Biologia **64**/3: 449—453, 2009
Section Botany
DOI: 10.2478/s11756-009-0089-4

Soil structure formation and management effects on gas emission

Rainer Horn & Stephan Peth

Institute of Plant Nutrition and Soil Science, Christian-Albrechts-University zu Kiel, Hermann-Rodewald-Str. 2, D-24118 Kiel, Germany; email: rhorn@soils.uni-kiel.de

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). 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; hydraulic properties; intra-aggregate pores; modelling; 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 < 2 mm) 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 & 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 & 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. At a given predrying intensity and texture, singular and coherent structure units are weaker than prisms. Blocky structure is weaker than subangular blocky structure which results in increasing values for the cohesion and angle of internal friction. (Horn et al. 1994, 2005).

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 & Horn (1999), Groenevelt & Grant (2002) and Grant et al. (2002).

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 & 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 O_2 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 (e.g., rhizospheres, decomposition hot spots, etc.) within the soil profile. 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 O_2 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. 1).

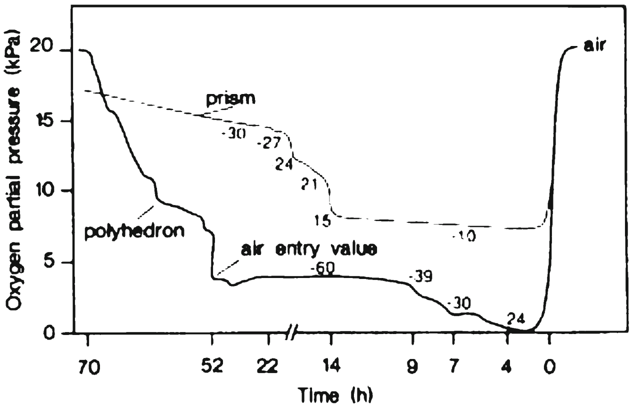

Fig. 1. Oxygen partial pressure as a function of soil water potential: changes inside a prism (loamy sand) and in a polyhedron (loamy clay) (taken from Zausig et al. 1990).

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 (35 Mg mass) a further decrease below these accepted minimum values was proofed (Stepniewski et al. 1994; Simojoki et al. 2008; Wiermann & Horn 2000).

Thus, it became obvious that even only a single wheeling with a heavy machine like a sugar beet harvester (35 Mg) 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. 2).

Effect of soil management on gas composition

Each reduction in conducting coarse pores also result

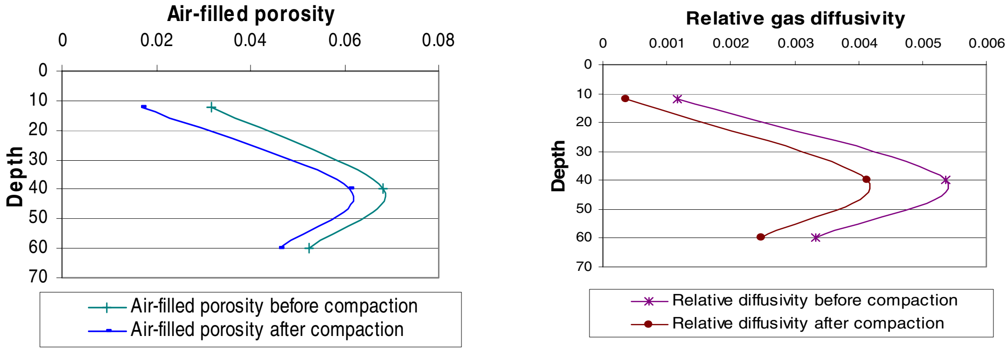

Fig. 2. Stress induced changes in gas diffusion and air filled porosity in a silty luvisol derived from loess (Simojoki et al. 2008). Mean ε_a (0–60 cm depth): Before compaction 0.0051, after compaction 0.0041. Compaction effect not significant ($p > 0.05$).

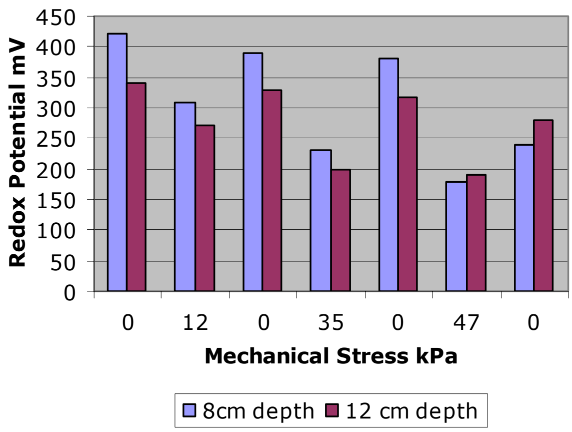

Fig. 3. Redox potential values as a function of applied cyclic mechanical stress (Cambisol Ah horizon, pH 5.2, matric potential: –60 hPa).

not only in a prevented CO_2 exchange to the atmosphere and a prevented O_2 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. 3 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 (0 kPa) 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. Consequently, 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 less aerated soil conditions e.g. from the completely aerated condition: NO_3^- (to N_2O or at last NH_4^+) or CO_2 (to CH_4 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. (1999) e.g. described the effect of N_2O emission due to wheeling throughout the year and also included N-fertilization (Fig. 4). In compacted soils N_2O emission was significantly increased after fertilization and especially if in addition rainfall had resaturated 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 pores conducting primarily gas and water. 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, which 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) 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 proof that Global warming potential (GWP), expressed in CO_2 units, is 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. 5).

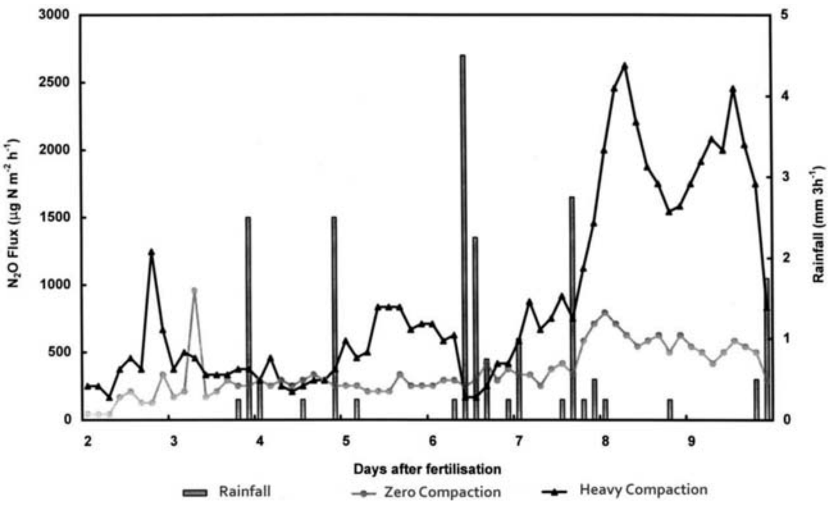

Fig. 4. Effect of soil compaction on the N_2O fluxes in soils (according to Ball et al. 1999).

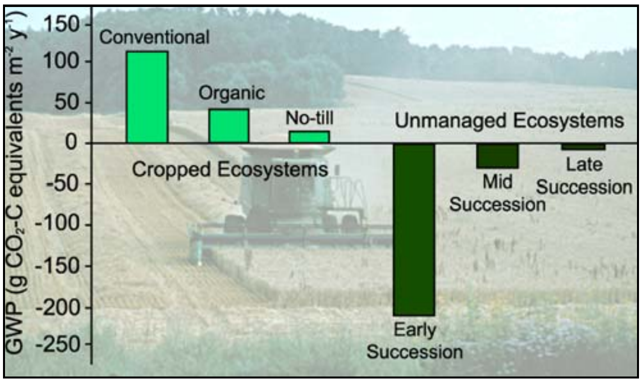

Fig. 5. Global warming potential (GWP), expressed in CO_2 units, are produced at higher rates by conventionally tilled, organic or bio- managed and no-till agricultural production systems. In contrast, unmanaged ecosystems produce less GWP, especially in the early stages of their plant succession. Photo and graph produced by E.P. Robertson, KBS/LTER at MSU. (With courtesy of Prof. Dr. A. Smucker – more detailed info are in Smucker and Hopmanns 2007).

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.

References

Ball B.C., Scott A. & Parker J.P. 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Till. Res. **53**: 29–39.

Baumgartl T. & Horn R. 1999. Influence of mechanical and hydraulic stresses on hydraulic poperties of swelling soils, pp. 449–457. In: van Genuchten M.Th., Leij F.J. & Wu L. (eds), Characterisation and measurement of the hydraulic properties of unsaturated porous media. University of California, Riverside.

Glinski J. & Stepniewski W. 1985. Soil aeration and its role for plants. CRC Press, Boca Raton, 287 pp.

Grant C.D., Groenevelt P.H. & Bolt G.H. 2002. On hydrostatics and matristatics of swelling soils, pp. 95–105. In: Raats P.A.C. et al. (eds), Environmental Mechanics: Water, Mass, and Energy Transfer in the Biosphere. Geophysical Monograph 129, AGU.

Groenevelt P.H. & Grant C.D. 2002. Curvature of shrinkage lines in relation to the consistency and structure of a Norwegian clay soil. Geoderma **106:** 235–247.

Hartge K.H. 1965**.** Vergleich der Schrumpfung ungestörter Böden und gekneteter Pasten. Wiss. Z-. Friedr Schiller Uni Jena, Math. Naturw. Reihe **14:** 53–57.

Horn R. 1976. Mechanical strength changes due to aggregate formation of a mesocoic clay. PhD Thesis, TU Hannover (in German).

Horn R. & Dexter A.R. 1989. Dynamics of soil aggregation in an irrigated desert loess. Soil Till. Res. **13:** 253–266.

Horn R., Taubner H., Wuttke M. & Baumgartl T. 1994. Soil physical properties and processes related to soil structure. Soil Till. Res. **30:** 187–216.

Horn R., Fleige H., Richter F.-H., Czyz E. A., Dexter A., Diaz-Pereira E., Dumitru E., Enache R., Rajkai K., de la Rosa D. & Simota C. 2005. SIDASS project part 5: Prediction of mechanical strength of arable soils and its effects on physical properties at various map scales. Soil Till. Res. **82:** 47–56.

Janssen I., Peng X. & Horn R. 2006. Physical soil properties of paddy fields as a function of cultivation history and texture. Adv. Geoecol. **38:** 446–455.

Or D. & Ghezzehei T.A. 2002. Modeling post-tillage soil structural dynamics: a review. Soil Till. Res. **64:** 41–59.

Simojoki A. 2001. Oxygen supply to plant roots in cultivated mineral soils. Pro Terra, 7; Doctoral Dissertation. Yliopistopaino, Helsinki. ISBN: 951–45–9926–8.

Simojoki A., Fazekas-Becker O. & Horn R. 2008. Macro- and microscale gaseous diffusion in a Stagnic Luvisol as affected by compaction and reduced tillage. Agricul. Food Sci. **17:** 267–277.

Smucker A.J.M. & Hopmans J.W. 2007. Soil Biophysical Contributions to Hydrological Processes in the Vadose Zone. Vadose Zone J. **6:** 267–268.

Stepniewska Z., Stępniewski W. Gliński J. & Ostrowski J. 1997. Atlas of Redox Properties of Arable Soils of Poland. Institute of Agrophysics PAS and Institute of Land Reclamation and Grassland Farming, Lublin-Falenty, Poland.

Stępniewski W., Gliński J. & Ball B.C. 1994. Effect of compaction on soil aeration properties, pp. 167–189. In: Soane B.D. & Overkerk C. (eds), Developments in Agricultural Engineering 11: Soil Compaction in Crop Production, Elsevier Science BV, Amsterdam.

Teepe R., Brumme R., Beese F. & Ludwig B. 2004. Nitrous oxide emission and methane consumption following compaction of forest soils. Soil Sci. Soc. Am. J. **68:** 605–611.

Toll D.G.1995. A conceptual model for the drying and wetting of soil, pp. 805–810. In: Alonso E.E. & Delage P. (eds.), Proc. Int. Conf. on Unsaturated Soils. Balkema, Rotterdam, Paris. ISBN: 9054105852.

Wiermann C. & Horn R. 2000. Effect of different tillage systems on the recovery of soil structure following a single compaction event. In: Horn R., van den Akker J.H. & Arvidsson J. (eds), Subsoil Compaction – Distribution, Processes and Consequences. Adv. Geoecol. **32:** 339–350.

Zausig J., Hell U. & Horn R. 1990. Eine Methode zur Ermittlung der wasserspannungsabhängigen Änderung des Sauerstoffpartialdruckes und der Sauerstoffdiffusion in einzelnen Bodenaggregaten. Z. Pflanzenern. Bodenkunde **153:** 5–10.

Received September 15, 2008
Accepted January 22, 2009