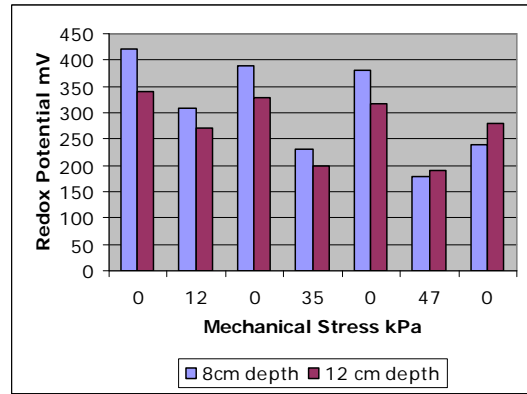


Fig. 5. Redox Potential values as a function of applied cyclic mechanical stress

Thus, all chemical elements which undergo a valence change depending on the actual Eh value at the given pH may be also mobilized and translocated to the more aerated soil volumes. Amongst the EH-sensitive elements are under more un-aerated soil conditions e.g. from the completely aerated condition: NO₃⁻ (to N₂O or at last NH₄⁺) or CO₂ (to CH₄ in case of complete anoxic conditions) as well as Fe (³⁺ to ²⁺) or Mn (⁴⁺ to ²⁺). Thus, also the chemical compositions of the gas composition in the soil or that of the seepage water are affected.

Ball et al. (2000) e.g. described the effect of N₂O emission due to wheeling throughout the year and also included N-fertilization (Fig.6).

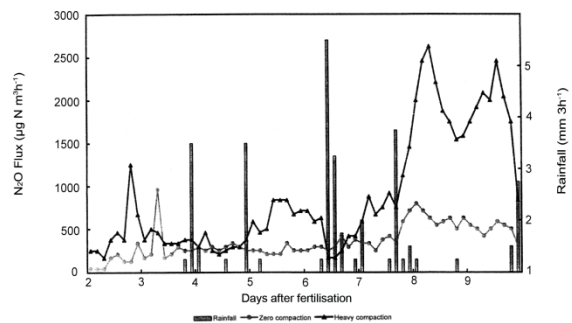


Fig.6. Effect of Soil Compaction on the N₂O Fluxes in Soils (according to Ball et al. 2000) Cambisol Ah horizon, pH 5.2, -60 hPa matric potential

In compacted soils N_2O emission was significantly increased after fertilization and especially if in addition rainfall had re-saturated the soil. Under zero compaction no intense changes were to be seen which can be explained by a higher water infiltration rate and a quicker re-aeration of the coarse and gas and water conducting pores. If we furthermore consider the compaction dependent reduction of CH_4 consumption in soils which is approx. 50%, we can also calculate the CO_2 equivalents from CH_4 consumption are texture dependent (Teepe et al. 2004): 47kg/ha a (silty clay loam), 157 (silt), 249 (sandy loam). Assuming that only 6% of the area was compacted, the reduction of the CH_4 consumption in terms of CO_2 equivalents resulted in 4, 11, 13 kg CO_2 /ha a, respectively. Based on the dataset of Stepniewska et al. (1997) a soil texture dependent resistivity values for a given redox potential value of 300 mV could be used to quantify the resistance against Eh changes. If 300 mV irrespective of the stress applied at a given texture is still available after 5 days, we could classify the soil as rigid. If on the other hand within less than 3 days the critical value is further declined a more severe stress effect has to be considered.

GLOBAL WARMING POTENTIAL AND CONSEQUENCES FOR SOIL MANAGEMENT

If based on numerous measurements about the global change effect of various tillage systems a general classification scheme is developed, we can prove that Global warming potential (GWP), expressed in CO_2 units, are produced at higher rates by conventionally tilled, than by organic or bio- managed and no-till agricultural production systems. In contrast, unmanaged ecosystems produce less GWP, especially in the early stages of their plant succession (Fig. 7).

CONCLUSIONS

- Soil structure formation, its conservation, and the formation of a continuous and accessible pore system are of main importance for a sustainable land use.
- The described general interactions make clear that a rigid pore system and a well structured soil with well developed aggregates, well accessible soil particle surfaces, a pore system with high pore continuity, high microbial i.e. bacterial activity govern not only sufficient O_2 imission but also CO_2 emission and the prevention of any kind of reductive processes in arable or forest soils due to land use effects.
- Soil conservation, reduced tillage systems and a site specific machine application are of major importance to sustain the available soil productivity and the dominant role of soils in ecosystem managements.

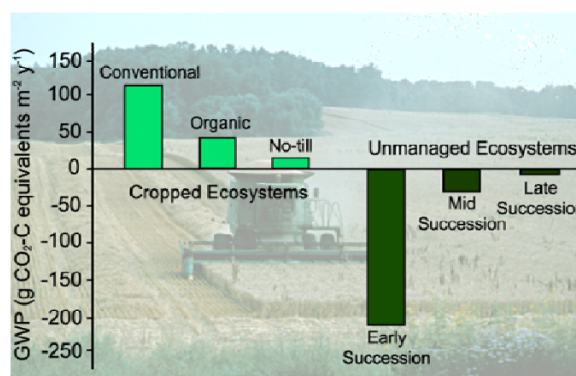


Fig. 7. Global warming potential (GWP), expressed in CO_2 units, are produced at higher rates by conventionally tilled, organic or bio- managed and no-till agricultural production systems. In contrast, unmanaged ecosystems produce less GWP, especially in the early stages of their plant succession. Photo and graph produced by E.P. Robertson, KBS/LTER at MSU. (With courtesy of A. Smucker 2006)

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