PLANT GROWTH IN RELATION TO SOIL PHYSICAL CONDITIONS

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PREFACE

Plant growth is closely related to soil physical conditions and processes. Agricultural field practices such as tillage and reconsolidation and other operations with heavy machinery have a significant effect on the physical behavior of soil. The alterations in the behavior affect in turn affect water and nutrient uptake, chemical concentration and movement, crop yield and environmental quality. On sloping areas these effects interact with the processes of runoff and erosion. Recently much new evidence on the soil physical conditions –plant relations under various land use and site conditions has been shown. New developments for measuring soil and plant properties allowed more precise quantification of the management practices effects on soil and plant structure and functions in space and time.

The aim of this volume is to provide overview on the effects of soil physical and physicochemical conditions and processes on productive functions of soils and environment. Suitability of some physical, physico-chemical and biological properties as indicators of soil quality is reviewed. Emphasis is given to the effects of soil stress and strain on ecological site functions and the role of structure stability and readily-dispersible clay in soil physical quality. Effects of soil physical and chemical stresses and weather conditions on root growth and functions, plant cellular structure and induction or break down plant defense system are presented. Some chapters focus on new methods for measurement and modelling of hydro-physical and thermal soil properties. Usefulness of dielectric spectroscopy in the characterization and quality control of agricultural materials is described. Finally, interactions of the soil conditions with heavy metal transformation are emphasized. Advices on how some plant parameters and soil physical quality can be measured are given.

We hope that this volume will be a useful source of information about the soil physical conditions and associated plant response and stimulate us to address further research needs, to the benefit of sustainable agricultural production and environment’s protection. Contributions of this volume were presented at Summer School in Lublin (17-18 September 2004) organized by Centre of Excellence AGROPHYSICS and the Institute of Agrophysics PAS in Lublin with financial support of European Commission and Polish State Committee for Scientific Research.

The Editors

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SOIL OXYGEN STRESS CONDITIONS AND PLANT DEFENSE SYSTEM INDUCTION (*TRITICUM AESTIVUM* L. AND *TRITICALE)*

Bennicelli R. P.

INTRODUCTION

WATERLOGGING AND CROP PRODUCTION

Present day representatives of the more than 300,000 plant species presently known to science occupy almost every terrestrial niche. However, although, their progenitors were aquatic, the land plants derived from them are relatively intolerant of free water in their surroundings, especially if it is slowly moving or immobile. The resulting effect is so severe that biochemical and morphological adaptations have emerged many times during evolution (Cook, 1999) to allow a sizeable minority of species to succeed in sporadically or permanently flooded areas on land. The ability of excess water to damage plants may seem counter-intuitive since water is chemically benign. However, certain physical properties of water, most notably its ability to interfere with free gas exchange – soil oxygen stress (Gliński and Stępniewski,1985), can injure and kill plants when they are totally submerged (Jackson and Ram, 2003) or even when only the soil is waterlogged (Vartapetian and Jackson, 1997).

Worldwide, it has been estimated that approximately 10 % of all irrigated farmland suffers from frequent waterlogging, which may decreases crop productivity by 20 %. But, in addition, many rainfed regions are also susceptible to temporary flooding. Furthermore, along with drought, salinity and mineral deficiency, flooding also has serious economic consequences for productivity of much arable farmland. Based on soil typing, Dudal (1976) estimated that 12 % of the World's soils are likely to suffer from excess water. Clearly, considerable transient and more persistent waterlogging of the soil and deeper submergence of crops occurs in much rainfed farmland world-wide. The extent of its occurrence remains speculative. This is because of a lack of useful definitions of what constitutes excess water content. Through such an approach we can appreciate that although statistically, floods are amongst the most common and widespread of all natural disasters and the effects are sometimes catastrophic it is the more mundane persistent inadequacies in soil drainage in the face of near-average or modestly excessive rainfall that constrain farm productivity year by year. Waterlogging damage to crops may sometimes occur when crops are irrigated. The dividing line between adequate and excessive irrigation is not well defined and it is probable that some of the benefits can be lost by heavy-handed irrigation. For example, ponding on the soil surface for more than a day is known to be harmful to wheat watered by flood-irrigation. Prolonged irrigation over many years in dry regions can cause waterlogging problems created by raising the water table.

The extent of damage to yield depends heavily on the stage of development as well as on more obvious factors such duration of waterlogging and temperature (Drew, 1997). For most crops, seed germination is probably the most vulnerable, reflecting both the fast metabolic rate of germinating seeds being coupled with complete inundation.

Once germinated, stages in subsequent development of crop plants influence susceptibility to flooding injury. Small cereal seedlings with their shoots below ground are highly susceptible (e.g., winter wheat – (Cannell et al. 1980) but thereafter tolerance rises until early reproductive stages when susceptibility again increases. Heightened vulnerability at or just before flowering has also been noted for several other crops including peas, wheat, sorghum, maize and cow peas (Cannell and Jackson, 1981) when inundated for one or more days. By contrast, several weeks of waterlogging in winter of young plants of crops such as autumn sown wheat or oil seed rape causes little yield loss because of compensatory growth in the following spring and the slower metabolic demands created by cool temperatures during the period of waterlogging.

Under optimal conditions the plant's content of reactive oxygen species (ROS) maintains, with the help of antioxidative defense system, at a level which is safe for the organism (Larson, 1988). Enzymes of superoxide dismutase and ascorbate – glutathione pathway eliminate the excess of H_2O_2 in chloroplasts, in the cytoplasm and in non photosynthesizing tissues (Foyer and Halliwell, 1976). Under stress conditions the formation of ROS can exceed the antioxidative potential of the cell and cause an oxidative damage (Halliwell, 1984).

The plant capability to activate the defense system against oxidative destruction may be a key link in the mechanism of plant tolerance to unfavorable conditions. Changes in the activity level of one or more antioxidative enzymes are connected with the plant resistance to stressor action (Allen, 1995).

Superoxide dismutases (EC 1.15.1.1.) are a family of metalloenzymes known to accelerate spontaneous transformation of free superoxide radicals (Fridovich, 1974). These active oxygen species (O_2^- , H_2O_2, $OH^{\cdot}$ and 1 O_2) are highly reactive and, in the absence of any protective mechanism, can damage cell wall structure and function (Kalashnikov *et a*l., 1992). Induction of SOD under anoxia is critical for survival of plants after re-exposure to oxygen (Monk *et a*l., 1987). Simultaneously, a significant rise in the lipid peroxidation product, malondialdehyde has been reported in rhizomes of flood-sensitive *Iris germanica* on return to air after oxygen deprivation, while its levels remained unchanged in flood-tolerant *Iris pseudocorus* (Gliński and Stępniewski, 1985).

AIM OF THE STUDY

The aim of the study was to elucidate the exact role of soil aeration parameters such as air-filled porosity (Eg), oxygen diffusion rate (ODR) and soil redox potential (Eh) on the induction of resistance response expressed by some important antioxidant protection physiological indicators related to soil oxygenation status: superoxide dismutase (SOD), glutathione reductase (GR), malondialdehyde (MDA), chlorophyll a + b level, as well as leaf stomatal resistance (Rd) (Bennicelli et al., 1998) in order to explain the differences in hipoxia and anoxia tolerance of cropped agricultural species as *Triticum aestivum L.* and *Triticale,* to determine the dividing line between adequate and excessive soil water content being the cause of the soil oxygen stress, starting the induction of plant defense system.

MATERIALS AND METHODS

The experiments were performed with the use of *Triticum aestivum L.* and *Triticale* in a growth chamber, in 30 plastic pots, 5.9 dm^3 in volume, filled with soil material from the Ap horizon of a brown loess soil (Eutric Cambisol). The pH in H_2O - 7.3 (pH in KCl - 7.1) containing 0.89% C_{org}, 15% of 1 -0.1mm fraction, 80% of 0.1-0.002 mm fraction, and 5% clay. Each pot contained 6.2 kg of soil (dry mass basis) packed to a bulk density 1.35 Mg m^{-3} corresponding to total porosity 48%. The air temperature was kept at 23±2°C and 12±2°C during the day and night, respectively. The day period was 12 hours with the light intensity of 190 Watt m^{-2}. The relative air humidity in the growth chamber was 45±5% during the day and 70±5% during the night. The experiment including five air-filled porosities (0, 8, 13, 19 and 24% as a control) in three replications (15 plants in each pot).

RESULTS

Under oxygen deficiency conditions experienced by the plant roots during the 12 days of flooding the soil a generalized adaptive response took place in the leaves, which were in the normal aerobic conditions. The relationship between Eg and ODR in experiments with *Triticale* and *Triticum aestivum* L. is shown in Fig. 1.

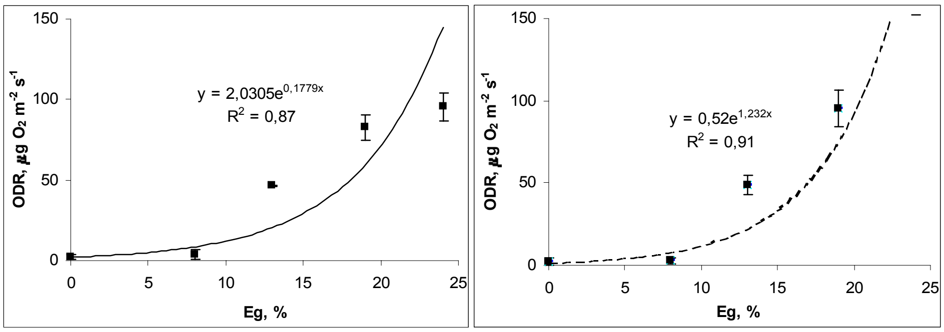

Fig. 1. Relationship between Eg and ODR in experiments with Triticale (left) and Triticum aestivum (right).

Stomatal diffusive resistance of the leaves express relations between soil and plant parameters in relation to soil aeration. The root hypoxia resulted in an increase of the value of leaf stomatal diffusive resistance vs. redox potential and oxygen diffusion rate, up to 60 s/cm in *Triticum aestivum* L- non tolerant of oxygen stress plant (Fig. 2).

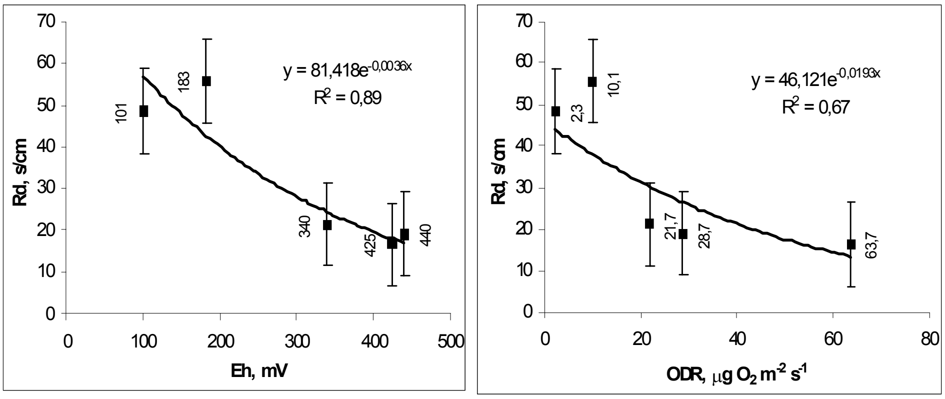

Fig. 2. Changes of stomatal diffussive resistance (Rd) in relation to Eh and ODR (Triticum aestivum L.). Mean value ± standard deviation.

Different soil oxygen stress conditions in the rhizosphere induced reactive oxygen species on cellular level (in roots and shoots) and the defense response of the plants was confirmed indirectly, through the increase of the activity of such enzymes as SOD and GR as well as by elevation of the degree of peroxidation of membrane lipids measured by the increase of MDA concentration (Fig. 3-5)

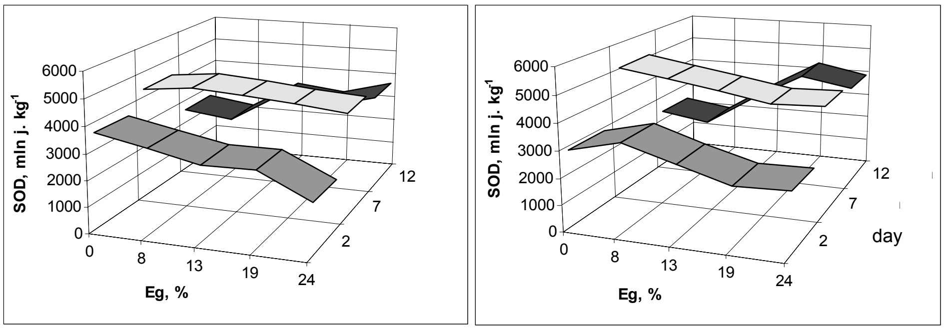

Fig. 3. *SOD activity in roots Triticale and Triticum aestivum after 2, 7, 12 days of oxygen stress at 5 levels of air porosity (Eg).*

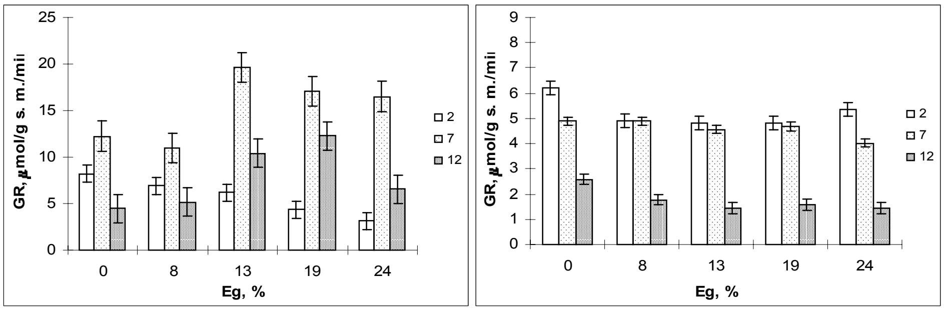

Fig. 4. Glutathione reductase activity (GR) activity in roots (left) and leaves (right) of Triticale after 2, 7 and 12 days of oxygen stress at 5 levels of air porosity (Eg). Mean value ± standard deviation.

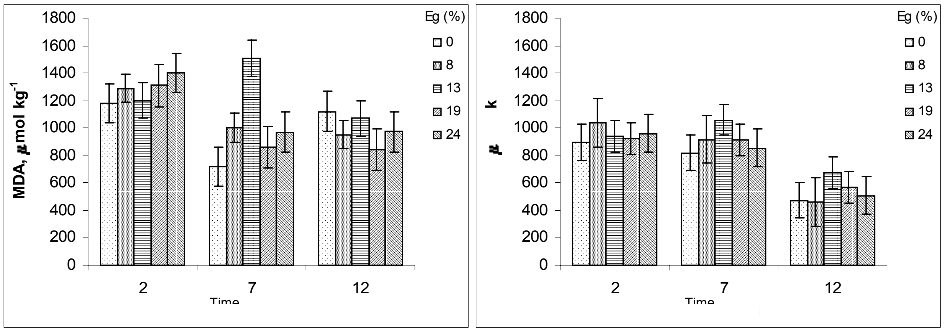

Fig. 5. Malondialdehyde (MDA)level in roots of Triticale (left) and Triticum aestivum L. (right) after 2, 7 and 12 days of oxygen stress at 5 levels of air porosity (Eg). Mean value ± standard deviation.

CONCLUSIONS

The aim of the paper was to investigate to what extent the capability of plants to survive anoxic conditions is connected with the induction of the defense system of two species of cereals such as winter wheat (*Triticum aestivum* L, var. Rosa) and *Triticale* (CZR 1406). The experiment was performed under laboratory conditions with the 20 days old seedlings in the phase of 4-6 leaves. The stress conditons were applied to roots during 12 days. Soil oxygenation status was characterised by air-filled porosity (Eg), oxygen diffusion rate (ODR) and redox potential (Eh). The physiological status of the plants was characterised by biomass production in leaves and shoots, by stomatal diffusive resistance of leaves (Rd), by activity of enzymes such as superoxide dismutase (SOD) and glutation reductase (GR) being components of the defense system, as well as by the chlorophyll a + b level and the concentration of malondialdehyde (MDA) being the product of lipid peroxidation.

As a result of the investigations performed the induction of plant defense system in the continuum atmosphere – plant – soil the following was stated under the conditions of oxygen stress imposed to the roots.

Decrease of air-filled porosity (Eg) from 24 to 0% connected with the differentiation of the soil moisture content caused a change from normoxic through hypoxic to anoxic conditions characterised by a decrease of ODR from 80 to 2 $\mu g\ O_2\ m^{-2}\ s^{-1}$ and of redox potential from 470 do 115 mV. This was accompanied by the increase of stomatal diffusive resistance, lowering the level of photosynthetic pigments and lowering the biomass of roots and shoots. Anoxic conditions in the rhizosphere induced reactive oxygen forms on cellular level (in roots and shoots) and the defense response of the plants was confirmed indirectly, through the increase of the activity of such enzymes as SOD and GR as well as by elevation of the degree of peroxidation of membrane lipids measured by the increase of MDA concentration.

Higher sensitivity to oxygen stress and break down of the defense system after 12 days of the anoxia duration was found for *Triticale*. On the basis of metabolic plant parameters the limiting values between normoxic and anoxic conditions such as Eg=13%, ODR $\cong$ 27 $\mu g\ O_2\ m^{-2}\ s^{-1}$, and Eh $\cong$ 400 mV were found.

REFERENCES

1. Allen R. D. 1995. Dissection of oxidative stress tolerance using transgenic plants. Plant Physiol 107: 1049-1054.
2. Bennicelli R. P., Stępniewski W., Zakrzhevski D. A., Balakhnina T.I., Stępniewska Z., Lipiec J. 1998. The effect of soil aeration on superoxide dismutase activity, malondialdehyde level, pigment content and stomatal diffusive resistance in maize seedlings. Environ and Experim Bot 39: 203-211.
3. Boyer J.S. 1982.Plant productivity and the environment. Science 218: 443-448.
4. Cannell R. Q., Belford R. K., Gales K., Dennis C. W., Prew R. D.1980. Effects of waterlogging at different stages of development on the growth of winter wheat. Journal of the Science of Food and Agriculture 31: 117-132.
5. Cannell R. Q., Jackson M. B. 1981. Alleviating aeration stresses. In H.M. Taylor [Ed.], Modifying the root environment to reduce crop stress, 141-192. American Society of Agricultural Engineers, St Joseph.
6. Cook C. D. K. 1999. The number and kinds of embryo-bearing plants which have become aquatic: a survey. Perspectives in Plant Ecology, Evolution and Systematics 2/1: 79-102.
7. Dudal R. 1976. Inventory of the major soils of the World with special reference to mineral stress hazards., Plant adaptation to mineral stress in problem soils, 3-13. Cornell University, Ithaca, New York.
8. Drew M. C. 1997. Oxygen deficiency and root metabolism: injury and acclimation under hypoxia and anoxia. Annu. Rev. Plant Physiol. Plant Mol. Biol., 48, 223-250.
9. Foyer C. H., Halliwel B. 1976. The presence of glutatione reductase in chloroplasts: a proposed role in ascorbic acid metabolism. Planta 133: 21-25.
10. Fridovich I. 1974. Superoxide dismutases. Adv. Enzymol. 41, 35-97.

11. Gliński J., Stępniewski W. 1985. Soil Aeration and its Role for Plants. CRC Press. Boca Raton, USA.
12. Halliwell B. 1984. Oxidative damage, lipid peroxidation and antioxidant protection in chloroplasts. Chem. Phys. Lipids 44: 327-340.
13. Jackson M. B., Ram P. C. 2003.Physiological and Molecular Basis of Susceptibility and Tolerance of Rice Plants to Complete Submergence. Annals of Botany 91: 227-241.
14. Kalashnikov J. E., Balakhnina T. I., Zakrzevsky D. A. 1994. Effect of soil hypoxia on activation of oxygen and the system of protection from oxidative destruction in roots and leaves of Hordeum vulgare. Rus. J. Plant Physiol., 41, 583-588.
15. Larson R. A. 1988. The antioxidants of higher plants. Phytochemistry 27 : 969-978.
16. Monk L. S., Fagerstedt K. V., Crawford R. M. M. 1987. Superoxide dismutase as an anaerobic polypeptide. A key factor in recovery from oxygen deprivation in Iris pseudocorus. Plant Physiol., 85, 1016-1020.
17. Vartapetian B. B., Jackson M. B. 1997. Plant adaptations to anaerobic stress. Annals of Botany 79: 3-20.

MICROBIOLOGICAL ASPECTS OF SOIL STRUCTURE FORMATION

Dąbek-Szreniawska M.

INTRODUCTION

Soil structure, one of the basic elements of soil fertility, is constantly affected by the action of various mechanical physicochemical and biological factors, and therefore can undergo remarkable changes. The formation of water-stable and durable soil aggregates is a complex process. The number and quality of the aggregates is influenced by many factors, e.g. fertilization, plant vegetation, action of atmospheric factors during the seasons of a year, and the action of microorganisms as well as higher organisms existent in soil. As it is known, microorganisms are important factor active in soil biochemical processes. It should be taken into consideration that with regard to using chemicals in agriculture there is a possibility of disturbance in the normal course of the life processes of soil microflora.

The formation of soil structure involves the physical forces of shrinking and swelling created by changes in water status of soils, freezing and thawing, tillage, or by movement of the larger biota in soils. Expansive properties of soils are controlled by the clay content. Thus changes of structural organisation are minimal in sands and maximal in clays. Plant roots, earthworms and other macrofauna large enough to move soil particles create pores recognisable by cylindrical shapes and smooth curved surfaces. Various visual and microscopic techniques aided by dyes are available to demonstrate the extent of biovoids in soils. Biology plays a major role in stabilization of soil structure. The major factors vary depending on the scale of soil structure. Both microflora and fauna are involved in the degradation of stabilizing agents. Fauna may comminute roots and hyphae which stabilized larger aggregates and microorganisms utilize mucilaginous stabilizing agents as an energy source resulting in a slow breakdown of structural stability. Further destruction of structure is caused by tillage and compaction by vehicles (Oades 1993).

POLYSACCHARIDES OF MICROBIAL ORIGIN

The main stimulus for the examination of soil polysaccharides of both bacterial and plant origin, was introduced by repeated reports concerning their effect on the soil structure (Acton et al. 1963, Harris et al. 1964, 1966a,b, Dąbek-Szreniawska 1972, 1974, 1977 a,b,c, Martin, Richards 1963, 1965, 1969, Martin et al. 1955, 1965, 1966, Martin 1971, Lynch and Bragg 1985 and others). Polysaccharides influence the soil characteristics, such as: ion exchange properties, carbon transformations, and biological activity (Torok 1960). The interest in understanding the relationship between physical properties and polysaccharide content in soil was intensified by reports, which pointed out that slimes produced by soil microorganisms might bind soil particles into stable aggregates. The slime substances produced in extra-cellular conditions by soil microorganisms are mainly polysaccharides and are formed as a result of decomposition of organic residues contained in soil. Extra-cellular production of polysaccharides by microorganisms is significant as a factor aiding their biological survival in unfavourable circumstances. Certain polysaccharides are able to retain water even for a long period of drought. Bacterial ability to form a capsule, which contains mostly polysaccharides, is also a very important barrier of protection against bacteriophages. Slime substances are conducive for the formation of soil aggregates as a sort of cementing agent. They are characterized by shorter of longer durability, which is the resistance to decomposition by other microorganisms, which affects the durability of soil aggregates.

Soil polysaccharides were subjected to a detailed examination concerning their contents and physicochemical properties. The major part of soil polysaccharides originates from primary plant substances. Plant material added to soil is immediately decomposed by the soil microorganisms. Even a complex substrate, such as cellulose, undergoes quick degradation due to combined action of endo- and exoenzymes of fungi and bacteria. Other plant polysaccharides, such as starch, hemicellulose, pectic substances and slimes, are still less durable. Thus, it may be a correct assumption that polysaccharide substances present in soil are to a considerable degree the product of microbial metabolism.

Some authors, e.g. Swincer et al. (1969) and Gupta and Sowden (1965) consider polysaccharides which were previously isolated from soil, to be of microbial origin. The presence of saccharides such as mannose, ramnose, and hexozamine prove the microbiological character of polysaccharides. Mentioned saccharides seldom can be found in plant material. The soil organisms exhibit the ability to synthesize polysaccharides containing the following saccharides: glucose, arabinose, galactose, fucose, mannose, ramnose, xylose, and uronic acids.

Complex extracellular and capsulated polysaccharide substances synthesized by various soil bacteria may often bind the soil particles into stable aggregates. However there is little information concerning more detailed knowledge on the structures of these substances. On the other hand, the studies with pure cultures probably would not be a satisfactory source of information about what they look like in the soil. The complexity of the natural environment, in this case of the soil, is certainly the reason why extracellular polysaccharides produced by microorganisms in soil are remarkably different from those obtained in laboratory.

Whistler and Kirby (1956) studied the composition of soil polysaccharides, and described their behaviour. The tested materials contained D-galactose, D-glucose, D-mannose, D-arabinose, D-xylose, L-ramnose and glucuronic acid. The presence of ribose and glucosamine was also suggested. The substances appeared to be more resistant to decomposition than many other plant polysaccharides. The studies showed that this was a mixture of polysaccharides contained presumably in capsules or in slimes and produced by microorganisms in extracellular condition. It was found that the material was characterised by a high ability to bind soil particles into aggregates. Similarly Bernier (1958) characterized polysaccharides from several samples of forest soil. An isolate was purified by means of chemical methods, and then was subjected to fractioning through precipitation, electrophoresis and acetilation. All the polysaccharides contained the following components: glucoronic acid, galactose, glucose, mannose, arabinose, xylose, fucose, and ramnose. The differences consisted in the percentages of the above components.

Many papers wer published concerning the effects of polysaccharides produced by soil microorganisms on the soil structure and the durability of polysaccharides was examined both in laboratory conditions and in soil.

Martin and Richards (1963) tested the speed of degradation and aggregating effect of polysaccharides of Chromobacterium violaceum and of various bacterial and vegetable polysaccharides, as well as of plant residues. The polysaccharide of C. violaceum was more effective in binding soil aggregates than all other substances, such as: dextran of Leuconstoc dextranicum, fructosan of Bacillus subtilis and fructosan of of Azotobacter indicum. The activity of polysaccharides added to soil in the amount of 0,5 per cent ceased after 60 days, while the Chromobacterium violaceum polysaccharide was still effective. Its durability was compared by the authors to the durability of the synthetic structure forming agent VAMA.

Rennie et al. (1954) introduced to soil the bacterial polysaccharides synthetized by Agrobacterium radiobacter, multiplied in the form of pure culture in laboratory conditions. Polysaccharides exhibited a distinct ability to aggregate dusty soil. The effect of bacterial slimes was compared with the structure-forming activity of the popular synthetic substance Krilium (polyacrylonitric), and also with the extract of soil slime substances. Both the bacterial slimes and Krilium had immediate effects on the improvement of soil structure. The addition of the substances in the quantity of only 0,02 g for 100 g of soil caused a 50% increase in the number of aggregates of diameter exceeding 0,1 mm. The addition of slime substances extracted from the soil to little-aggregated soil distinctly increased the degree of aggregation.

Clapp et al. (1962) examined 16 polysaccharides of Rhizobium and their effect on the stability of soil aggregates in 10 soil samples of different characteristics. Some of the tested Rhizobium polysaccharides were more effective as soil structure-forming factors than synthetic structure-forming compounds.

Molska (1966), while examining the effect of microorganisms on the water-stability of soil aggregates, introduced to the soil previously multiplied, slime producing microorganisms, such as: Azotobacter chroococcum, Rhizobium leguminosarum, Rhizobium meliloti, Beijerinckia indica (Brasilian strain), and others. The microorganisms were added to the soils in amounts more or less corresponding to the ratioes of artificial structure-forming substances (0,1 and 0,5 %) and in bigger amounts(1%). The water stability was increased permanently as a result of the highest slime ratio. The lowest ratio of the slime of 0,1 % caused a slight increase in the aggregates water stability. The best plastic characteristics of the soil were obtained after the addition of the highest ratioes of A. chrooccocum slime. In all the soil samples used in the experiments the activity of 1% slime ratioes of A. chroococcum and R. leguminosorum were the strongest and this was observed for 40 days of the vegetation hall experiment. During this time, particularly in the humus soil, essential differences were noted between waterstability indicators of control soil samples and those containing slimes.

Martin et al. (1965) were comparing the speed of decomposition and the soil aggregating ability of the Azotobacter indicum (Beijerinckia) polysaccharides, of other polysaccharides produced by Chromobacterium radiceum, Agrobacterium radiobacter, Azotobacter chroococcum, Bacillus subtilis, Bacillus polimyxa and of other organic substances. In acidic and neutral soil an average amount of 19 per cent of A. indicum polysaccharide substance was decomposed within 8 weeks. Comparatively, at the same time, other substances were decomposed e.g. in 39% (C. violaceum polycaccharide), in 51% (corn stems), in 67% (A. chroococcum polysaccharide) and in 84% (glucose). Only peat was more resistant to decomposition than A. indicum polysaccharide. All the polysaccharides greatly influenced binding soil particles into waterstable aggregates.

It was presumed that the resistance to decomposition of some polysaccharides may be connected with their ability to form complexes resistant to microbial decomposition. Apparently such complexes exist in the most stable fraction of soil humus. Polysaccharides containing residual of uronic acid or hydroxyl groups in the position of the second and third carbon, such as mannose, can form complexes or salts with metal cations. The soil polysaccharides can contain both the uronic acid units and mannose or similar saccharides, and probably they exist in the form of salts or complexes with metals. Martin et al. (1966, 1971) determined the speed of decomposition of bacterial and plant polysaccharides and also of their complexes or salts with metals such as: aluminium, zinc, copper, iron. Decomposition of the substances took place in soil. Certain metals considerably influenced the durability of tested polysaccharides. Generally, copper most effectively reduced the decomposition of polysaccharides, of both plant and bacterial origin. The specific effect of metals depended also on the type of polysaccharide. Zn and Al only slightly affected the decomposition of Azobacter chroococcum polysaccharide, while Cu and Fe reduced its decomposition by 50 per cent.

Martin and Richards (1969) confirmed previous studies, pointing moreover, that combination of polysaccharides with metals such as: iron, copper, zinc, aluminium, could considerably influence not only their durability, but also their ability to aggregate the soil particles. As it was noted, the iron salt of C. violaceum polysaccharide was much less effective in binding soil aggregates than the original polysaccharide material; also iron reduced binding activity of A. indicum polysaccharides, while copper increased its effect on aggregation.

Martin et al. (1959) tested the effect of 20 fungi strains on soil aggregation. The best which increased aggregation by 31 to 77 per cent after 20 days of incubation. The highest level of aggregation was noted while using the pure culture of E. purpurescens, which bound the soil both by means of mycelium threads and by producing slime substances. Other species, such as Aspergillus versicolor, volutella sp., Diplodina sp., Pyrenochaeta sp., Stachybotrys atra, Stemphylium consortiale and volutella sp., had a considerable effect on the aggregation. Substances produced during the metabolism of E. purpurescens strain, polysaccharides of

Phaescopulaviopsis sp. and S. atra components soluble in alcohol, remarkably affected the aggregates formation. The substance obtained from E. purpurescence was very resistant to decomposition. The authors noticed morover, that with the addition of sucrose to the soil, the fungi were much more active than when the soil was supplemented with mixed grass.

Fungi showed the ability of both bacteria and fungi to influence the stability of soil aggregates. (Harris et al. 1963, 1964, 1966a, b). The presence of small aggregates (with diameters less than 2 mm was connected with the bacterial character of their formation, while the aggregates with more than 2mm diameters resulted from the activity of fungi. The authors noted the presence of small water-stable aggregates, observing at the same time underdeveloped spawn of fungi during the first days of incubation, which idicated that bacteria were resposible for the aggregates stabilization in the first stage. Fungi, though, are more active in the stabilization of aggregates when the first period of their incubation in soil is over. The increase in durability of aggregates during the later period was connected with the better development of mycelium in the aggregates. Fungi such as: Alternaria, Sclerotium, Cladosporium, Cephalosporium, and Pseudogymnoascus effected aggregate stability even without the presence of sucrose, while Aspergillus fumigatus, Penicillium variabile, and Mucor were binding aggregates only in the presence of sucrose. The development of particular fungi took place at different times, e.g. Mucor silvaticus and Alternaria were considerably developed in aggregates after 4 days at a temperature of 15 centigrade, while species of Cephalosporium appeared numerously at the same temperature after 22 days.

In many cases it is very difficult to state clearly if the binding of soil aggregates by fungi should be ascribed simply to physical tangling of soil particles by the mycelium or to the production of cementing substances by fungi. However, in comparison with bacteria cells isolated from slime which show very little ability to aggregate soil then, the mycelium threads may play an important part in the process of formation of the aggregated soil structure.

ORGANIC SUBSTANCES

The formation of soil aggregates is remarkably influenced by organic substances, which may exist in the soil as plant residues (as well as in other forms). Plant vegetation is closely connected with the microbiological decomposition of plant residues and, at the same time, with the formation of soil aggregates. The plant residues present in soil serve the soil microorganisms as a source of energy during the multiplication and metabolic processes. The decomposition of plant residues by microorganisms results in formation of the substances active in the cementing of soil particles into aggregates. The plant residues, which are not decomposed, have little or no capability of binding soil into water-stable aggregates. However, the cementing process can result from the action of microorganisms. The stability of aggregates is a temporary phenomenon and will persist as long as the soil cementing products of microbial metabolism in the form of available substance, cementing soil particles into aggregates. Attention should be drawn to the papers, in which authors observed that the addition of organic substance to soil caused an increase of aggregation.

Griffith and Jones (1965) while examining the formation of aggregated soil structure with regard to the action of soil microorganisms, found that the microorganisms decompose the organic substance present in soil and change the structure of the substance in such a way that it can then be a factor facilitating the formation of soil aggregates.

Dąbek-Szreniawska (1972) studied the influence of various carbon sources on the formation of slime material by several azotobacter strains. Special attention was given to the viscosity and to the capacity of slime producing bacteria of binding soil aggregates as a natural structure-forming factor. As carbon sources various compounds were used. It appears that the kind of carbon source in the medium affected the count of cells and the production of slime materials by the Azotobacter strains selected. Depending on the carbon source, a biomass of various viscosity was obtained of the Azotobacter strains. The viscosity of the biomass affected the increase of the water stability of soil aggregates. This effect depended on the species of the azotobacter strains, and on the type and variety of soil as well.

The role of selected bacteria in the formation of water-stable soil aggregates independently of other micro-organisms was carried out in the next experiments. The introduction of 0.4% quantity of biomass of high viscosity of micro-organisms of the genera *Arthrobacter, Bacillus* and *Cytophage* per weight of dry soil into nonsterilized and sterilized soil without any addition of a carbon source did not cause an increased water stability of aggregates in the majority of experiments. In the presence of a carbon source such as glucose, the water stability of aggregates increased both in non-sterilized and sterile soil under the influence of *Arthrobacter* and *Bacillus* strains. In the presence of cellulose, the *Cytophage* strain increased the water stability of soil aggregates, and this state was maintained longer by the association of micro-organisms in non-sterilized soil than by a specific microorganism in sterilized soil independently of the action of other bacteria. From the obtained results Dąbek-Szreniawska (1977a) concluded that the process of soil aggregate formation is not only affected by specific micro-organisms but their association as well. The equilibrium between synthesis and decomposition of aggregate-binding substances is connected with environment conditions and the content of nutritive substances which affect microbiological activity. The observed structure-forming effect of slime-producing bacteria isolated from soils requires further studies to determine the chemical composition and sorptive properties of the slime as well as the aggregate durability in field conditions.

Adu and Oades (1978) added six fungi and two bacteria to samples of aggregates in which either ^{14}C-labelled glucose or starch was thoroughly distributed in macro- and micropores or in control samples where the labelled substrates were added to the preformed aggregates and considered to be mainly in macropores. The release of $^{14}CO_2$ was monitored over a 24-day incubation. In the control samples with substrates mainly in macropores, the bacteria were as active as fungi in releasing $^{14}CO_2$ from both soils. When the substrates were distributed in macro- and micropores in aggregates made from a fine sandy loam, the fungi were more efficient than bacteria in releasing $^{14}CO_2$.

Dąbek-Szreniawska and Wilke (1996) measured the respiration of aggregate fractions of 3 soils. The soils examined: grey-brown developed from loess, brown developed from sand and rendzina differ as to the content of carbon and microorganisms biomass. An attempt was made to determine the relation between the quantity of bacteria and fungi. There was some correlation between the size of aggregates and microorganism respiration activity. As a rule the highest microorganism respiration activity was found for the fraction of 0.5-0.05 mm which may be connected with the organic matter content and optimum water-air relations within aggregates.

INFLUENCE OF PLANT AND VEGETATION

Acton et al. (1963) added to the two kinds of soil: Trossachs and Oxbow finely mixed straw, which improved aggregation. The percentage of aggregates of diameter bigger than 0,1 and 0,5 mm was greatly increased. The percentage of aggregates bigger than 0,5 mm was the greatest after one week of incubation; later on a decrease in aggregate content was observed. It might be interesting to say, that simultaneously the amount of slime substance of microbial origin reached its maximum within one week; after this time the amount of slime substance decreased.

Interesting observations were reported by Webber (1965), who investigated the effect of polysaccharides of plant residues, such as rye, oat, Winter wheat and others. He also reported, that durability of particular polysaccharides was different during the vegetation period, and that the plants influenced the aggregate stability in a much higher degree than they affected the amount of polysaccharides.

Some authors observed changes in the formation of aggregates with relation to the seasons of the year and to the king of cultivated plant. Stefanson (1968) reported that the stability of soil aggregates decreased in autumn, reached its minimum in winter, and then increased in spring to reach its maximal value in summer. The seasonal changes in aggregate stability were indistinct in salt soil containing calcium carbonate $CaCO_3$. When considering the subject, the role of microorganisms should be taken into account. The optimal climatic conditions for the production of slime substances by microorganisms are in spring and summer, which is also reflected in the increased number of water-stable aggregates during this time, while during other seasons aggregate decomposition can be observed.

Dąbek- Szreniawska et al. (2000) observed the relations between fertilization, cultivation system and water-stability of soil aggregates and number of microorganisms. The results showed that the number of bacteria and fungi and water stability of aggregates sampled from under plants cultivated with organic fertilization were higher in comparison to the conventional cultivation.

Balashov and Dabek-Szreniawska (2001) studied the effects of ecological and monoculture management practices on the relationships of water-stable aggregation with organic matter content and respiration activity in a pseudopodzolic loamy sand (Orthic Luvisol) soil located in Pulawy, Poland. The ecological management practice, compared to the other one, contributed to a greater increase in the total organic C content and amount of the only 0.43-1.0-, 1.0-3.0- and 3.0-5.0-mm water-stable aggregates in the loamy sand Orthic Luvisol.

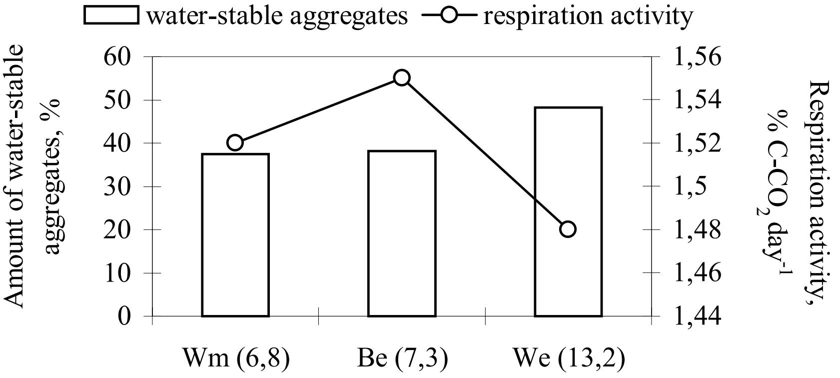

Fig.1. *Amount of water-stable aggregates and their respiration activity in soil at winter wheat monoculture (Wm) and ecological management of spring barley (Be)and winter wheat (We). Total C content in soil (g kg^{-1}) is given in parenthesis*

Fig. 1. Amount of water-stable aggregates and their respiration activity in soil a winter wheat monoculture (Wm) and ecological management of spring barley

However a total amount of water-stable aggregate-size fractions did not increase with increasing total organic C content if their respiration activity was rather high, probably as a result of a low physical protection of occlused organic matter against microorganisms in the pores of water-stable aggregates (Fig.1.) A high susceptibilit of attached organic matter to the microbial mineralization resulted in decreasing favourable effects of the ecological management practice on the water-stable aggregation of loamy sand Orthic Luvisol.

INORGANICS, TEMPERATURE, pH, AERATION AND MOISTURE

Inorganic substances, water content, temperature aeration and pH, affect the formation and decomposition of soil aggregates. These factors also effect the activity of soil microorganisms, so it should be expected that they influence the microbial character of the aggregate formation and decomposition, as well.

Acton et al. (1963) combined with the organic substance nitrogen compounds in the form of ammonium nitrate NH_4NO_3, in order to estimate their effect on soil aggregation, on the production of slime substances by microorganisms and on the amount of polysaccharides in soil. The addition of the nitrogen compounds, particularly in bigger quantities, distinctly decreased the percentage of aggregates with diameter larger than 0,5 mm and 0,1 mm as compared with the number of aggregates in soil supplemented with straw. The addition of phosphorus fertilizer, though, did not change the amount of aggregates in soil.

The nitrogen compounds added to the soil caused simultaneous decrease of the amount of slime substances as compared with that in the straw-enriched soil. These observations were confirmed by Harris et al. (1966a, b), who noticed that the presence of nitrogen compounds in organic fertilizers shortened the period of durability of soil aggregates. The decrease was assumed, to be due to the lower proportion of ratio of carbon to nitrogen, which was conducive to the rapid decomposition of aggregate binding substances, synthesized by microorganisms.

The *Arthrobacter* genus is represented in soil by numerous species. These microorganisms can survive unfavourable environmental conditions, e.g. drought and frost. Some species of the *Arthrobacter* have synthetized slimes characterizing themselves by a high viscosity tested by the viscometric method. In these studies Dąbek-Szreniawska (1977a,b) determined the influence of a bacterium strain of the *Arthrobacter* genus on the water stability of soil aggregates. This strain has been characterized by a high ability to form a large amount of slime substances on synthetic media. In this paper the influence of the *Arthrobacter* strain on the aggregate composition of soil was presented. The studies were carried out with parallel investigations of the effect of this strain on the aggregate water stability of pseudo-podzolic soil formed from loamy sand. Simultaneously the addition of plant residues, mineral fertilizers, bentonite and synthetic structure-forming substance Verdickung AN was performed. Positive results on aggregation were obtained more often when the *Arthrobacter* sp. biomass was used with the plant residues. The value of the dispersion index for aggregates sieved in the dry state increased with time to a value of 11.6. This value points to the very small soil dispersion. Simultaneously the value of the dispersion index of the soil sieved in the wet state increased to 3.5. The high value of this index was also noted for soil treated with the structure-forming substance. It shows a positive effect on the formation of greater aggregate fractions. The lower value of the dispersion index after wet sieving involves the higher values of dispersion. A value < 1 indicated a 50% soil dispersion and this situation can be seen both in the case of pure soil, at the initial time of the experiment, for aggregates sieved in the wet state and in the case of soil with the addition of mineral fertilizers themselves. It was observed that the increasing of the amount of the individual aggregate fraction was not always connected with an increased water stability. However, in the case of the best aggregate water stability a decrease in soil dispersion occurred.

Dąbek-Szreniawska (1977c) observed the influence of some chemical substances on the water stability of soil aggregates formed under the effect of slime of the bacterium strain of *Arthrobacter* genus. The experiments were carried out on the basis of previous studies concerning the influence of the bacterium strain of *Arthrobacter* genus on the water stability of aggregates and on the composition of soil aggregation in the presence of plant residues, mineral fertilizers and bentonite (1974, 1977). The studies comprised such substances as: calcium, sodium and lead compounds which are often introduced into soil together with fertilizers or occur as contaminations of the soil environment (e.g. glazed frost removing agents, development of transport and communication facilities). It appears from the experiments carried out that the introduction into the soil of higher amounts of such chemical substances as calcium, sodium and lead compounds exert a significant influence on the water stability of soil aggregates formed under the effect of slime biomass of *Arthrobacter* sp. Calcium increased itself waterstability of the aggregates aswel as in the presence of Arthrobacter. But sodium and lead decreased the stability of aggregates.

The effect of structure-forming keratin-carbamide fertilizer on the distribution and number of microorganisms in soil aggregates and non-fractioned soil was the aim of the following experiments (Dąbek-Szreniawska 1993). The Hattori's method of washing and ultrasonification used in the research allowed to observe habitation of microbes on the outer surface and the inner part of soil aggregates (1969). It is the fertilization that has the greatest differentiating effect on the microbe density of fractions. The introduction of keratin-carbamide fertilizer resulted in increased number of microorganisms grown on the medium for *Pseudomonas* and on the minimum medium and DNB medium. Fertilization decreased the number of *Arthrobacter* and *Bacillus* colony forming units (CFU).

The presence of Cu, Zn, Fe ions stopped the decomposition of slime substances of polysaccharide produced by the soil microorganisms through the formation of salts or metallic complexes with these polysaccharides (Martin, Richards 1969, Martin 1971). The durability of polysaccharide slime substances with an ability to cement soil aggregates, is related to the durability of the aggregates. This question is dealt with in the chapter on soil polysaccharides.

Aldrich and Martin (1954) tested the effect of unchangeable cations on the formation of soil aggregates. They observed the effect of sodium compounds. In soil of high sodium contents formation of soil aggregates was much lower despite the addition of organic substance. The authors conclude that sodium added to soil disperses the inorganic colloids and substances causing the aggregate binding, among others substances produced by microorganisms.

Harris et al. (1966a) observed that in the temperature range between 15 and 35 centigrade the speed of aggregate formation increased as a result of fungi used in the experiment. The higher temperature of incubation, the earlier aggregate stabilization was started by spore-forming soil microorganisms; however, the aggregate stability was transient at higher temperatures.

The influence of oxygen conditions and moisture on soil microorganisms is remarkable and it is closely connected with the formation of soil structure. The problem was presented in several papers.

Harris et al. (1966a, b) reported a disadvantageous effect of too large a water content on the formation of soil aggregates. The authors also tested the effect of aerobic conditions on aggregation and found that continuous incubation with oxygen access caused a decrease in the durability of soil aggregates. High aggregate stability, which remained for 8 weeks, was observed during soil incubation without oxygen. The number of water-stable aggregates was quickly reduced as soon as the soil was introduced to aerobic conditions. The studies were conducted with and without the access of sucrose as a source of energy. The authors presumed, that anaerobic microorganisms with the access of sucrose produced the substances binding the aggregates. Once sucrose was exhausted, and lacking other available source of energy, these microorganisms were no longer able to utilize substances produced by themselves. On the other hand, aerobic microorganisms quickly used up suchrose, synthetised substances, among others those active in cementing the aggregates, and then, lacking other sources of energy, they decomposed the substances, causing at the same time a decrease in aggregate durability. Greszin (1960), however, presents a somewhat different observation, that in the presence of organic substance the number of formed macro-aggregates was higher in aerobic rather than in anaerobic conditions.

The influence of pH on the formation and aeration of soil aggregates by microorganisms was dealt with by Harris et al. (1966b), who found that soil aggregate formation may depend on pH conditions of soil. The pH conditions unfavorable for the development of microflora active in soil aggregate formation are thereby unfavorable for the very formation of the aggregates.

MECHANISMS OF AGGREGATE FORMATION

The formation of soil aggregates by microorganisms can result from the action of various mechanisms. The soil aggregates can be formed by adsorption phenomenon and by physically sticking soil particles together, as well as through the cementing of soil particles by microbial slimes.

Estermann and McLaren (1959) observed that soil fractions with small-sized particles easily adsorbed bacteria on the surface. Besides, negatively charged adsorbents repel rather than attract bacteria of negative charge. As a result, cations can cause increased adsorption by a decrease of electrokinetic potential between the bacterial cells and the soil clots of negative charge. Attention was drawn to the fact, that the type of organism is more significant than the type of adsorbent. Gram-positive, immobile microorganisms are characterized by the highest ability to adhere to soil particles.

The role of minerals in the formation of soil aggregates was also studied by Harris et al. (1966b). The formation of complexes between polysaccharides produced by microorganisms and montmorillonite decreases the rate of decomposition of the polysaccharides. Probably, polysaccharide and montmorillonite complex is resistant to microbial decomposition. Also Hattori (1970) observed the formation of complexes between E. coli cells and loam particles. Pyrophyllite and kaolinite complexes combined with E. coli cells underwent interadhesion of adhered to other loam particles and formed aggregates. The “cell – loam particle” complexes treated with sodium ions were stable in acidic medium and nonstable in alkaline medium.

The loam particles treated with Cu^{++}, Co^{++} or Fe $^{++}$ underwent stronger adhesion with bacterial cells than loams treated with Na^{+}, and the complexes were stable in alkaline medium but labile in acidic medium.

Lahav (1962) studied the adsorption of sodium bentonite on Bacillus subtilis cells. The effect of sodium bentonite (molecules smaller than the bacterial cells) on the electrophoretic mobility of Bacillus subtilis was tested in solutions of sodium chloride and of sodium phosphate with different concentrations of hydrogen ions and ionic force. It was noted that the adsorption of sodium bentonite on bacteria was a reversible process. Bacterial population consists of two types of microorganisms, which means that the addition of bentonite affected the electrophoretic mobility of one bacterial type while the other type remained unaffected. The first type represented bacteria adsorbing bentonit, and the second type representing those not adsorbing it on their surface. The presence of both bacterial types was found only in the presence of bentonite. The effect of bentonite on bacterial mobility was said to depend on pH, ionic force, and contents of electrolytes. The lower were the pH values and the higher was the ionic force, the more effective was bentonite action. The action appeared to be stronger in the presence of chlorine ions than in the presence of orthophosphate. Adsorption of the mineral on the bacterial cells was measured qualititatively with the microelectrophoretic method applied.

Dąbek.-Szreniawska (1974) studied the influence of the bacterial biomass of *Arthrobacler* sp. on the formation and waterstability of aggregates in the soil with simultaneous addition of plant fragments, mineral fertilizers (NPK, Ca) and bentonite. The introduction of the bacterial biomass of *Arthrobacter* sp. resulted in increased waterstability of soil aggregates. The highest increase in the waterstability of aggregates occurred under the influence of bacterial biomass with a simultaneous addition of plant residues after 3 months. Bentonite generally increased the durability of aggregates. The mineral fertilizers NPK caused a decrease in the waterstability of aggregates formed by adding bacterial biomass.

In the discussion concerning mechanisms taking part in the adsorption of the mineral's molecules on the surface of bacterial cells, three hypotheses were put forward (Marshall 1971):

a) adsorption of the molecules could proceed through on the surfaces of bacteria and mineral particles ("face-to-face adsorption");
b) adsorption of the molecules could proceed through on their edges ("edge adsorption");
c) adsorption could result from both mentioned mechanisms ("mixed adsorption").

Martin (1971) and Martin et al. (35) note in surveys concerning the role of microorganisms and organic substance in the process of aggregates formation, that four factors function in the process:

1) products synthesized by microorganisms,
2) bacterial cells and mycelium threads of fungi,
3) substances produced by microorganisms as products of decomposition of plant residues,
4) substances soluble in water, contained in plant residues.

Whistler and Kirby (1956), Bernier (1958), Acton et al. (1963), Metha et al. (1960, 1961), Swincer et al. (1969) and Martin (1971), subjected soil polysaccharides to and extensive analysis. The main motive of their studies was repeating reports about the role of polysaccharides in the formation of soil structure: A theory was developed concerning the formation of soil aggregates by long-chained polysaccharides, and mostly by polysaccharides produced by microorganisms. The theory was based on the following evidence:

1) many polysaccharides, produced by microorganisms, when added to soil cause the formation of water-stable aggregates;
2) soil is inhabited by organisms able to produce polysaccharides which can bind soil particles;
3) polysaccharides are present in soil and, if extracted and added to soil, they cause its aggregation;
4) there is a statistical correlation between the content of polysaccharides in soil and the degree of aggregation.

Metha et al. (1960, 1961) remark that besides polysaccharides there are many other active substances responsible for aggregation, such as humic acids and proteins. Hence, we cannot exclude the contribution of other factors which can also influence the aggregation. To explain the question the authors presented a proof based on chemical analysis. The studies were based on the argument that if the chemical compounds decomposing polysaccharides simultaneously destroyed soil aggregates, then the polysaccharides would contribute to aggregation. Natural and synthetic aggregates were subjected to the action of chemical compounds in other to destroy polysaccharides. The authors proved that artificial aggregates stabilized by addition of polysaccharides lost stability as a result of the action of 0,01 M sodium hyperiodate and borate buffer. This might prove that in this case the aggregation was influenced by polysaccharides. However, the differences between the behaviour of natural and synthetic aggregates during the contact with chemical compounds indicate thatt polysaccharides cannot be solely responsible or the natural soil aggregation. The aggregation results from the combined action of soil factors.

Polysaccharides are constant factors or metabolic products of all forms of living organisms. The polysaccharide fraction in soil is the second largest fraction of soil humus and its percentage is estimated to be 10-30%. Martin and Haider (1970) reported that the fraction of humic acids and polysaccharides of soil humus is 90 % of the total humus. According to the authors, the polysaccharide fraction can be formed in a way similar to that of the humin fraction. The existence of a considerable polysaccharide fraction in relatively stable form depends on the following:

a) input of microbial and plant polysaccharides, resistant to decomposition;
b) certain plant and microbial polysaccharides, or products of their partial degradation, form salts or complexes with metal ions, minerals or humic complexes, which are resistant to decomposition;
c) new complexes of polysaccharide molecules characteristic of or specific to the soil environment are re-produced indefinitely;
d) all or some of the above factors are involved.

The high binding activity of polysaccharides results from the following properties (Martin1971, Harris et al. 1966b):

1) length and linear structure, which are conducive to filling the space between soil particles;
2) an elastic nature allowing them to cover a large number of points on the soil particles, which makes Van der Waals forces more effective
3) high number of hydroxyl groups, which can take part in hydrogen bindings;
4) the existence of carboxyl groups (COOH), which promote the formation of ionic bindings by divalent and trivalent cations with points of ion exchange on the surfaces of loam particles.

On the basis of the presented review it can be said, that the formation of soil aggregates by microorganisms is conditioned by many factors.

Ladd et al. (1996) concluded that in considering biological activity in relation to the properties of the soil matrix, the following view has been taken:

1) Substrates in soil are predominantly chemically complex. Fresh plant and animal residues are comprised of varying proportions of particulate and soluble components, which determine the extent to which such residues are initially rapidly decomposed upon entering soil. The majority of substrates in soils are particulate and can only be colonized by organisms on their outer surfaces. Thus, particle size and surface area of the substrates control their rates of decomposition. Coating of substrate surfaces with inorganic materials confers on particulate substrates various degrees of protection from decomposition.
2) The soil microbiota are the major agents of decomposition; the activities of phyllosphere and rhizosphere microbiota, and of soil enzymes, are also significant at times and under suitable conditions. In addition to rhizospheres, decomposing organic particles represent concentrations of biological activity in the soil matrix (...)
3) Microbial biomass is the major organic product of substrate metabolism, and biomass turnover is the major mechanism for the accumulation of dead microbial residues.
4) The rates of decomposition of carbon and nitrogen of microbial biomass and products are influenced by their location in the soil. During the early phases of decomposition, biomass associated with particulate residues is less protected than biomass formed from the metabolism of soluble substrates that have diffused into the soil matrix. Clay soils have a greater capacity for the protection of biomass within the soil matrix than do sands.
5) Interactions of microbial metabolites and products with clay surfaces stabilize the organic materials. Particle-size fractionation of dispersed soils commonly reveals a concentration of soil organic matter and microbial biomass in fine silt-size/coarse clay-size materials. Clay fractions isolated from soils may be artifacts that contain both very old and modern carbon.

Thus it may be said, that the microbial binding of soil aggregates proceeds in a complex way, with many physicochemical and biological factors involved. Hence, the mechanisms of aggregate formation have a multifaceted nature, both chemical and physical, which is reflected in the aggregate structure and, obviously, in their durability. This subject demands further study, which may lead to the improvement of soil structure by means of natural structure-forming substances produced by soil microorganisms and on the basis of the complex of mechanisms which are at their disposal.

REFERENCES

1. Acton C.J., Rennie D.A., Paul E.A. 1963: The relationship of polysaccharides to soil aggregation. Can. J. Soil Sci. 43, 201-209.
2. Adu J.K., Oades J.M. 1978: Utilization of organic materials in soil aggregates by bacteria and fungi. Soil Biol. Biochem. 10 (20), 117-122.
3. Aldrich D.G., Martin J.P. 1954: A chemical microbiological study of the effects of exchangeable cations on soil aggregation. Soil Sci. Soc. Am. Proc. 18, 276-281.
4. Balashov E. V., Dąbek-Szreniawska M. 2001: Organic matter transformation and water-stable aggregation in a loamy sand Orthic Luvisol as affected by management practices. Biogeochemical Processes and Cycling of Elements, P.S.H.S., 361-363.
5. Bernier B. 1958: Characterization of polysaccharides isolated from forest soil. Biochem. Journal. 70, 590-598.
6. Clapp C.E., Davis R.J., Waugman S.N. 1962: The effect of rhizobial polysaccharides on aggregate stability. Soil Sci. Soc. Am Proc. 26, 466-469.
7. Dąbek-Szreniawska M. 1972: The influence of carbon on the production of slime material by some Azotobacter strains. Polish J. of Soil Sci., 5, 59-67.
8. Dąbek-Szreniawska M. 1974: The influence of *Arthrobacter* sp. on the waterstability of soil aggregates. Polish J. of Soil Sci. 7, 169-179.
9. Dąbek-Szreniawska M. 1977a: The role of selected bacteria in the formation of water-stable soil aggregates independently of other micro-organisms. Zesz. Probl. Post. Nauk Rol. 197, 339-354.
10. Dąbek-Szreniawska M. 1977b: The influence of *Arthrobacter* sp. on soil aggregation. Zesz. Probl. Post. Nauk Rol. 197, 319-328.
11. Dąbek-Szreniawska M. 1977c: The influence of some chemical substances on the water stability of soil aggregates formed by adding bacterial slimes. Zesz.Probl. Post. Nauk Rol. 197, 329-336.
12. Dąbek-Szreniawska M. 1993: Effect of keratin-carbamide fertilization on microorganisms in soil aggregates. Polish J. of Soil Sci., 26, 49-57.
13. Dąbek-Szreniawska M., Wilke B.M. 1996: Microbiological activity within various fractions of soil aggregates. Zesz. Probl. Post. Nauk Rol., 436, 1-7.
14. Dąbek-Szreniawska M., Wyczółkowski A.I. Jończyk K., Kuś J. 2000: Relation between fertilization, cultivation system and water stability of soil aggregates and number of microorganisms. Acta Agrophysica, 38, 47-57.
15. Estermann E.F., McLaren A.D. 1959: Stimulation of bacterial proteolysis by adsorbents. J. Soil Sci. 10, 64-78.
16. Geoghegan M.J., Brian R.C. 1948: Influence of various carbohydrates and proteins on aggregation of soil particles. Biochem. J. 43, 14-15.
17. Greenland D.J., Lindstrom G.R., Quirk J.P. 1962: Organic materials which stabilize natural aggregates Soil. Sci. Soc. Am. Proc. 26, 366-371.

18. Greenwood D.J. 1961: The effect of oxygen concentration on the decomposition of organic materials in soil. Plant and Soil. 14, 360-376.
19. Greszin J.P. 1960: The effect of aerobic and anaerobic conditions on the change in the properties of sod-podzolic soil (according to data from laboratory experiments.) Soil Fer. 23, 382 (abstr.).
20. Griffiths E., Jones D. 1965: Microbiological aspects of soil structure. 1. relationships between organic amendments, microbial colonization and changes in aggregate stability. Plant and Soil. 23, 17-33.
21. Gupta U.C., Sowden F.J. 1965: Studies on methods for the determination of sugars and uronic acids in soils. Can. J. Soil Sci. 45, 237-240.
22. Harris R.F., Allen O.N., Cherters G., Attoe O.J. 1963: Evaluation of microbial activity in soil aggregate stabilization and degradation by the use of artificial aggregates. Soil Sci. Soc. Am. Proc. 27, 542-545.
23. Harris R.F., Chesters G., Allen O.N. 1966: Soil aggregate stabilization by the indigenous microflora as affected by temperature. Soil Sci. Soc. Am. Proc. 30, 205-210.
24. Harris R.F., Chesters G., Allen O.N. 1966b: Dynamics of soil aggregation, advances in agronomy. 18, 107-169.
25. Harris R.F., Chesters G., Allen O.N., Attoe O.J. 1964: Mechanisms involved in soil aggregate stabilization by fungi and bacteria. Soil Sci. Soc. Am. Proc. 28, 529-532.
26. Hattori T. 1969: Fractionation of microbial cells in soil aggregates. Soil Biol. 11, 30-31.
27. Hattori T. 1970: Adhesion between cells of e. coli and slay particles. J. Gen. Appl. Microbiol. 16, 351-359.
28. Kułakow E.W. 1960: Zakonomiernosti raspriedielienija organiczeskich ostatkow w profile czarnoziemnych poczwsiewiernowo Kazachstana. Poczwowiedienije 3, 12-20.
29. Ladd J.N., Foster R.C., Nannipieri P., Oades J.M. 1996: Soil structure and biological activity. Soil Biochemistry 9, 23-77.
30. Lahav N. 1962: Adsorption of sodium bentonite particles on Bacillus substilis. Plant and Soil 17, 191-208.
31. Maeda N. 1957: Studies on the formation of soil aggregate (preliminary report). influence of water content and sucrose. Soil and Plant Food (Tokyo) 3.
32. Marshall K.C. 1971. Sorptive interactions between soil particles and microorganisms. Soil Biochemistry Vol. 2, Marcell Dekker eds. 409-445.
33. Martin J.P. 1971: Decomposition and binding action of polysaccharides in soil sci. Biol. Biochem. 3, 33-41.
34. Martin J.P., Ervin J.O., Shepherd R.A. 1965: Decomposition and binding action of polysaccharides from Azotobacter indicus (Beijerinckie) and other bacteria in soil. Soil Sci. Soc. Am. Proc. 29, 397-400.
35. Martin J.P., Ervin J.O., Shepherd R.A. 1966: Decomposition of the iron, aluminium, zine and copper salts or complexes of some microbiol. and plant polysaccharides in soil. Soil Sci. Soc. Am. Proc. 30, 196-200.
36. Martin J.P., Haider K. 1970: Microbial activity in relation to soil humus formation. Soil Sci. 111, 54-63.
37. Martin J.P., Richards S.J. 1963: Decomposition and binding action of a polysaccharide from chromobacterium violaceum in soil. J. Bacteriol., 85, 1288-1294.
38. Martin J.P., Richards S.J. 1965: Microbes affect physical properties of soil california agriculture. 19, 14-15.

39. Martin J.P., Richards S.J. 1969: Influence of the copper, zinc, iron and aluminium salts of some microbial and plant polysaccharides an aggregation and hydraulic conductivity of sandy loam. Soil Sci. Soc. Am. Proc. 33, 421-423.
40. McCalla T.M., Haskins F.A., Frolik B.F. 1957: Influence of varius factors on aggregation of peorian loess by microorganisms. Soil Sci, 84, 155-161.
41. McCalla T.M. 1945: Influence of microorganisms and some organic substances on soil structure. Soil Sci. 59, 287-297.
42. Mehta N.G., Streuli H., Muller M., Deuel H. 1960: Role of Polysaccharides in soil aggregation. J. Sci. Food Agr. 11, 40-47.
43. Mehta N.G., Dubach P., Deuel H. 1961: Carbohydrates in the soil. Adv. Carbohydrate Chem., 16, 335-355.
44. Nishio M., Hattori T., Furusaka Ch. 1968: The growth of bacteria in sterilized soil aggregates. The Reports of the Institute for Agricultural Research Tohoku University, 19, 37-43.
45. Molska I. 1966: Wpływ drobnoustrojów na wodoodporność gruzełków glebowych. Roczniki Gleboznawcze, 16, 67-84.
46. Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. Geoderma, 56, 377-400.
47. Parr J.F., Reuszer H.W. 1959: Organic matter decomposition as influenced by oxygen level and method of application to soil. Soil Sci. Soc. Am. Proc. 23, 214-217.
48. Rennie D.S., Truog E., Allen O.N. 1954: Soil aggregation as influenced by microbial gums, level of fertility and kind of crop. Soil Sci. Am. Proc. 18, 399-403.
49. Schwarts S.M., Freeman P.G., Russell C.R. 1958: Soil conditioning properties of modified agricultural residues and related materials: II persistence of soil stabilizing activity as a function of type and extent of modification. Soil Sci. Soc. Am. Proc. 22, 409-414.
50. Smith H.E., Schwarts S.M., Gugliemel L.A., Freeman P.G., Russell C.R. 1958: Soil conditioning properties of modified agricultural residues and related materials: i. aggregate stabilization as a function of type and extent of chemical modification, Soil Sci. Soc. Am. Proc. 22, 405-409.
51. Stefanson R.C. 1968: factors determining seasonal changes in the stabilities of soil aggregates. Trans 9th Internat. Congr. Soil Sci. Adelaide, Australia, 2, 395-402.
52. Swaby R.J. 1949: The relationship between microorganisms and soil aggregation. J. Gen. Microbiol. 3, 236-254.
53. Swaby R.J. 1964: The influence of humus on soil aggregation, Soil Sci. 1, 182-194.
54. Swincer G.D., Oades J.M., Greenland D.J. 1969: The Extraction Characterization and Significance of Soil Polysaccharides. Adv in Agron. 21, 195-235.
55. Toogood J.A., Lynch D.L. 1959: effect of cropping systems and fertilizers on mean weight-diameter of aggregates of brenton plot soils. Can. J. Soil Sci. 39, 151-156.
56. Torok L. 1960: Data on characteristic processes during the changes in humic acids. Soil Fert. 23, 190 (abstr.).
57. Webber L.R. 1965: Soil polysaccharides and aggregation in crop sequences. Soil Sci. Soc. Am. Proc. 29, 39-42.
58. Whistler R.L., Kirby K.W. 1956: Composition and behavior of soil polysaccharides. J. Am. Chem. Soc. 78, 1755-1759.

BIOLOGICAL AND PHYSICO-CHEMICAL PROPERTIES IN THE RELATION TO THE CULTIVATION SYSTEM OF SOIL

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INTRODUCTION

Interest in the quality and health of soil has been stimulated by recent awareness that soil is vital to both production of food and fiber and global ecosystems function. Soil health, or quality, can be broadly defined as the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Soil quality and health change over time due to natural events or human impacts. Criteria for indicators of soil quality and health relate mainly to their utility in defining ecosystem processes and integrating physical, chemical, and biological properties; their sensitivity to management and climatic variations; and their accessibility and utility to agricultural specialists, producers, conservationists, and policy makers (Doran et al. 1998).

Arshad and Coen (1992) and Arshad and Martin (2002) described the guidelines that can be followed to identify critical limits for the key indicators and the procedure for monitoring changes in soil quality trend. Although, selection of soil indicators will vary with societal goals, the followings seem to be suitable indicators for crop production in most cases: organic matter, topsoil-depth, infiltration, aggregation, pH, electrical conductivity, suspected pollutants and soil respiration. Crop yield can be used as an integrator of the foregoing soil indicators.

The aim of this paper is to discuss some biological and physico-chemical properties in relation to cultivation.

CULTIVATION EFFECTS ON SOIL

Sokołowska et al. (1999) were carried out investigations on the soil from the long-term static field experiments in Osiny near Puławy. The experiment was established on grey-brown podzolic soil (Haplic Luvisol) formed from boulder clay (1-0.1 mm - 69%, 0.1-0.05 mm - 11%, 0.05-0.02 mm - 8%, <0.02 mm - 14%; organic carbon - 0.99%). The field experiment consisted of two cultivation systems: conventional (with mineral fertilisers, herbicides and fungicides) and organic farming (compost, mechanical and manual weeding). Each year during the experiment, 1996-1998, 33 t/ha of compost was applied in organic farming, whereas in the conventional cultivation system we used 120 kg of N (in 3 doses, in the form of ammonium nitrate and urea), 80 kg of P_2O_5 (1 dose, superphosphate) and 100 kg of K (1 dose, KCl). The cropping systems were as follows: in the case of conventional cultivation - rape, winter wheat and spring barley; in the case of organic farming system - potato, spring barley, red clover, red clover and winter wheat. A detailed description of the soil profile, experimental layout and treatments have been given by Kuś (1998). All the soil samples were taken three times (i.e. at the seedling stage, stem elongation stage and after harvest of cereals) from the arable humus layer of the field each year in three years' period. Representative samples were airdried and sieved through a sieve of 1 mm mesh. All measurements were repeated three times and the average values were used for the specific surface area calculation and for plotting the figures.

The surface area of soil samples was evaluated from adsorption and from desorption isotherms. It is now generally accepted to use the Brunauer-Emmett-Teller (BET) method to derive specific surface area from the data on physical adsorption.

The adsorption-desorption isotherms of water vapour were measured by gravimetric method using a vacuum chamber. The soil sample with the weight of approximately 3 g was put into a glass vessel and placed over sulphuric acid solution. The sample was then equilibrated with water vapour for two days. The amount of adsorbed water vapour was computed as the difference between the weight of the sample with adsorbed water and dry sample dried in an oven at 105°C. The relative water pressures were obtained from the density of sulphuric acid solutions. The adsorption measurements were repeated three times keeping the temperature constant, T = 20°C ± 0.5°C. This procedure agrees with the Polish standard PN-Z-19010-1 for measuring the surface area of soils (Sokołowska et al. 1999).

Table 1. The BET surface area (m^2/g) for the investigated soil samples with different crop and sampling time

Crop	Sampling period							
	II	III	I	II	III	I	II	III
	1996			1997			1998	
Barley, organic farming	24.7	20.4	16.3	14.6	16.5	23.7	23.0	18.4
Barley, conventional	18.9	17.4	13.0	11.6	10.8	13.3	21.2	15.5
Winter wheat, organic farm-	25.3	17.7	25.6	20.3	21.3	17.7	21.7	16.2
Winter wheat, conventional	13.7	8.2	13.0	12.4	8.5	14.2	12.3	15.1
Red clover, organic farming	n.d	13.3	17.8	11.8	12.3	13.2	13.2	14.5

Abbreviations: I - seedlings; II - stem elongation stage; III - after harvest;

In Table 1 values of specific surface area were collected. In general, specific surface area of the samples from organic farming was significantly higher than that obtained for the samples originating from conventional cultivation. For all the studied samples and for different crops, the BET specific surface area estimated from the adsorption isotherm ranged from 12 to 25 m^2/g and from 8 to 21 m^2/g for organic farming and for conventional cultivation, respectively. In the case of organic farming, the average specific surface areas of the soil samples taken from the field with barley and winter wheat were 20.2 m^2/g and 24.7 m^2/g. These results show that cereal species do not influence significantly the specific surface area, since the standard deviation is 3.6 and 3.8, respectively. Note that pretty similar results were found for conventional cultivation system. Specific surface area for red clover was almost the same as that evaluated for cereals in the conventional cultivation system (Table 2).

Table 2. Average surface area ($S_{aver.}$) and its standard deviation *(σ)* from adsorption measurements

Cropping system and method of cultivation	$S_{aver.}$ [m^2/g]	σ
Barley organic farming	19.7	3.8
Barley conventional farming	15.2	3.7
Winter wheat organic farming	18.3	5.7
Winter wheat conventional	12.2	2.5
Red clover organic farming	13.7	2.0
Barley + winter wheat organic farming	20.2	3.6
Barley + winter wheat conventional farming	13.7	3.4

Abbreviations: I - seedlings; II - stem elongation stage; III - after harvest;

The sampling period did not practically influence adsorption of water vapour and the obtained specific surface areas (see Tables 1 and 2). The authors did not find any straight and simple relation between the surface area and the sampling period. From the above research the authors drew the following conclusion (Sokołowska et al. 1999): The amount of adsorbed water vapour on the soil samples depends on the method of the soil cultivation. A straight and simple relationship between the surface area and the sampling period was not found. The specific surface areas of soil samples from organic farming are significantly higher than those originating from conventional soil system.

In next research Sokołowska et al. (1999) focused on the changes in the physicochemical properties of soil after 3 years of the red clover cropping. The samples were taken from humus horizon of the grey-podzolic soil (Haplic Luvisol) formed from boulder clay. Soil acidity, organic carbon, organic matter susceptibility to oxidation and specific surface area were determined. Mercury intrusion porosimetry was used to soil pore structure investigation. Generally, the changes of the physicochemical properties of the podzolic soil after 3 years of the red clover cropping was not observed. The sampling period did not have an unequivocal influence on soil acidity, content of organic carbon and organic matter susceptibility to chemical oxidation and specific surface area.

Soil acidity, organic carbon, organic matter susceptibility to oxidation, specific surface area and water vapour adsorption isotherms were determined by Sokołowska et al. (1998) in the soil samples under ecological and conventional cultivation of barley. Mercury intrusion porosimetry was used to soil structure investigation. Authors found relation between basic chemical, physico-chemical and structural properties of soil and the method of cultivation. In comparison to the conventional soil cultivation, under ecological cultivation were characterized by significantly better investigated parameters. Soil acidity and the content of organic carbon were higher, while the organic matter susceptibility to chemical oxidation was lower. Soil samples from ecological cultivation also possessed better structure and exhibited higher specific surface area.

Dąbek-Szreniawska et al. (2002) carried out the research on soil from the long-term static field experiments in Osiny near Puławy. The field experiment consisted of two cultivation systems: „conventional" with mineral fertilizers and „ecological" with organic fertilizers. Microbiological and physico-chemical measurements were carried out. The number of microorganisms was presented by standard methods. Soil acidity, organic carbon, specific surface area and water vapour adsorption isotherms were determined.

Biological processes of organic matter transformation play the major role in development and activity of terrestial ecosystems. Microorganisms take part in different geochemical processes and their rate depends on microbiological activity. Biological activity and fertility of the soil are mostly connected with organic matter. Most of the soil organic matter is derived from plant residues, roots excreta and partly from microbial and microfauna biomass. The mineralization of the soil organic matter generally range from 2-5% per year. This transformation depends on climatic conditions and applied cultivation system applied. The effect of the long-term tillage causes a decrease in the organic matter of the soil, which in turn disturbs nutrition cycle, and degrades the soil's fertility and quality. The cultivation of properly chosen plants in the plant rotation system and application of farmyard manure allow the high productivity of soil to be maintained (Kobus 1995).

Mazur et al. (1993) stated that the progress in agriculture was connected with using the plant rotation system as well as organic and mineral fertilization. It allowed to gain high crop yields to be obtained but at the same time the problem of ecological changes in natural environment occurred.

Nawrocki (1995) stressed out that agricultural technology should be safe for the environment.

Badura (1995) pointed out the important role of microorganisms in the processes of soil structure formation, in the establishment of Eh, pH values and energy equilibrium in terrestrial ecosystems. Microorganisms are indispensable in decay processes and transformation of organic substances and humus formation in soil (Martin, Haider 1970, Smyk 1969/70, Myśkow 1984). Microorganisms are one of the essential factors responsible for soil fertility and are partly responsible for the formation of some soil chemical and physical properties. Stotzky (1997) stated that increased knowledge of how individual physicochemical factors affect microbes in soil may provide some clues as to how to manipulate such factors.

Dąbek-Szreniawska et al. (2002) described the relations between the number and activity of microorganisms, soil's physical and chemical properties. The aim of this research was to determine the changes in the number of microorganisms and some physicochemical properties of soil under ecological and conventional cultivation of winter wheat. Determination of the number of microorganisms was performed by counting colony forming units (c.f.u.) of oligotrophics and zymogenous microorganisms on Fred, Waksman medium (1928). Estimation of amonifying microorganisms and nitrate reductors most probable number (MPN) was made according to Pochon-Tardieux (1962) and of fungi on Martin‘s medium (1950). For the analyses of the results there was used 95% LSD method.

Physico-chemical analyses of soil samples were performed by Carlo Erba Mercury Porosimeter, Series 2000 as in the previous work (Hajnos et al. 1998, Sokołowska et al. 1999). The applied mercury pressures allowed us to study pores with equivalent radii ranging from 3.7 to 7500 nm. Before porosimetric analyses, the samples were oven-dried at 105°C and then outgassed up to 10^{-3} Pa to remove physically adsorbed water from their surface. The pore radii were calculated from Washburn equation. The surface tension and the contact angle of mercury were assumed to be 480 dynes/cm and 141.3°, respectively. Using cylindrical pore model the bulk density, surface area, average pore radius and the total porosity were calculated (Gliński et al. 1991, Hajnos et al. 1998). The cumulative pore size distribution (CPSD) curves and the pore size distributions (PSD) for soil samples taken each year at three specified sampling times were analysed. Organic carbon was determined acc. to Tyurin (1931) and pH was determined by electrometric method acc. to PTG. The surface area of soil samples was evaluated from adsorption and from desorption isotherms.

Table 3. pH of the soil under winter wheat

Cultivation system	Water								
	1996		1997			1998			
	II	III	I	II	III	I	II	III	average
Ecological	6.91	6.10	6.28	6.54	6.30	6.69	6.41	6.25	6.44
Conventional	5.92	4.85	6.31	6.45	6.38	6.54	6.44	6.40	6.16
	KCl								
Ecological	5.3	5.95	5.61	5.68	5.43	6.07	5.58	5.24	5.61
Conventional	4.90	4.10	5.91	5.51	5.63	6.11	5.74	5.48	5.42

Abbreviations: I - seedlings; II - stem elongation stage; III - after harvest;

Table 4. Organic carbon content (%) in the soil under winter wheat.

Cultivation System	1996		1997			1998			average
	II	III	I	II	III	I	II	III	
Ecological	1.55	1.58	1.26	0.95	1.008	0.99	0.94	0.95	1.15
Conventional	1.24	1.19	0.66	0.74	0.84	0.85	0.87	0.83	0.90

Abbreviations: I - seedlings; II - stem elongation stage; III - after harvest;

Tables show of some of the physicochemical characteristics of the soil samples taken from the experimental fields under winter wheat cultivation at seedlings stage (I), stem elongation stage (II) and after harvest (III).

Table 5. The BET surface area (m^2/g) for investigated soil samples under winter wheat

Sampling period	1996		1997			1998				
	II	III	I	II	I	I	II	III	S_{aver}	s.d.
From adsorption Isoterms										
Ecological system	25.3	17.7	25.6	20.3	21.3	17.7	21.7	16.2	18.3	5.7
Conventional system	13.7	8.2	13.0	12.4	8.5	14.2	12.3	15.1	12.2	2.5
From desorption isoterms										
Ecological system	29.1	21.5	27.5	24.2	27.5	20.9	25.8	21.6	24.8	3.2
Conventional system	15.7	9.0	13.8	16.6	12.8	16.6	14.5	17.1	14.5	2.7

Explanation: I - seedlings; II - stem elongation stage; III - after harvest; s.d. – standard deviation; aver.- average

Table 6. Structural parameters for soil samples under winter wheat obtained from mercury porosimeter data.

Ecological Cultivation System										
Period (year)	1996		1997			1998			Average	*s.d.*
Sampling	II	III	I	II	III	I	II	III		
Total pore volume (mm^3/g)	71.6	69.7	68.5	50.5	74.4	74.4	37.7	5.9	62.8	*13.4*
Bulk density (g/cm^3)	2.12	2.16	2.15	2.15	2.15	1.84	2.22	2.16	2.12	*0.11*
Average pore radii (μ)	1.03	0.99	0.58	0.79	0.99	1.55	1.93	1.79	1.08	*0.44*
Total porosity (%)	15.11	15.0	14.5	10.9	16.0	13,7	8,4	12,1	13.21	*2.56*

Conventional Cultivation System										
Period (year)	1996		1997			1998			Average	*s.d.*
Sampling	II	III	I	II	III	I	II	III		
Total pore volume (mm^3/g)	35.8	45.1	34.4	43.7	45.7	52,6	38,2	7,3	42.8	*6.22*
Bulk density (g/cm^3)	2.29	2.24	2.14	2.26	2.32	2,05	2,27	2,2	2.22	*0.08*
Average pore radii (μ)	1.23	2.48	1.93	1.58	1.98	1,93	1,58	0,4	1.63	*0.62*
Total porosity (%)	8.3	10.0	8.0	10.0	10.6	10,8	8,7	10,5	9.61	*1.11*

Explanation: I - seedlings; II - stem elongation stage; III - after harvest; s.d.- standard deviation

It has been found earlier (Sokołowska et al. 1999) that the specific surface areas of soil samples from organic farming are significantly higher than those originating from conventional soil system. Higher values of the total porosity and lower average pore radii point on more pronounced microporous structure of soil samples from the organic farming system. This relationship was observed in the experiment for each year sample (Tables 5 and 6). Similar results were achieved by Sokołowska et al. (1998a) for soil samples under spring barley. Schjonning et al. (1994) and Rose (1991) also reported a decrease of bulk density in plots receiving farmyard manure. The density effect can be ascribed to increased volume of micropores as well as to decreased particle density in soil amended with organic manure.

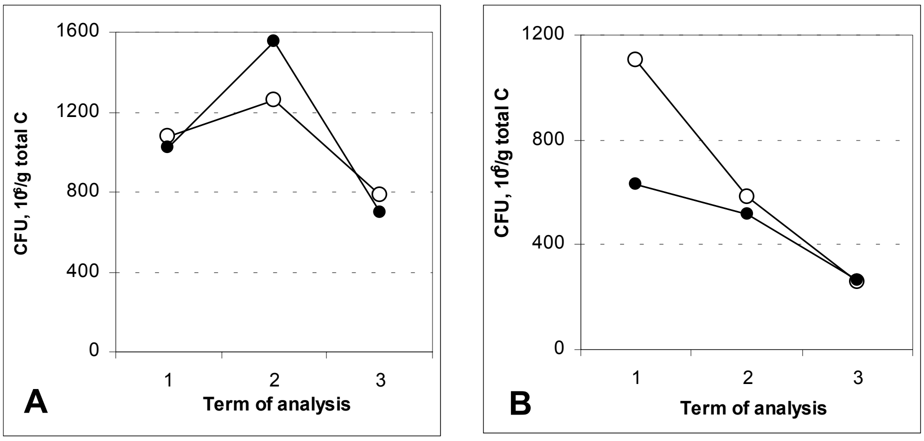
The relatively better physical properties of the soils from the organic farming (ecological system) is most probably connected with the content of organic matter, which is important in the development of soil structure (Hajnos et al. 1998, Sokołowska et al. 1998b, Sokołowska et al. 1999). Organic matter plays an important role in the formation of soil structure and its fertility and in the protection of the soil environment. Protective properties of the soil organic matter arise from the nature and number of its functional groups reacting with mineral and organic compounds (Martin-Haider 1970, Dąbek-Szreniawska 1972). Maintaining or increasing the level of organic matter in soil, by means of proper choice of cultivated plants, manuring and melioration with clay minerals, is an important research goal (Myśkow 1984, 1989).

Table 7. The number of microorganisms under winter wheat in 1997

Microorganisms	Cultivation system	Term of analyses		
		I	II	III
Oligotrophics CFU x 10^6/1 g of dry soil	Ecological	7,92 s.d. 3,35	5,29 s.d. 0,78	2,67 s.d. 0,79
	Conventional	7,30 s.d. 3,55	4,29 s.d. 0,29	2,15 s.d. 0,28
Zymogenous CFU x 10^6/1 g of dry soil	Ecological	12,90 s.d. 2,54	14,73 s.d. 2,38	7,04 s.d. 2,09
	Conventional	7,08 s.d. 1,87	8,29 s.d. 2,16	6,59 s.d. 2,088
Fungi CFU x 10^5/1 g of dry soil	Ecological	1,75 s.d. 0.12	5,94 s.d. 0.88	3,55 s.d. 0.42
	Conventional	1,34 s.d. 0.24	2,71 s.d. 0.59	2,99 s.d. 0.21
Ammonifiers MPN x 10^6/1 g of dry soil	Ecological	1,132	6,697	1,525
	Conventional	3,758	6,379	1,429
Nitrate reducers MPN x 10^6/1 g of dry soil	Ecological	1,925	3,348	0,410
	Conventional	0,752	9,569	1,869

Explanation: I - seedlings; II - stem elongation stage; III - after harvest; s.d.- standard deviation represents standard error based on three or five replicates

Presented Table 7 and figures 1 - 2 illustrate the microbiological research from 1997 because the mean values are closest to the ones obtained this year. For the analyses of the results there was used LSD 95% method. The values of microorganisms in relation to 1g of organic carbon are illustrated on the graphs - Fig. 1 and 2. The differences in the number of microorganisms was observed with respect to the vegetation seasons of winter wheat. The stimulating influence of organic fertilization (ecological system) on the number of zymogenous bacteria and fungi was stated in the second vegetation season of the winter wheat – stem-elongation stage (Fig. 1 and 2 and Table 7). Fungi (Fig. 7) seem to be most attracted to organic fertilization in the second term of analyses. This fact was tilization in the second term of analyses. This fact was supported by the high number of fungi in organically fertilized fields as opposed to their numbers in mineral fertilized soil (the conventional system). The number of oligotrophics (Fig.1) per 1 g of total organic carbon in the examined soil in the first term of the analyses (seedling of winter wheat) shows a visible difference between conventional ecological cultivation in favour of the former. In the first and third term of analyses the differences are clearly distinguishable and differences are significant in both fertilizations and, what may be seen in the graphs, the number of oligotrophics decreases. It may be explained by the fact that oligotrophics can survive on a relatively low amount of easily oxidizeable carbon and other biogenic elements from the soil. These elements are utilised very intensively by growing plants. This fact may cause the decrease in the number of oligotrophics.



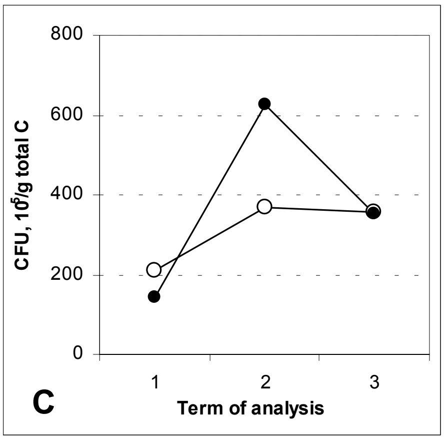


Fig. 1. *Number of microorganisms (in terms of colony forming units, CFU) per unit of total organic C content in Orthic Luvisol under winter wheat at stages of seedlings (1) and stem elongation (2) and after harvesting (3).*
A: zymogenous; B: oligotrophics;
C: fungi.
empty points: mineral fertilization, filled points: organic fertilization

There was observed the tendency of the growth of amonifying microorganisms (Fig. 2) in the spring (1- seedlings) in mineral fertilized soil than in organic fertilized soil. In later vegetation periods (2- stem elongation stage, 3- after harvest) in the under – wheat soil the number of the amonifying microorganisms was similar in both fertilizations. The graphs show that nitrate reducing microorganisms were more numerous in the organic fertilized soil. Their dominance was varied in connection with vegetation period of winter wheat.

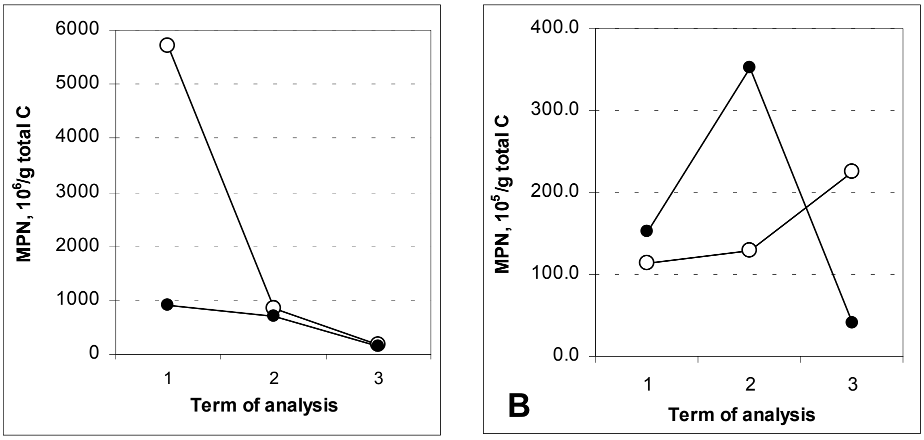


Fig. 2a. Number of microorganisms (in terms of most probable number, MPN) per unit of total organic C content in Orthic Luvisol under winter wheat at stages of seedlings (1) and stem elongation (2) and after harvesting (3) A: ammonifying; B: nitrate-reducers empty points: mineral fertilization, filled points: organic fertilization

Table 3 shows that the soil under ecological cultivation with organic fertilization tended to have higher content of organic carbon and slight decrease of soil pH (Table 4) both in H_2O and KCl in comparison to conventional cultivation with mineral fertilization.

The changes of the organic carbon and pH content are little but visible. The average organic carbon and pH content is slightly higher in ecological samples. Samples inhomogenity had influence on achieving the biological and physico-chemical results.

There is an increasing interest in ecological farming systems because they may reduce some of the negative effects of chemicals on the environment. Microorganisms received particular attention because they usually constitute the major fraction of the soil biomass (Badura 1985).

Reganold et al. (1987) stated that the organically farmed soil after 5 years of cultivation had significantly higher organic matter content, thicker top-soil depth, higher polysaccharide content and less soil erosion than the conventionally farmed soil.

Sokołowska et al. (1990b) showed that the removal of dissolved organic matter alters the surface properties of the soil.

Dąbek-Szreniawska (1992), Myśków et al. (1994), Dąbek-Szreniawska et al. (1993, 1996, 2002), described the relations between the microbial activity and their number and soil physical and chemical properties. The authors drew the conclusion that there was a close relation between cultivation system and soil microbiological and physico-chemical properties.

Fraser et al. [9] stated that soil chemical properties were significantly influenced by chemical management and the application of beef feedlot manure in the organic management system. Total organic carbon, Kjeldahl nitrogen and potentially mineralizable nitrogen in manure-amended surface soils (0-7.5 cm) were 22 to 40% greater than nonmanured soils receiving fertilizer and/or herbicide. Soil bulk density and organic carbon content of the surface from 0 to 7.5 cm layer of manure-treated soils were 5% lower and 36% greater, respectively, than those of chemically treated soil. Soil chemical properties were significantly influenced by the type of management and crop growth at the time of sampling. Soil pH was the lowest (6.5 to 6.9) in soils planted by continuous corn, which received fertilizers, herbicides, and insecticides. On the basis of the research of Dąbek-Szreniawska et al. (2002) it was concluded that the number of soil microorganisms was influenced by the content of organic carbon in the soil, which is, in turn, related to the cultivation system and vegetation stage of the plant. These conclusions are compatible to results of other authors (Reganold et al. 1987, Myśkow et al. 1994).

Martyniuk and Wagner (1978) examined the soil samples from field plots under long-term management systems using standard plate count procedures. Samples collected at monthly intervals from the different plots showed a mean value for bacteria plus actinomycetes of 7 x 10^7/g soil. The mean for fungi was 4 x 10^5/g soil. Microbial populations were low for untreated soils, intermediate for soils treated with chemical fertilizers, and high for soils that received annual applications of manure. Soils cropped to wheat had greater numbers of microorganisms than those cropped to corn.

Martyniuk et al. (1999) studied the comparison of microbial and biochemical characteristics of soil. The research was based on a field experiment established in 1994 at the IUNG Experimental Farm. The studies included fields planted to winter wheat and spring barley cultivated in three systems: conventional, integrated and ecological. Soils under wheat were analysed in 1996, 1997 and 1998 and under barley in 1997 and 1998. The soil samples were analysed for: numbers of bacteria and fungi by plate dilution method on soil extract agar and Martin's medium, respectively; microbial biomass using fumigation-incubation method; soil respiration by titration; dehydrogenese activity using TTC as a substrate; acid and alkaline phosphatase activity with p-nitro-phenol as a substrate for these enzymes. The analysis of the obtained results has shown that microbial and biochemical characteristics of the tested soil samples differed significantly. Soil under spring barley and winter wheat grown in an ecological system had generally higher biological activity than soil under these crops grown in conventional and integrated systems. These differences were detected during the all three growing seasons, indicating long-lasting changes in soil biological characteristics. Higher activity of soil microorganisms in ecological system was probably connected with higher amounts of organic matter incorporated into the soil after growing of grass-red clover mixture in this system.

Dąbek-Szreniawska (1992) determined the numbers of microorganisms in separate soil size fractions (1-0.2, 0.2-0.02, 0.02-0.005 mm). The numbers of bacteria per 1 g or 1 cm increased with a decrease in particle size: the increase being, however, lower than the corresponding increase in the surface area of the particle. The differences in the number of bacteria for the same fractions are very likely the result of different organic matter contents. Consequently, the highest number of bacteria were found in the humus-rich, medium loam. The amount of bacteria depends on the culture medium used in experiment: the amount of bacteria on the DNB medium was higher than that on the soil extract medium. The amount of cellulolytic bacteria is about 10-fold lower in sandy loam when compared to the soils of a heavier texture. CO_2 production following the amendment of soil with cellulose was not correlated with the number of cellulolytic bacteria developing under the conditions of the culture. Sacharase activity depend on the soil texture: the lowest values were found in sandy loam, the highest in medium loam.

Dąbek-Szreniawska et al. (1996) found relations between the number of selected groups of soil microorganisms, water stability of soil aggregates, soil porosity and the organic matter content on the basis of field experiment. Two types of soil were used simultaneously for the research: chernozemic rendzina and brown soil. Rotation system was used in plant cultivation. Chemical, physical and microbiological analyses were carried out on the control object and on objects with organic fertilizers and mineral fertilizers N, P, K. Differences in the sum of fractions of organic C, chiefly in the easily oxidizing fractions in experimental fields on rendzina, in comparison to those on brown soil, can be the result of the predominance of zymogenous bacteria over autochtonous bacteria in the rendzina. Easily oxidizable fractions of C contained in the organic substance of particular fields can be utilized by a high ratio of zymogenous bacteria in the soil samples. It should be noted that characteristic differences in the number of bacteria have been observed in the two types of soils examined. The number of autochtonous microorganisms in brown soil was twice as much as in rendzina. Zymogenous microorganisms constitute more than 90% of the total number of microorganisms in rendzina. Under the cultivation of red clover an increase of water stability of soil aggregates was stated.

Dąbek-Szreniawska et al. (1993) determined the distribution of soil microorganisms in the soil taking into account soil surface area (by water vapour adsorption), soil porosity by mercury intrusion, water content - and others soil characteristics. Microorganisms play an important role in general transformation of organic substances for plants. Thus the knowledge of their distribution and function in soil became indispensible for giving optimum conditions of most favourable growth and plant productivity. In natural conditions each soil shows definite structure, which is dependent on: the number and size of elementar particles and aggregates and their mutual distribution in space of soil. The structure of the soil has an influence on the air-water conditions of the soil and soil aggregates are the factor regulating conductibility of water in the soil. One of the basic features of aggregates is their porosity. Size of pores in soil influences the distribution of microorganisms and also the excessibility of substances and water for microorganisms distributed in soil. In particular places within aggregates content of water, oxygen concentration and organic substances are different. The greatest differentiation can be found between particles creating surface and wall of bigger pores and smaller pores within aggregates. Taking these differences into acount we can distinguish two environments in soil aggregates: outer (external) and inner (internal), external -means surface of aggregates and non capillar pores - more than 3 *μm* of diameter, internal -means capillar pores less than 3 *μm* of diameter. Two soils were used in these experiments: chernozem rendzina and brown loessial soil. The object of analysiss were aggregates of 7-5 mm, 3-1 mm and =<0,5 mm diameter and nonfractionated original soil. Chosen soils differed as to the place they were taken and physical and chemical characteristics. The samples of the soils were taken from humus layer. Chernozem rendzina was as to the granulometric composition heavy clay soil and brown loessial soil was formed of silt. Chernozem soil contained twice as much more of smaller pores - of less than 3.0μm than brown loessial soil. It was reflected in less humidity of brown loessial soil (Table 2). There were also differences between the size of specific surface area in the investigated soils and organic carbon and nitrogen content. The mentioned qualities came about three times greater in chernozem soil than in brown-loessial soil. The distribution of such groups microorganisms were determined using washing-ultrasonifi-cation method acc. to Hattori’s method (1969): Arthrobacter, Pseudomonas, oligotrophics, ammonifiers and fungi. Microorganism distribution in the soil depended on type of the soil, size of aggregates and on the composition and characteristics of both soils.

In chernozem rendzina, oligotrophic bacteria, fungi, and ammonifiers distributed mainly in the inner part of aggregates. Such species of bacteria as Arthrobacter, and Pseudomonas don't show statistically significant differentiation in the outer and inner part of aggregates. The differentiation of the number of microorganisms as regards to chernozem rendzina may result of the smaller content of non capillar pores of radious 7.5 r=1.5μm and higher content of capillar pores of radious 1.5 to 0.5 μm in chernozem soil than brown loessial soil, also in size of specific surface area. The greatest differences of the number of microorganisms in outer and inner environment of both soils may be onnected with the biggest specific surface area of outer parts of aggregates and moreover with the smaller percentage of non capillar pores of radious 1.5-0.5 μm**,** and higher of capillar pores of radious 0.5-0.25 μm.

Runowska-Hryńczuk and Hryńczuk in a long-term field experiment, 8^{Ih} rotation studied chemical and biological changes in soil induced by diversified fertilization. Four-field crop rotation was used in the experiment. After the fourth rotation a marked decrease in yield was observed, especially on the treatment with mineral fertilization only. And after the sixth rotation a collapse of yield to 60 % occurred due to strong acidification of the soil and a slight drop in humus. For this reason, liming was applied for root crops at four-year interval.

The liming gave rise to higher pH, bacteria count and soil respiration ability, and to a minor degree it affected the accumulation of humus. However, the differences among the treatments persisted; the highest values of studied parameters being found on treatments fertilized with farm manure and combined of manure+nitrogen fertilization, the lowest - on treatments with mineral fertilization.

Soil microorganisms and fungi produce such hydrophobic organic substances and tissues as extracellular polysaccharides, hyphal roots and cell walls which can be more or less strongly involved into the formation, stabilization and self-recovery of different size fractions of water-stable aggregates (Guggenberger et al. 1999). Therefore, a validated development of management practices for maintaining sustainable land use should require evaluating the role of mineralisable organic matter for each of the water-stable aggregate-size fractions in arable soils. Balashov and Dąbek-Szreniawska (2001) studied the effects of ecological and monoculture management practices on the relationships of water-stable aggregation with organic matter content and respiration activity in a pseudopodzolic loamy sand (Orthic Luvisol) soil located in Pulawy, Poland. The ecological management practice, compared to the other one, contributed to a greater increase in the total organic C content and amount of the only 0.43-1.0-, 1.0-3.0- and 3.0-5.0-mm water-stable aggregates in the loamy sand Orthic Luvisol. However a total amount of water-stable aggregate-size fractions did not increase with increasing total organic C content if their respiration activity was rather high, probably as a result of a low physical protection of occlused organic matter against microorganisms in the pores of water-stable aggregates. A high susceptibility of attached organic matter to the microbial mineralization resulted in decreasing favourable effects of the ecological management practice on the water-stable aggregation of loamy sand Orthic Luvisol.

Organic matter is a major soil component which is influenced by tillage. Alvarez et al. (1995) quantified the effect of no-till, chisel tillage and plow tillage on the content and depth disribution of organic carbon and microbial biomass after 12 years of each tillage system. In the no-till and chisel tillage systems, crop debris accumulated within the top 5 cm of soil, especially in the no-till system. Consequently, organic carbon was 42-50% higher (*P*=0.01) in the no-till soil than in the soil from the plow and chisel tillage systems. Biomass carbon and soil basal respiration (0-10 day period) were noticeably stratified under no-till and chisel tillage. Carbon inputs from crops were estimated to be similar between tillage systems. Consequently, in situ accumulation of labile forms of organic matter under a no-till system may be ascribed to a decrease in the mineralization intensify of the soil organic matter. Soil temperature determinations suggested that plowed plots were warmer than no-tilled plots, and this phenomenon could lead to a decrease of microbial respiration in straw-covered soil.

Campbell et al. (1991) determined the effects of crop rotations and various cultural practices on soil organic matter quantity and quality in a Rego, Black Chernozem with a thin A horizon were determined in a long-term study. Variables examined included: fertilization, cropping frequency, green manuring, and inclusion of grass-legume hay crop in predominantly spring wheat (*Triticum aestivum* L.) production systems. Generally, fertilizer increased soil organic C and microbial biomass in continuous wheat cropping but not in fallow-wheat or fallow-wheat-wheat rotations. Soil organic C, C mineralization (respiration) and microbial biomass C and N increased (especially in the 7.5- to 15-cm depth) with increasing frequency of cropping and with the inclusion of legumes as green manure or hay crop in the rotation. The influence of treatments on soil microbial biomass C (BC) was less pronounced than on microbial biomass N. Carbon mineralization was a good index for delineating treatment effects. Analysis of the microbial biomass C/N ratio indicated that the microbial suite may have been modified by the treatments that increased soil organic matter significantly. The treatments had no effect on specific respiratory activity (CO_2-C/BC). However, it appeared that the microbial activity, in terms of respiration, was greater for systems with smaller microbial biomass.

In a sustainable agriculture farming systems experiment, soils managed under organic farming practices had greater microbial abundance and activity, and higher numbers of bacterial-feeding nematodes during crop growth, than those managed under conventional farming practices (Gunapala et al. (1998). Microbial activity was most suppressed when field soils were dry but responded to organic matter amendment very rapidly when favorable moisture contents were restored.

Dąbek-Szreniawska et al. (1999) determined the relation between the number of microorganisms, plant crop and physico-chemical characteristics of the soil. In addition, the work focused on presentation of organic and mineral fertilizers and the plant cultivated (winter wheat) and their influence on the number of oligotrophics and zymogenous bacteria and fungi. Groups of examined microorganisms utilized in higher degree added organic substance than mineral one. The number of soil microorganisms related to the crops when it was counted per 1 cm^3 of soil solution.

Wyczółkowski et al. (1999) observed that the time of vegetation and phenological phase of the plant have to the greater extent the influence on differenciation of the number of microorganisms than the cultivation system and fertilization. The number of microorganisms in the soil is clearly connected with the stage of plant growth. The number of soil microorganisms related to the crops when it was counted per I/cm^3 of soil solution. Both, the number of the microorganisms and the crops increased after mineral fertilization of the soil.

An understanding of the nature of soils in natural and human influence ecosystems is essential if progress is to be made in the determination and monitoring of soil quality. Nortcliff (2002) discussed the problem of the changing circumstances which have resulted in the increased awareness of the importance of soil as a key component of both natural and human influenced environmental systems. These changed circumstances and the recognition of the often crucial role that soils play within these systems has resulted in a demand for measures of soil quality, similar to those used in the characterisation of water and air. Any index of soil quality must consider soil function and these functions are varied and often complex. A soil which is considered to be of high quality for one function may not be so for other functions. As a consequence there are potentially many soil properties which might serve as indicators of soil quality, and research is required to identify the most suitable.

REFERENCES

1. Arshad M.A., Martin S., 2002: Identifying critical limits for soil quality indicators in agro-ecosystems. Agriculture, Ecosystems and Environment 88, 153-160.
2. Arshad M.A., Coen G.M. 1992: Characterization of soil quality: Physical and chemical criteria. American J. Alter. Agric. 7, 25-29.
3. Badura L. 1985: Microorganisms in the soil eco – subsystems – their occurrence and functions. Postępy Mikrobiologii, 24, 153-183, (in Polish).
4. Balashov E. V., Dąbek-Szreniawska M. 2001: Organic matter transformation and water-stable aggregation in a loamy sand Orthic Luvisol as affected by management practices. Biogeochemical Processes and Cycling of Elements, P.S.H.S., 361-363.
5. Campbell, C.A., Biederbeck, V. O., Zentner, R.P. and Lafond, G. P. 1991: Effect of rotation and cultural practices on soil organic matter, microbial biomass and respiration in a thin Black Chernozem. Can. J. Soil Sci. 71: 363-376.
6. Dąbek-Szreniawska M. 1972: Microbiological aspects of the formation of the soil aggregates. Problemy Agrofizyki, 4, ed. Ossolineum, (in Polish).
7. Dąbek-Szreniawska M. 1992: Results of microbiological analysis related to soil physical properties. Zesz. Probl. Post. Nauk Rol., 398, 1-6.
8. Dąbek-Szreniawska M., Wyczółkowski A., Stawiński J. 1993: The distribution of soil microorganisms in soils and its relations to physicochemical soil characteristics. Medelingen van de Faculteit Landbouwwetenschappen, Universiteit Gent, 58, (4a), 1787-1790.
9. Dąbek-Szreniawska M., Wilke B. M. 1996: Microbiological activity within various fractions of soil aggregates. Zesz. Probl. Post. Nauk Rol., 436, 13-19.
10. Dąbek-Szreniawska M., Wyczółkowski A., Józefaciuk B., Księżopolska A., Szymona J., Stawiński J. 1996: Relations between soil structure, number of selected groups of soil microorganisms, organic matter content and cultivation system. Int. Agrophysics, 10, 31-35.
11. Dąbek-Szreniawska M., Wyczółkowski A. I., Kuś J.. 1999: Relations between kind of fertilization, the number of oligotrophics, zymogenous and fungi and winter wheat crop. Acta Agrophysica, 23, 17-29.
12. Dąbek-Szreniawska M., Sokołowska Z. , Wyczółkowski A. I., Hajnos M., Kuś J., 2002: Biological and physico-chemical changes in orthic luvisol in relation to cultivation system. Int. Agrophysics, 16, 15-21.
13. Dechnik I. 1972:The specific surface of soils as an indicator of basic elements of their potential fertility. Part I. Correlation between the specific surface and colloidal fraction and humus compounds as an element of the estimation of the potential soil fertility. Annales Universitatis Mariae Curie-Skłodowska Lublin-Polonia, 27, 107-125 (in Polish).

14. Doran J., Liebig M., Santana D. P. 1998: Soil Health and Global Sustainability 16th World Congress of Soil Science. Symposium N°: 36, Montpellier, France; August 20-26.
15. Fraser D.G., Doran J.W., Sachs W.W., Lesoing G.W. 1988: Soil microbial populations and activities under conventional and organic management. J. Environ. Qual., 17,585-590.
16. Fred E.B., Waksman S.A. 1928: Laboratory manual of general microbiology. McGraw-Hill Book Company Inc., New York, London.
17. Gliński J., Konstankiewicz K., Moreno F., Stawiński J. 1991: Microscopic and porosimetric analyses of soil under different tillage methods and compaction. Polish J. Soil Sci., 24, 211.
18. Gunapala N., Venette R.C., Ferris H., Scow K.M. 1998: Effects of soil management history on the rate of organic matter decomposition Soil Biol. Biochem. 30, 14, 1917-1927.
19. Hajnos M., Sokołowska Z., Dąbek-Szreniawska M., Kuś J. 1998: Influence of cultivation system (ecological and conventional) on porosity of podzolic soil. Polish J. Soil Sci. 31, 33-41.
20. Kanazawa S., Asakawa S., Takai Y. 1988: Effect of fertilizer and manure application on microbial numbers, biomass, and enzyme activities in volcanic ash soils. Soil Sci. Plant Nutr., 34, 429-439.
21. Kobus J. 1995: Biological processes and soil fertility formation. Zesz. Probl. Post. Nauk Roln., 209-219, (in Polish).
22. Kuś J. 1998: Preliminary comparisment of three systems of plant cultivation (conventional, integrated and ecological). Rocz. Akad. Roln. Poznan, Rocz. AR Pozn. CCCVII, Roln 52: 119-126 (in Polish).
23. Martin J.P., Haider K. 1971: Microbial activity in the relation to soil humus formation, Soil Sci., 111, 54-63.
24. Martyniuk S., G.H. Wagner, 1978: Quantitative and qualitative examination of soil microflora associated with different management systems SOIL SCI. 125, 343-349.
25. Martyniuk S., Gajda A., Kuś J. 1999: Microbiological and biochemical properties of soil under chreals grown in conventional, integrated and ecological systems. Role of Soil in Functioning of Ecosystems, Congress of the Polish Society of Soil Science and International Scientific Conference, Lublin 267-268.
26. Mazur T., Mineev M., Debreczeni B. 1993: Fertilization in biological agriculture. Wydawnictwo Art, Olsztyn (in Polish).
27. Martin J.P. 1950: Use of acid, rose bengal and streptomycin in the plate method for estimation fungi. Soil sci. 69, 215-232.
28. Myśków Wł. 1984: Agricultural importance of humus and the ways of its quantity modification in soil. Instytut Uprawy Nawożenia i Gleboznawstwa. Puławy (in Polish).
29. Myśków Wł. 1989: Protective function of the soil organic matter (in : Wybrane zagadnienia związane z chemicznym zanieczyszczaniem gleb, A. Kabata-Pendias ed., Ossolineum, Polish Academy of Sciences. 41-67 (in Polish).
30. Myśków W., Stachyra A., Zięba S., Masiak D. 1994: A new index for evaluation of soil fertility. Microbiol. Res. 149, 321-325.

31. Nawrocki S. 1995: Natural soil bases of ecological agriculture in a functional area "Green lungs of Poland”. Białostocki Oddział Polskiego Towarzystwa Gleboznawczego, 12-18 (in Polish).
32. Nortcliff S. 2002 Standardisation of soil quality attributes Agriculture, Ecosystems and Environment 88, 161-168
33. Pochon J., Tardieux P. 1962: Techniques d’analyse en microbiologie du sol. Edition de Tourelle, St. Monde.
34. Reganold J. P., Elliott L.F., Unger Y.L. 1987: Long-term effects of organic and conventional farming on soil erosion. Nature, 330, 370-372.
35. Runowska-Hryńczuk B., Hryńczuk B. 1998: Biological and chemical changes in soil due to long-term application of manure and mineral fertilization Zesz. Probl. Post. Nauk Rol. Z. 460: 191-198.
36. Schjonning P., Christensen B.T., Carstensen B. 1994: European J. Soil Soil Sci., 45, 257.
37. Rose D.A. 1991: Advances in Soil Organic Matter Research. Sp. Publ. (Ed. Wilson W.S.), Cambridge 90, 197.
38. Smyk B. 1969/70: Soil-sickness in the light of microbiological and agrobiological investigations. Postępy Mikrobiologii, 8, 205-224 (in Polish).
39. Sokołowska Z., Hajnos M., Bowanko G., Dąbek-Szreniawska M., Wyczółkowski A. 1998a: Changes in selected physico-chemical properties of soil under ecological and conventional cultivation. Zesz. Probl. Post. Nauk Roln., 460, 351-360,.
40. Sokołowska Z., Hajnos M., Sokołowski S. 1998b: Effect of leaching of dissolve organic carbon on fractal dimension of soils, 231-239. Fractals and beyond: Complexities in the sciences. World Scientific Publishing Co. Pte. Ltd.
41. Sokołowska Z., Hajnos M., Dąbek-Szreniawska M. 1999: Relation between adsorption of water vapor, specific surface area and kind of the cultivation system. Polish J. Soil Sci. 32, 3-12.
42. Sokołowska Z., Hajnos M., Bowanko G., Dąbek-Szreniawska M. 1999: Physicochemical properties of the grey-brown podzolic soil under red clover cropping. Acta Agrophysica, 23, 155-165.
43. Stotzky G. 1997: Soil as an environment for microbial life. Modern Soil Microbiology, Marcel Dekker Inc., New York.
44. Turski R. [ed.] 1998: Soil Science. Publisher Agricultural Academy of Lublin, Poland, pp.219 (in Polish).
45. Tyurin I.V. 1931: A new modification of the volumetric method of determining soil organic matter by means of chromic acid. Pochvovedenye 26, 36-47.
46. Wyczółkowski A.I., Dąbek-Szreniawska M., Wyczółkowska M., Kuś J. 1999: Relations between kind of fertilization and number of microorganisms of nitrogen cycle under winter wheat Acta Agrophysica, 23, 185-197

EFFECTS OF READILY-DISPERSIBLE CLAY ON SOIL QUALITY AND ROOT GROWTH

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INTRODUCTION

The importance of knowing soil physical quality for sustainable agricultural development under environmental protection conditions has been pointed out many times (Czyż, 2003; Dexter and Czyż, 2000; Dexter et al., 2001; Dexter, 2004a,b,c).

Soil quality includes the capacity of the soil to sustain crop growth in a safe and healthy manner, but at the same time in a way that is not detrimental to the resource base or to the environment (Wilson, 2000). Soils represent a considerable part of the natural resources, and consequently, rational land use and adequate management systems are important elements of sustainable agricultural development.

Soil physical quality is often used as a qualitative, general term. Its quantification by a single measure is rather difficult and up to now usually a combination of a range of properties has usually been used. However, Dexter (2004a,b,c) has proposed the use of a measure of soil physical quality, *S*, which is intended to be easily and unambiguously measurable using standard laboratory equipment. *S* is defined as the slope of the soil water retention curve at its inflection point. This curve must be plotted as the logarithm (to base e) of the water potential against the gravimetric water content (kg kg^{-1}). At the inflection point the curve has two characteristics: its position (θ_i, $\ln h_i$), and its slope, $S = d\theta/d(\ln h)$.

The slope of the water retention curves at the inflection point can be measured directly from graphs or by fitting the curve to a mathematical function and then calculating the slope at the inflection point in terms of the parameters of the function. In these investigations the water retention curves were fitted to the van Genuchten (1980) equation with the Mualem (1986) constraint ($m = 1-1/n$). The fitting and use of an equation has the advantage of providing a standard and objective procedure for determination of the position of inflection point and its slope, *S*.

The slope, *S*, indicates the extent to which the soil porosity is concentrated into a narrow range of pore sizes, a larger values of *S* means the presence of a better-defined micro-structure, and consequently a good physical quality of the soil. In turn, soil physical degradation, such as compaction, can change the pore size distribution and consequently the shape of the water retention curve. Compaction reduces both the water content at saturation, θsat, and the slope of the retention curve at the inflection point. As a result, a small value of *S* represents a soil that is structureless (homogeneous), whereas a greater value of the slope *S* corresponds to a soil that has a well-developed micro-structure.

Dexter and Czyż (2000a) described micro-structure as being perhaps the most important structural feature in most soils. Micro-structure is usually represented by compound particles of about 20-250 μm diameter which are usually stabilised by organic matter acting like glue to hold the primary particles together and also by polyvalent cations (such as Ca^{++}) which can form bridges between organic matter and clay surfaces (Dexter, 1988). The most important feature of micro-structure is the pore space between micro-aggregates, which often takes the form of micro-cracks, being important for water storage for plant use and for the transport of water to plant roots in response to transpirational demand (Dexter and Czyż, 2000a).

Clay plays a key role in the structural stability of soils. If the clay is not stable, then soil micro-aggregates and aggregates cannot exist (Dexter, 2002). When clay disperses, the soil is unstable when wet or in water. On drying, the clay that was dispersed acts like a cement between the larger soil particles. Therefore, a high content of readily-dispersible clay results in soil which is both too weak when wet and too strong when dry (Czyż et al., 2002). The opposite of dispersion is flocculation in which assemblages of clay particles are formed which remain stable when in contact with water.

Soils with high contents of readily-dispersible clay in the presence of water may experience the collapse of their structure with the consequent loss of the inter-aggregate pores and soil homogenization (Czyż et al, 2002). Problems associated with clay dispersion include: anaerobic soil that is unsuitable for plant root growth, reduced infiltration of water with associated increased risk of run-off, flooding and erosion (Dexter and Czyż, 2000b; Czyż et al., 2002). Also, such soils can form crusts at the surface or can hard set, both of which characteristics are associated with poor crop emergence and increased energy requirement for tillage (Dexter and Czyż, 2000b; Czyż et al., 2002).

For optimum growth, plant roots need supplies of both water and oxygen and both of these have to be supplied by or through the soil (Dexter, 1988). For this there must exist a continuous network of air-filled pores at field capacity (Dexter, 2002). In addition, for roots to penetrate the soil, this must be sufficiently weak to enable the roots to make new pores (root channels) by overcoming the soil strength and pushing the root tips forward or there must be pre-existing pores of suitable size within which they can elongate with little or no restriction (Dexter, 1988; 2002).

Due to the large effects of readily-dispersible clay in soils, the aim of these investigations was to develop an understanding of the interactions between the dispersible clay and the recently-proposed measure S of soil physical quality which is also a good indicator of soil rootability.

MATERIALS AND METHODS

Sample collection and characterization

The soil samples used in these investigations were collected during the summer of the year 2003 from the arable layer (0-20 cm) in 5 different locations around Poland. The samples were from field plots where spring cereals (spring wheat and spring barley) were grown. Samples collected for the measurement of all physical properties were stored in sealed plastic bags and were kept at their field water content until they were needed for analysis.

The soils were characterized using standard methods and the results are given in Table 1. The sand content (not shown) is defined as 1-(silt+clay), kg kg^{-1}. According to the FAO/USDA soil classification system, the figures from Table 1 illustrate the generally sandy nature of the Polish soils (Czyż et al., 2002).

Table 1. Physical characteristics for the arable layer (0-20 cm) of the soils used

Location	Silt kg kg^{-1}	Clay kg kg^{-1}	FAO/USDA soil texture class	Organic matter kg kg^{-1}	Bulk density Mg m^{-3}
HUTA	0,32	0,03	sandy loam	0,0122	1,574
KĘPA	0,67	0,23	silt loam	0,0222	1,438
OSINY	0,26	0,04	sandy loam	0,0126	1,609
ROGÓW	0,76	0,12	silt loam	0,0171	1,314
ŻELISŁAWKI	0,25	0,10	sandy loam	0,0177	1,534

Water retention characteristics

Undisturbed soil samples were wetted from below to saturation for 24 hours and then dried down to 11 distinct water potentials. The water retention characteristics were measured using sand- and kaolin- tables (Eijkelkamp) for the low pressures applied (-10, -20, -40, -80 and –250 hPa) and ceramic pressure plate extractors (Soil Moisture Inc.) for the high values of pressure applied (-500, -1000, -2000, -4000, -8000 and –15000 hPa). After a period of equilibration, ranging between 2 - 4 days at low values of the suction and 12 – 14 days at high values of the suction, the samples were removed and their water content was measured gravimetrically.

The mean values of water content for every value of suction were then fitted to the van Genuchten (1980) equation:

$$\theta = \left(\theta_{\mathrm{sat}} - \theta_{res}\right) \cdot \left[1 + \left(\alpha h\right)^{n}\right]^{-m} + \theta_{res} \qquad (1)$$

with the Mualem (1986) restriction $m = 1 - 1/n$,

where: θ_{sat} is the water content at saturation (kg kg^{-1}),

θ_{res} is the residual water content (kg kg^{-1}),

α is an adjustable scaling factor (hPa^{-1}),

h is the water suction (equal to the modulus of the matric potential (hPa),

m, n are adjustable shape factors.

Eq. (1), which is highly non-linear, was fitted to the experimental data using the Levenberg-Marquardt method. This produced estimates of the values of the parameters of θ_{sat}, θ_{res}, α and m.

Measurement of readily-dispersible clay

The method used for determination of readily-dispersible clay is that described by Czyż et al., (2002) and Dexter and Czyż (2000b), and is rather similar to that described by Kay and Dexter (1990), Watts and Dexter (1997) and Watts et al. (1996), but was adapted for Polish sandy soils.

The amount of readily-dispersible clay in water using a standard dilution and shaking procedure was measured using turbidimetry. For each soil sample 10 sub-samples were used. About 5g of soil were weighed and placed in 150ml plastic bottles and then were shaken with 125ml distilled water in a standardized way (four inversions end-over-end). The bottles were then allowed to stand for 18 hours so that the larger particles would sediment, leaving only dispersed colloids (in this case, mostly clay) in suspension. A 30ml sample of this suspension was extracted by pipette from the centre of each bottle and was transferred to a glass turbidity cell.

Also, 10 sub-samples of the same soil sample were prepared for determination of total clay. In this case, about 18g of soil were weighed and placed in 750-1000ml Berzelius glasses and were stirred with 500ml distilled water for 30min. Then 125ml from this suspension was poured into the plastic bottles and allowed to stand for 18 hours so that the larger particles would sediment, leaving only colloids (clay) in suspension. A 30ml sample of this suspension was extracted by pipette from the centre of each bottle and was transferred to a glass turbidity cell.

The turbidity was measured by light-scattering using a Hach 2100 AN ratio turbidimeter. Turbidity values are linearly proportional to the concentration of colloids (clay) in suspension. The turbidimeter readings were expressed as NTU (Nephelometric Turbidity Units) and were normalized by dividing by the concentration of the original soil in the water to give NTU/(g L^{-1}). The mass of soil was corrected to dry mass for this calculation.

To determine the effects of air-drying of soil samples, some samples were air-dried for comparison with samples that had been stored at their field water content. To test the reversibility of the effects of air-drying, some air-dried samples were re-wetted by saturating them for 24 hours and then storing them on a sand table at –40 hPa water suction for up to two weeks before measurement of content of readily-dispersible clay as described above.

Calculation of the Soil Physical Quality Index, *S*

The slope (*S*) at the inflection point of the water retention curve was used as a measure of soil physical quality. *S* is given in terms of the parameters of the van Genuchten (1980) equation by

$$S = -n\left(\theta_{sat} - \theta_{res}\right)\cdot\left[1+\frac{1}{m}\right]^{-(1+m)} \qquad (2)$$

where the various terms are as defined in Eq. (1).

RESULTS AND DISCUSSION

Water retention of the soils was measured at 11 different water potentials and the resulting data were then fitted to the van Genuchten (1980) equation. The fitted parameters were then used to calculate S using Eq. (2). The resulting values of S together with the fitting parameters are presented in Table 2. The range of values in Table 2 show that these soils have very different pore size distributions which is mainly due to differences in their micro-structure.

Table 2. Parameters of the van Genuchten equation and the values of slope, S

Location	θ_{sat} (kg kg^{-1})	θ_{res} (kg kg^{-1})	n (-)	α (hPa^{-1})	S value (-)
HUTA	0,1912	0,0051	1,418	0,0387	0,0388
KĘPA	0,2273	0,0000	1,159	0,0194	0,0238
OSINY	0,1479	0,0054	1,253	0,0773	0,0206
ROGÓW	0,3021	0,0125	1,305	0,0399	0,0478
ŻELISŁAWKI	0,1795	0,0073	1,221	0,0640	0,0235
mean	0,2207	0,0082	1,264	0,0537	0,0325
s.d.	0,0730	0,0133	0,129	0,0529	0,0170
s.e.	0,0177	0,0032	0,031	0,0128	0,0041

The amount of readily-dispersible clay was measured on soil samples that had been stored at field water content. A calibration between turbidity measurements and mass of dispersed clay gave a mean value of 1 NTU/(g L^{-1}) = 0.23 g/(100 g soil). For the soils investigated, the mean content of clay that is readily dispersible was found to be 0,42 g/(100 g soil). This value is slightly smaller than that found by Czyż et al. (2002) for 210 Polish soils (0,48 g/100 g soil).

Usually, large values of the dispersibility means that the clay is loosely bound in the soil aggregates and that the soil is susceptible to dispersion and cementation during wetting and drying processes (Elmholt et al., 2000; Dexter, 2002). Reorientation and hardening of the dispersed clay minerals can result in a dense and mechanically-strong soil (Kay and Dexter, 1992). With these mechanisms, the result is the destruction of the existing soil structure, and as a consequence, this readily-dispersible clay is expected to contribute to the agricultural problems which were described in the introduction.

In this work, we looked for a correlation between dispersibility of clay and the soil physical quality, S. Our results are shown in Fig. 1. Regression analysis showed that soil which contained more readily-dispersible clay also tended to have lower values of the soil physical quality, as given approximately by the power-law equation:

$$S = \underset{(\pm 0{,}00024)}{0{,}00014}\, RDC^{\underset{(\pm 0{,}39)}{(-2{,}44)}} \qquad \textit{Conf. interval} = 0{,}95;\quad r^2 = 0{,}82 \qquad (3)$$

where *S* is the soil physical quality and *RDC* is the content of readily-dispersible clay, NTU/(g L^{-1}).

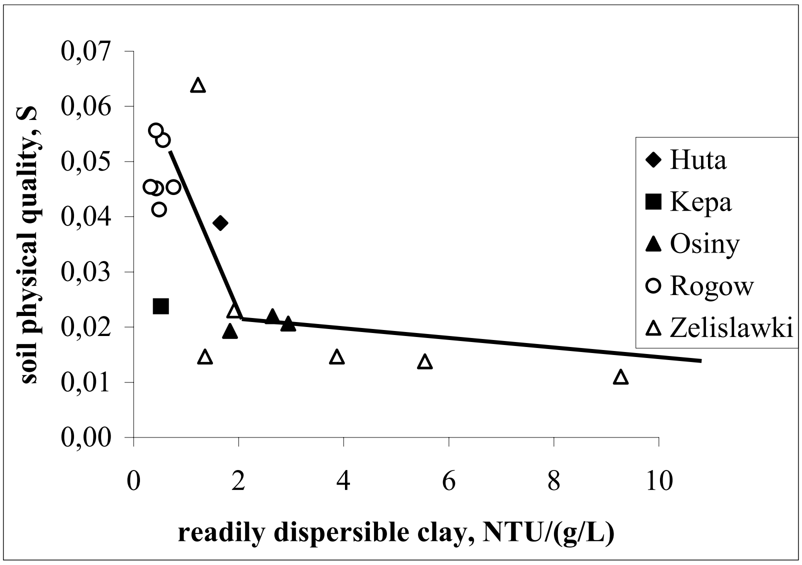

Fig. 1. *Values of the measure of soil physical quality, S, plotted as a function of the content of readily-dispersible clay.*

Alternatively, two lines can be drawn as shown in Fig. 1. At values of readily-dispersible clay greater than about 2,0 NTU/(g L^{-1}), the soil is "saturated" with dispersible clay and severe physical degradation of the soil is apparent. On the basis of practical experience, Dexter (2004a) suggested that the boundary between soils with good and poor physical quality occurs at approximately $S = 0,035$. He also associated values of $S < 0,020$ with very poor soil physical condition.

In addition, Dexter (2004a) has shown that *S* predicts soil rootability better than bulk density. Jones (1983) produced two lines by which he delineated the boundaries between soils with few roots and no roots, and between soils with many roots and few roots. Analogously, Dexter (2004a), using pedo-transfer functions showed that root growth is not expected to occur for values of $S < 0,020$ and that only a few roots will grow if $0,020 < S < 0,030$. According to this approach, unrestricted root growth requires values of $S > 0,030$ (see Figs. 9A and 9B in Dexter, 2004a).

An important aspect concerning the determination of readily-dispersible clay is related to the soil sample condition at the time of measurement. We have found that the contents of readily-dispersible clay measured on air-dry soil samples were around 20 times smaller than when measurements were made on samples that had been stored at field water content. Fig. 2 illustrates this phenomenon, and the regression line is given by the following equation:

$$RDC_{wi} = 20{,}5\ RDC_{dry} - 1{,}9 \qquad p = 0{,}008; \quad r^2 = 0{,}66 \qquad (4)$$
$$(\pm 5{,}6) \qquad\qquad (\pm 1{,}5)$$

where RDC_{wi} is the readily-dispersible clay measured at field water content, and RDC_{dry} is the readily-dispersible clay measured on air-dried soil samples, both in units of NTU/(g L^{-1}).

If the soil is allowed to air dry, the cementing materials (e.g. dispersed clay) will precipitate or flocculate at intergranular points at low water contents (Kay and Dexter, 1992). If this material deposition occurs near or at the ends of microcracks, then the micro-cracks will be stabilized and this will result in an increase of the tensile strength of the soil (Kay and Dexter, 1992). Also, as soil dries, it is compressed by effective stresses due in part to the pore water pressure and in part to the surface tension in the water menisci. Such compression is non-reversible. Therefore, to determine the physical properties of soil as they occur in the field, samples must never be allowed dry to lower water contents than they have ever experienced in the field.

The irreversibility of the effects of drying is shown by the fact that re-wetting of air-dried soil for up to two weeks had no significant effect on the content of readily-dispersible clay.

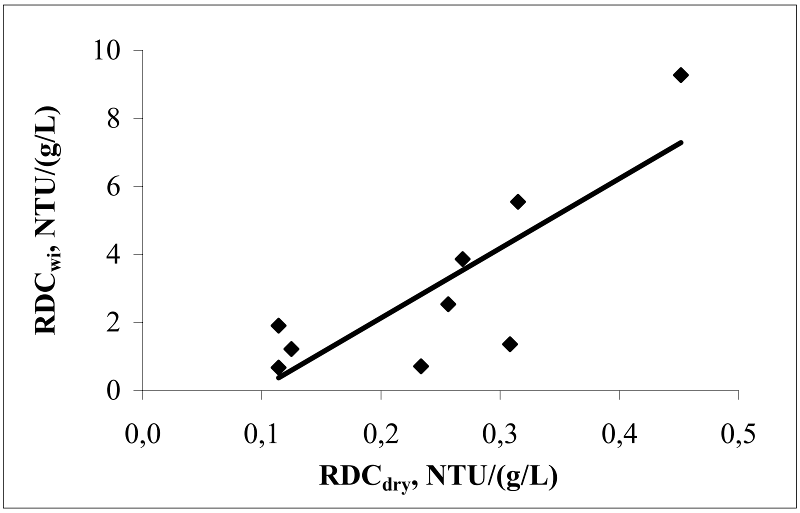

Fig. 2 *Comparison of the values of readily-dispersible clay obtained after different conditions of sample storage. Values on the x-axis were obtained with soil samples that had been air-dried whereas the values on the y-axis were obtained with samples that had been stored at field water content.*

As soil strength increases, root elongation rate decreases due to the increasing resistance of the soil particles to displacement (Clark et al., 2003). Strong soil can be a severe problem in agriculture as it can limit the development of root systems by restricting the access to water and nutrients.

CONCLUSIONS

Soil physical quality, as defined here by the slope (*S*) of the water retention curve, can be easily measured. Almost every soil physics laboratory has the equipment necessary for water retention measurements. Dexter (2004a,b,c) suggested that the measure *S* provides a scale which can be used to compare easily the physical quality of different soils or the effects of different soil management practices.

Increasing amounts of readily-dispersible clay have been shown to degrade the physical quality of Polish soils. This readily-dispersible clay is expected to have negative effects on other physical properties, such as soil aeration, infiltration of water, and soil strength.

Soil samples must never be dried to lower water contents than they have ever experienced in the field or the physical properties will be significantly and irreversibly changed.

It is suggested that the presence of high contents of readily-dispersible clay in soils has negative effects on root development due to reduced aeration in wet soil and increased strength of drier soil.

REFERENCES

1. Clark, L. J., Whalley, W. R. and Barraclough, P. B., 2003. How do roots penetrate strong soil? Plant and Soil 255, 93-104.
2. Czyż, E. A., 2003. Podatność na destrukcję gleb użytków rolnych Polski (The sensitivity of Polish agricultural soils to destruction) (in Polish with English summary). Pamiętnik Puławski 132, 21-31.
3. Czyż, E. A., Dexter, A. R. and Terelak, H., 2002. Content of Readily-Dispersible Clay in the Arable Layer of Some Polish Soils. In: Pagliai M. and Jones R. (Eds). Sustainable Land Management-Environmental Protection. Advances in Geoecology 35, 115-124.
4. Dexter, A. R., 1988. Advances in characterization of soil structure. Soil Till. Res. 11, 199-238.
5. Dexter, A. R., 2002. Soil Structure: The Key to Soil Function. In: Pagliai M. and Jones R. (Eds). Sustainable Land Management-Environmental Protection. Advances in Geoecology 35, 57-69.
6. Dexter, A. R., 2004a. Soil physical quality. Part I: theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201-214.
7. Dexter, A. R., 2004b. Soil physical quality. Part II: friability, tillage, tilth and hard setting. Geoderma 120, 215-226.
8. Dexter, A. R., 2004c. Soil physical quality. Part III: unsaturated hydraulic conductivity and general conclusions about S-theory. Geoderma 120, 227-239.
9. Dexter, A. R. and Czyż, E. A., 2000a. Soil Physical Quality and the Effects of Management. In: Wilson M. J. and Maliszewska-Kordybach B. (Eds.). Soil Quality, Sustainable Agriculture and Environmental Security in Central and Eastern Europe, NATO Science Series, 2. Environmental Security – Vol. 69, 153-165.
10. Dexter, A. R. and Czyż, E. A., 2000b. Effects of soil management on the dispersibility of clay in a sandy soil. Int. Agrophysics 14, 269-272.

11. Dexter, A. R., Czyż, E. A., Niedźwiecki, J. and Maćkowiak, C., 2001. Water retention and hydraulic conductivity of a loamy sand soil as influenced by crop rotation and fertilization. Arch. Acker- Pfl. Boden., 46, 123-133.
12. Elmholt, S., Debosz, K., Munkholm, L. J. and Schjønning, P., 2000. Biotic and abiotic binding and bonding mechanisms in soils with long-term differences in management. Proceedings from Workshop on Soil Stresses, Quality and Care, Aas, Norway, 10-12 April. DIAS Report No. 38. The Danish Institute of Agricultural Sciences, 53-61.
13. Jones, C. A., 1983. Effect of soil texture on critical bulk densities for root growth. Soil Sci. Soc. Am. J. 47, 1208-1211.
14. Kay, B. D. and Dexter, A. R., 1990. Influence of aggregate diameter, surface area and antecedent water content on the dispersibility of clay. Can. J. Soil Sci. 70, 655-671.
15. Kay, B. D. and Dexter, A. R., 1992. The influence of dispersible clay and wetting/drying cycles on the tensile strength of a red-brown earth. Aust. J. Soil Res. 30, 297-310.
16. Mualem, Y., 1986. Hydraulic Conductivity of Unsaturated Soils: Prediction and Formulas. In: Klute, A. (Ed.). Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 2nd Ed., Amer. Soc. Agron., Monograph 9, 799-823.
17. van Genuchten, M. Th., 1980. A closed-form expression for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892-898.
18. Watts, C. W. and Dexter, A. R., 1997. The influence of organic matter in reducing the destabilization of soil by simulated tillage. Soil Till. Res. 42, 253-275.
19. Watts, C. W., Dexter, A. R., Dumitru, E. and Arvidsson, J., 1996. An assessement of the vulnerability of soil structure to destabilisation during tillage. Part I. A laboratory test. Soil Till. Res. 37, 161-174.
20. Wilson, M. J., 2000. Soil Quality, Sustainable Development and Environmental Security: Introduction to General Concepts. In: Wilson M. J. and Maliszewska-Kordybach B. (Eds.), Soil Quality, Sustainable Agriculture and Environmental Security in Central and Eastern Europe, NATO Science Series, 2. Environmental Security – Vol. 69, pp. xi-xv.

STRESS STRAIN DEPENDENT CHANGES OF SOIL STRUCTURE IN ARABLE AND FOREST SOILS – CONSEQUENCES FOR THE ENVIRONMENT

Horn R.

ABSTRACT

The stress strain processes in structured unsaturated arable and forest soils very much depend on the internal soil strength and on the existing hydraulic and mechanical boundary conditions, which affect soil deformation by compaction and shearing to a great extent. As soon as the internal soil strength defined as the precompression stress value is exceeded by external forces, an intense virgin compression process and in combination with shearing forces at high pore water pressure values a complete homogenisation of the soil profile down to depth occur.

In situ stresses and strain will be determined by the Stress State transducer System (SST) while the Displacement of soil particles will be described by the DTS (Displacement Transducer System). During the determination of the stress strain processes and the shear parameters also the changes in the pore water pressure and gas exchange must be determined by mini - tensiometers installed inside the undisturbed soils as the stress and time dependent changes in the compacted and sheared soil greatly affect the total strength system. Consequently both the hydraulic and the gas fluxes will be affected by such mechanical properties, which result in an intense alteration of ecological and mechanical properties of the site. The consequences of such compaction and shearing on strength and sustainable land use have to be considered with respect to the sustainability of the system.

Keywords: shear stress, precompression stress, strength, hydraulic conductivity, structured soils

INTRODUCTION

Soils undergo intensive changes in their physical, chemical, and biological properties during natural soil development and as a result of anthropogenic processes such as plowing, sealing, erosion by wind and water, amelioration, excavation and reclamation of devastated land. In agriculture and in forestry, soil deformation by compaction and shearing as well as erosion by water are classified as the most harmful processes which not only end in a reduction of the productivity of the site but are also responsible for groundwater pollution, gas emissions and higher energy requirements to obtain a comparable yield. In forestry, especially tree harvesting and clear cutting by heavy machinery has reached a level which from the stress point of view is identical to that one in agriculture. It induces not only an intense soil deformation by shearing and kneading which finally results in an increased soil erosion by water, but it also results in an organic matter loss, groundwater pollution, and gas emission which have the potential to cause global changes.

These interrelationships have been described by Soane and van Ouverkerk (1994) and recently by Horn et al. (2000). The mechanical processes in itself are very often described as it is also true for the hydraulic mechanisms, but there are no data about the coupled processes in unsaturated structured soils. Thus, in the following the effect of mechanical stress on soil deformation and its consequences for pore functions will be described.

STRUCTURE EFFECTS ON MECHANICAL PARAMETERS

Soil Strength

As stress is applied, soil deformation occurs at the weakest point in the soil matrix and further increase in stress results in the formation of failure zones. Therefore, the strength of the failure zone is equal to the energy required to create a new unit of surface area or to initiate a crack. Consequently, soil stability is related to strength distribution in the failure zones. In principle, soil structure will be stable if the applied stress is smaller than the strength of the failure zone, i.e. if the bond strength at the points of contact exceeds the external stress.

In homogenized soil substrates, soil strength expressed as precompression stress is the smaller,

- the higher the clay content at given bulk density values,
- the smaller the bulk density values at given texture,
- the smaller the amount of organic material at comparable grain size distribution,
- the wetter the soil.

Pedogenic effects on mechanical strength defined as precompression stress were often quantified and show e.g. a clear interrelation to clay migration in Hapludalfs with a reduced strength in the clay deriched Al horizon and an increase in the precompression stress in the clay enriched Bt horizon due to aggregation. Calcium precipitation in the corresponding horizon of Mollisols also leads to a strength increase. Thus, at given internal parameters, aggregation always results in higher strength. Anthropogenic effects like the yearly ploughing and the tractor traffic create strong plowpans and plow layers with precompression stress values like the contact pressure of the tractor tyre or even higher due to lug effects (up to 300%). In addition, strength decreases in the A horizon due to plowing and seedbed preparation can be followed until texture dependent values are reached (Fig. 1).

The strength values differ for various soil types, and they consequently depend on texture, structure, pore water pressure, organic matter and bulk density. Based on more than 160 soil profiles the effect of structure on strength can be derived for clayey, silty/loamy and sandy material both for the topsoil and the subsoil and various aggregate classes. In addition a clear difference between the topsoil and the subsoil strength can be defined (Fleige and Horn 2002). In addition it can be seen that conservational tilled soils have a more equally distributed strength pattern than conventionally tilled sites. Especially the higher strength values in the topsopil due to a more pronounced structure formation, the only slight increase in the former plowpan layer (as a relict of the former conventional tillage with smaller units) and the slightly higher values in the deeper Bt horizon due to deeper rooting and more pronounced water uptake at deeper depth characterize the main processes for different tillage systems.

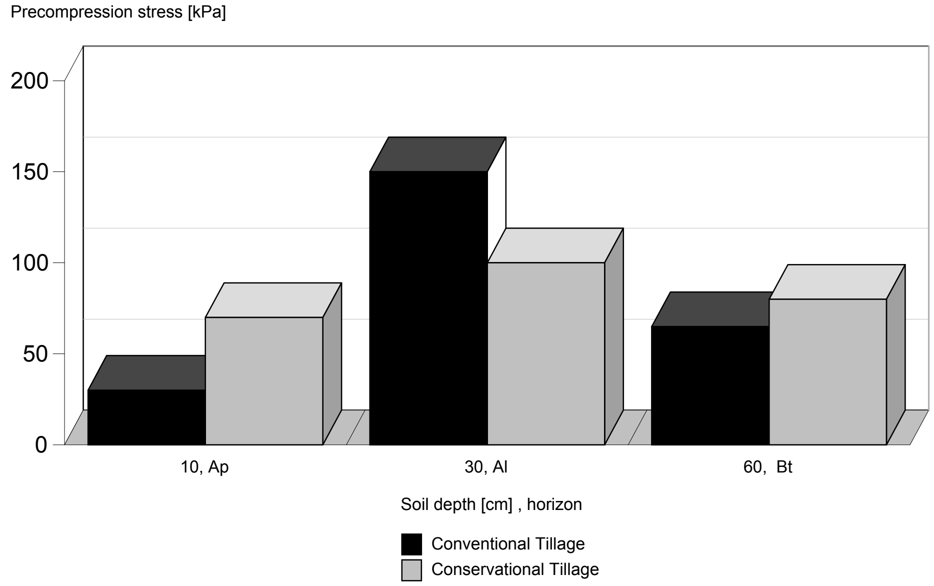

Fig. 1. *Precompression stress [kPa] in different soil depths of a Hapludalf derived from loess under conventional and conservational tillage systems at a pore water pressure of -6 kPa*

However strength changes from conventional to e.g. reduced tillage (like with the Horsch system) require time. During long term experiments carried out in Kiel from more than 9 years at a Hapludalf derived from glacial till it was found out that such changes in mechanical and ecological properties can be only verified after long term treatments with the same machines (lighter than the depth dependent precompression stress). While there were no significant changes in the bulk density to be seen (apart from the fact that the reduced tilled site = „conservation“ had always higher values in all soil horizons as compared to the conventionally treated one) the precompression stress became much stronger in the reduced as compared to the conventionally tilled one (Fig. 2).

It always showed the first changes in the top soil after approximately 3 years in the conservation tillage plot while only after another 2 years the first changes could be detected at about 30 cm. In the deeper depth such changes became significant after more than 7 years. This strength regain can be explained by the effect of particle rearrangement in combination with the drying intensity effects as these sites showed more negative pore water pressure values down to deeper depth than the conventionally tilled site as a consequence of a more prevented root penetration through the plowpan layer.

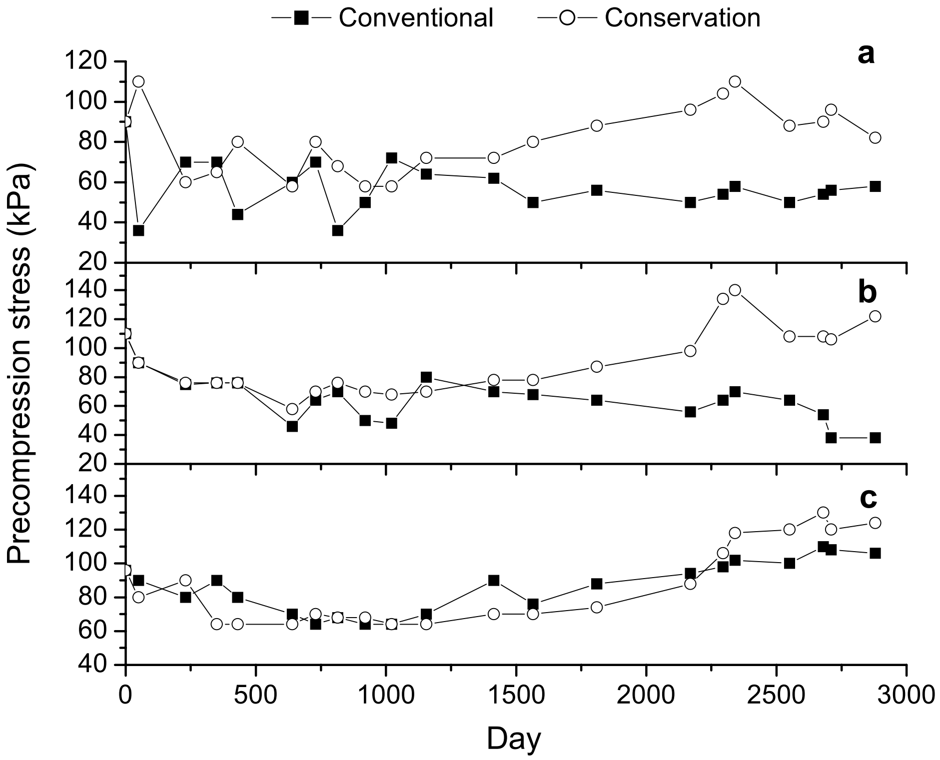

Fig. 2. *Changes in the precompression stress (kPa) at constant pore water pressure (-30kPa) in a Hapludalf derived from glacial till as a function of time (days d) after starting the experiment in 1991. (a= 10-15cm depth, b= 30 – 35 cm depth, c=55-60 cm depth)*

Stress Distribution in Soils

Any load, applied at the soil surface is transmitted to the soil in three dimensions via the solid, liquid and gas phases. If air permeability is high enough to allow immediate deformation of the air filled pores, soil settlement is mainly affected by fluid flow.

Under in situ conditions, stress attenuation is greater in soils with comparable physical and chemical properties if they are more aggregated. If however internal strength values are smaller than the external forces applied, repeated traffic results in increased soil strength. For example, if the wheeling experiment will be carried out under wetter soil conditions e.g. at pF 2.5 in a loessial Hapludalf (which was repeatedly traversed at constant water content), horizontal minor stresses decrease while the major vertical stress increases. These soil strength changes increase the concentration factor values (as a consequence of deeper stress transmission), and each loading consequently results in a smaller effective stress relative to neutral stress (i.e. less negative pore water pressure). In contrast to this, dry and /or very strong soils (because of plowpans or other kind of hardpans) are less sensitive to soil deformation and/or only after several wheeling events they show more intense stress propagation to depth. It can be seen that repeated wheeling result in an increase of the octahedral shear stress and the major principle stress (σ_1) while the mean normal stress remains the same (Fig. 3).

Such stress distribution processes are however not only valid in arable soils but they can be also found in forest management practices. In an interdisciplinary project on the effect of forest harvesting techniques on stress and strain distribution we could analyse the stress and strain distribution in Cambisols derived from weathered rocks in the Black Forest region.

The highest stresses at a depth of 20 cm were recorded under the "Königstiger" Chain-Harvester. The vehicle has had an empty weight of 28Mg and worked in a typical harvest scenario which included the arrival, the harvest with sawing, chopping of branches, cutting the trunks and the departure. The experiments were carried out without a protecting brushwood cover.

The stresses of the heaviest vehicle, the "Hannibal" chain-harvester with a weight of 40 Mg were below those of the "Königstiger" due to a protecting brushwood cover of 60 cm height. The cover protected the soil but was not able to reduce the stresses to the approximate precompression stress. The high stress values for the HSM 904 (8 Mg) make clear, that even smaller forest vehicles are able to compact the soils. The HSM whole wood skidders reached under full load and without protecting soil cover stresses as high as the much larger harvester. But of course for an evaluation of the impact the smaller contact areas of the wheel based vehicles have to be taken into account.

The high maximum stress for the logging horse is a single event, when the hoof hit exactly the sensor. In all other cases the impact on the soil was mostly zero. Taken the very small contact area of the horse hoofs into account, the influence of logging horses on soils was the smallest of all methods.

Effect of Stress Application and Attenuation on Soil Strain

If externally applied stresses are smaller than the internal soil strength, no further soil deformation will occur. If, however, strength is exceeded by the external forces additional stress/strain processes have to be considered. The extent to which soil strain occurs during traffic and the extent to which various tillage implements (conventional/conservation) deform a soil at a given pore water pressure, has been determined by Wiermann (1998). The effect of tillage treatment in a loessial Hapludalf resulted in a pronounced vertical (up to 8 cm) and horizontal forward and backward (up to 2 cm) displacement. Under conservation tillage, these soil de-formations are smaller because of a higher internal soil strength leading to a maximum vertical displacement of < 4 cm after 2 traffic events and a much less pronounced horizontal displacement (Wiermann 1998). With increasing aggregate development, soil strength increases and aggregate deterioration is less pronounced during displacement and alteration of the pore system due to the infilling of inter-aggregate pores by smaller particles. During tree harvesting as well as during transportation the soil displacement under the Hannibal Harvester without a protecting lopping cover was the strongest so far measured. The rut depth was 20 cm while the vertical displacement from 20 cm was as deep as 36 cm. Interesting is the high soil volume displacement which results in only a slight volume compaction of four cm depth (Δ 20 cm height = 16 cm sensor displacement). The compaction rates under wheel based vehicles were in general higher than those under chain based vehicles. The lopping cover during the "Hannibal" and combined "Hannibal" and Forwarder experiment showed a strong decrease of soil displacement, but the absolute values were still very high. The Forwarder driving caused higher soil deformation with minor subsoil displacement. The displacements under the horse hoof were up to 9 cm, but again the contact area is extremely small.

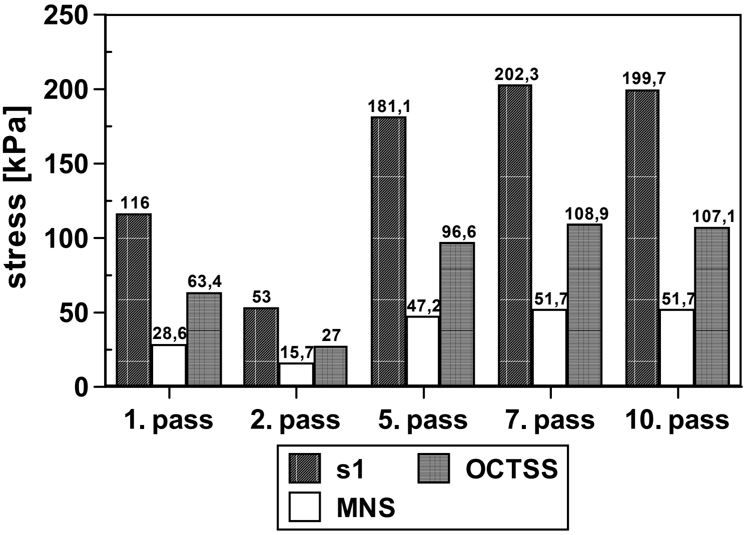

Fig.3. Effect of repeated wheeling on stress distribution at a depth of 15 cm. (Hiwassee clay, water suction: approx: pF 3, tractor front wheel load: 3.8 Mg, 16.9R30; rear wheel load: 5.5 Mg, 18.4 R46)

Nevertheless, all stresses which are not attenuated to levels below soil strength result in volume alterations, even if the applied stresses vary for different soil types, land uses and management systems, and environmental conditions.

Slip Effect on Soil Displacement

Stress strain effects are further altered by the intensity of slip as many management systems increase either the effectivity of pulling by the application of rubber belt driven systems and/or by higher slip during management operations.

Generally, pure shearing always results in a volume constant displacement of particles which results in a complete disconnection of the pore spaces. This can be also defined as an increased tortuosity (Hartge and Horn 1999).

If soils are wheeled with rubber belts fixed during this experiment on a well defined and equiped Gantry System, the wheeling on a dry sandy loam verifies the intense horizontal and to a smaller extent at the same time also a vertical displacement of a sensor fixed at a depth of 10 cm below the rut which results in a tangential displacement. The octahedral shear stresses exceed by far the internal soil strength at the given vertical stress and underline the enormous soil deformation by shearing**,** which resulted during this wheeling event in an inclination by 50° counter clockwise. Consequently, a very pronounced homogenisation due to shearing of the existing pore system in addition to the vertical compaction and an additional soil particle rearrangement during such dynamic loading event .

If the slip effect is increased e.g. by the application of rubber belt driven machine units the shear effect gets more important which on the one hand will not primarily result in soil compaction but it will lead to a complete disturbance of the pore system and functioning. The particle displacement at a given depth of 10 cm and at 15 and 30 % slip resulted in a tangential particle backwards up to 3 or 6 cm in the horizontal direction and 1 or 3 cm downwards (Horn and Rostek 2000). A corresponding effect can be also detected, if the energy is transmitted by a wider tire even at lower tire inflation pressure as compared to smaller tire in a Hapludept derived from sand loess.

EFFECT OF SOIL DEFORMATION ON HYDRAULIC PROPERTIES

The consequences of soil deformation on changes in total pore volume and pore functioning can be derived from Fig. 4. If the pore diameter gets reduced due to soil

compaction primarily the gas and saturated water fluxes will be reduced . Due to stress and/or shearing even at constant pore volume will the pore size distribution and especially the hydraulic conductivity be intensely reduced.

Thus, because divergent processes also occur during land management a further and normally more detrimental deterioration of

- the pore system because of particle parallelisation and reduction in pore space,
- the mechanical properties because of soil weakening even at higher bulk density,
- pore functioning due to increased tortuosity, and
- possibly a delayed or reduced plant growth which may result in yield decline must be considered.

The effect of static stresses applied to undisturbed Bt soil samples from a Hapludalf derived from loess reveals no constancy of data at a given mechanical stress applied. After exceeding the internal soil strength gets the saturated hydraulic conductivity much smaller with increasing stress while with decreasing matric potential the unsaturated hydraulic conductivity is comparably the higher the more the soil was stressed before.

However, because natural or anthropogenic stresses create an anisotropic pore system, also the saturated and unsaturated hydraulic conductivity behave as a tensor. Consequently the degree of anisotropy (at first defined by Mualem 1984) of the pore system as a function of pore water pressure and mechanical stress are affected by internal soil strength and by various kinds of shear processes or elasto plastic soil deformation (Tigges 2000).

It has to be expected that the degree of anisotropy correlates with natural soil formation processes like ice lense formation or overburden stress or with stress strain effects. It will also depend on the predrying because the most negative pore water pressure also determines the maximum predrying or preshrinkage soil strength. This coincides with the mechanical precompression stress as can be derived from the effective stress equation (for more detailed informations see also Baumgartl and Horn 1999, Fredlund and Rahardjo 1993).

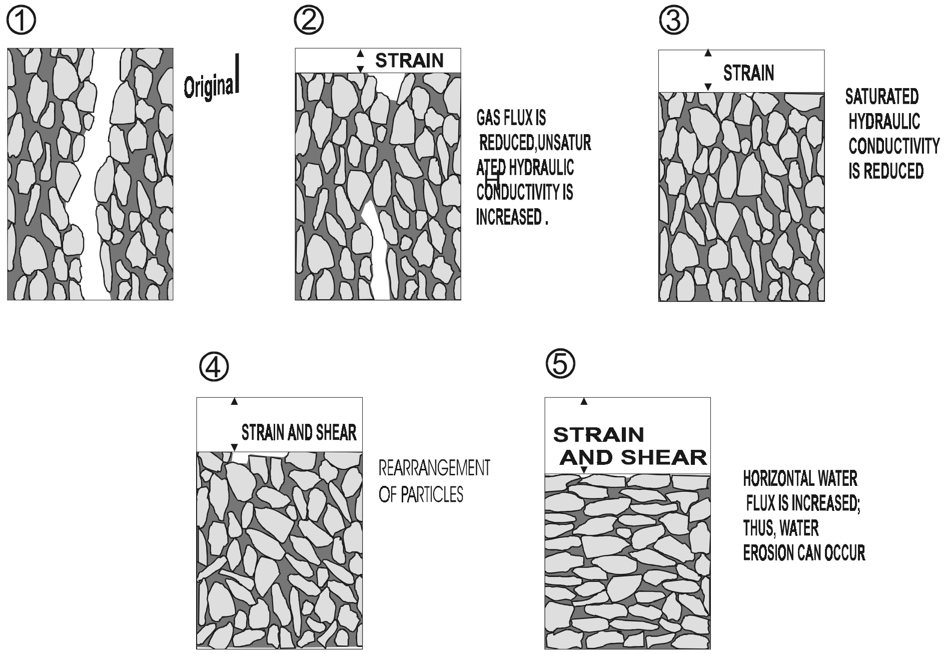

Fig. 4. *Stress and strain effects on pore functions*

In order to underline the stress and shear effects on pore continuity and gas fluxes through structured soil samples can air permeability tests be performed. The higher the slip, the more pronounced is also the air permeability change. At constant slip, the air permeability declined at a depth of 20 cm under a wide tire with decreasing inflation pressure, while at a smaller slip rate under a standard tire the air permeability even remained constant.

CONSEQUENCES FOR PREDICTION MODELS

The effects of soil mechanics and soil hydraulics can be expected to be linked. Thus, if stresses are applied to soils, they also affect the hydraulics and vice versa which underlines the necessity to determine both the mechanical properties as well as the hydraulic functions under well defined boundary conditions in order to lateron derive a coupled model to predict these interrelations (Richards 1992)

CONCLUSIONS

1. The rigidity of the pore system can be described both by stress strain as well as hydraulic stress/ shrinkage (i.e. moisture ratio) = strain relations. Virgin soils show normal shrinkage and virgin compression behaviour, while predrying and prestress application results in a strength increase which can be defined by the precompression stress or initial residual shrinkage behavior.
2. If previous maximum predrying or mechanical stress equilibration is exceeded, and/or if the strengthening effect of organic acids due to suction dependent increased hydrophobisation is vanished, than the rigidity of the intraaggregate pore system as well as that one of the bulk soil is lost and an additional soil normal shrinkage, soil compaction or further rearrangement of particles will occur as long as the particle mobility is given by the pore system.
3. Stress dependent changes of the hydraulic properties occur in the virgin compression load range and result in a reduced saturated hydraulic conductivity, while under unsaturated conditions the stress dependent reduction of the pore diameters results in increased unsaturated fluxes if compared with the unstressed pore system. Shearing results in a further alteration of the pore functions.
4. Mechanical and hydraulic processes are interrelated and affect each other.

REFERENCES

1. Baumgartl, T. und R.Horn 1999: Influence of mechanical and hydraulic stresses on Hydraulic poperties of swelling soils. In: van Genuchten, M., F.J.Leij, L.Wu (Hersg.): Characterisation and measurement of the hydraulic properties of unsaturated porous media: 449 – 457; University of California, Riverside Publ.
2. Fleige, H. and R.Horn 2002: Soil mechanical parameters derived from the CA Database Subsoil Compaction. In: Pagliai,M.(ed).Advances in Geoecology 32, 258-268

3. Fredlund,D.G. and H.Rahardjo 1993: Soil mechanics for unsaturated soils. J.Wiley Sons. New York, 517 pgs
4. Hartge, K.H., and R. Horn. 1999. Einführung in die Bodenphysik. 3rd Ed. Enke Verlag, Stuttgart
5. Horn, R. Rostek,J. 2000: Subsoil Compaction processes – state of knowledge. 44 – 55, in: R,Horn, J.H. van den Akker, J.Arvidsson 2000: Subsoil Compaction – Distribution, Processes and Consequences. Advances in Geoecology 32, ISBN 3-923381-44-1, 462 .
6. Horn, R, J.H. van den Akker, J.Arvidsson 2000: Subsoil Compaction – Distribution, Processes and Consequences. Advances in Geoecology 32, ISBN 3-923381-44-1, 462.
7. Koolen, A.J., and H. Kuipers. 1985. Agricultural soil mechanics. Springer Verlag, Berlin, Germany.
8. Mualem,Y. 1984:Anisotropy of unsaturated soils. Soil Sci. Soc. Amer. J. 48,505 – 509
9. Richards, B. 1992: Modelling interactive load-deformation and flow processes in soils, including unsaturated and swelling soils. Proc. 6th. Aust-NZ Conf. On Geomechanics. 18–37
10. Soane ,B.D. and van Ouwerkerk,C. (eds) 1994: Soil Compaction in Crop Production. Elsevier ISBN:0444-88286-3662 pp.
11. O´Sullivan, M. E.A.G.Robertson, and J.K.Henshall 1999. Shear effects on gas transport in soils.Soil and Tillage Res.50, 73-85
12. Tigges, U. 2000: Untersuchungen zum mehrdimensionalen Wassertransport unter besonderer Berücksichtigung der Anisotropie der hydraulischen Leitfähigkeit. PHD Thesis, (in German) . Schriftenreihe des Instituts für Pflanzenernährung und Bodenkunde, CAU Kiel H. 55, ISSN: 0933-680X
13. Wiermann, C. 1998: Auswirkungen differenzierter Bodenbearbeitung auf die Bodenstabilität und das Regenerationsvermögen lößbürtiger Ackerstandorte. Schriftenreihe Institut für Pflanzenernährung und Bodenkunde, CAU Kiel, H.45, ISSN: 0933-680X

STRESS STRAIN DEPENDENT CHANGES OF SOIL STRUCTURE IN ARABLE AND FOREST SOILS – CONSEQUENCES FOR THE ENVIRONMENT

Horn R.

ABSTRACT

The stress strain processes in structured unsaturated arable and forest soils very much depend on the internal soil strength and on the existing hydraulic and mechanical boundary conditions, which affect soil deformation by compaction and shearing to a great extent. As soon as the internal soil strength defined as the precompression stress value is exceeded by external forces, an intense virgin compression process and in combination with shearing forces at high pore water pressure values a complete homogenisation of the soil profile down to depth occur.

In situ stresses and strain will be determined by the Stress State transducer System (SST) while the Displacement of soil particles will be described by the DTS (Displacement Transducer System). During the determination of the stress strain processes and the shear parameters also the changes in the pore water pressure and gas exchange must be determined by mini - tensiometers installed inside the undisturbed soils as the stress and time dependent changes in the compacted and sheared soil greatly affect the total strength system. Consequently both the hydraulic and the gas fluxes will be affected by such mechanical properties, which result in an intense alteration of ecological and mechanical properties of the site. The consequences of such compaction and shearing on strength and sustainable land use have to be considered with respect to the sustainability of the system.

Keywords: shear stress, precompression stress, strength, hydraulic conductivity, structured soils

INTRODUCTION

Soils undergo intensive changes in their physical, chemical, and biological properties during natural soil development and as a result of anthropogenic processes such as plowing, sealing, erosion by wind and water, amelioration, excavation and reclamation of devastated land. In agriculture and in forestry, soil deformation by compaction and shearing as well as erosion by water are classified as the most harmful processes which not only end in a reduction of the productivity of the site but are also responsible for groundwater pollution, gas emissions and higher energy requirements to obtain a comparable yield. In forestry, especially tree harvesting and clear cutting by heavy machinery has reached a level which from the stress point of view is identical to that one in agriculture. It induces not only an intense soil deformation by shearing and kneading which finally results in an increased soil erosion by water, but it also results in an organic matter loss, groundwater pollution, and gas emission which have the potential to cause global changes.

These interrelationships have been described by Soane and van Ouverkerk (1994) and recently by Horn et al. (2000). The mechanical processes in itself are very often described as it is also true for the hydraulic mechanisms, but there are no data about the coupled processes in unsaturated structured soils. Thus, in the following the effect of mechanical stress on soil deformation and its consequences for pore functions will be described.

STRUCTURE EFFECTS ON MECHANICAL PARAMETERS

Soil Strength

As stress is applied, soil deformation occurs at the weakest point in the soil matrix and further increase in stress results in the formation of failure zones. Therefore, the strength of the failure zone is equal to the energy required to create a new unit of surface area or to initiate a crack. Consequently, soil stability is related to strength distribution in the failure zones. In principle, soil structure will be stable if the applied stress is smaller than the strength of the failure zone, i.e. if the bond strength at the points of contact exceeds the external stress.

In homogenized soil substrates, soil strength expressed as precompression stress is the smaller,

- the higher the clay content at given bulk density values,
- the smaller the bulk density values at given texture,
- the smaller the amount of organic material at comparable grain size distribution,
- the wetter the soil.

Pedogenic effects on mechanical strength defined as precompression stress were often quantified and show e.g. a clear interrelation to clay migration in Hapludalfs with a reduced strength in the clay deriched Al horizon and an increase in the precompression stress in the clay enriched Bt horizon due to aggregation. Calcium precipitation in the corresponding horizon of Mollisols also leads to a strength increase. Thus, at given internal parameters, aggregation always results in higher strength. Anthropogenic effects like the yearly ploughing and the tractor traffic create strong plowpans and plow layers with precompression stress values like the contact pressure of the tractor tyre or even higher due to lug effects (up to 300%). In addition, strength decreases in the A horizon due to plowing and seedbed preparation can be followed until texture dependent values are reached (Fig. 1).

The strength values differ for various soil types, and they consequently depend on texture, structure, pore water pressure, organic matter and bulk density. Based on more than 160 soil profiles the effect of structure on strength can be derived for clayey, silty/loamy and sandy material both for the topsoil and the subsoil and various aggregate classes. In addition a clear difference between the topsoil and the subsoil strength can be defined (Fleige and Horn 2002). In addition it can be seen that conservational tilled soils have a more equally distributed strength pattern than conventionally tilled sites. Especially the higher strength values in the topsopil due to a more pronounced structure formation, the only slight increase in the former plowpan layer (as a relict of the former conventional tillage with smaller units) and the slightly higher values in the deeper Bt horizon due to deeper rooting and more pronounced water uptake at deeper depth characterize the main processes for different tillage systems.

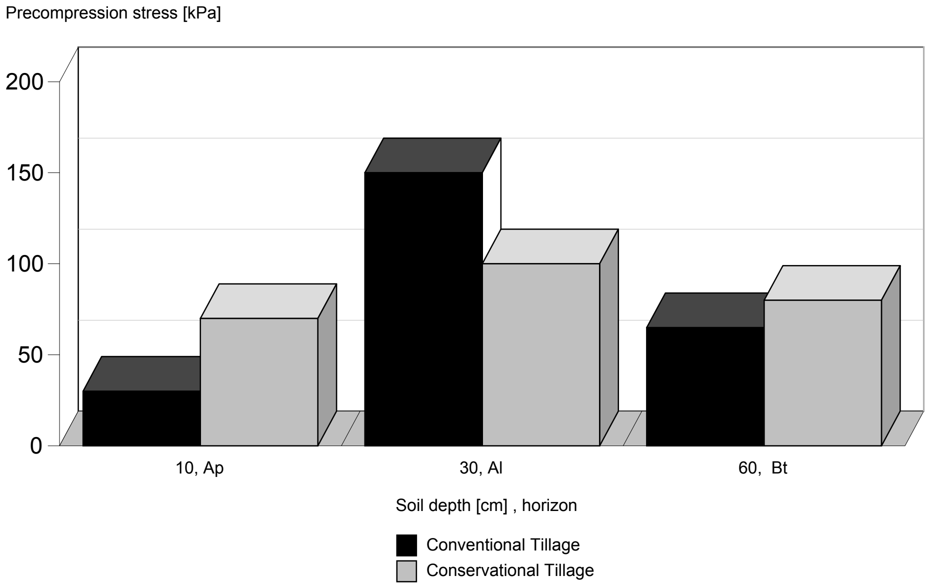

Fig. 1. *Precompression stress [kPa] in different soil depths of a Hapludalf derived from loess under conventional and conservational tillage systems at a pore water pressure of -6 kPa*

However strength changes from conventional to e.g. reduced tillage (like with the Horsch system) require time. During long term experiments carried out in Kiel from more than 9 years at a Hapludalf derived from glacial till it was found out that such changes in mechanical and ecological properties can be only verified after long term treatments with the same machines (lighter than the depth dependent precompression stress). While there were no significant changes in the bulk density to be seen (apart from the fact that the reduced tilled site = „conservation“ had always higher values in all soil horizons as compared to the conventionally treated one) the precompression stress became much stronger in the reduced as compared to the conventionally tilled one (Fig. 2).

It always showed the first changes in the top soil after approximately 3 years in the conservation tillage plot while only after another 2 years the first changes could be detected at about 30 cm. In the deeper depth such changes became significant after more than 7 years. This strength regain can be explained by the effect of particle rearrangement in combination with the drying intensity effects as these sites showed more negative pore water pressure values down to deeper depth than the conventionally tilled site as a consequence of a more prevented root penetration through the plowpan layer.

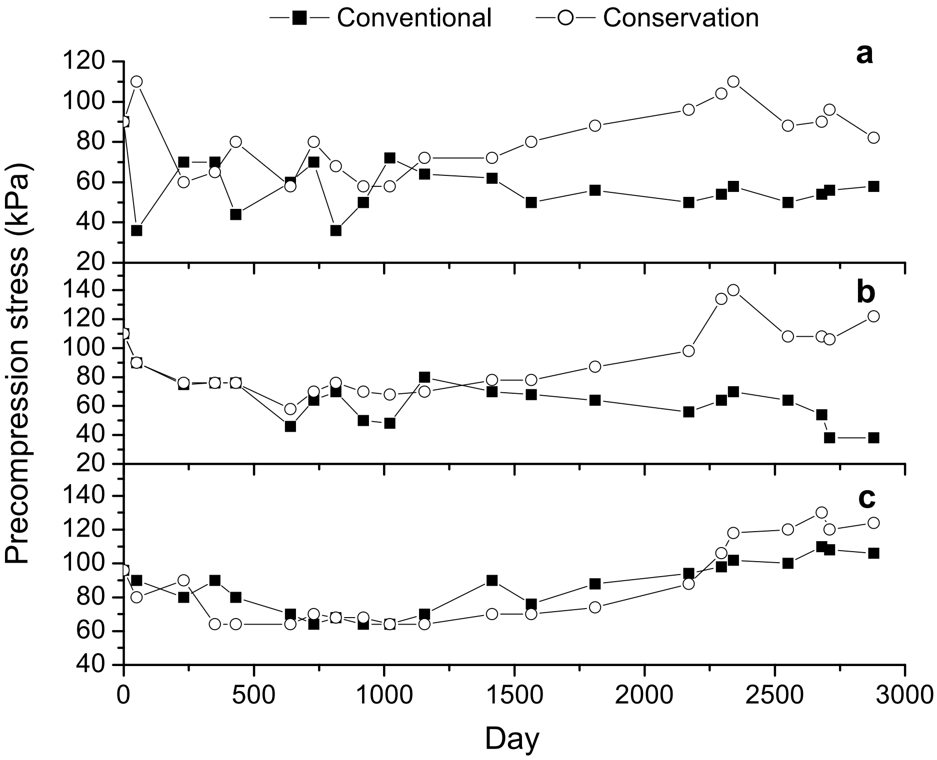

Fig. 2. *Changes in the precompression stress (kPa) at constant pore water pressure (-30kPa) in a Hapludalf derived from glacial till as a function of time (days d) after starting the experiment in 1991. (a= 10-15cm depth, b= 30 – 35 cm depth, c=55-60 cm depth)*

Stress Distribution in Soils

Any load, applied at the soil surface is transmitted to the soil in three dimensions via the solid, liquid and gas phases. If air permeability is high enough to allow immediate deformation of the air filled pores, soil settlement is mainly affected by fluid flow.

Under in situ conditions, stress attenuation is greater in soils with comparable physical and chemical properties if they are more aggregated. If however internal strength values are smaller than the external forces applied, repeated traffic results in increased soil strength. For example, if the wheeling experiment will be carried out under wetter soil conditions e.g. at pF 2.5 in a loessial Hapludalf (which was repeatedly traversed at constant water content), horizontal minor stresses decrease while the major vertical stress increases. These soil strength changes increase the concentration factor values (as a consequence of deeper stress transmission), and each loading consequently results in a smaller effective stress relative to neutral stress (i.e. less negative pore water pressure). In contrast to this, dry and /or very strong soils (because of plowpans or other kind of hardpans) are less sensitive to soil deformation and/or only after several wheeling events they show more intense stress propagation to depth. It can be seen that repeated wheeling result in an increase of the octahedral shear stress and the major principle stress (σ_1) while the mean normal stress remains the same (Fig. 3).

Such stress distribution processes are however not only valid in arable soils but they can be also found in forest management practices. In an interdisciplinary project on the effect of forest harvesting techniques on stress and strain distribution we could analyse the stress and strain distribution in Cambisols derived from weathered rocks in the Black Forest region.

The highest stresses at a depth of 20 cm were recorded under the "Königstiger" Chain-Harvester. The vehicle has had an empty weight of 28Mg and worked in a typical harvest scenario which included the arrival, the harvest with sawing, chopping of branches, cutting the trunks and the departure. The experiments were carried out without a protecting brushwood cover.

The stresses of the heaviest vehicle, the "Hannibal" chain-harvester with a weight of 40 Mg were below those of the "Königstiger" due to a protecting brushwood cover of 60 cm height. The cover protected the soil but was not able to reduce the stresses to the approximate precompression stress. The high stress values for the HSM 904 (8 Mg) make clear, that even smaller forest vehicles are able to compact the soils. The HSM whole wood skidders reached under full load and without protecting soil cover stresses as high as the much larger harvester. But of course for an evaluation of the impact the smaller contact areas of the wheel based vehicles have to be taken into account.

The high maximum stress for the logging horse is a single event, when the hoof hit exactly the sensor. In all other cases the impact on the soil was mostly zero. Taken the very small contact area of the horse hoofs into account, the influence of logging horses on soils was the smallest of all methods.

Effect of Stress Application and Attenuation on Soil Strain

If externally applied stresses are smaller than the internal soil strength, no further soil deformation will occur. If, however, strength is exceeded by the external forces additional stress/strain processes have to be considered. The extent to which soil strain occurs during traffic and the extent to which various tillage implements (conventional/conservation) deform a soil at a given pore water pressure, has been determined by Wiermann (1998). The effect of tillage treatment in a loessial Hapludalf resulted in a pronounced vertical (up to 8 cm) and horizontal forward and backward (up to 2 cm) displacement. Under conservation tillage, these soil de-formations are smaller because of a higher internal soil strength leading to a maximum vertical displacement of < 4 cm after 2 traffic events and a much less pronounced horizontal displacement (Wiermann 1998). With increasing aggregate development, soil strength increases and aggregate deterioration is less pronounced during displacement and alteration of the pore system due to the infilling of inter-aggregate pores by smaller particles. During tree harvesting as well as during transportation the soil displacement under the Hannibal Harvester without a protecting lopping cover was the strongest so far measured. The rut depth was 20 cm while the vertical displacement from 20 cm was as deep as 36 cm. Interesting is the high soil volume displacement which results in only a slight volume compaction of four cm depth (Δ 20 cm height = 16 cm sensor displacement). The compaction rates under wheel based vehicles were in general higher than those under chain based vehicles. The lopping cover during the "Hannibal" and combined "Hannibal" and Forwarder experiment showed a strong decrease of soil displacement, but the absolute values were still very high. The Forwarder driving caused higher soil deformation with minor subsoil displacement. The displacements under the horse hoof were up to 9 cm, but again the contact area is extremely small.

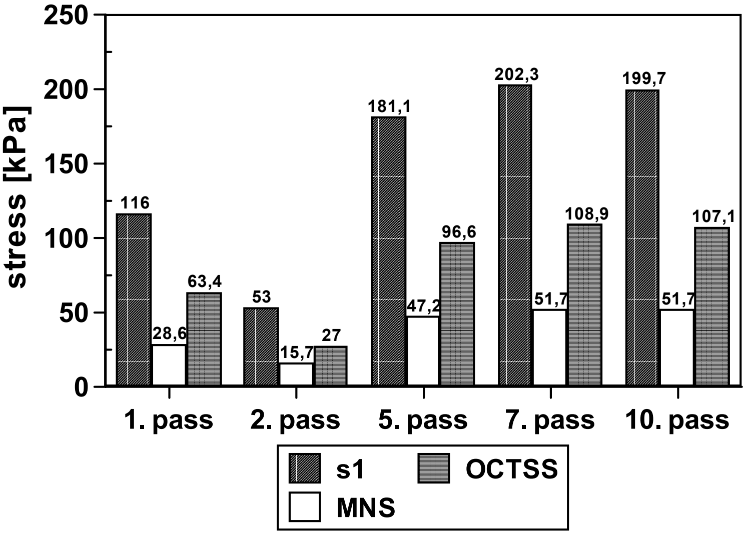

Fig.3. Effect of repeated wheeling on stress distribution at a depth of 15 cm. (Hiwassee clay, water suction: approx: pF 3, tractor front wheel load: 3.8 Mg, 16.9R30; rear wheel load: 5.5 Mg, 18.4 R46)

Nevertheless, all stresses which are not attenuated to levels below soil strength result in volume alterations, even if the applied stresses vary for different soil types, land uses and management systems, and environmental conditions.

Slip Effect on Soil Displacement

Stress strain effects are further altered by the intensity of slip as many management systems increase either the effectivity of pulling by the application of rubber belt driven systems and/or by higher slip during management operations.

Generally, pure shearing always results in a volume constant displacement of particles which results in a complete disconnection of the pore spaces. This can be also defined as an increased tortuosity (Hartge and Horn 1999).

If soils are wheeled with rubber belts fixed during this experiment on a well defined and equiped Gantry System, the wheeling on a dry sandy loam verifies the intense horizontal and to a smaller extent at the same time also a vertical displacement of a sensor fixed at a depth of 10 cm below the rut which results in a tangential displacement. The octahedral shear stresses exceed by far the internal soil strength at the given vertical stress and underline the enormous soil deformation by shearing**,** which resulted during this wheeling event in an inclination by 50° counter clockwise. Consequently, a very pronounced homogenisation due to shearing of the existing pore system in addition to the vertical compaction and an additional soil particle rearrangement during such dynamic loading event .

If the slip effect is increased e.g. by the application of rubber belt driven machine units the shear effect gets more important which on the one hand will not primarily result in soil compaction but it will lead to a complete disturbance of the pore system and functioning. The particle displacement at a given depth of 10 cm and at 15 and 30 % slip resulted in a tangential particle backwards up to 3 or 6 cm in the horizontal direction and 1 or 3 cm downwards (Horn and Rostek 2000). A corresponding effect can be also detected, if the energy is transmitted by a wider tire even at lower tire inflation pressure as compared to smaller tire in a Hapludept derived from sand loess.

EFFECT OF SOIL DEFORMATION ON HYDRAULIC PROPERTIES

The consequences of soil deformation on changes in total pore volume and pore functioning can be derived from Fig. 4. If the pore diameter gets reduced due to soil

compaction primarily the gas and saturated water fluxes will be reduced . Due to stress and/or shearing even at constant pore volume will the pore size distribution and especially the hydraulic conductivity be intensely reduced.

Thus, because divergent processes also occur during land management a further and normally more detrimental deterioration of

- the pore system because of particle parallelisation and reduction in pore space,
- the mechanical properties because of soil weakening even at higher bulk density,
- pore functioning due to increased tortuosity, and
- possibly a delayed or reduced plant growth which may result in yield decline must be considered.

The effect of static stresses applied to undisturbed Bt soil samples from a Hapludalf derived from loess reveals no constancy of data at a given mechanical stress applied. After exceeding the internal soil strength gets the saturated hydraulic conductivity much smaller with increasing stress while with decreasing matric potential the unsaturated hydraulic conductivity is comparably the higher the more the soil was stressed before.

However, because natural or anthropogenic stresses create an anisotropic pore system, also the saturated and unsaturated hydraulic conductivity behave as a tensor. Consequently the degree of anisotropy (at first defined by Mualem 1984) of the pore system as a function of pore water pressure and mechanical stress are affected by internal soil strength and by various kinds of shear processes or elasto plastic soil deformation (Tigges 2000).

It has to be expected that the degree of anisotropy correlates with natural soil formation processes like ice lense formation or overburden stress or with stress strain effects. It will also depend on the predrying because the most negative pore water pressure also determines the maximum predrying or preshrinkage soil strength. This coincides with the mechanical precompression stress as can be derived from the effective stress equation (for more detailed informations see also Baumgartl and Horn 1999, Fredlund and Rahardjo 1993).

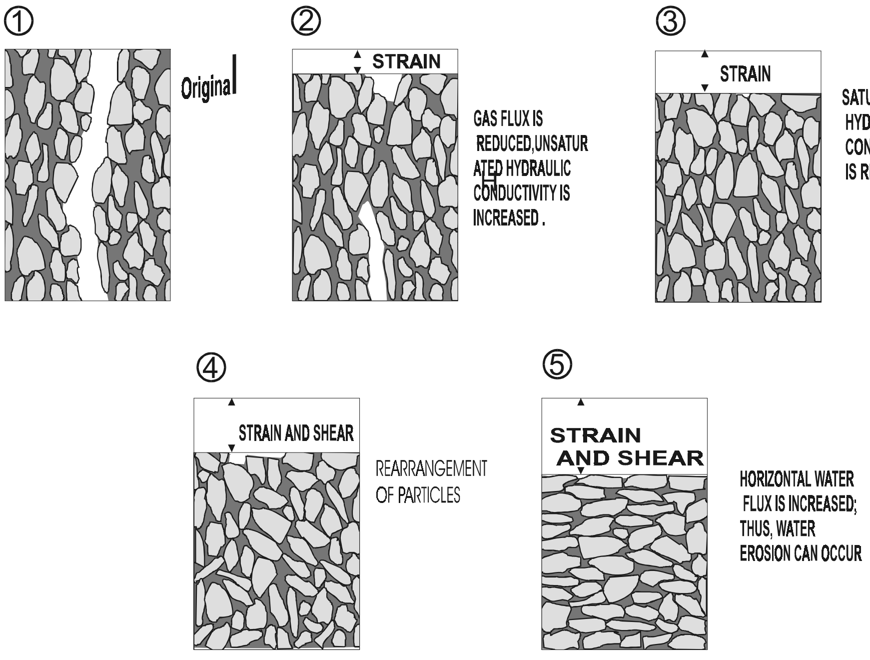

Fig. 4. *Stress and strain effects on pore functions*

In order to underline the stress and shear effects on pore continuity and gas fluxes through structured soil samples can air permeability tests be performed. The higher the slip, the more pronounced is also the air permeability change. At constant slip, the air permeability declined at a depth of 20 cm under a wide tire with decreasing inflation pressure, while at a smaller slip rate under a standard tire the air permeability even remained constant.

CONSEQUENCES FOR PREDICTION MODELS

The effects of soil mechanics and soil hydraulics can be expected to be linked. Thus, if stresses are applied to soils, they also affect the hydraulics and vice versa which underlines the necessity to determine both the mechanical properties as well as the hydraulic functions under well defined boundary conditions in order to lateron derive a coupled model to predict these interrelations (Richards 1992)

CONCLUSIONS

1. The rigidity of the pore system can be described both by stress strain as well as hydraulic stress/ shrinkage (i.e. moisture ratio) = strain relations. Virgin soils show normal shrinkage and virgin compression behaviour, while predrying and prestress application results in a strength increase which can be defined by the precompression stress or initial residual shrinkage behavior.
2. If previous maximum predrying or mechanical stress equilibration is exceeded, and/or if the strengthening effect of organic acids due to suction dependent increased hydrophobisation is vanished, than the rigidity of the intraaggregate pore system as well as that one of the bulk soil is lost and an additional soil normal shrinkage, soil compaction or further rearrangement of particles will occur as long as the particle mobility is given by the pore system.
3. Stress dependent changes of the hydraulic properties occur in the virgin compression load range and result in a reduced saturated hydraulic conductivity, while under unsaturated conditions the stress dependent reduction of the pore diameters results in increased unsaturated fluxes if compared with the unstressed pore system. Shearing results in a further alteration of the pore functions.
4. Mechanical and hydraulic processes are interrelated and affect each other.

REFERENCES

1. Baumgartl, T. und R.Horn 1999: Influence of mechanical and hydraulic stresses on Hydraulic poperties of swelling soils. In: van Genuchten, M., F.J.Leij, L.Wu (Hersg.): Characterisation and measurement of the hydraulic properties of unsaturated porous media: 449 – 457; University of California, Riverside Publ.
2. Fleige, H. and R.Horn 2002: Soil mechanical parameters derived from the CA Database Subsoil Compaction. In: Pagliai,M.(ed).Advances in Geoecology 32, 258-268

3. Fredlund,D.G. and H.Rahardjo 1993: Soil mechanics for unsaturated soils. J.Wiley Sons. New York, 517 pgs
4. Hartge, K.H., and R. Horn. 1999. Einführung in die Bodenphysik. 3rd Ed. Enke Verlag, Stuttgart
5. Horn, R. Rostek,J. 2000: Subsoil Compaction processes – state of knowledge. 44 – 55, in: R,Horn, J.H. van den Akker, J.Arvidsson 2000: Subsoil Compaction – Distribution, Processes and Consequences. Advances in Geoecology 32, ISBN 3-923381-44-1, 462 .
6. Horn, R, J.H. van den Akker, J.Arvidsson 2000: Subsoil Compaction – Distribution, Processes and Consequences. Advances in Geoecology 32, ISBN 3-923381-44-1, 462.
7. Koolen, A.J., and H. Kuipers. 1985. Agricultural soil mechanics. Springer Verlag, Berlin, Germany.
8. Mualem,Y. 1984:Anisotropy of unsaturated soils. Soil Sci. Soc. Amer. J. 48,505 – 509
9. Richards, B. 1992: Modelling interactive load-deformation and flow processes in soils, including unsaturated and swelling soils. Proc. 6th. Aust-NZ Conf. On Geomechanics. 18–37
10. Soane ,B.D. and van Ouwerkerk,C. (eds) 1994: Soil Compaction in Crop Production. Elsevier ISBN:0444-88286-3662 pp.
11. O´Sullivan, M. E.A.G.Robertson, and J.K.Henshall 1999. Shear effects on gas transport in soils.Soil and Tillage Res.50, 73-85
12. Tigges, U. 2000: Untersuchungen zum mehrdimensionalen Wassertransport unter besonderer Berücksichtigung der Anisotropie der hydraulischen Leitfähigkeit. PHD Thesis, (in German) . Schriftenreihe des Instituts für Pflanzenernährung und Bodenkunde, CAU Kiel H. 55, ISSN: 0933-680X
13. Wiermann, C. 1998: Auswirkungen differenzierter Bodenbearbeitung auf die Bodenstabilität und das Regenerationsvermögen lößbürtiger Ackerstandorte. Schriftenreihe Institut für Pflanzenernährung und Bodenkunde, CAU Kiel, H.45, ISSN: 0933-680X

SURFACE PROPERTIES OF PLANT ROOTS AND THEIR ALTERATION UNDER ALUMINUM STRESS

Józefaciuk G., Szatanik-Kloc A.

This paper summarizes main results of investigations of selected properties of plant root specific surface, performed in Department of Physical Chemistry of Agricultural Materials IA PAS. Particular attention is given to surface charge, acidity, area and energy. Some discussion and a literature background is attached, as well.

INTRODUCTION

Soon after the existence of exchange properties of plant tissues was demonstrated by Devaux (1916), many workers realized that the cation exchange capacity (CEC) of plant roots plays very important role in cation interchange between plants and soil colloids (Hoagland and Broyer 1936, Jenny and Overstreet 1939). The CEC of plant roots was found to be closely correlated to uronic acid, present as polymerized galacturonic acid in pectic substances (Knight et al. 1961). The magnitude of root CEC was used for an explanation how various plant species survive environments with low level of cations availability (Gray et al. 1953), why plants uptake different proportion of mono and divalent cations (Huffaker and Wallace 1958, Wiklander and Elgabaly 1955), how plants compete in nutrient deficient mixed populations (Woodward et al. 1983), what are the mechanisms of aluminum toxicity (Keltjens 1995). Significant positive correlation between pectin content in cell walls (CEC) and Al sorption was found by Schmol and Horst (2001), who postulated that Al binding by pectin matrix is an important step in the expression of Al toxicity. However, there have been several conflicting reports on the relationship between Al resistance and root CEC: from positive correlations (Allan et al. 1990; Ramirez et al., 1986), by no correlations (Munn and McCollum, 1976; Wagatsuma, 1983; Ishikawa et al., 2001a), to negative correlations (Mugwira and Elgawhary, 1979).

Cation exchange properties of plant roots result from the presence of a negative charge on root components, developed from dissociation of acidic functional groups occurring on various molecules from which the root tissue is composed. Because of various chemical character and/or various locations in the macromolecule the acidic strength of these groups is different. The weaker the acidic character of a given group, its dissociation (and neutralization) requests higher pH value and therefore the charge developed on the root surface (and the actual CEC value) strongly depends on the reaction of the root environment. A number of methods have been introduced to estimate the CEC of plant materials. The most popular are measurements of exchange acidity, cation activities with ion-selective electrodes, ion exchange in salt and buffer solutions, isotopic exchange, or potentiometric titration (Williams and Coleman 1950, Heintze 1964, Morvan et al. 1979). In general the CEC value depends on the material used (living, fresh or dried), plant age, as well as on the measuring conditions e.g. the kind and concentration of exchange cation, pH, equilibration time etc. (Graham and Baker 1951, Epstein and Leggett 1954). Among the methods of root CEC determination, the back-titration (Nederlof 1993) is among the best, because this can easily measure the dependence of the root charge on pH. In this method the root suspension is titrated with a base (OH-) starting from low pH upwards. During the titration the base is consumed by acidic groups on root surface and by acids present in the supernatant. The amount of base consumed by the root itself is equivalent to the root surface charge increase thus to estimate the latter value an amount of base consumed by the supernatant should be subtracted from this consumed by the whole suspension. From back-titration curves, the acidic strength of surface charge generating groups can be easily characterized. Any pH value during the titration can be associated with dissociation constant (pK) of defined surface acidic groups, while the amount of base consumed by the root surface around this pH value is directly related to an amount (fraction) of these groups. Knowing the dependence of pK and fractions of charge-generating groups (distribution function of surface dissociation constants), the average surface dissociation constant can be easily calculated.

Surface area of plant root system is a key parameter for description of absorption of water and nutrients by plants (Nye 1973, Silberbrush and Barber 1983). Usually the surface area of plant root of a few square centimeters per gram, measured by immersion of the roots in water or in electrolyte solutions, is reported (Carley and Watson 1966, Ansari et al. 1995). In these methods a very thick layer of water (solution) adhered to the surface and shading real surface details is taken as a measure of the surface area. Certainly the finest roots do not contribute to this value and the external geometrical surface of root is measured. Very high root surface areas result from direct calculation of the geometric field of root + root hair (from length and diameter). Dittmer (Vilee 1978) estimated the surface area of one rye plant roots of 765 square meters. Close to the latter value, the specific surface area of roots can be estimated from water vapor adsorption isotherm, a function relating the amount of adsorbed gas (vapor) to its equilibrium pressure during the pressure increase at a constant temperature (Szatanik-Kloc and Jozefaciuk 1997, Szatanik-Kloc et al. 2001; Jozefaciuk and Szatanik-Kloc 2001). The idea of the estimation of the surface area is to find a number of adsorbate molecules which cover the root adsorbing surface as a monolayer, and to multiply this number by the area occupied by a single molecule.

Chemically different groups of atoms of various kind and polarity (e.g. carboxylic, hydroxylic, phosphate, amine, peptide, aliphatic and/or aromatic chains and radicals each located on various cell components: walls, membranes, protoplasts, nucleic acids, phospholipids, etc.) are present on root surfaces. As a result of such complex composition and geometry surfaces of plant roots are highly heterogeneous. Among many methods developed to characterize such surfaces an analysis of adsorption isotherm is probably the easiest and most convenient one (Gregg and Sing 1967). The idea of estimation of the surface heterogeneity is that different surface groups (sites) bind adsorbate molecules with different forces (and energies) and in turn influence the adsorption pathways. The heterogeneity of adsorbing surface can be characterized by the adsorption energy distribution function showing the input of different energy sites to the total adsorption.

PLANT MATERIALS

The data described in this paper (presented in Jozefaciuk and Szatanik-Kloc 2001, 2003, 2004; Szatanik-Kloc et al. 2004, and in Szatanik-Kloc and Jozefaciuk 2001a,b) were obtained from studies performed on seven cereal plants differing in tolerance on Al-stress. The Al-sensitive plants were three wheat *Triticum* L. varieties (*Henika*, *Lanca* and *Omega*), triticale *Triticale* (*Debo*) and a very sensitive barley *Hordeum* (*Ars*). The Al resistant plants were wheat *Triticum* L. (*Inia 66/16*) and rye *Secale* L. (*Dankowskie Zlote*). The plants were grown in a nutrient solution at pH=7 and after they reached the shooting stage, the pH of the growing solutions was adjusted to the value of 4.0 and aluminum chloride was added to reach different Al levels.

CHARGE AND ACIDITY OF ROOT SURFACE UNDER Al STRESS

Variable charge vs. pH dependencies determined using the back-titration method for the cereal roots are practically the same for the control and pH4 (no aluminum) treated roots. Aluminum treatments lead in general to the decrease of the variable charge of roots developed at low and intermediate pH values. In a high pH range the variable charge of the Al-stressed roots increases faster than this of the control roots that may be due to acid-base reactions of strongly bound aluminum or to a production of any variable charge constituents of weakly acidic character and high variable surface charge by the stressed roots. The root variable charge developed at low and intermediate pH's decreases consecutively with the increase of the Al stress concentration that is presented in Table 1.

Table 1. Variable charge (μMole g^{-1}, dry mass) for the control and the Al-stressed roots of selected cereal plants.

	treatment				
Plant variety	control (pH=7)	pH=4, Al=0	5ppm Al	10ppm Al	20ppm Al
Triticale *Debo*	806	801	774	721	536
Wheat *Henika*	1281	1250	940	814	628
Wheat *Inia*	947	932	830	791	690
Barley *Ars*	1557	1500	811	745	647
Wheat *Lanca*	924	911	799	698	670
Wheat *Omega*	915	909	877	864	809
Rye *Dankowskie Zlote*	572	584	597	606	549

Variable charge of the roots measured using back-titration method in the pH range between 3.0 to 7.0 appears to be closely correlated with the root CEC. Also, the root variable charge developed at pH=7.0 is least dependent on the pH. Therefore, along with the total amount of the variable charge, the latter value may be also used as the indicator of the Al-stress impact on plants. Table 2 illustrates the above statement.

Table 2. Variable charge developed at pH=7 (μMole g^{-1}, dry mass) for the control and the Al-stressed roots of selected cereal plants.

	treatment				
Plant variety	control (pH=7)	pH=4, Al=0	5ppm Al	10ppm Al	20ppm Al
Triticale *Debo*	597	595	484	408	251
Wheat *Henika*	716	738	566	394	273
Wheat *Inia*	557	568	556	472	385
Barley *Ars*	849	822	436	364	276
Wheat *Lanca*	719	710	520	430	386
Wheat *Omega*	649	644	535	442	396
Rye *Dankowskie Zlote*	394	395	382	360	285

The charge of the control roots is the highest for Al sensitive barley *Ars* and the lowest for Al resistant rye *Dankowskie Zlote*, i.e. it may reflect the Al tolerance of the plants. If one takes the dry mass decrease during the aluminum stress (Jozefaciuk and Szatanik-Kloc 2002) as a measure of the Al-tolerance, the plants considered may be ranked as following: barley *Ars* (most sensitive), wheat *Lanca,* *Henika, Omega* and *Inia*, triticale *Debo* and rye *Dankowskie Zlote* (most resistant). The decrease in the magnitude of surface charge of the considered plants is in similar order. It can be concluded that the charge of the whole roots reflects the Al-tolerance of the cereal plants. However, Klein and Horst (2001) stated that the CEC of cell wall material of 0-5mm zone and not this of the whole roots could differentiate Al resistance (and an amount of Al adsorbed) of plants within the same family. The decrease in the root charge due to the stress may be due to the outflow of the charged components from the cell interior connected with the frequently observed strong damage of the cell walls by aluminum (Wagatsuma et al. 1987). Similarly, Ishikawa et al. (2001b) attributed a remarkable decrease in K concentration in roots of Al-sensitive species after aluminum treatment to cells destruction induced by Al ions and the increase in plasma-membrane permeability of root-tips cells. Al ions rapidly alter the plasma membrane of the root-tip in the Al-sensitive plant species, resulting in its permeability increase (Ishikawa et al, 2001a). Ofei-Manu et al. (2001) stated that the plasma membrane strength of the root-tip cells may govern Al tolerance. The intensity of the decrease in variable charge is apparently consistent with the order of the tolerance of the cereal plants on the Al-stress: the largest decrease was noted for barley and the smallest for rye. The overall decrease in the surface charge may be due also to a frequently observed decrease in the amount of (charged) root hairs in Al-stressed roots (Balsberg-Pahlsson 1995). The decrease in the root charge leads to smaller adsorption of all cations thus lowering both the nutrient supply and the further Al accumulation in the roots.

Distribution functions of surface dissociation constants for most of the considered control roots are U-shaped with maximum amounts of charge-generating groups having the lowest and the highest pK values. The pK distributions for wheat *Inia* and *Henika* contain a well-developed peak around pK=7. For all of the mentioned plants the fraction of weakly acidic sites strongly increases due to the Al-stress, whereas the fraction of strongly acidic sites follow different trends for different plants. The pK=7 peak (wheat *Inia* and *Henika*) decreases sharply just at the lowest Al-stress concentration and shifts towards lower pK values. Average values of surface dissociation constants of the roots under Al stress are shown in Table 3.

An increase in pK due to the Al-stress indicates a weakening of overall surface acidity and increase in proton binding forces. One may conclude that the remaining components of the damaged cells are less acidic than these present in the cytosol. Also the root hairs may be stronger acidic than the rest of the root material. However, while growing under the stress the plants may produce some weakly acidic components that bind aluminum and protect root surfaces against its sorption thus increasing the average pK value.

Table 3. Average values of surface dissociation constants (pK) for the control and the Al-stressed roots of selected cereal plants.

	treatment				
Plant variety	control (pH=7)	pH=4, Al=0	5ppm Al	10ppm Al	20ppm Al
Triticale *Debo*	5.5	5.6	6.0	6.2	6.7
Wheat *Henika*	6.5	6.4	6.3	6.7	6.9
Wheat *Inia*	6.4	6.3	6.1	6.3	6.5
Barley *Ars*	6.5	6.4	6.6	6.8	7.0
Wheat *Lanca*	5.3	5.3	5.8	6.0	6.2
Wheat *Omega*	5.9	5.9	6.2	6.6	6.7
Rye *Dankowskie Zlote*	5.9	6.0	6.0	6.2	6.5

ROOT SURFACE AREAS AND ENERGIES UNDER Al STRESS

The surface areas of the considered cereal plant roots (control samples) do not differ much among particular plants which indicates that the overall extent of the physicochemically active surface can be generally similar for roots of all cereal plants. The smallest surface area is noted for barley *Ars* and wheat *Henika* and the largest for wheat *Omega* all being Al-sensitive species. Al-resistant plants, rye *Dankowskie Zlote*, triticale *Debo* and wheat *Inia* as well as Al-sensitive wheat *Lanca* have intermediate surface areas. The root surface area increases with the Al concentration increase which is presented in Table 4.

Table 4. Surface areas (m^2 g^{-1}, dry mass) for the control and the Al-stressed roots of selected cereal plants.

	treatment				
Plant variety	control (pH=7)	pH=4, Al=0	5ppm Al	10ppm Al	20ppm Al
Triticale *Debo*	355	349	355	418	479
Wheat *Henika*	321	317	321	397	458
Wheat *Inia*	373	385	386	431	484
Barley *Ars*	320	292	505	560	636
Wheat *Lanca*	361	364	411	557	614
Wheat *Omega*	393	398	393	457	526
Rye *Dankowskie Zlote*	348	353	367	381	393

The surface area of barley roots increases markedly (around 1,5 times) just at the lowest Al stress whereas for the rye the highest stress lead to the root surface area increase by less than 30%. Generally, for the described wheat varieties, the increase in root surface area begins at 10ppm Al stress. The smallest increase in root surface area is noted for *Inia* and the highest for *Lanca*. Triticale *Debo* reacts similarly as wheat *Inia* and *Omega*. The rise of surface area can be attributed to various morphological and ultrastructural changes in the root surface and cell build-up induced by aluminum: cells deformation, breaking cell walls, formation of cracks or openings, increasing the distance between the cells (loosening of the tissue), as were observed in other experiments (Wagatsuma et al. 1987, Matsumoto 1988, Ikeda and Tadano 1993). The extent of the cell damage depend on the plant tolerance against Al. Most of detrimental Al effects are considered to occur in the root apex. However, the apex accounts for only small (around 1%) portion of the root and therefore it seems difficult to address the observed large changes in surface areas to the alteration of the apex only. One can suspect that the above changes reflect severe damage of the root hairs, as far as the specific surface area measured using water vapor adsorption technique may include root hairing, as mentioned above. If the root hairs persist the stress undamaged, the root specific area should decrease, because the root hairing is suppressed under the Al stress (Balsberg-Pahlsson 1995, Foy et al. 1978, Klimashevskij 1990).

Adsorption energy distribution functions for the cereal roots under discussion are practically the same for the control and pH4 treated roots. In the control roots of rye *Dankowskie Zlote* and wheat *Inia* low adsorption energy sites dominate. High energy sites prevail in roots of other plants considered. In addition to the latter sites, low energy sites are present in roots of wheat *Henika*, *Omega* and barley *Ars*, whereas medium energy sites are present in roots of triticale *Debo* and its parent progeny wheat *Lanca*. A similarity of the energetic character of the root surfaces of these two plants is seen.

Adsorption energy distribution functions of roots of rye *Dankowskie Zlote*, wheat *Inia* and triticale *Debo* remain practically not altered after aluminum stress except of a slight increase in low-energy sites for the rye and the wheat. For other plants these changes are more pronounced, leading generally to an increase in fraction of lowest energy sites and a decrease in fraction of the highest energy sites after aluminum stress. For wheat *Henika* and *Lanca*, and for barley *Ars* the effect of Al concentration is seen. The higher the concentration, the larger decrease in high energy sites and the larger increase of low energy sites is noted. The decrease in high energy sites fraction after Al treatment may be due to blocking of these sites by strongly bound aluminum: highly polar carboxylic groups are blocked by weakly polar Al-OH groups, which can also contribute to the rise of low energy adsorption centers. Additionally, the increase of weak energy sites may be due to any reaction of the plant on aluminum leading to an evolution of weakly polar and hardly soluble root extrudates which do not bind Al thus protecting the roots.

Summarical input of various energy sites is reflected in the average adsorption energy which in turn is related to the average chemical composition of the surface and its polarity. The average adsorption energy and its changes due to the stress conditions for the roots considered are presented in Tab. 5.

Table 5. Average adsorption energies (in units of thermal energy, RT) for the control and the Al-stressed roots of selected cereal plants.

	treatment				
Plant variety	control (pH=7)	pH=4, Al=0	5ppm Al	10ppm Al	20ppm Al
Triticale *Debo*	3.4	3.5	3.5	3.8	3.9
Wheat *Henika*	3.4	3.4	3.3	3.1	2.8
Wheat *Inia*	2.8	2.8	2.8	2.7	2.6
Barley *Ars*	3.3	3.2	2.9	3.1	3.0
Wheat *Lanca*	3.8	3.9	3.6	3.1	2.7
Wheat *Omega*	2.9	2.9	3.0	3.1	2.9
Rye *Dankowskie Zlote*	2.4	2.4	2.4	2.3	2.3

The smallest value of the average adsorption energy occurs for roots of Al-resistant rye *Dankowskie Zlote* and wheat *Inia*. However, barley Ars, the most Al sensitive among the others, has the average adsorption energy lower than wheat *Henika* and *Lanca*, and triticale *Debo*.

In general the average adsorption energy decreases with the increase of Al treatment concentration for all plants but triticale *Debo*. For wheat *Omega* and barley *Ars* at 10Al stress an increase of average energy is observed. For rye *Dankowskie Zlote* the smallest effect of Al on average energy occurs.

The specific surface area of the control plant seems not to be related to the Al tolerance and this can not be used to distinguish Al resistant and Al sensitive species. However, the rise of root surface area during the stress may be due to the sensitivity of a plant to aluminum. The average adsorption energy of the control roots, similarly as the surface area, is not a good indicator of the plant tolerance on aluminum. Also, the lack of similar trends in changes of average adsorption energy with the Al-stress concentration indicates that changes in adsorption energy do not reflect Al tolerance of plants. The average adsorption energy reflects the presence of all adsorption sites on the root surface. However, only highly energetic centers should be responsible for Al binding. These centers can be located on highly polar surface groups of high surface negativity which are characteristic for Al-sensitive plants (Wagatsuma 1983, Wagatsuma and Akiba 1989). The relative amount of highly energetic centers is the largest for barley *Ars* and the lowest for rye *Dankowskie Zlote* and wheat *Inia*. Large amount of highly energetic adsorption sites may characterize Al sensitive plant species. However, this is difficult to explain the behavior of triticale *Debo* which usually reacts as Al-resistant plant despite having similar energetic surface features as its Al-sensitive parent progeny wheat *Lanca*.

ROOT SURFACE CHARGE DENSITY UNDER ALUMINUM STRESS

Surface charge density (SCD) may be calculated by dividing the amount of surface charge by the surface area. The SCD value for the considered cereal plants is shown in Table 6.

Table 6. Surface charge density (mC m^{-2}) for the control and the Al-stressed roots of selected cereal plants.

	treatment				
Plant variety	control (pH=7)	pH=4, Al=0	5ppm Al	10ppm Al	20ppm Al
Triticale *Debo*	0.22	0.22	0.21	0.17	0.11
Wheat *Henika*	0.39	0.38	0.28	0.20	0.13
Wheat *Inia*	0.24	0.23	0.21	0.18	0.14
Barley *Ars*	0.47	0.49	0.15	0.13	0.10
Wheat *Lanca*	0.25	0.24	0.19	0.12	0.11
Wheat *Omega*	0.22	0.22	0.22	0.18	0.15
Rye *Dankowskie Zlote*	0.16	0.16	0.16	0.15	0.15

The magnitude of root surface charge density may reflect the Al tolerance of the cereal plants, as well. The highest surface charge density is noted for Al-sensitive barley *Ars* and wheat *Henika* and the smallest for Al-resistant wheat *Inia* and rye *Dankowskie Zlote*. This may be connected with that the higher the SCD, the higher the surface potential and the higher relative adsorption of multivalent cations. High surface charge density is equivalent to high surface negativity. Similarly to our findings, Wagatsuma and Akiba (1989) reported that root protoplasts of aluminum-tolerant plant species have low surface negativity. Also, Yermiyahu at al. (1997b) observed that vesicles isolated from Al-sensitive wheat root tips, having more negative surface-charge density, sorbed more Al than these prepared from Al-tolerant wheat of less negative SCD. Values of average surface dissociation constant is the highest for wheat *Henika* and barley *Ars* and the lowest for wheat

Lanca and triticale *Debo*, thus this appears to have nothing common with the tolerance of plants on Al.

As compared to the control roots, the variable charge density decreases sharply with the increase of the Al-stress concentration. Marked decrease in the surface charge density of plant roots in Al-environments may lead to significant depression of the relative amount of multivalent aluminum ions present at the root cation exchange sites. In this way plant can minimize the further uptake of aluminum.

GENERAL COMMENTS

Similar surface characteristics for roots grown at pH 7 and 4 indicate that the physicochemical properties root tissue are rather well defined for a given plant and that these are not sensitive to the influence of protons alone. Aluminum induced changes in the root surface characteristics may be caused by possible alteration of the surface chemical composition i.e. production of some organic compounds by the plant itself and/or the incorporation of aluminum within the tissue of root matrix as well as by overall damage of the root tissue.

Toxic aluminum level markedly affects surface properties of plant roots. Root surface area and relative amount of highly energetic adsorption centers increase, and amount of low energy adsorption centers decreases under influence of aluminum. The decrease in root variable charge, weakening of surface acidity and decrease in surface charge density is observed under the stress. For the Al-sensitive plants these changes are more pronounced.

The younger plant roots are more susceptible for the Al stress, as their surface areas increased to a larger extent Józefaciuk and Szatanik-Kloc 2001 Szatanik-Kloc et al. 2001).

REFERENCES

1. Allan D L, Shann J R and Bertsch P M 1990. Role of root cell walls in iron deficiency of soybean (Glycine max) and aluminum toxicity of wheat (Triticum aestivum). In: Plant Nutrition - Physiology and Applications, Ed. Van Beusichem M L. pp. 345-349. Kluwer Academic Publishers, Dordrecht.
2. Ansari S A, Kumar P, Gupta B N 1995 Root surface area measurements based on adsorption and desorption of nitrite. Plant Soil 175, 133-137.
3. Balsberg-Pahlsson A M 1995 Growth, radicle and root hair development of Deschampsia flexuosa (L.) Trin. seedlings in relation to soil acidity. Plant and Soil 175, 125-132.
4. Carley H E, Watson R D 1996 A new gravimetric method for estimating root-surface areas. Soil Sci. 102, 289-291.

5. Devaux H 1916 Action rapide des solutions salines sur les plantes vivantes, deplacement reversible d'une partie des substances basiques contenues dans la plante. Compt. Rend. Acad. Sci. Paris 162, 561-563.
6. Epstein E and Leggett J E 1954 The absorption of alkaline earth cations by barley roots. Kinetics and mechanism. Am. J. Bot. 41, 785-791.
7. Graham E R and Baker W L 1991 Ionic saturation of plant roots with special reference to hydrogen. Soil Sci. 72, 435-442.
8. Gray B, Drake M and Colby W G 1953 Potassium competition in grass-legume associations as a function of root cation exchange capacity. Soil Sci. Soc. Am. Proc. 17, 235-239.
9. Gregg S J, Sing K S W 1967 Adsorption, Surface Area and Porosity. Academic Press London and New York, 35-223.
10. Heintze S G 1964 Studies on cation exchange capacities of roots. Plant and Soil 4, 365-383.
11. Hoagland D R and Broyer T C 1936 General nature of the process of salt accumulation by roots with description of experimental methods. Plant Physiol. 11, 471-507.
12. Huffaker RC and Wallace A 1958 Possible relationships of cation-exchange capacity of plant roots to cation uptake. Soil Sci Soc. Am. Proc. 22, 392,394.
13. Ikeda H, Tadano T 1993 Ultrastructural changes of the root tip cells in barley induced by a comparatively low concentration of aluminum. Soil Sci. Plant Nutr. 39, 109-117.
14. Ishikawa S, Wagatsuma T and Tawaraya K 2001a Effects of temporary contact with Al ions on the plasma-membrane permeability of root-tip cells in seven plant species. In Plant nutrition – Food security and sustainability of agro-ecosystems. Eds. W J Horst et al. pp 510-511. Kluwer Academic Press. The Netherlands.
15. Ishikawa S, Wagatsuma T, Takano T, Tawaraya K, and Oomata K 2001b The plasma membrane intactness of root-tip cells is a primary factor for Al-tolerance in cultivars of five species. Soil Science Plant Nutr. 47, 489-501.
16. Jenny H and Overstreet R 1939 Cation interchange between plant roots and soil colloids. Soil Sci. 54, 177-189.
17. Józefaciuk G, Szatanik-Kloc A 2001 Aluminum-induced changes in the surface and micropore properties of wheat roots: A study using the water vapor adsorption-desorption technique. Plant Soil 233, 95-108.
18. Józefaciuk G., Szatanik-Kloc A. 2003 Changes in specific area and energy of root surface of cereal plants in Al-solution cultures. Water vapor adsorption studies. Plant and Soil 250 (1), 129-140
19. Józefaciuk G., Szatanik-Kloc A. 2004 Decrease in variable charge and acidity of root surface under Al treatment are correlated with Al tolerance of cereal plants. Plant and Soil 260 (1), 137-145.
20. Keltjens W G 1995 Magnesium uptake by Al-stressed maize with special emphasis on cation interactions at root exchange sites. Plant and Soil 171, 141-146.
21. Klein M and Horst W J 2001 Cation-specific exchange capacity of cell wall material isolated from roots of plant species differing in Al resistance. In Plant nutrition – Food

security and sustainability of agro-ecosystems. Eds. W J Horst et al. pp 266-267. Kluwer Academic Press. The Netherlands.

22. Klimashevskij E L 1990 Genetic aspects of mineral nutrition of plants. Nauka, Moscow (in Russian).
23. Knight A H, Crooke W M and Inkson R H E 1961 Cation-exchange capacities of tissues of higher and lower plants and their related uronic acid contents. Nature 192, 142-143.
24. Matsumoto H 1988 Changes of the structure of pea chromatin by aluminum. Plant and Cell Physiol. 29, 281-287.
25. Morvan C, Demarty M and Thellier M 1979 Titration of isolated cell walls of Lemna minor L. Plant Physiol. 63, 1117-1122.
26. Mugwira LM and Elgawhary SM 1979 Aluminum accumulation and tolerance of trificale and wheat in relation to root cation exchange capacity. Soil Sci. Soc. Am. J. 43, 736-740.
27. Munn D A and McCollum R E 1976 Solution culture evaluation of sweet potato cultivar tolerance to aluminum. Agron. J. 68:989-91.
28. Nederlof M M, De Wit J C, Riemsdijk W H and Koopal, L K 1993 Determination of proton affinity distributions for humic substances. Environmental Sci. Technol. 27, 846-856.
29. Nye P H 1973 The relation between the radius of a root and its nutrient-adsorbing power. J. Exp. Bot. 24, 783-786.
30. Ofei-Manu P, Wagatsuma T, Ishikawa S and Tawaraya K 2001 The plasma membrane strength of the root-tip cells and root phenolic compounds are correlated with Al tolerance in several common woody plants. Soil Science Plant Nutr. 47, 359-375
31. Ramirez R, Rodriguez H H and Williams J E. 1986 Relacion entre la capacidad de intercambio cationico radical del sorgo y la tolerancia a la toxicidad del aluminio. Agronomía Tropical. 36, 115-128.
32. Schmol N and Horst W J 2001 Cell-wall composition modulates aluminum toxicity. In Plant nutrition – Food security and sustainability of agro-ecosystems. Eds. W J Horst et al. pp 262-263. Kluwer Academic Press. The Netherlands.
33. Silberbrush M, Barber S A 1983 Sensitivity of simulated phosphorus uptake to parameters used by a mechanistic-mathematical model. Plant and Soil 74, 93-100.
34. Szatanik-Kloc A., Józefaciuk G. 1997. Effect of pH and aluminum on surface properties of barley roots as determined from water vapor adsorption. Acta Physiologiae Plantarum. 19, 3, 327-332.
35. Szatanik-Kloc A., Józefaciuk G. 2001 Effect of aluminum on microstructure of plant sieve roots as estimated from water vapor desorption isotherms. w: „Physical Methods in Agriculture", I. Blahovec and M. Libra (Eds). Czech University of Agriculture. 304-307
36. Szatanik-Kloc A., Józefaciuk G., Masłowski J., Muranyi A., Farkas C., 2001 Changes in the surface properties of the young sieve roots after 24h aluminum stress. Int. Agrophysics 15, 201-206
37. Vilee C A 1978 Biology. PWRIL Warsaw. p 228.

38. Wagatsuma T 1983 Characterisation of adsorption sites for aluminum in the roots. Soil Sci Plant Nutr, 29, 499-415.
39. Wagatsuma T, Akiba R 1989 Low surface negativity of root protoplasts from aluminum-tolerant plant species. Soil Sci. Plant Nutr. 35, 443-452.
40. Wagatsuma T, Kaneko M, Hayasaka Y 1987 Destruction process of plant root cells by aluminum. Soil Sci. Plant Nutr. 33, 161-175.
41. Wiklander L, Elgabaly M M 1956 Relative uptake of adsorbed monovalent and divalent cations by excised barley roots as influenced by the exchange capacity. Soil Sci. 80, 91-93.
42. Williams D E, Coleman N T 1950 Cation exchange properties of plant root surfaces. Plant and Soil 2, 243-256.
43. Woodward R A, Harper K T and Tiedemann A R 1984 An ecological consideration of the significance of cation-exchange capacity of roots of some Utah range plants. Plant and Soil 78, 169-180.
44. Yermiyahu U, Brauer D K and Kinraide T B 1997 Sorption of aluminum to plasma membrane vesicles isolated from roots of Scout 66 and Atlas 66 cultivars of wheat. Plant Physiol. 115, 1119-1125.

RESPONSE OF POTATO TUBER MICROSTRUCTURE TO WEATHER CONDITIONS DURING VEGETATION

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INTRODUCTION

Increasing requirements concerning the quality of crops are especially important in the case of potato which is one of the plants most commonly grown in the world and Poland is one of the world leaders in its production. The problem of better utilisation of potato entails the selection of varieties with stable and uniform quality features – not just improved resistance to diseases caused by viruses, fungi and bacteria, but also better resistance to mechanical damage. Plant tissue as a material is highly susceptible to mechanical damage, both external and internal, and such damage causes irreversible changes in its structure, colour and taste, i.e. a deterioration of the quality of both the material and the product.

For a number of years studies have been conducted on selected potato varieties of various applications. The studies have a broad cognitive spectrum for the characterization of the particular varieties with the inclusion of such physical properties as the cellular structure of the parenchyma and the mechanical conditions for its damage. The practical aspect of the studies is related to a better assessment of the material and its planned utilization, and to the selection of physical parameters in technological processes and minimization of damage to tubers (Konstankiewicz, 2002; Zgórska, 2003).

Work initiated in the area of studies on the occurrence of internal damage in the parenchyma of potato tuber showed that cracking is the decisive process in the destruction of the cellular structure. The cracking processes in such structures, non-homogeneous and discrete as they are, are closely related to the type of structure, specific for particular potato varieties, and to the production technology applied and the resultant conditions of deformation (Zdunek and Konstankiewicz, 2004).

In the course of the multi-year experiment, the climatic conditions in the closest vicinity of the plots cultivated have also been recorded. The results obtained show the relationship between changes in temperature and precipitation during the tuber growth period and changes in the cell structure of the tubers, observed immediately after the harvest. The consequences of the changes may affect other properties of the tubers. The paper presents examples of results for two selected potato varieties during three successive cultivation seasons.

MATERIALS AND METHODS

The studies have been conducted since 1999 on several varieties of potato (Solanum tuberosum L.) with different applications. Examples of the experimental material used for purposes of this paper included tubers of two Polish potato varieties: Danusia and Kuba, from three successive harvest years: 1999, 2000, 2001 (Zgórska, 2003; Frydecka-Mazurczyk and Zgórska, 2003).

The cultivation conditions remained unchanged throughout the whole experiment: a light pseudopodzolic soil with a low amount of stones, organic fertilization (approx. 2.5 t of manure) in autumn, P+K fertilization (P_2O_5 - 90kg/ha, K_2O – 130kg/ha) before the winter ploughing; N fertilization(90kg/ha) in spring. Cereal plants were the forecrop for the potato.

During the growing experiment the dry matter and the starch content were determined in the tubers.

Throughout the experiment continuous records have been kept of the climatic conditions at the experimental fields that are presented in Table 1.

Table 1. Weather conditions during growing season.

RAINFALL [mm]					TEMPERATURE [°C]				
1999									
	VI	VII	VIII	IX		VI	VII	VIII	IX
Σ	170.9	29.6	8.8	18.9	M	18.6	21.2	18.1	16.1
D	87.9	-45.4	-55.2	-34.1	D	1.9	3	0.4	3
2000									
	VI	VII	VIII	IX		VI	VII	VIII	IX
Σ	21.1	94.8	40.3	40.0	M	17.2	16.1	17.7	10.9
D	-59.9	18.8	-22.7	-12.0	D	0.5	-2.1	0.0	-2.2
2001									
	VI	VII	VIII	IX		VI	VII	VIII	IX
Σ	68.3	103.5	33.8	74.9	M	14.5	20.2	18.9	11.5
D	-12.7	27.5	-28.2	21.9	D	-2.1	2.0	1.2	-1.5

Σ = sum of precipitation, M = Mean temperature, D = Deviation from normal

The weather conditions varied considerably during the particular years. In 1999 there was increased precipitation at the beginning of tuber growth, but in subsequent months the level of precipitation was noticeably lower than normal. At the same time ambient temperature was higher than normal through all the months. Generally, the season was dry and warm. In 2000, in turn, June was the month of the least precipitation, the next low precipitation period being August and September, while temperatures were close to normal or below. In 2001 the beginning of the tuber growth season was dry and cool. Also in August the level of precipitation was less than normal, while temperatures were above average. The end of the season was wet and cool.

In each of the years of the experiment, tubers were harvested at full technical ripeness, which usually occurred at the end of September. Only healthy and undamaged tubers of uniform size were qualified for cellular structure investigation. Tubers of the varieties studied were stored under controlled conditions: 15 days at a temperature of about 15°C, and then 15 days of gradual decreasing of the temperature to 4°C and long-term storage. Relative humidity of air in the storage room was maintained at the level of approximately 95% at all the stages of storage.

Cellular structure

Microscope observations were made using an optical confocal microscope (Tandem Scanning Light Microscope – TSRLM) which permits observation of biological samples in their natural condition, without fixing or polishing. Plan 10/0.25 and 20/0.4 lenses were used, which permitted the obtaining of images containing from several to over a dozen sections of complete cells each (Konstankiewicz, 2002; Konstankiewicz et al., 2001, 2002).

The continuous precision system of lens travel within the x-y plane applied permitted a full observation cycle (approx. 20 images) to be completed within a few minutes, which, under the conditions of constant room temperature (~20°C) and relative humidity (50 – 60%), allowed for the hazard of sample drying to be avoided. The system provided good quality images which were then subjected to analysis according to an original method developed earlier by the authors.

Microscope observations and image analysis were performed for the parenchyma tissue of potato tubers, for the inner and outer cores, for each variety and three successive years of cultivation. Five replications were made for every measurement series, which yielded several thousand photographs of microscope images of sections of the cellular structure of potato tissues. Parameters of the structure were determined, related to the size and shape of each cell, obtaining mean values for a large population of objects, as well as distributions of parameters for particular varieties and years of cultivation.

RESULTS

For presentation of results only two potato varieties have been chosen, representing different directions of utilization and characterized by good morphological and quality features: 1) *v. Danusia* – a medium-late variety, edible, high-yielding, resistant to potato cyst nematode. Large tubers, oval in shape, with very shallow eyes. Useful both for direct consumption and for processing – for frozen and sterilized food products; 2) *v. Kuba* – a medium-early variety, with high starch content, resistant to potato-cyst nematode. Tubers spherical-oval shaped, with medium shallow eyes. The variety is useful for industrial processing as well as for potato chips and dried food products.

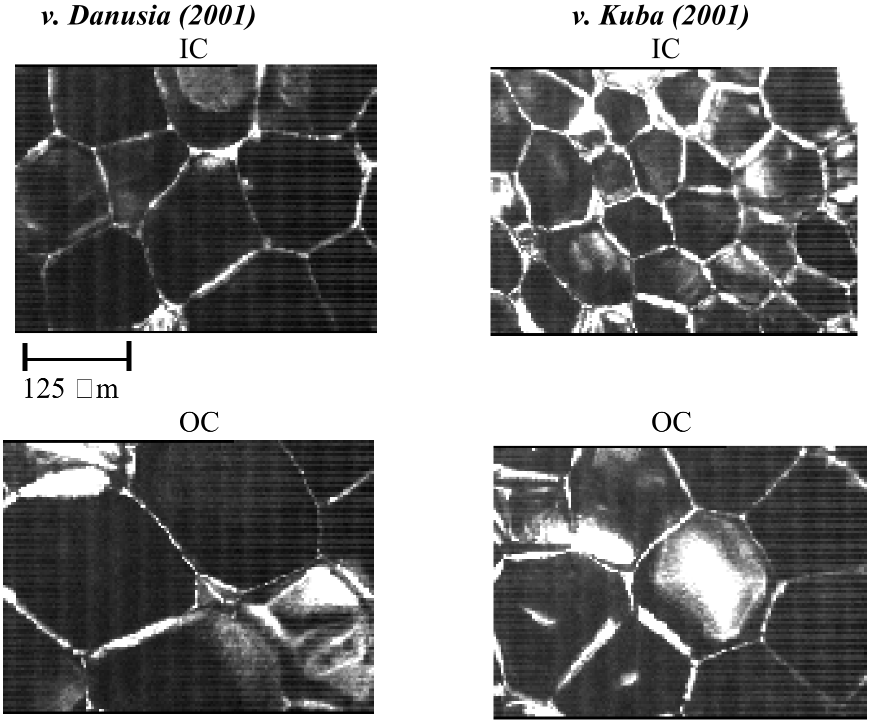
The varieties selected showed, respectively, low and medium level resistance to internal damage to the tuber parenchyma in a static impact test (impact energy of 0.62 J).

The dry matter and the starch content determined in the tubers during the growing experiment are shown in Table 2. Within three growing periods, both parameters remained better reproducible for *Danusia* than for *Kuba* variety.

Table 2. Characteristics of the potato varieties; OC – outer core, IC – inner core.

		Dry matter [%]			Starch [%]		
		1999	2000	2001	1999	2000	2001
v. Danusia	OC	21.7	21.9	21.2	15.3	15.4	15.1
	IC	17.2	17.8	18.5	11.2	11.3	12.1
v. Kuba	OC	24.7	26.9	20.9	18.7	20.6	13.7
	IC	19.0	20.5	19.6	13.2	14.8	13.0

Microscopic Images of the inner (IC) and outer (OC) core of the two potato varieties under study are presented in Fig. 1, whereas the cell surface area distributions obtained for the flat section of the tubers are shown in Fig. 2.


v. Danusia (2001)

v. Kuba (2001)

IC

IC

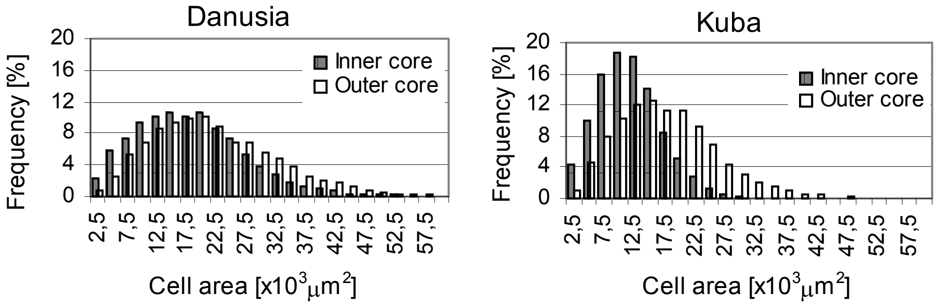
OC

OC

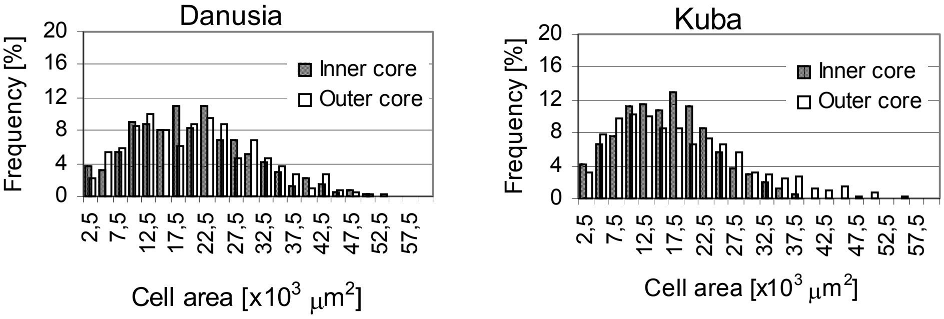
Fig.1. *Microscopic Images of the inner (IC) and outer (OC) core of the two potato varieties - TSRLM CONFOCAL 2002 microscope, Plan 20/0.4 lens.*

The response of the cellular structure of the two potato varieties under study differed between the two varieties. In 2001, the content of smaller cells, both in the inner and the outer core, increased notably. The changes observed were variety related. *V. Kuba* proved to be much more sensitive to weather changes – the surface area of inner core cells decreased nearly be half, while their content almost doubled; dry mass and starch content decreased as well.

1999



2000



2001

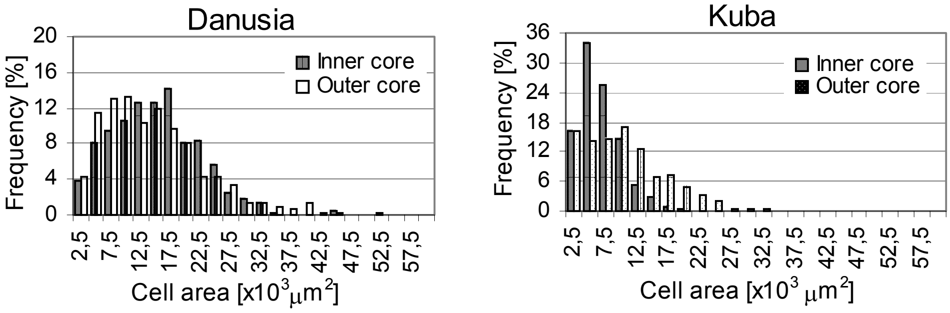


Fig. 2. *Distributions of the cell surface area of the two potato varieties, taking into consideration the outer and inner core and three years of harvest.*

CONCLUSIONS

The results obtained indicate that there is an effect of weather conditions during the vegetation period, and especially during tuber growth, on the cellular structure of potato tubers as examined at harvest, at technical ripeness.

The study confirms results obtained earlier, showing that the cellular structure of the parenchyma tissue of potato tuber is its characteristic feature, labile and dependent on a number of factors, the weather included. Its correct characterization and utilization in other research programs requires the structure parameters, especially those related to cell size, to be quantitatively determined every time.

REFERENCES

1. Konstankiewicz K., 2002. Investigation of mechanical properties of potato tuber tissue of selected varieties to use of them in practical aspect. State Committee for Scientific Research, Poland, Grant N°5P06F01317.
2. Konstankiewicz K., Czachor H., Gancarz M., Król A., Pawlak K., Zdunek A., 2002. Cell structural parameters of potato tuber tissue. Int. Agrophysics, 16, 2, 119-129.
3. Konstankiewicz K., Pawlak K., Zdunek A., 2001. Quantitative method for determining cell structural parameters of plant tissues. Int. Agrophysics, 15, 161-164.
4. Zdunek A., Konstankiewicz K., 2004. Acoustic Emission in Investigation of Plant Tissue Micro-cracking. Transactions of the ASAE, 47(4).
5. Zgórska K., 2003. Examination of physicochemical properties of potato tubers of selected cultivars in the aspect of their usability in food processing. State Committee for Scientific Research, Poland, Grant N°5P06G03518.
6. Zgórska K., Frydecka-Mazurczyk A., 2003. Dry matter and sugars content of different parts within potato tubers at harvest and storage time. Acta Horticulturae, 11, 600, 711-715.

THE EFFECTS OF SOIL COMPACTION ON PLANT ROOT GROWTH, FUNCTION AND STOMATAL DIFFUSIVE RESISTANCE

J. Lipiec, A. Nosalewicz

INTRODUCTION

The problems related to soil compaction are found throughout the world (Van Ouwerkerk and Soane, 1994). Increasing intensity of vehicular traffic is a major factor causing soil compaction and shearing (Horn, 2003). Compaction is also caused by natural factors such as rainfall impact, soaking and internal water suction. The presence of silica, oxides or salts of iron and aluminium may increase the soil hardness. Hard layers in the subsoil are mostly ploughpans and fine-textured B-horizons, which can seriously restrict drainage and root penetration. Alterations in pore-size distribution due to soil compaction influence several aspects of the soil such as air (Gliński and Stępniewski, 1985; Dexter and Czyż, 2000, water (Walczak, 1977), strength (Gliński and Lipiec, 1990), heat (Usowicz et al., 1995, biological activity (Stępniewska et al., 1990) which in turn affect root growth, stomatal resistance and consequently crop production (Sojka, 1992; Bennicelli et al., 1998). The interactions between root growth and water and nutrient uptake play an important role in the environmental quality (Lipiec and Stępniewski, 1995). In this paper root growth and functions and stomatal resistance in response to soil compaction are discussed.

ROOT GROWTH

A common response of root system to increasing compaction level is a decreased root size, retarded root penetration and smaller rooting depth (Gliński and Lipiec, 1990). Figure 1 shows the effects of compaction in the plough layer on root distribution of spring barley grown at various sites. Irrespective of soil type and site soil compaction resulted in higher concentration of roots in upper soil (0-10 cm) and reduced root size in deeper soil, mostly due to excessive mechanical impedance.

The negative effect of soil strength on root growth can be alleviated by the presence of pores having diameter greater than roots because roots can by pass the zones of high mechanical impedance (Hatano and Sakuma, 1990; Gliński and Lipiec, 1990). The pores can also benefit in poorly aerated soils since they drain at higher water potential and remain air-filled for longer compared to smaller pores. Importance of continuous and stable macropores for the root growth (Whalley and Dexter, 1994; Håkansson and Lipiec, 2000) and biological activity in the macropore sheath (Pierret et al., 1999) has been shown.

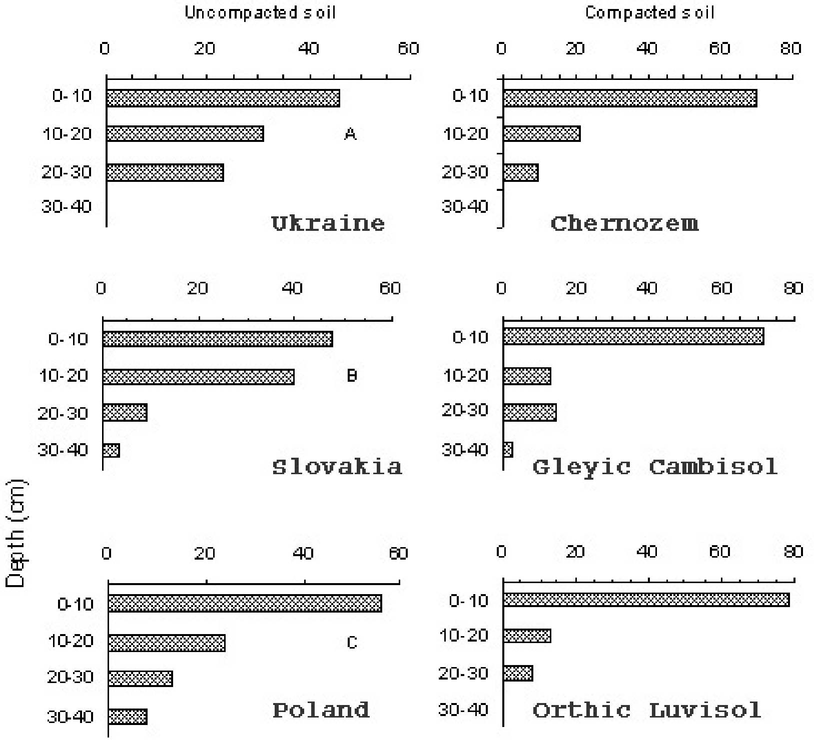


Fig. 1. Relationship between root distribution of spring barley and soil bulk density in the plough layer (after Lipiec et al., 2003).

WATER AND NUTRIENT UPTAKE

Reduced root size in deeper soil results in greater distances between the nearest roots and affects water and nutrient uptake. For spring barley the distances on horizontal planes within the depth 30 cm were below 5.8 mm for uncompacted soil and augmented up to almost 64 mm at depth 20-30 cm in most compacted soil. Absorption of water and nutrients takes place commonly in the soil adjacent to the root surface from 2 to 8 mm (Yamaguchi and Tanaka, 1990). As a consequence not absorbed nutrients in compacted soil can be subjected to leaching.

In general a restricted root system resulted in a lower water uptake from deeper soil layers (Lipiec and Simota, 1994). However root water uptake rate (per unit of root) may increase in a compacted soil. This was reported for bean (Huang, quoted by Smucker and Aiken, 1992), maize (Veen et al., 1992; Lipiec et al., 1993), barley (Lipiec et al., 1992) and rice (Gliński and Lipiec, 1990). This increase was mostly attributed to increased root-soil contact area and to a higher unsaturated hydraulic conductivity and a greater water movement towards the roots.

Total nutrient uptake is commonly reduced by soil compaction despite increase in nutrient inflow rate per unit length or surface of the roots (Lipiec and Stępniewski, 1995). Fig. 2 shows that when the 'degree of compactness' (the ratio of the actual to a specified maximum reference bulk density) (Håkansson, 1990) exceeded 89 %, considerable reduction of the N concentration in spring barley occurred, to a larger extent in straw than in grain. The barley yield reduction, which was concomitant with the lower N concentration in the most compacted soil, resulted in the reduced total N uptake by 30 % for grain and by almost 50 % for straw. Considerable reduction in uptake of other nutrients (phosphorus and potassium) has also been reported (Lipiec and Stępniewski, 1995). This effect was relatively greater in the case of less mobile phosphorus.

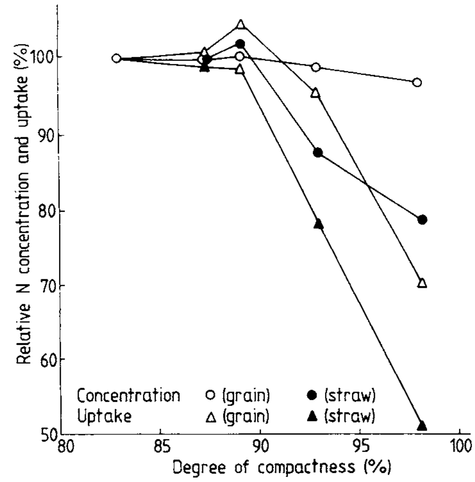


Fig. 2. Relative concentration and uptake of nitrogen (control plots 100 %) by spring barley in relation to the 'degree of compactness' (after Lipiec and Stępniewski, 1995).

The results presented above imply that biomass allocation (carbon economy) reduced and more efficient root system can be favourable. However, from the environmental point of view lower root size and uneven spatial distribution in compacted soil may increase likelihood of ground water contamination through leaching due to increased distances between the nearest roots (Yamaguchi and Tanaka, 1990). The higher rates of fertilisers applied on compacted soil to overcoome crop yield losses, increase the potential for utrient losses (Lipiec and Stępniewski, 1995).

Root-divided experiments

Experiments with roots divided between soil of different bulk density and soil water status are useful to study the effects of spatial distribution of mechanical impedance, soil wetness and aeration on root growth and function (Stępniewski and Bennicelli, 1992; Whalley et al., 2000; Nosalewicz and Lipiec, 2002). Such distribution in the field is often a result of uneven soil compaction by agricultural implements (Arvidsson and Håakansson, 1991; Walczyk, 1995, Ferrero et al., 2004).

Effects of horizontal strength discontinuity

Figure 3 illustrates the effect of a split root system of wheat between two column compartments with loose (L) and strongly compacted soil (SC) at given soil matric potential on water uptake in growth-chamber experiment. Reduced water uptake in strongly compacted compartment was partly compensated by greater water use in loose compartment. However, this compensatory effect was much less pronounced in treatment with loose and moderately compacted soil.

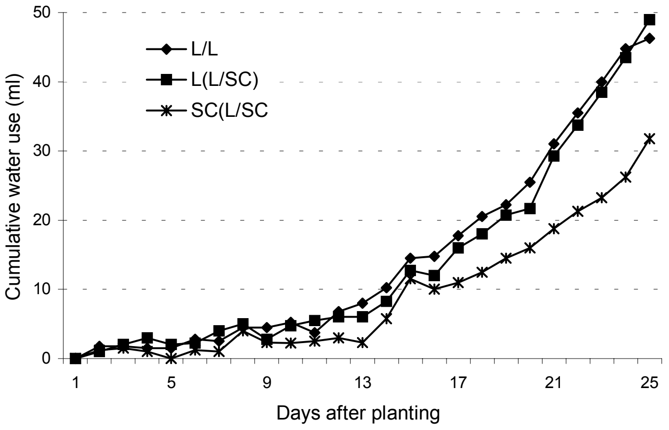


Fig. 3. *Cumulative water use from loose and moderately compacted soil compartments in treatment L/SC and loose soil in treatment L/L.*

Compensatory root growth in the aerated part vs. anoxic part induced by flooding with various gases or by adjusting the water content was reported (Stępniewski et al., 1994; Whalley et al., 2000). Kang et al. (1998) indicated that the controlled alternate irrigation of the root-divided plants is an effective and water-saving irrigation method and have the potential to be used in the field.

Effects of vertical strength discontinuity

Root growth and water use are highly affected by vertical strength discontinuity that frequently occurs in the field between the aggregated seedbed and the soil below and between the plough layer and the subsoil. Results of column experiments revealed that root size of maize in subsoil (below 30 cm) compared to total root size was below 38 % while water use - from 54 to 74% (Lipiec et al., 1993). In another study with incessant water supply it was shown that water uptake by wheat roots was greater from the upper subsoil layer (25-35 cm) than from deeper layer (35-45 cm) (Fig. 4). Irrespective of layer total water use and root water use efficiency were greater for the silty loam than loamy sand.

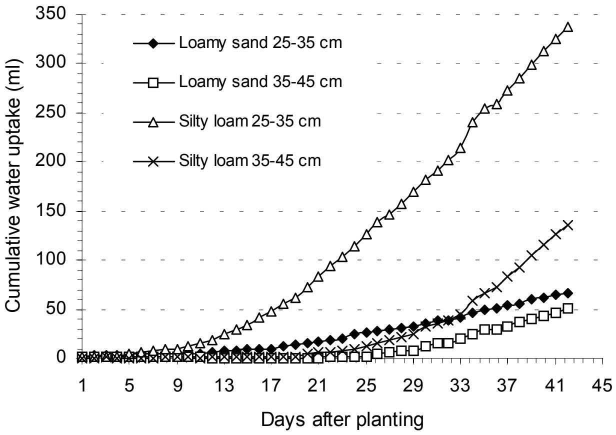


Fig. 4. Cumulative water uptake from the loamy sand and silty loam subsoils (after Lipiec et al., 2002).

The vertical strength discontinuity occurs usually together with vertical variation in soil water potential. How both factors can be controlled in split root systems was described by Whalley et al. (2000).

The results above indicate plasticity of root water absorption in response to small-scale uneven distribution of soil compaction. The alterations in the root water use efficiency due to spatial distribution of soil strength are of importance in modelling plant water use (Novak, 1995; Walczak. et al., 1997).

STOMATAL DIFFUSIVE RESISTANCE

The stomatal resistance responses to soil compaction are related to soil water status (Tardieu and Davies, 1993). In growth chamber experiment with transient wetting the stomatal resistance and its variation over the growth period were considerably higher in a severely compacted soil than in low or medium compacted soil (Fig. 5.). A substantial increase of stomatal resistance in most compacted soil occurred when soil matric potential increased from -415 to -220 hPa (increasing soil wetness). The highest stomatal diffusive resistance in most compacted soil has also been reported during droughty growing season (Lipiec and Gliński, 1997).

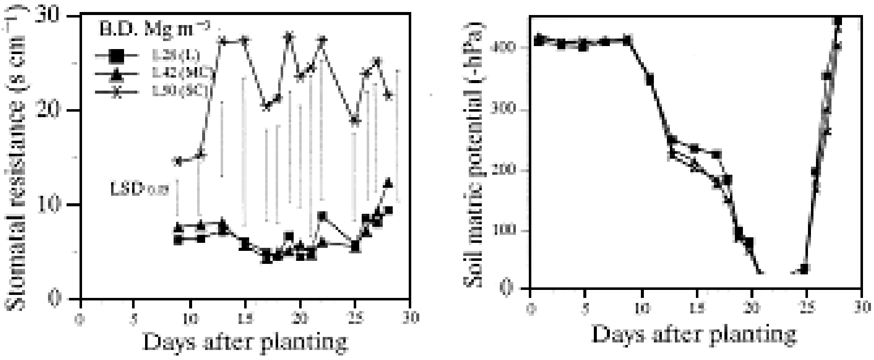


Fig. 5. Stomatal resistance in maize and soil matric water potential as a function of days after planting (after Lipiec et al. 1996).

Several mechanisms are suggested for stomatal closure. One mechanism under poor aeration is reduced water flow through roots (Gliński and Stępniewski, 1985). Accumulation of abscissic acid (ABA) in leaves seems to induce stomatal closure through its effect on the potassium ion regulation of guard cell turgor (Sojka, 1992; Tardieu, 1994; Agnew and Carrow, 1985b). The stomatal resistance of maize grown in poorly aerated soil was considerably higher in lower than upper leaves (Lipiec et al., 1996) and may imply the upward movement of plant hormones or other substances to the shoots (Box, 1986; Tardieu, 1994). This can be supported by recent study (Bennicelli et al., 1998) indicating that superoxide dismutase (SOD, metalloenzyme, protects aerobic organisms against oxygen activated toxicity) activity in roots increased earlier (after two days of oxygen stress) while that of in the leaves started to increase later (after 8 days). Increased abscissic acid content in leaves have also been observed under dry soil (Gliński and Lipiec, 1997). Some authors (Tardieu,1994; Hartung et al., 1994) point out that ABA increase in plants grown in compacted soil is a result of root dehydration due to a limited water supply to the roots. Ali et al. (1999) reported that the increased leaf stomatal resistance occurred even before a measurable change in leaf water potential. Stomatal resistance is also dependent on time during the day (Novak, 1995; Lipiec and Gliński, 1997). The differences in stomatal resistance between compaction treatments were more pronounced as the day progressed, mostly due to substantial increase in strongly compacted soil.

The stomatal resistance is negatively correlated with photosynthesis rate (Sojka, 1992; Bennicelli et al., 1998) and this together with decreased leaf area may largely account for crop yield reduction in compacted soil. Crop yield responses to soil compaction are discussed in earlier papers (Lipiec and Simota 1994; Lipiec et al., 1991).

CONCLUSIONS

A characteristic response of root system to increasing soil compaction level is a decreased root size, retarded root penetration and shallower rooting depth. Root growth distribution in response to soil compaction is related to distribution pattern of pores. Total water and nutrient uptake in most compacted soil is considerably reduced. Split root experiments showed that reduced root growth and water uptake in strong and poorly aerated soil was compensated for in adjacent loose and well-aerated soil. Stomatal diffusive resistance was increased in most compacted soil under wet and dry conditions. Several mechanisms are suggested for stomatal response to soil compaction.

Acknowledgements

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REFERENCES

1. Agnew, M.L., Carrow, R.N. 1985. Soil compaction and moisture preconditioning in Kentucky bluegrass. II. Stomatal resistance, leaf water potential and canopy temperature. Agron. J., 878-884.
2. Ali, M., Jensen, C.R., Mogensen, V.O., Andersen, M.N. and Henson, I.E. 1999. Root signalling and osmotic adjustment during intermittent soil drying sustain grain yield of field grown wheat. Field Crops Research, 62, 35-52.
3. Arvidsson, J., Håkansson, I., 1991. A model for estimating crop yield losses caused by soil compaction. Soil Till. Res. 20, 319-332.
4. Bennicelli, R.P., Stępniewski, W., Zakrzhevsky, D.A., Balakhnina, T.I., Stepniewska, Z. and Lipiec, J. 1998. The effect of soil aeration on superoxide dismutase activity, malondialdehyde level, pigment content and stomatal diffusive resistance in maize seedlings. Environmental and Experimental Botany, 39, 203-211.
5. Box, J.L. 1986. Winter wheat grain yield responses to soil oxygen diffusion rates. Crop Sci., 26, 355-361.
6. Dexter, A.R., Czyż, E.A., 2000. Soil physical quality and the effects of management. In Wilson, M.J., Maliszewska-Kordybach, B. (Eds.), Kluwer Academic Publisher, pp. 153-165.
7. Ferrero, A., Usowicz, B., Lipiec, J., 2004. Effects of tractor traffic on spatial variability of soil strength and water content of grass covered and cultivated sloping vineyard. Soil and Tillage Research (accepted for publication).
8. Gliński, J. and Lipiec, J.. 1990. Soil Physical Conditions and Plant Roots. CRC Press, Boca Raton, FL, U.S.A., 250pp.
9. Gliński, J. and Stępniewski, W. 1985. Soil Aeration and Its Role for Plants. CRC Press, Boca Raton, FL, U.S.A., 200pp.

10. Håkansson, I. 1990. A method for characterizing the state of compactness of the plough layer. Soil tillage Res., 16, 105-120.
11. Håkansson, I, Lipiec, J. 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. (accepted).
12. Hartung, W., Zhang, J. and Davies, W.J. 1994. Does abscisic acid play a stress physiological role in maize plants growing in heavily compacted soil?. Journal of Experimental Botany, vol. 45, No 271, 221-226.
13. Hatano. R., Sakuma, T. The role of macropores on rooting pattern and movement of water and solutes in various field soils. Trans. 14th. Inter. Congr. Soil Sci. II, 130-135.
14. Horn, R. 2003. Stress-strain effects in structured unsaturated soils on coupled mechanical and hydraulic processes. Geoderma, 116, 77-88.
15. Kang, S., Liang, Z., Hu, W., Zhang, J. 1998. Water use efficiency of controlled alternate irrigation on root-divided maize plants. Agric. Water Manage. 38, 69-76.
16. Lipiec, J., Gliński, J. 1997. Field soil compaction: effects on soil physical properties and stomatal resistance of wheat. Proc. Int. Sympsium 'Soil, Human, and Environment Interactions' (Ed. Z. Cao), China Science and Technology Press, 422-427.
17. Lipiec, J., Håkansson, I., Tarkiewicz, S. and Kossowski, J. 1991. Soil physical properties and growth of spring barley related to the degree of compactness of two soils. Soil Tillage Res., 19, 307-317.
18. Lipiec, J., Hatano, R., Słowińska-Jurkiewicz, A. 1998. The fractal dimension of pore distribution patterns in variously-compacted soil. Soil and Tillage Res., 47, 61-66.
19. Lipiec, I., Ishioka, T., Hatano, R., Sakuma, T. 1993. Effects of soil structural discontinuity on root and shoot growth and water use of maize. Plant and Soil, 157, 65-74.
20. Lipiec, J., Ishioka, T., Szustak, A., Pietrusiewicz, J., Stepniewski, W. 1996. Effects of soil compaction and transient oxygen deficiency on growth, water use and stomatal resistance of maize. Acta Agric. Scand. Sect. B, Soil and Plant Sci., 46, 186-191.
21. Lipiec, J., Kossowski, J., Tarkiewicz, S.1992 . Spring barley yield and root growth in response to the degree of compactness of soil and weather conditions. Proc. Int. Conference "Soil Compaction and Soil Management' 8-12 June 1992, Tallinn, Estonia.
22. Lipiec J, Medvedev, V.V., Birkas, M., Dumitru, E., Lyndina, T.E., Rousseva, Fulajtár, E. 2003. Effect of soil compaction on root growth and crop yield in Central and Eastern Europe. Int. Agrophysics, 17, 61-69
23. Lipiec, J., Nosalewicz, A., Smarz, M., 2002. Root growth and water uptake of wheat as affected by soil compaction. Proc. Inco-Copernicus Conf. 'Experiences with the impact of subsoil compaction on soil nutrients, crop growth and environment, and ways to prevent subsoil compaction' 15-19 June 2001, Busteni, Romania, 171-177.
24. Lipiec, J., Simota, C. 1994. Role of soil and climate factors influencing crop responses to compaction in Central and Eastern Europe. In: B.D. Soane and C. Ouwerkerk van (Editors), Soil Compaction in Crop Production. Elsevier, Amsterdam, Netherlands, pp.365-390.
25. Lipiec, J., Stepniewski, W. 1995. Effects of soil compaction and tillage systems on uptake and losses of nutrients. Soil Tillage Res., 35, 37-52.
26. Nosalewicz, A. and Lipiec, J. 2002. Effect of localised soil compaction and wetness on early root growth and functions. Acta Agrohysica, 78, 199-208 (in Polish).

27. Novak, V. 1995. Vyparovanie vody v prirode a metody jeho urcovania. VEDA, Vydavatelstvo Slovenskej Akademie Vied, Bratislava, 253pp.
28. Pierret, A., Moran, C.J., Pankhurst, C.E. 1999. Differentiation of soil properties related to the spatial association of wheat roots and soil macropores. Plant and Soil, 211, 51-58.
29. Smucker, A.J.M., Aiken, R.M. 1992. Dynamic root response to water deficits. Soil Sci., 154, 4, 281-289.
30. Sojka, R.E. 1992. Stomatal closure in oxygen-stressed plants. Soil Sci., 154, 269-280.
31. Stępniewska, Z., Lipiec, J., Dabek-Szreniawska, M., Bennicelli, R. and Stepniewski, W. 1990. The influence of anaerobic conditions on enzymatic activity in brown-grey (Lessive) soil (horizon Ap). Folia Soc. Sci. Lublinensis, s. Geogr., 1, 1: 33-59.
32. Stępniewski, W., Bennicelli, R. 1992. Effect of localized anoxia on maize response. In: Kutschera, L., Hubl, E., Lichtenegger, E., Persson, E., Sobotik, M. (Eds.) Root Ecology and ist Practical Application, vol. 3. ISRR Symp., Univ. Bodenkultur, Wien, pp. 137-138.
33. Stępniewski, W., Bennicelli, R., Gliński, J., Stępniewska, Z. 1994. Split rhizotron technique for localized anoxia studies. Trans. 15th Congr. ISSS, Acapulco, Mexico 2b: 237-238.
34. Tardieu, F. 1994. Growth and functioning of roots and root systems subjected to soil compaction. Towards a system with multiple signalling?. Soil Tillage Res., 30, 217-234.
35. Tardieu, F., Davies, W.J. 1993. Root-shoot communication and the whole-plant regulation of water flux. In: Smith, J.A.C., Griffiths, H. (Eds.), Water Deficits: Plant Responses from Cell t to Community, BIOS Scientific, Oxford, pp 147-162.
36. Usowicz, B., Tarkiewicz, S., Lipiec, J., 1995. Compaction effects on soil thermal properties. Proc.Intern. Symp. "Soil Tillage - Present and Future" 22-23 June 1995, Cluj-Napoca, Romania, vol. II, 312-321.
37. Walczak, R., 1977. Model investigations of water binding energy in soils of different compaction. Zesz. Probl. Post. Nauk Roln. 197, 11-43.
38. Walczak, R.T., Witkowska-Walczak, B., Baranowski, P. 1997. Soil structure parameters in models of crop growth and yield prediction. Physical submodels. Int. Agrophysics, 11, 111-127.
39. Walczyk, M. 1995. Thechnical and technological aspects of compaction of agricultural soils by tractor aggregatess. Zesz. Nauk. Akad. Roln., Kraków, 202, 5-107 (in Polish with English summary).
40. Whalley, W.R., Dexter, A.R. 1994. Root development and earthworm movement in relation to soil strength and structure. Arch. Acker-Pfl. Boden, 38, 1-40.
41. Van Ouwerkerk, C., Soane, B.D. 1994. Conclusions and recommendations for furtherresearch on soil compaction in crop production. In: B.D. Soane and C. Ouwerkerk van (Editors), Soil Compaction in Crop Production. Elsevier, Amsterdam, Netherlands, pp.627-642.
42. Veen, B.W., van Noordwijk, M., de Willigen, P., Kooistra, M.J. 1992. Root-soil contact of maize, as measured by a thin-section technique. III. Effects on shoot growth, nitrate and water uptake efficiency. Plant Soil, 139, 131-138.
43. Yamaguchi, J., Tanaka, A. 1990. Quantitative observation on the root system of various crops growing in the field. Soil Sci. Plant Nutr., 36, 483-493.

SOIL COMPACTION AS A FACTOR OF SOIL PRODUCTIVITY AND ECOLOGICAL FUNCTIONS IN THE UKRAINE

Medvedev V.V.

INTRODUCTION

Bulk density is an integral index of the physical state of soils, influencing water, air and thermal conditions and consequently the productivity of agricultural crops. Rather a large number of various experiments (field, micro-field, vegetation, expedition) were carried out in the Ukraine. They allow describing the geography of the equilibrium bulk density, its differentiation along the soils profile, impact on the soil regimes, changes in the process of agricultural use. In this article the results of these investigations are summarised.

SOURCES OF INFORMATION

The data are collected in three databases. In the first of them the data on the measurements of the bulk density along the profile of the majority of the country's soils are accumulated. It consists of more than 8000 data of the bulk density from 507 soil sections. The availability of other data in this database (on the peculiarities of the territory, its use, physic-chemical and other properties of soils) made it possible to form the selections of different thematic directions and analyse bulk density in connection with other characteristics. In the second database the data on the dynamics of compaction in relation to different tillage technologies, fertilizers, tools, mobile aggregates from 220 literary sources were included. In the third database the data of 80 experiments are put in order. Those experiments were conducted to find out the optimum bulk density at cultivation of different agricultural crops. Databases were described in detail in papers (V.V. Medvedev a. oth., 2000; 2000a).

RESULTS OF THE INVESTIGATIONS

The geography of bulk density.

The map of the bulk density of soils in the Ukraine on a scale of 1:2500000 is given on fig.1. The zonal character of this property draws the attention. The borders of the zones, especially between Polesie and Forest Steppe are quite clear. The border between the Forest-Steppe and Steppe is somewhat uncertain but clear as well. Other natural outlines – Small Forest Steppe, brawn forest region of the Carpathians and Transcarpathians, the Black Sea Lowland, Dry Steppe with solonets soils, Vinnitsa island of grey forest soils, Transdonets region, Sivash and others are quite isolated.

The general tendency is as follows: the maximum equilibrium bulk density of soils in the upper genetic horizon is thought to be equal to the Polesie Flat. Here soddy-podzolic loamy sand, sandy and clay-sandy soils dominate. The average weighted value of the equilibrium bulk density is 1.6 g/cm^3. Minimum – less than 1.25 g/cm^3 – the Forest Steppe where chernozemic (typical and podzolized) and grey (dark-grey) soils dominate. To the south and southeast the bulk density increases again, but its values don't exceed 1.5 g/cm^3. Here, as it is known, are the soils of the heaviest granulometric texture. They are in this or other way, solonets like soils.

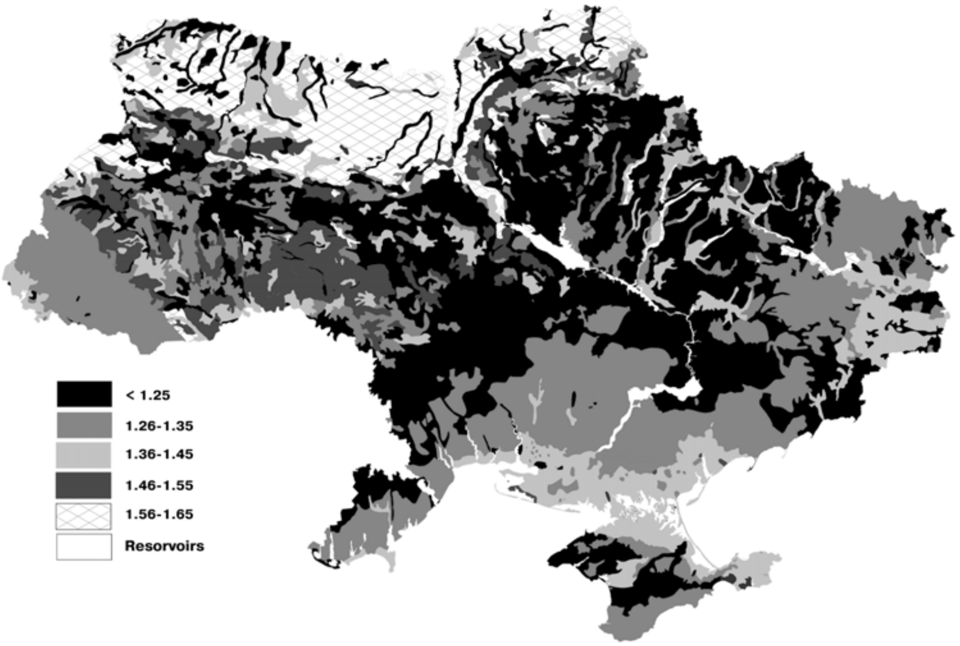


Fig.1. *Equilibrium bulk density (g/cm^3) of the upper horizon of the soils in the Ukraine*

Differentiation of the bulk density along the profile.

Curves, characterizing the changes of the bulk density along the profile of different soils though somewhat different can be referred to the same type: minimum values – in the first genetic horizon (it is so called quasi equilibrium bulk density of the soil layer, which is periodically subjected to the tillage), flowing, but rather rapid increasing of values in 2-3 horizons, fading, levelling and fixating the values in the low horizons and in the rock. Some aspects of great importance should be marked:

- differences in granulometric texture and quantity of humus weakly affect onto the character of the profile distribution of the bulk density;
- the highest values in compaction are marked between 1 st (2nd) genetic horizons and rock;
- the most differentiated profile as for compaction is the characteristic feature for chernozemic soils, the least differentiated – for the soils with the expressed podzolic or solonets soils;

- as for the soils of polygenetic nature (meadow–chernozem, meadow-chestnut, alluvial, gleyic, brown forest and some others) the undirected deviations in indices of the bulk density in certain genetic horizons are possible.

The above information implies that the soil's bulk density is succeded to the compaction of the rock, its mineralogical and texture composition. The process of soil formation decreases the bulk density and forms the typical profile of its distribution: for the soddy process – clearly differentiated, for podzolic and solonets – the least differentiated, for all others-uncertainly differentiated, complicated (fig.2).

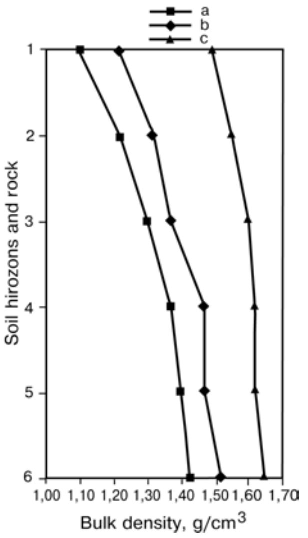


Fig.2. *The main types of differentiation of the profiles on their bulk density (a-strong; b – medium; c – weakly differentiated).*

Impact on water-air and other regimes.

Water regime is a complex of processes of entering, re-distribution, accumulation and evaporation (transpiration) of moisture in the soil depends upon the bulk density. Probably, only in the very first moments the atmospheric moisture enters into the surface layer of the soil through the large pores and cracks almost independently from the bulk density (fig.3). All the following stages of moisture's migration in the soil in one or another way directly or indirectly are stipulated by the bulk density. The movement of moisture inside the soil in the same way depends upon the bulk density. In the loosen soil the depth of wetting is usually more, in the dense one-less, at the same time, the larger possibility of the rise of surface and inside surface runoff is very high. Any over falls of the bulk density in the soil profile decelerate ascending and descending flows of moisture.

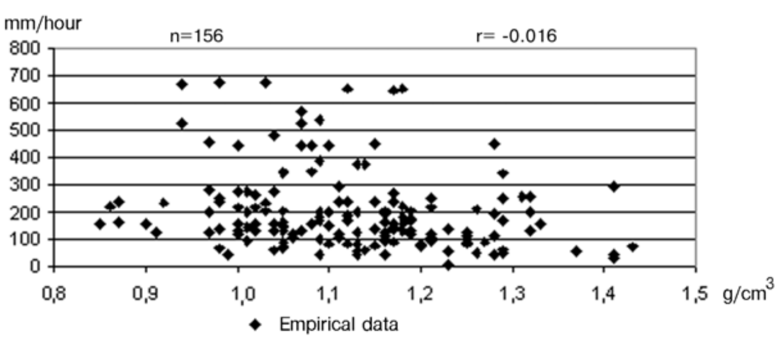


Fig.3. *Bulk density (g/cm^3) and water permeability (mm/hour) during the first hour of measurement (average data for chernozems podzolized, typical, ordinary and southern)*

At physical evaporation and transpiration almost the same principles apply: unnecessarily loosen soil looses its moisture quicker (dense one-worse) and optimum transpiration (the largest production of dry mass per unit of water used) is observed at the moderate compaction (Table 1).

Table 1. Expense of moisture from typical chernozem (heavy loam) depending upon the bulk density and moisture (FC = field capacity)

BD	M	TE	PE	PE%	T	OM	TC
1.0	0.6	4560	1015	22	3545	7.8	745
	0.8	6380	1160	18	5220	9.2	566
	1.0	6920	1680	24	5240	9.0	580
1.2	0.6	7800	1110	14	6690	10.9	615
	0.8	9160	1320	14	7820	13.9	563
	1.0	9190	1210	13	7980	15.6	510
1.4	0.6	7620	1670	22	5950	9.0	660
	0.8	8780	1460	17	7320	11.4	640
	1.0	7900	1700	22	6200	8.7	715

Abbreviations: BD = Bulk density, g/cm^3; M = Moisture, to FC; TE = Total Evaporation, ml/vessel; PE= Physical Evaporation, ml/vessel; PE% = Physical evaporation, % to total; T = Transpiration, ml/vessel; OM = Oat Mass, g/vessel; TC = Transpiration Coefficient, ml/g

At the fig.4 the generalized data are given. They demonstrate the dependence of porosity of aeration (air-capacity of soil at the moisture corresponding to the field water capacity) on the bulk density. Air-capacity of soil at the field water capacity an inverse, quite stable linear connection with the bulk density.

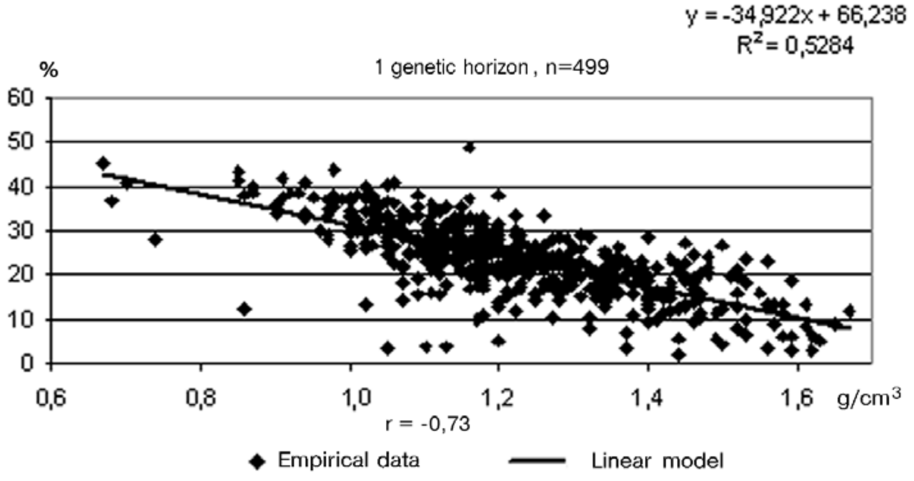


Fig.4. The dependence of porosity of aeration (%) upon the bulk density of soils (g/cm^3)

In chernozem typical (heavy loam) at the field water capacity the critical air capacity (<15%) occurs at the bulk density of 1.25-1.30 g/cm^3 whereas in soddy-podzolized loamy sand soil at the bulk density of 1.60-1.65 g/cm^3.

Bulk density is the most important regulator of the processes of entering of oxygen into the soil and isolation of carbonic acid from it and thus, of the composition of soil air. The rate of diffusion also depends upon the bulk density. For example the coefficient of air diffusion in the heavy loam podzolized soil at the bulk density of 1.1 g/cm^3 is 0.18-0.22 and at 1.5 g/cm^3 – 0.02-0.09. As a result, nitrification depending upon the providing of soils with oxygen changes. At overcompaction, on the contrary, the ammonificational processes begin dominating. So the changes in number of microorganisms – bacteria, actinomycetes and fungi can be observed as well as the activity of ferments, which notably decreases at compaction.

With increasing bulk density increasing of water permeability swiftly falls and the erosion loss grows less swiftly (fig.5). The critical values of water permeability (for chernozemic loamy soils) at which the formation of pools, slaking and run off are 30-40 mm/hour. At the same time, the bulk density of the upper layer is usually higher 1.2-1.3 g/cm^3, but erosion loss can be considerably higher than 10 t/ha.

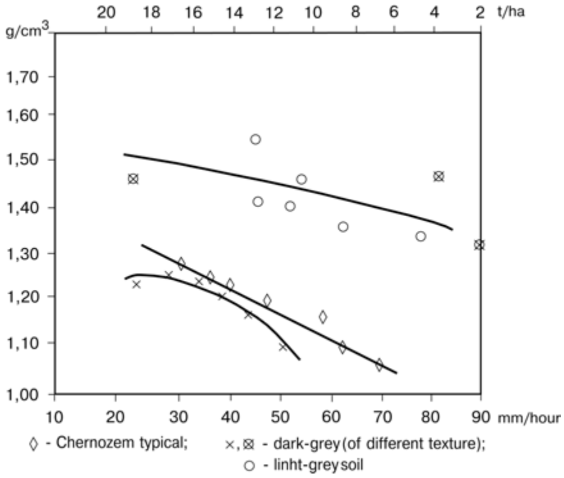


Fig.5. *Change of filtration (mm/hour) and erosion loss (t/ha) from the bulk density (g/cm^3) of soils*

Reaction of agricultural crops on different bulk density of the tilled layer was found out in special model experiments conducted with the using of the theory of the planning of the experiment (V.V. Medvedev a oth., 2004). The latter has allowed to obtain a number of advantages – to reduce the number of variants, automatize the data processing, considerable improve the form of the representation of the results and, what is essential, formalize the regularities as models with a certain degree of reliability. Besides the bulk density, fertilizers (different combinations and dozes), the depth of their incorporation, moistening, structural composition of the sowing layer were investigated. Thus, it became possible to describe the reaction of plants with account of many factors. The latter, as it was proved, often corrected the reaction of plants onto the bulk density. In the conditions of sufficient moisture the range of the optimum parameters widened, in droughty conditions, on the contrary, this range got narrow, and the optimum parameters aimed at moderately increased values. Almost in the same way, the sufficient provision with nutrients was corrected with consideration of the bulk density. The plants reacted on the bulk density differently, depending upon the type of fertilizers. Nitric fertilizers improved the effect of the optimum bulk density, phosphorus had the some influence at the lack of moisture. Potash fertilizers corrected, but weakly, the reaction of plants on the parameters and the range of the values of the optimum bulk density.

Plants reacted onto the bulk density in some parts of the tilled layer differently – the less strongly in the above seed layer, the strongest - in under seed layer. Also it was clearly observed the reaction of plants onto the bulk density dependently upon the phase of their development – they were very sensitive to unnecessarily loosen and unnecessarily dense soils at seeds growing and at the initial stage of roots' formation. In the first case strong but weak from the point of view of productivity root system formed, in the second, weak branching thin one quite efficient.

The reaction of plants onto the optimum bulk density improved (i.e. crops yield increased), when the bulk density in the tilled layer was differentiated, to be exact, formed moderately compacted interlayer above the seeds which didn't prevent the appearing of sprouts and at the same time increased the efficiency of using of moisture at the expense of reducing of unproductive evaporation.

After all, different plants reacted differently onto the compaction of the tilled layer. Grain crops are not so sensitive, row crops and especially fine seed crops are more sensitive (V.V. Medvedev, 1990).

Generally the reaction of plants can be described by the quadratic equation $y=a+bP+cP^2$, where y – crop yield, P – bulk density; a, b, c – the parameters of the curve. The theoretical optimum – maximum value y was discovered at the optimum bulk density. At the fig.6 (as an example) the optimum bulk density corresponded to the range of parameters at K=0.05, where K – the ratio of the actual crop yield to the maximum one, assumed to be 1.

The optimum model of the root layer concerning the bulk density (table 2) was the result of the work, described in detail in the book (V.V. Medvedev and others, in print).

Table 2. The optimum model of root layer in relation to the bulk density

Layers	Depth, cm	Bulk dens., g/cm^3 (average)
Surface	*0-4*	*1.10-1.30(1.20)*
Above seed interlayer	*4(6)-6(8)*	*1.20-1.30(1.25)*
Seed	*8-10*	*1.15-1.25(1.20)*
Under seed	*10-15*	*1.10-1.20(1.15)*
Low part of tilled and subsurface	*15-40*	*≤1.35(1.35)*

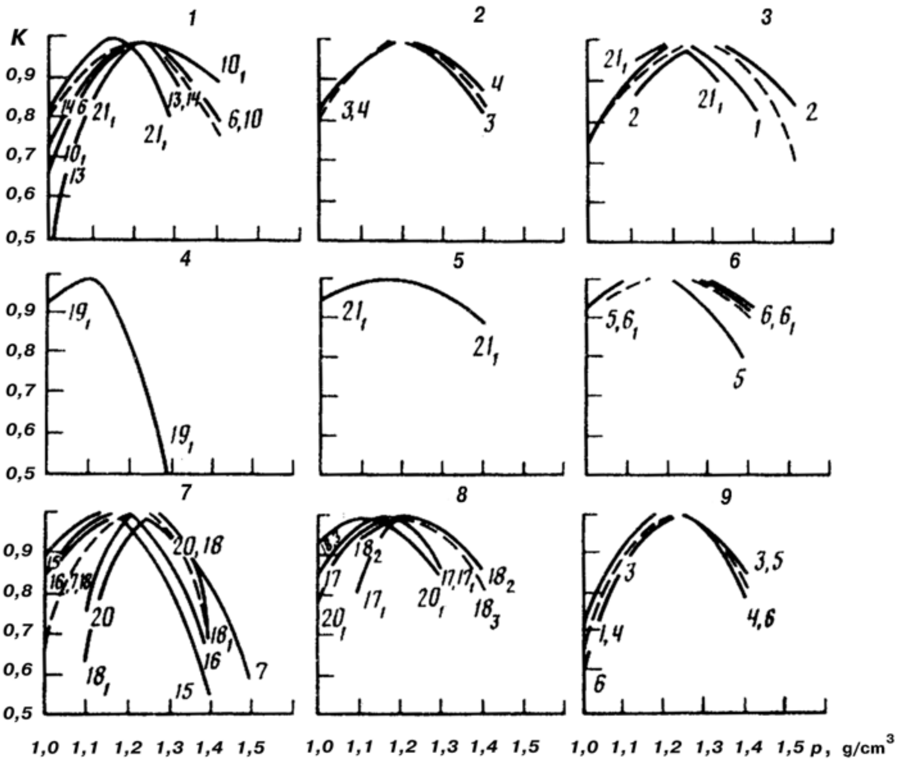


Fig.6. *Optimum parameters of compaction of chernozem typical medium loamy (1-5) and heavy loamy – light loamy (6-9) at cultivation of different agricultural crops:1 – winter crops, К =1-6,78 (p-1,22)^2; 2 – sugar beet, К=1-4,37(p-1,21)^2; 3 - maize, К =1-4,17 (p-1,24)^2; 4 – pea, К =1-10,83 (p-1,08)^2; 5 – spring crop, К =1-2,07 (p-1,17)^2; 6 – sugar beet, К =1-2,50 (p-1,20)^2; 7 – winter crops, К =1-8,33 (p-1,21)^2; 8 – spring crop, К =1-4,37 (p-1,19)^2; 9 – maize, К =1-6,81 (p-1,24)^2; Continuous lines – the dependences of the crop yield in a concrete experiment, interrupted one – generalized dependence.*

CONCLUSIONS

On the ground of the results of the created databases for the bulk density of soils in the Ukraine the corresponding map in the scale of 1:2500000 was made, the peculiarities of the profile distribution of the bulk density were determined, its influence on the main soils regimes was described.

At maintaining the bulk density in optimum range favourable conditions for growth, development and yield of crops are provided, i.e. the productive function of soils. Simultaneously, the regimes of moisture, air, and biological activity are optimised and the erosion processes are minimized, the soils stability and their normal ecological functioning are reached.

REFERENCES

1. Medvedev V.V. 1990. Variability of optimal soil bulk density and its causes. Soil Science, v. 5, 20-30 (in Russian).
2. Medvedev V.V., Laktionova T.M., Lyndina T.E., Plisko I.V. 2000. Experience of forming and practice use of databases in soil science. News of Agrarian Science for Southern region. Odessa, v.1, 202-209 (in Ukrainian).
3. Medvedev V.V., Lyndina T.E., Laktionova T.M. 2000a. Databases "Overcompaction of soils in the Ukraine" and their practice aspects. Supplement of 2nd Workshop and International Conference on Subsoil Compaction. Godollo, Hungary, 13-18.
4. Medvedev V.V., Lyndina T.E. 2004. Mathematical planning in experiments on "soil-fertilizer- yield" interactions. International Adrophysics, 18, 31-38.
5. Medvedev V.V., Lyndina T.E., Laktionova T.M. Soil bulk density (genetic, ecological and agronomical aspects). In print (inRussian).

CROP GROWTH ON LOESS SOIL OF VARIOUS EROSION CLASS

Rejman J.

ABSTRACT

Spring wheat and spring barley growth (root mass, plant height, canopy cover) was studied on soils of various erosion class developed from loess. Results showed that crop growth was similar in its initial phase, and started to differentiate from phenological phase of flowering. Differences among plants growing on soils of various erosion class were maintained till harvest and affected yields. Yields of spring wheat and barley were the largest on colluvial soil, then on slightly, moderately and very severely eroded soils. Analysis of soil parameters and weather conditions showed that for differentiation of yields seems to be responsible factors deciding on root mass distribution.

INTRODUCTION

Long term agricultural land use and erosion have caused substantial variation of soils in hilly loess areas. In the effect, different soil horizons take part in structure of present plow layer. To describe the changes, classification based on description of soil profiles was proposed by Turski et al. (1992). In the classification, soil with full sequence of horizons is described as non-eroded, when Bt1 horizon is directly below plow layer – slightly, Bt2 – moderately, BC – severely, and Cca – very severely eroded. Introduction of different soil horizons into plow layer affects soil properties, its productivity and differentiation in soil loss rates (Licznar et al., 1991; Rejman et al., 1998; Turski et al., 1992). Similar classification were applied to moraine areas of west and north Poland (Marcinek, 1994; Koćmit et al.; 2001). Loss of topsoil and inclusion of deeper soil horizons to the arable layer is believed to reduce soil productivity by affecting soil properties (Schertz et al., 1984, Bakker et al., 2003). As one the most important factor responsible for crop decrease seemed to be reduction of available water content (Becher et al., 1985; Frye et al., 1982). However, studies conducted on soils developed from deep loess deposits showed that incorporation of deeper soil horizons to arable layer only initially causes deterioration of soil properties. With further erosion and mixing of Cca horizon with arable layer, some properties as total porosity and water characteristics of the soil were gradually improved (Turski et al., 1992; Licznar et al., 1991).

Soil productivity and plant yields in hilly loess areas are generally analyzed in terms of site location in topography (top of the hills, slopes and valley bottom), (Orlik, 1992; Mazur, 1996). With site location, degree of erosion is assumed. The analysis concluded that yield on site location varied in dependence to microclimate conditions. Generally, yields were highest at bottom valley, then on tops of hills, and on slopes of northern and southern inclination (Mazur, 1996). Similar classification of yields obtained Mazur and Dechnik (1996) in pot experiments. However, according to Turski et al. (1992), soils of different erosion classes and colluvial can be found at the same landscape position. It means that without previous localization of erosion classes inside the investigated area, the evaluation of the effect of erosion on soil productivity is more complicated. Results of four-year field experiment showed that plant yields decreased with erosion class and loss of topsoil (Rejman et al., 2002).

The aim of this work was to analyze plant growth on soils of various erosion classes and to find which factors were directly responsible for yield decrease.

METHODS

Field experiments were conducted on soils developed from loess at Czesławice site (51^{0}22’N; 22^{0}44’E) in the years 1994-95. Twelve runoff plots, 20 m long and 3 m wide were located on one field (4 ha) on slightly, moderately, very severely eroded and colluvial soil (9-10% slope of southern-east inclination). Some soil characteristics are presented in Table 1.

Table 1. Average values, standard deviations and coefficients of variation of some properties of loess soil, Czeslawice (n – number of measurement points).

Soil erosion class		Sand 1-0.05mm	Silt 0.05-0.002mm	Clay <0.002 mm	OM	WSA >1mm	Useful water retention (-15.5– -1550 kPa)	pH
		%						
Slightly eroded (n=8)	Average	16.8	71.0	12.2	0.84	13.1	19.48	5.5
	Std.dev.	2.2	3.3	1.8	0.19	7.1	3.83	0.06
	CV, %	13.1	4.6	14.8	22.6	54.2	19.7	1.1
Moderately eroded (n=5)	Average	19.2	67.8	13.0	0.87	14.6	17.36	5.5
	Std.dev.	3.3	1.9	1.6	0.14	8.2	2.26	0.39
	CV, %	17.2	2.8	12.3	16.1	56.3	13.0	7.1
Very severely eroded (n=4)	Average	17.2	72.8	10.0	0.86	9.8	21.33	6.7
	Std.dev.	1.9	1.5	0.8	0.07	3.5	2.64	0.24
	CV, %	11.0	2.1	8.0	8.1	35.9	12.4	3.6
Colluvial (n=30)	Mean	18.6	73.2	8.2	1.05	14.4	20.22	5.9
	Average	3.1	3.1	1.7	0.22	4.1	2.07	0.61
	CV, %	16.7	4.2	20.7	21.0	28.6	10.2	10.3

Plots were separated from each other by plastic borders driven 10 cm into soil. At the lower parts of the plots runoff collectors were placed. Four of the plots were kept under continuous fallow during a year, and eight plots with plants (spring wheat in 1994 and spring barley in 1995). Wheat was sieved on 112, and harvested on 235 day of the year, whilst barley was sieved on 103, and harvested on 216 day. During vegetation, plant and soil parameters, and soil loss were measured every two weeks and sometimes every week. Plant height was measured every 2 m along plot borders, and canopy cover was determined on the basis of color photos analysis. Photos were taken from 2 m height and covered an area of about 0.5 m^2 (1 photo per plot). Root mass was measured once (3 days before harvest) in 1995. To determine root mass, soil cores of 100 cm^3 were taken from soil depth till 30 cm, and then roots were separated from soil and litter on sieves. Then separated roots were dried at temperature 65 ^{0}C and weighed. Yields were evaluated on the basis of grain that was collected from the area of 1 m^2 (3 replicates). Soil parameters (bulk density and soil moisture) were determined from cores of 100 cm^3. All soil cores were taken in 3 replicates, both from different depths as from various soils. Additionally, soil moisture at depth of 5 cm was measured with TDR probes in 1994 (in similar way as plant height). Weather characteristics were taken form meteorological station of Agriculture University in Lublin, located about 200 m from runoff plots.

RESULTS

Weather conditions

Although sum of daily average temperatures was much higher for vegetation period of spring wheat (132 days - 2107 ^{0}C) in comparison to spring barley (104 days - 1714 ^{0}C), average daily temperatures were similar (16.0-16.3 ^{0}C). Precipitation was more differentiated. During wheat vegetation, total rainfall amount was 265.7 mm, whereas during barley – 195.9 mm. It seems that distributions of temperature and rainfall were more favorable for wheat development. After initial period of rainfall, there was sunny weather from 157 to 219 day of the year. In contrast to wheat, during almost the whole vegetation of barley prevailed very wet weather (1995), (Fig.1).

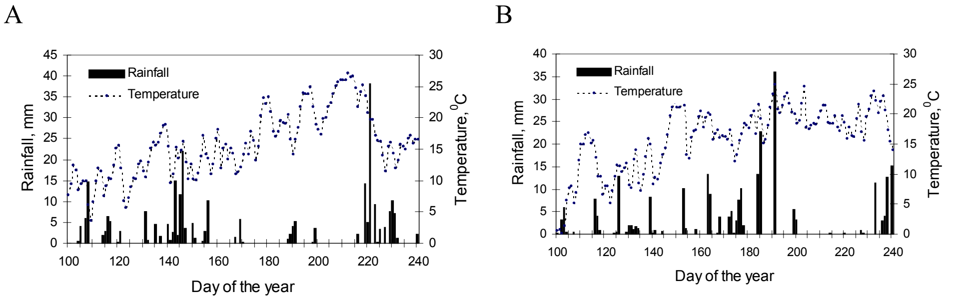


Fig.1. *Distributions of rainfall and average daily temperatures at chosen period of 1994 (A) and 1995 (B), Czesławice.*

Soil parameters

Average values of bulk densities in the upper soil layer (5-10cm) for spring wheat ranged from 1.29 (14 day after sowing) to 1.43 Mg m^{-3} at harvest, and for spring barley from 1.16 (28 days after sowing) to 1.40 Mg m^{-3} at harvest. For whole vegetation period, average bulk density on eroded soils for wheat ranged from 1.32 to 1.43 Mg m^{-3} and for spring barley - from 1.29 to 1.40 mg m^{-3}. For both crops, largest values were found on moderately eroded, and the smallest on very severely eroded soil. Differences were observed from beginning of vegetation and were maintained till harvest. Distribution of average bulk density under spring barley is presented in Figure 2. With increase of soil depth, bulk density increased and was the largest for moderately eroded soil (1.47 Mg m^{-3}) at depth of 25-30cm.

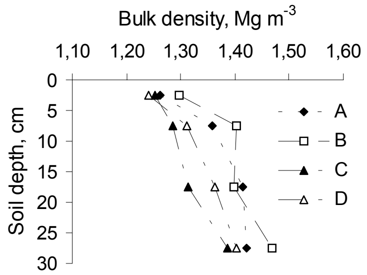


Fig. 2. Bulk density at different soil depth, soil erosion class: A – slightly, B – moderately, C –very severely and D –colluvial (average from 8 measurement terms)

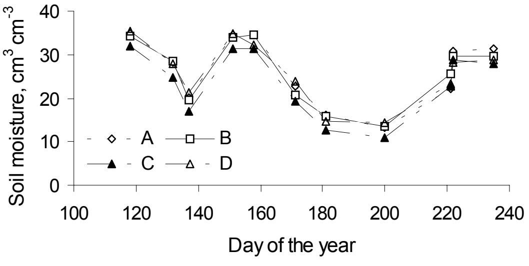
For both crops, soil moisture conditions at the beginning of vegetation were very similar (34 –35% vol.), (Fig. 3). Then, soil moisture content follow the rainfall pattern (Fig. 2). For wheat, soil moisture between 180 and 200 day of the year dropped to 13-15%, and then increased to 24-28%. For barley, soil moisture decreased till 14% in 160 day, then increased to 30% in 180 day, and finally dropped till 12% before harvest.

During spring wheat vegetation, average soil moisture content ranged from 23.5 to 26.2 % and was the smallest for very severely eroded soil. For other soils, average values were very similar. During spring barley vegetation, differences between average values were smaller (20.5-22.1%), and smallest values were found on moderately and very severely eroded soil.

Crop growth and yields

Measurements of plant height and canopy cover showed that in initial phases of growth, plants on soils of various erosion classes were similar (Tables 3 and 4). Canopy cover started to differentiate for spring wheat from 29 and for spring barley from 52 day after sowing. Differences in plant height started to be seen later and appeared from 68 and 67 day after sowing of wheat and barley, respectively. These differences were maintained till harvest. Weakest plant growth was observed on very severely eroded soil, whereas on other soils plant growth was more equal.

Spring wheat



Spring barley

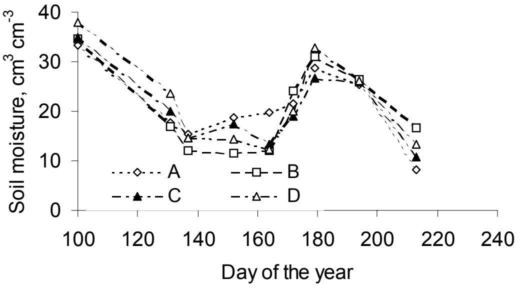


Fig. 3. *Distribution of soil moisture content at 5 cm depth during crop vegetation; soil erosion class: A – slightly, B – moderately, C –very severely and D –colluvial.*

Dry root mass of spring barley in 0-30 cm layer was the largest on colluvial soil (29.4 t ha^{-1}), then on slightly and moderately eroded (28.8 t ha^{-1}), and the smallest on very severely eroded (24.0 t ha^{-1}). Most regular root mass distribution in soil layer 0-30 cm was found in colluvial and slightly eroded soil (Fig. 4). In moderately eroded soil, root mass was concentrated in upper 20 cm (especially in the layer 0-5cm), and was smallest in layer 25-30 cm.

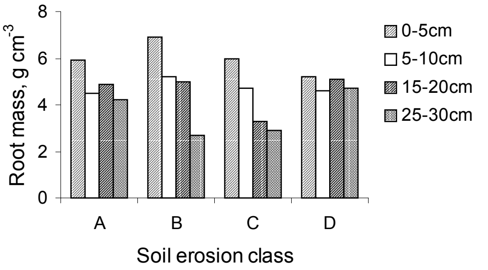


Fig.4. *Root mass of spring barley at different soil depth before harvest (erosion classes: A - slightly; B - moderately, C- very severely eroded, and D- colluvial)*

Table 2. Growth of spring wheat and spring barley on soils of various erosion class (A – slightly, B – moderately, C –very severely eroded and D –colluvial).

Day of the year	Plant heigth, cm						Canopy cover, %					
	A	B	C	D	Avg	std	A	B	C	D	Avg	std
						Spring wheat						
103	0	0	0	0	0	-	0	0	0	0	0	-
118	12.1	12.4	12.5	12.6	12.4	0.22	22.1	22.4	22.8	22	22.3	0.36
132	20.5	20.0	20.3	20.0	20.2	0.24	41.9	47.1	47.2	42.5	44.7	2.84
151	48.2	47.4	45.8	46.2	46.9	1.10	81.6	79.5	75.8	70.1	76.7	5.03
158	62.3	61.5	60.8	61.5	61.5	0.61	86.8	86.3	77.1	76.2	81.6	5.73
171	70.5	68.3	62.8	67.5	67.3	3.26	76.2	79.8	69.2	78.2	75.9	4.67
181	100.1	96.6	89.4	91.5	94.4	4.88	-	-	-	-	-	-
200	102.0	98.4	93.8	96.0	97.5	3.53	72.2	62.0	64.4	68.4	66.7	4.49
221	102.6	98.4	92.0	97.0	97.5	4.37	72.2	62.0	61.5	64.0	64.9	4.98
						Spring barley						
112	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	0.0	-
137	17.4	17.1	16.9	16.2	16.6	0.49	57.9	49.4	50.4	56.0	53.2	3.96
152	33.8	32.8	32.5	34.0	33.3	1.06	70.2	65.7	54.2	69.6	61.9	10.89
164	50.3	52.4	50.1	52.9	51.5	1.94	71.2	58.9	49.5	70.8	60.2	15.06
172	68.9	67.9	65.9	70.3	68.1	3.09	64.6	60.0	49.1	67.1	58.1	12.73
179	74.4	73.3	65.8	74.8	70.3	6.36	61.8	58.1	44.4	61.1	52.8	11.81
194	73.1	73.5	67.3	78.1	72.7	7.69	60.2	56.2	44.0	60.4	52.2	11.60

Abbreviations: avg – average, std – standard deviation

Yields of spring wheat were higher than spring barley by 1.9 t/ha (Table 3). Both, wheat and barley yields were largest on colluvial soil. Yields on slightly eroded soil was 97 and 92%, on moderately eroded – 95 and 83%, and on very severely eroded 84 and 74% of yield on colluvial soil, for wheat and barley, respectively.

Table 3. Yields on loess soil of various erosion classes

Soil erosion class	Yield, Mg ha^{-1}	
	Spring wheat	Spring barley
Slightly eroded	6.01^{cb}	4.09^{bc}
Moderately eroded	5.84^{b}	3.69^{ab}
Very severely eroded	5.21^{a}	3.29^{a}
Colluvial	6.17^{cd}	4.45^{c}

* Numbers for a given soil not followed by the same letter are significantly different at the 5% level

DISCUSSION

Similar crop growth on soils of various erosion class was observed in earlier stages of plant development. Relatively earlier start to differentiate canopy cover. However, due to the fact that analysis of canopy cover were based on photos that were taken in the same place, more valid seemed to be measurements of plant height. Height of both spring wheat and spring barley started to differentiate from 67-68 day after sowing and the differences were maintained till harvest. Period of plant height differentiation corresponded with phenological phase of flowering. This crucial period came on about 170 day of the year for spring wheat and was characterized by sunny weather, whereas this period for spring barley (about 180 day of the year) was characterized by numerous rainfalls. Both, yields of wheat and barley were the highest on colluvial soil and this corresponds well with results obtained by Orlik (1992), Mazur (1996) and Dechnik and Mazur (1996). With loss of topsoil (represented by erosion classes), yields started to decrease. Especially low yields (by 0.8 t/ha in comparison to slightly eroded site) were fund on very severely eroded soil. Plow layer of this soil was formed directly from Cca horizon, and theoretically this soil was thought to have better physical and chemical properties responsible for crop growth in comparison to slightly and moderately eroded soils (Turski et al., 1992; Licznar et al., 1991). Results obtained in this study showed, that during whole vegetation period, bulk density of very severely eroded soil was generally smaller by about 0.1 Mg m^{-3}, and soil moisture content by 2-3% (volumetric) then on other studied soils. Analysis showed also that root mass on very severely eroded soil was much smaller in comparison to other soils. Drop of root mass on very severely eroded soil was observed from 15 cm depth. Similar decrease of root mass was observed also on moderately eroded soil from 25 cm depth, and this corresponded with an increased bulk density (1.47 Mg m^{-3}) at this depth.

CONCLUSIONS

Studies conducted on soils of various erosion class developed from loess showed that:

1. Similar crop growth on soils of various erosion class was observed in earlier stages of plant development. Crop growth of both spring wheat and spring barley started to differentiate phenological phase of flowering and differences were maintained till harvest.
2. Yields of spring wheat and barley were the largest on colluvial soil, then on slightly, moderately and very severely eroded soils.
3. For differentiation of yields seems to be responsible factors deciding on root mass distribution.

REFERENCES

1. Bakker M.M, Govers G., Rounswell M.D.A. 2003. The crop productivity – erosion relationship; an analysis based on experimental work. Catena. 57, 55-76.
2. Becher, H.H., Schwertmann, U., Sturmer, H. 1985. Crop yield reduction due to reduced plant available water caused by water erosion. [in:] Swaify S.A., Moldenhauer W.C. and Lo A. (Eds.) Soil erosion and Conservation , SCSA, Ankeny, Iowa, 365-373.
3. Frye, M.W., Ebelhar, S.A., Murdock, L.W., Blevins, R.L. 1982. Soil erosion effects on properties and productivity of two Kentucky soils. Soil Sci. Soc. Am. J. 46, 1051-1055.
4. Koćmit A., Chudecka J., Podlasinski M., Raczkowski B., Roy M., Tomaszewicz T. 2001. Spatial variability of soil on eroded slope in morain area of West Pomerania. Folia Univ. Agric. Stetin, 217, 97-102.
5. Licznar, M., Drozd, J., Licznar, S.E., 1991. Erosion effect on soil fertility and yielding ability of topogenic soils upon area of lessive soils (in Polish). [in:] Mazur Z., Pałys S., Grodzieński W. (Eds.) Erozja gleb i jej zapobieganie. Akademia Rolnicza w Lublinie, 7-19.
6. Marcinek J. 1994. Extension of accelerated erosion in Great Poland (in Polish). Roczniki AR w Poznaniu, 266, 63-75.
7. Mazur Z. 1996. Crop yields in cofigurated loessial terrain in the light of many-year studies (in Polish). Prace naukowe IUNG, K11/1, Pulawy, 17-27.
8. Mazur Z., Dechnik I., 1996. Plant crops and some chemical properties of soil from eroded terrain in monolith experiment (in Polish). Prace naukowe IUNG, K11/1, Pulawy, 29-38.
9. Orlik T. 1991. Yields of plants in a four-year crop rotation system on eroded loessial soil. [in:] Mazur Z., Pałys S., Grodzieński W. (Eds.) Erozja gleb i jej zapobieganie. Akademia Rolnicza w Lublinie, 205-215.
10. Rejman J., Dębicki R., Paluszek J. 2001. Soil loss and crop yields in eroded loess area under soil conservation practices. [In:] Helming K. (Ed) Multidisciplinary Approaches to soil Conservation Strategies. ZALF Bericht No 47, 53-58, Muencheberg (Germany).
11. Rejman, J., Turski, R., Paluszek, J., 1998. Spatial and temporal variations in erodibility of loess soil. Soil and Tillage Research 46, 61-68.
12. Schertz, D.L., Moldenhauer, W.C., Franzmeier, D.P., Sinclair, H.R.Jr.. 1984. Field evaluation of the effect of soil erosion on crop productivity. [in:] Mc Cool D.K. (Ed.) Erosion and soil productivity, Publication ASAE 8-95, 9-17.
13. Turski, R., Słowińska-Jurkiewicz, A., Paluszek, J., 1992. The effect of erosion on the spatial differentiation of the physical properties of Orthic Luvisols. International Agrophysics 6, 123-136.

SOIL AGGREGATES STABILITY IN RELATION TO PLANT GROWTH

Shein E.V.

INTRODUCTION

It is well known that physical properties have the optimal diapasons for plant growth. For instance, the optimal diapason for soil density in clay soils ranges from 1.10 to 1.30 g/cm^3. This optimal diapason of soil density is commonly used for soil-plant conditions estimation. The optimal ranges are also known for agronomically valuable aggregates (with diameters from 0.25 to 10 mm) of which contribution should be higher than 40% (Vadiunina, Korchagina, 1986). Special experiments conducted by Medvedev and Lyndina (2004) showed that the optimal aggregate size is from 2 to 5 and from 2 to 0.25 mm. They give an insight into the importance of the fraction with aggregate size less than 5 mm and associate this with more effective nutrient movement towards plant roots. Moreover, a soil under lower moistened conditions should rather consist of smaller aggregates (2 to 0.25 mm), than under humid, well-moistened conditions. However, the major issues are: why does the range of density differ in clay and sand soils (Fig.1 demonstrates that the optimal interval of density in clay soils stretches from 1.0 to 1.3 g/cm^3, but in sandy soils – from 1.2 to 1.6 g/cm^3) and why the optimal range of aggregate size is shifted from greater diameters (2-5 mm) to smaller ones (1-2 mm) in more dry conditions as experiments of Medvedev and Lyndina demonstrated).

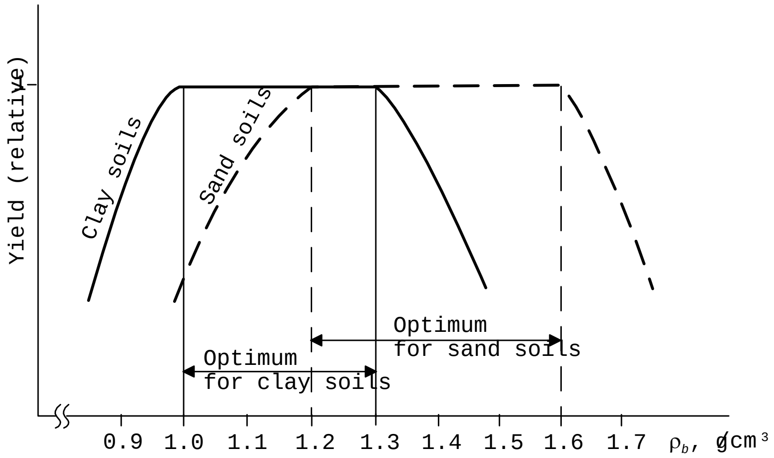


Fig.1. *The schematic sketch of soil bulk density (ρb, g/cm3) influence on relative yield on soils different in texture.*

The main reason is that the fundamental physical properties (soil density, aggregate distribution, etc.) provide optimal soil water-air regimes and normal functioning of soil-plant system. Thus, the optimal aggregate size domination along with the interval of soil density are used as the conditions of favorable water-air regime, which parameters are well understood: air content must be over 10% by volume, and soil water content must range from field capacity to 70% of the field capacity. In these conditions, nutrients are available in soils and plant roots are capable to absorb nutrients and water. For instance, shortage of water is the primary factor, because sandy soils have low water retention. In this case, water retention increase is connected with bulk density growth: more dense sandy soils contain can improve water supply for plants. The optimal range of sandy soil density lies between 1.2–1.6 g/cm^3 in contrast to 1.0-1.3 g/cm^3 in clay soils. And the difference between optimal aggregate size in dry and moist soils can be explained by the fact that in dry conditions, smaller aggregates are important for water retention, though in humid ones a greater portion of larger aggregates is appropriate inasmuch as they intense water drainage and provide optimal aeration.

Yet we must find the answer to the next question of what soil properties play affect mostly optimum bulk density and aggregate size. mentioned above. To our mind, these properties are the aggregate stability, the stability soil aggregates in water and mechanical stability of the loosened arable layer.. Soil organic matter plays a key role in aggregate formation. However, some aspects of soil structure formation and steady functioning, related primarily to the specific nature of soil organic matter, should be specified.

Physicochemical and biological activity of soil organic substances is determined by more than 40 parameters. One of the major humus substances (HS) properties is their relation to water, since the water-organic-mineral interactions serve the corner stone of stable aggregate formation and functioning. This work represents the results of soil HS amphiphilous (hydrophobic-hydrophilic) components heterogeneity.

The main tasks of this work are: (1) to investigate the hydrophobic-hydrophilic components content in soil aggregate of different stability and genesis; (2) to study the conditions of amphiphilic HS formation and (3) to formulate the hypothetic physical model of hydrophobic-hydrophilic components influence on stable soil aggregate formation.

MATERIALS AND METHODS

Method of hydrophobic fractioning was used to separate hydrophobic and hydrophilic components of HS. HS were isolated from mineral soil horizons by the 0.1M $Na_4P_2O_7$ + 0.1N NaOH solution at the soil:solution ratio 1:10. The extract of HS was purified from mineral impurities by centrifugation (8000 rpm; 15 min) and filtration through a 0.45-µm membrane filter. Hydrophobic interaction chromatography was operated on Octyl-Sepharose CL-4b (Pharmacia). The sample volume was 100 ml; filtration rate was 1 ml/min; effluent was monitored at 280 nm; a 1 x 10 cm column was used. First fraction was eluted from column in the flow of the start buffer (pH 8.0, 0.05 M TRIS/HCl buffer with 2M $(NH_4)_2SO_4$), second fraction – on the background of negative gradient (2M-0) $(NH_4)_2SO_4$, third – by the flow of pure 0.05 M TRIS/HCl buffer, forth and fifth fractions - 0.05 MTRIS/HCl with 0.4% SDS. The gradient elution was supplemented with the elution of the last fraction with a 0.2N NaOH + 5 mM EDTA solution. The first two fractions (fractions 1 and 2) eluted from the column in the presence of ammonium sulfate had predominantly hydrophilic properties (we shall name them hydrophilic fractions), and the following fractions (fractions 3, 4, 5 and 6) were hydrophobic. We also have investigated the HS from the aggregate fraction <0.25 mm and water-stable fractions (after wet sieving) 0.5-1.0, 1.0-2.0 and 2.0-3.0 mm of horizon A (10-15 cm) of the ordinary loamy chernozem, unmown steppe (Kamennaya Steppe, Voronezh region). Humic (C_{HA}) and fulvic (C_{FA}) acids content was determined by the traditional method and ration (C_{HA}:C_{FA}) was estimated (Orlov, Grishina, 1981).

We have also investigated the aggregate stability by sieving in water – a traditional method of soil physics (Vadiunina, Korchagina, 1986). Soils of different types were analysed: pale-high-podzolic soil, ordinary chernozem, red ferralitic soils, etc.

RESULTS AND DISCUSSION

Table 1 lists the relative content of chromatographic fractions. In soils of humid areas (in boreal climatic conditions) with very weak soil aggregate structure, HS compose a multi-component system of hydrophobic and more hydrophilic compounds. In chernozems and dark chestnut soil an increase of hydrophobic fractions relative content was observed in the humus-accumulative horizons. In these horizons, soil structure is characterized by grainy aggregate composition and high water stability. This indicates that the increase of hydrophobic substances intensifies formation of grainy aggregate composition. We should note that soil aggregate stability does not correspond with C_{HA}:C_{FA} ratio universally: in red ferralitic soils with high soil aggregate stability this ratio is not sizeable, though the hydrophobic components are marked in HS there.

To set off the role of hydrophobic soil organic components from other HS components and to find out the significance of hydrophobic HS in water stability of aggregates, the HS composition of the stable and instable soil aggregates from ordinary chernozem was analyzed. Table 2 presents amphiphilic composition (hydrophilic and hydrophobic components) of aggregates from ordinary chernozem. Though HS from water unstable aggregate fraction <0.25 contains near 50% of hydrophilic components, HS from water stable aggregates consist of hydrophobic components essentially (55.2-57% of HS fractions 3-6). This indicates that the proportion of hydrophobic components in water stable aggregates is augmented. Hence, it has been proposed that HS hydrophobic components provide more effective stability of soil aggregates. These components, generated and remained stationary in soil profile, form the hydrophobic surfaces of soil mineral particles.

Table 1. Relative content of chromatographic and other HS fractions (Milanovskii, Shein, 2002)

Soil type/ Horizon/ Depth, cm	Granular organization and stability of aggregates ↓	HS fractions, relative % Hydrophobicity increase →						C_{HA}: C_{FA}
		1	2	3	4	5	6	
Pale-strongly-podzolic soil/ A2/ 0-12		100	0	0	0	0	0	0.66
Ordinary chernozem/ A1/ 0-20		24	16	29	27	3	1	Not det.
Dark chestnut soil/ A1/ 10-25		25	7	20	37	3	8	2.20
Red ferralitic soil/ $A1_1$/ 0-10		39	21	17	19	1	3	0.72

Table 2. Relative content of amphiphilic HS components in aggregate fractions of chernozem

Aggregate fraction, mm	Carbon, %	HS fractions, % Hydrophobicity increase →					
		1	2	3	4	5	6
<0.25	5.06	33.21	17.43	12.75	9.10	25.64	2.48
		50.64		49.36			
0.5-1.0	5.02	28.9	15.9	14.66	10.43	27.63	2.49
		44.80		55.20			
1.0-2.0	4.98	27.37	15.09	14.83	10.6	27.88	4.22
		42.49		57.51			
2.0-3.0	5.14	28.56	16.23	14.19	9.26	28.82	2.94
		44.79		55.21			

As a rule, HS amphiphilic molecules consist of hydrophilic and hydrophobic components. In the presence of water, hydrophilic compounds are connected with soil mineral surfaces, which are also hydrophilic. Thus, these polarized mineral and organic compounds form a stable linkage. At the same time, another part of the same HS molecule, the hydrophobic one, forms the stable hydrophobic linkage to the same part of another molecule. This gives us the possibility to propose the hypothetic model of soil stable aggregate formation under influence of amphiphilic (with hydrophilic and hydrophobic compounds) HS (Fig.2).

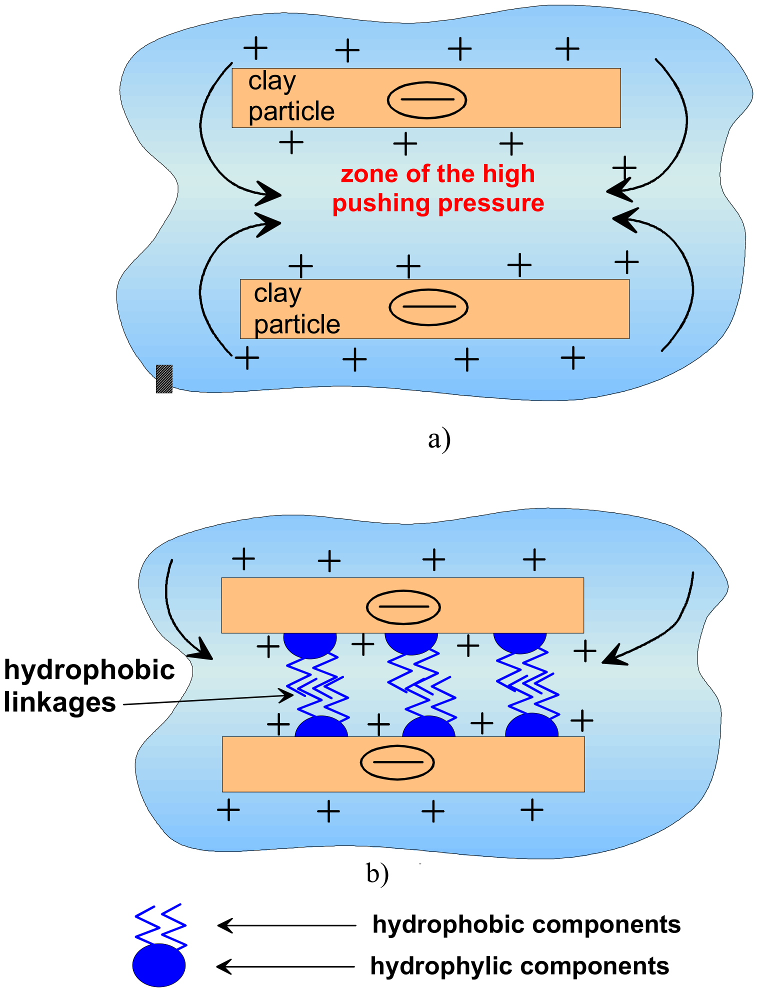


Fig.2. *The schematic sketch of stable aggregate formation due to amphiphilic humus components.*

In the absence of amphiphilic HS soil mineral particles are repelled from each other. This process is caused by the influence of exchangeable cations on soil mineral particles. Heightened osmotic pressure between the particles provokes water movement into interparticle space, and mineral particles become repelled. The process of interparticle repulsion takes place because of heightened water pressure between soil mineral particles (Fig.2, a). Water pressure increase occurs in the condition of capillary and film soil water capable to move and enter into interparticle space. As a result, this aggregate with two mineral particles is unstable. To the contrary, if the amphiphilic molecules of HS present in interparticle space, polarized parts (hydrophilic) are combined readily with hydrophilic surface of soil mineral particles (Fig.2, b). At the same time the hydrophobic parts of HS molecules form chemical hydrophobic combinations with each other. New energy connections, holding particles together, are formed. These connections of hydrophobic organic nature provide both water and, presumably, mechanical stability of soil aggregate. That kind of aggregates provides the wide range of optimal water-air conditions in soil as the basic factor for plant growth.

CONCLUSIONS

1. The optimal soil water-air regime is the major requirement for plant growth. The main factor supporting this optimal regime is a soil structure with granular water-stable aggregates.
2. Amphiphility of humus substances is one of the most important properties of humus, which can explain the contradictory results in the role of organic matter in aggregate stability. Water stability and granular quality is connected with the presence of hydrophobic and hydrophilic components.
3. A possible mechanism of aggregate water stability related to soil organic matter is elucidated: hydrophobic ends of amphiphilic substances are directed to interpolar space of clay minerals, which favors their linking and decreases the disjoining pressure of water, which would decompose soil aggregates in the absence of a hydrophobic surface.

Acknowledgement
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REFERENCES

1. Medvedev V.V., Lyndina T.E. 2004. Mathematical planning in experiments of “soil-fertilizer-yield” interactions. International Agrophysics, Vol.18, pp.31-39.
2. Milanovskii E.Yu., Shein E.V. 2002. Functional role of amphiphilic humus components in soil structure formation and soil genesis. Eurasian Soil Science, Vol.35, pp.1064-1075.
3. Orlov D.S., Grishina L.A. 1981. Laboratory manual on humus chemistry. Moscow: Moscow State Univ. Press (in Russ.).
4. Vadiunina A.F., Korchagina Z.A. 1986. Methods of investigation of soil physical properties. Moscow, Agropromizdat (in Russ.).

DIELECTRIC PROPERTIES OF AGRICULTURAL MATERIALS

Skierucha W., Wilczek A., Walczak R.T.

INRTODUCTION

Real-time and non-invasive monitoring of physical and chemical properties of agrophysical objects, i.e. food products and agricultural materials, as well as the environment of their growth, storage and transportation is necessary to improve quality as well as quantity of agricultural production and to minimize the loss. The development of technology in the recent years has increased the number of methods and decreased the price of monitoring tools for application in Agrophysics. Data transmission facilities, accurate and battery operated converters of physical and chemical properties into electrical signals and measurements in high frequency range are a few examples of the observed progress. The use of dielectric spectroscopy, the technique for measuring dielectric properties of materials in radio (RF) and microwave (MW) frequency ranges in application to agrophysical monitoring is the subject of the study.

Application of dielectric spectroscopy for agricultural materials is aimed to identify relationships between their dielectric properties and important quality characteristics and to develop scientific principles for measuring these characteristics through interaction of radio frequency and microwave electromagnetic fields with the materials and products. Other areas of application of microwaves in agriculture are (Venkatesh and Raghavan, 2004): microwave heating and drying (microwave ovens), microwave aquametry as an effective tool for non-destructive moisture sensing, insect control, seed germination and sterilization of food products.

Dielectric spectroscopy has some advantages over other physicochemical measurements: sample preparation is relatively simple, varieties of sample size and shapes can be measured, measurement conditions can be varied under a wide range of temperatures, humidities, pressures, etc., the technique is extremely broad band (mHz - GHz) thus enabling the investigation of diverse processes, over wide ranges of time and scale.

BASIC THEORY

As the wave enters from one medium, e.g. free space or a coaxial cable, to another, e.g. soil or other agricultural material, a part of its energy of is reflected from the material and the rest is transmitted through it. This is due to the difference of the velocity of travel of electromagnetic waves in different media. If the material is lossy there will be attenuation or insertion loss acsoss the material.

The fundamental electrical property through which the interactions between the applied electric field and the material are described is the complex relative permittivity of the material ε^*:

$$\varepsilon^{*} = \varepsilon' - j\varepsilon'' \tag{1}$$

where *ε'* is the dielectric constant and *ε''* is the dielectric loss factor, *j* is an imaginary unit. Dielectric material has an arrangement of electric charge carriers that can be displaced or polarized in the external electric field. There are different polarization mechanisms in a material and each has a characteristic resonant frequency or relaxation frequency. As the frequency increases the slower mechanisms do not contribute in the overall *ε'*. The loss factor *ε''* will correspondingly have a local maximum at each critical frequency (Fig. 1).

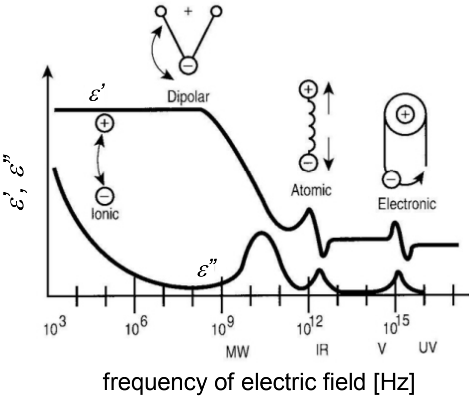

Fig. 1. *Frequency response of dielectric mechanisms (HP AN 1217-1); MW, IR V and UV are respectively microwave, infrared, visible and ultraviolet spectrum*

There are different mechanisms of polarization of charge carriers in a material: electronic polarization, atomic, orientation and ionic polarizations. Water is an example of a substance with strong orientation polarization. Ionic conductivity, σ [S/m], present at low frequencies only introduces losses into a material and the measured loss of material can be expressed as a function both the dielectric loss, ε_d'' and conductivity, σ:

$$\varepsilon'' = \varepsilon_d'' + \frac{\sigma}{2\pi f \varepsilon_0} \tag{2}$$

where f is the frequency of the applied electric field, ε_0 is the dielectric permittivity of free space.

Because water is present in all agricultural materials and its influence on the majority of agricultural properties is dominant, the specific property of water causing the orientation polarization is of primary area of interest of dielectric spectroscopy (Kraszewski, 2001).

DETERMINATION OF MOISTURE OF AGRICULTURAL MATERIALS

The Cole-Cole equation models the permittivity of free water and other polar substances:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \left(j\omega\tau_{rel}\right)^{1-\alpha}} \tag{3}$$

where: ε_∞ is the relative high frequency permittivity, ε_s is the relative static permittivity and $\tau_{rel} = 1/f_{rel}$ is the relaxation time (inverse of relaxation frequency f_{rel}) of orientation polarization defined as the time at which the permittivity equals $(\varepsilon_s + \varepsilon_\infty)/2$, α is an experimental correction (Blackham and Pollard, 1997).

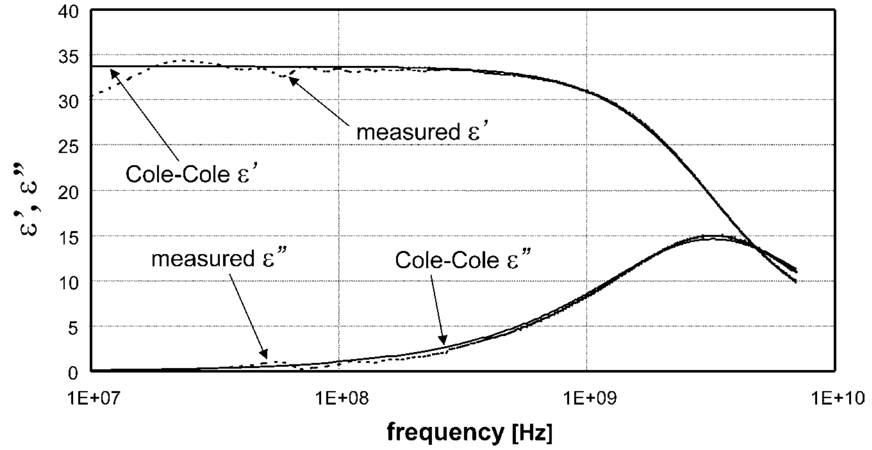

Fig. 2. *Frequency change of real and imaginary parts of the complex dielectric permittivity of methanol for Cole-Cole modelled data and measured using open-ended coaxial probe*

The comparison of measured and the modelled data of complex dielectric permittivity of methanol is presented in Fig. 2. The measured data were collected by the 20 kHz – 8 GHz Rohde&Schwarz ZVCE Vector Network Analyzer (VNA) using an open–ended coaxial probe method (Stuchly and Stuchly, 1980; Blackham and Pollard, 1997). It enables to calculate, on the base of the measured S_{11} parameter, the complex reflection coefficient and the complex admittance at the end of the probe. The values of $\varepsilon_\infty, \varepsilon_s, \tau_{rel}$ and α are 4.45, 33.7, 4.95×10^{-11}s and 0.036, respectively.

There are numerous methods for the determination of the real and imaginary values of the complex dielectric permittivity of materials (Ryynänen, 1995). The further discussion will concentrate on two of them: open-ended coaxial probe and time domain reflectometry methods.

OPEN-ENDED COAXIAL PROBE METHOD

Fundamental to use the open-ended coaxial probe (Fig. 3) is an accurate model relating the reflection coefficient at its end to the permittivity of the material contacting with the probe. The model used in the presented example is the lumped capacitance circuit model (Stuchly and Stuchly, 1980).

To determine the complex dielectric permittivity of the material, ε^*, it is necessary to perform calibration and application of appropriate model of the probe.

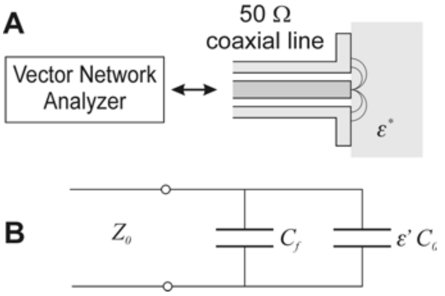

Fig. 3. *A. Open-ended coaxial probe in the form of coaxial line open to the space with material of unknown dielectric permittivity ε^*, B. Modelling the discontinuity of electromagnetic field by lumped capacitance C_f and C_0*

The applied lumped capacitance model of the probe assumes the presence of capacitance at the end of the probe. Its value depends on the complex dielectric permittivity of the material the probe was pressed to (Fig. 3). The complex value of the admittance of the probe end, Y_L^*, is:

$$Y_L^* = j\omega C_f + j\omega C_0\varepsilon^* = j\omega(C_f + C_0\varepsilon') + \omega C_0\varepsilon'' \qquad (4)$$

where C_f represents the part of admittance that is independent from the dielectric sample, C_0 is a part of admittance for air as dielectric.

Before performing measurements on unknown materials the open-ended coaxial probe should be calibrated on media with known dielectrical properties, usually distilled water, methanol or air to find the values of C_f and C_0.

The described measurement method and the lumped capacitance model were verified by measuring the dielectric permittivity of teflon. It was found that the C_f value is negligible and C_0 calculated from (4) equals to the C_0 coefficient of the correction polynomial obtained during calibration. Consequently the model (4) may be simplified to:

$$Y_L^* = \omega\, C_0\varepsilon^* = j\omega\, C_0\varepsilon' + \omega\, C_0\varepsilon'' \qquad (5)$$

The value of C_0 describes the geometry of the probe and the frequency range of its application. The bigger its value, the larger dimensions it has and the better accuracy in applications for the materials of small values of dielectric permittivity, and simultaneously the high frequency range of measurement is limited. This limitation comes from the fact that in case of materials of high dielectric permittivity and at high frequencies, the changes of the dielectric permittivity of the material causes very small changes of the phase shift of the reflection coefficient. This drastically decreases the accuracy of measurement and the need to apply calibration media of small value of dielectric permittivity.

TIME DOMAIN REFLECTOMETRY METHOD

Time Domain Reflectometry method for the determination of dielectric permittivity is widely accepted method, especially for soil moisture determination (Topp et al., 1980; Malicki and Skierucha, 1989; Malicki and Walczak, 1999), for its advantages: simplicity of operation, accuracy and fast response, usually does not need calibration, is non-destructive, portable systems are available, is able to automatize and multiplex probes. The applied frequency in Time Domain Reflectometry (TDR) method is not exactly defined as it can be done for Frequency Domain Reflectometry (FDR) represented by open-ended coaxial probe method. The application of a step pulse or a needle pulse of very short rise time, t_r, corresponds to the frequency range with the upper limit, $f_{\max}$, that can be calculated by the following engineering formula (Strickland, 1970):

$$t_r = 0.35 f_{\max}^{-1} \tag{6}$$

For example: to accomplish the condition $f_{max} > f_{prog}$ = 1.75 GHz the required rise time, t_r, of the pulse should be not longer than 200 ps. The probe in TDR method is a waveguide consisting of two or three parallel metal rods inserted into the tested medium. The velocity of propagation of the pulse in this waveguide, v, is modified by the dielectric permittivity of the waveguide surroundings. In calculations it is usually assumed that the dielectric loss of the material does not influence the velocity of propagation of the pulse. The real part of the medium complex dielectric permittivity, the dielectric constant, is the indicator of its moisture, θ. For the probe length L, the bulk dielectric constant of the material, ε_b, and indirectly its moisture can be calculated using the following relation (Malicki and Skierucha, 1989):

$$v = \frac{2L}{t} = \frac{c}{\sqrt{\varepsilon_b}} \qquad \Rightarrow \qquad \varepsilon_b(\theta) = \left(\frac{c}{2L}t\right)^2 \tag{7}$$

where: t is the measured time the pulse covers the distance $2L$, c is the velocity of light in free space.

Lossy media attenuate the TDR reflected pulse and this makes the method practically useless for electrical permittivity of materials exceeding 4 dS/m.

The relations between the bulk dielectric permittivity, ε_b, of different types of soil, grain as well as wood and moisture, θ, determined by gravimetric method is presented in Fig. 4. These relations are calibrations of the method for individual materials. Generally all selected materials have different calibrations, although when the highest accuracy is not required there might be one calibration applied for a group of materials, as it is presented for soil.

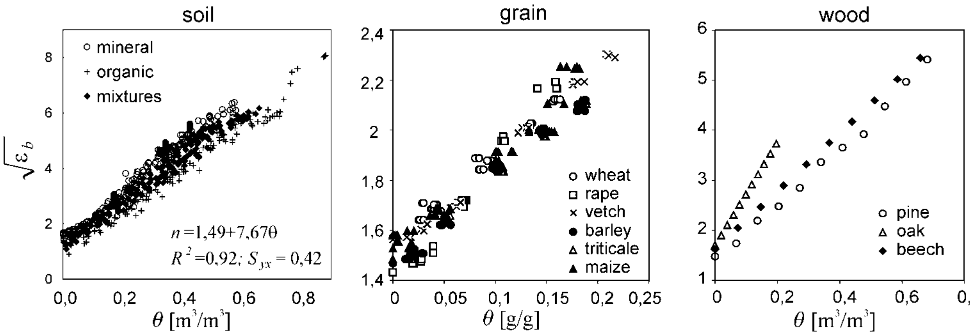

Fig. 4. *Relation between the bulk dielectric permittivity, ε_b, of different types of soil, grain as well as wood and material moisture, θ, determined gravimetrically*

The parallel waveguide can have the length ranging from 5 cm to 50 cm or more and the tested material constitutes its propagation medium, therefore as opposite to the open-ended coaxial method, the propagation velocity is an average along the probe rods and the volume of measurement is much larger. For small samples of material or in cases when it is not possible to insert the rods into it, the open-ended coax method is more suitable.

The frequency of the measured ε_b is not precisely defined, as it is a superposition of sinusoidal waves making the final step or needle pulse. Also, for the frequencies in the range 05-1.5 GHz the real and imaginary parts of the dielectric permittivity do not change for the majority of agricultural materials. In the case of the open-ended coaxial probe the user has the whole frequency spectrum for analysis.

CONCLUSIONS

- Dielectric spectroscopy is increasingly being recognised as a tool for materials characterisation and has advantages, which could be of particular benefit in the characterisation, manufacture and quality control of agricultural materials.
- Open-ended coaxial probe and time-domain reflectometry methods are universal tools of dielectric spectroscopy for the measurement of dielectric properties of agricultural materials.
- The open-ended coaxial probe and time-domain reflectometry methods need further developments in the field of modelling (to provide models of tested media and identify the measured quantities with indicators of material properties) and hardware (to decrease the price of the meters).
- The work on standardization of these methods for the application in aquametry is required by research and industry.

REFERENCES

1. Blackham D.V. and Pollard R.D., 1997. An Improved Technique for Permittivity Measurements Using a Coaxial Probe. IEEE Trans. Instr. Meas., 46(5), 1093-1099.
2. HP AN 1217-1: Basics of measuring the dielectric properties of materials.
3. Kraszewski A., 2001. Microwave aquametry: An Effective Tool for Non-destructive Moisture Sensing. Subsurface Sensing Technologies and Applications, vol. 2(4), 347-362.
4. Malicki M.A. and Skierucha W., 1989. A manually controlled TDR soil moisture meter operating with 300 ps rise-time needle pulse. Irrigation Science. 10:153-163.
5. Malicki M.A. and Walczak R.T., 1999. Evaluating soil salinity status from bulk electrical conductivity and permittivity. European Journal of Soil Science, 505-514.
6. Nelson S.O., Trabelsi S., Kraszewski A.W., 2001. RF Sensing of Grain and Seed Moisture Content. IEEE Sensors Journal, vol. 1(2), 119-126.
7. Ryynänen R., 1995. The Electromagnetic Properties of Food Materials: A review of the Basic Principles. Journal of Food Engineering, 16, 409-429.
8. Strickland J.A., 1970. Time-Domain Reflectometry measurements. Tektronix Inc. Beaverton, Oregon 97005.
9. Stuchly M.A. and Stuchly S.S., 1980. Coaxial Line Reflection Method for Measuring Dielectric Properties of Biological Substances at Radio and Microwave Frequencies - A Review. IEEE Trans. Instr. Meas., IM-29(3), 176-183.
10. Topp G.C., Davis J.L., Annan A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research. 16:574-582.
11. Venkatesh M.S. and Raghavan G.S.V., 2004. An Overview of Microwave Processing and Dielectric Properties of Agri-food Materials. Biosystems Engineering, 88(1), 1-18.

MEASUREMENT AND MODELING OF THE SOIL HYDROPHYSICAL CHARACTERISTICS

Sławiński C., Walczak R. T., Witkowska-Walczak B.

INTRODUCTION

Soil hydrophysical characteristics: pF curve, saturated hydraulic conductivity and unsaturated hydraulic conductivity plays a key role in creation of plant growth conditions. They determined water availability for plant root system and water movement with chemicals to the deeper layers of soil profile. The knowledge of soil water hydrophysical characteristics is necessary for the study of some processes in the soil such as infiltration, drainage, solute movement and water availability for plants as well as for a description and prediction of water and solute transport processes, to quantify the effects of a land use and soil management on the soil structure related processes. The spatial distribution of water characteristics in the soil is also an important factor in the investigations of plant cover and hydrological changes caused by climate change. Also most of the models of water movement in soil profile use the moisture retention curve, coefficient of saturated hydraulic conductivity and the relationship between coefficient of unsaturated hydraulic conductivity and soil water contents or soil water potential. For this reason, important efforts are therefore being undertaken to elaborate and develop methods and models for soil water characteristics determination.

Determination of soil water retention curve and hydraulic conductivity

Static retention curve

The dependence between soil water potential and soil water content, called the soil water retention curve (Fig. 1), is a basic hydrophysical soil property.

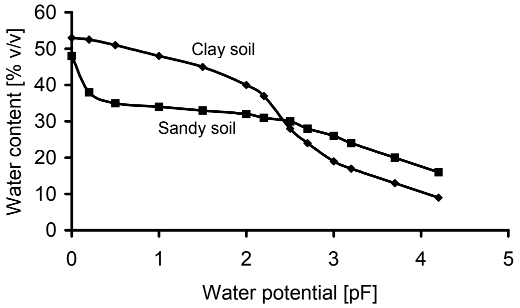

Fig. 1. *Static retention curves*

The static soil water retention curve is determined in Richards chambers or on the sandy-gypsum blocks. It is determined for the state of thermodynamic equilibrium which is obtained after the specific time.

Hydraulic conductivity coefficient and dynamic retention curve

Unsaturated hydraulic conductivity is one of the most important physical soil characteristics. Applying TDR techniques [1, 2] and the instantaneous profile method (IPM) the measurement of hydraulic conductivity coefficient $k(\psi)$ and also dynamic retention curve $\theta(\psi)$ has become much faster and effective. It was demonstrated, that this method gives accurate results for various initial and boundary conditions applied to the soil sample. The instantaneous profile method (IPM) rest on simultaneously measurements of water content and water potential dynamic in the process of drying or wetting the soil column (Fig. 2, 3).

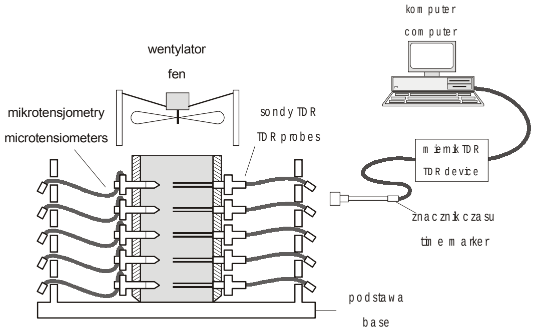

***Fig. 2** TDR set-up for water content and water potential dynamic measurements*

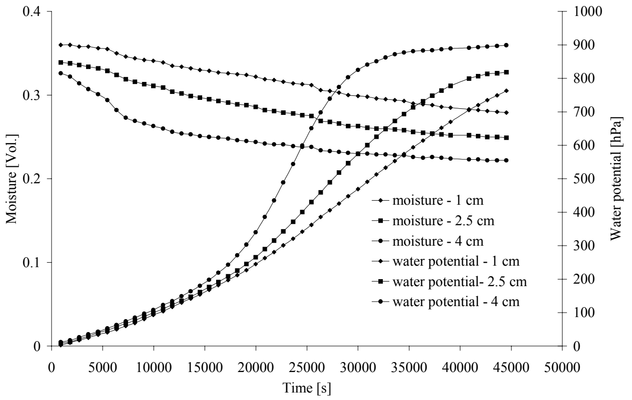

***Fig. 3** Water content and water potential dynamic in soil column (evaporation process)*

Assuming that the process of water transport takes place under isothermal conditions and is one-dimensional, the Darcy's low is valid for the proposed experimental conditions. The water flow can be described with the use of the following equation:

$$q(z,t) = -k(\psi)\left(\frac{\partial \psi(z,t)}{\partial z} - 1\right) \qquad (1)$$

Alternatively the flux can be calculated from the equation:

$$q(z,t) = -\int_{z=z_0}^{z} \frac{\partial \theta(z,t)}{\partial t} dz \qquad (2)$$

Comparing these equations it is possible to calculate the hydraulic conductivity *k(ψ)* from the equation:

$$k(\psi) = \frac{\int_{z=z_0}^{z} \frac{\partial \theta(z,t)}{\partial t} dz}{\left(\frac{\partial \psi(z,t)}{\partial z} - 1\right)} \qquad (3)$$

Using this method it is possible to determine relationship between hydraulic conductivity coefficient and water potential (Fig. 4) and so called dynamic retention curve (Fig. 5).

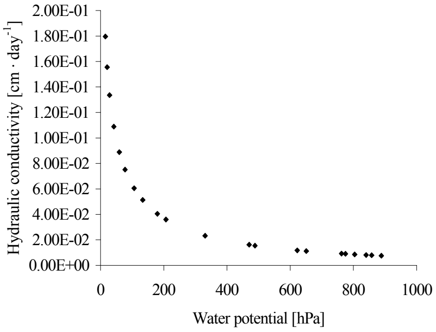

Fig.4. *Hydraulic conductivity coefficient as a function of water potential*

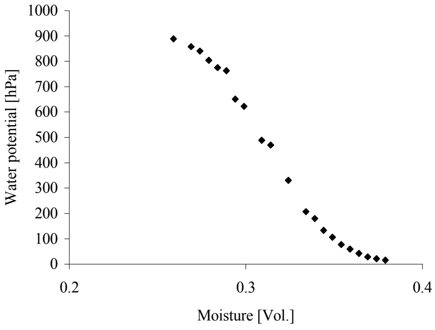

Fig. 5. *Dynamic retention curve*

Estimation of the hydrophysical characteristics on the base of physical parameters of soil structure

Retention curve

In the Institute of Agrophysics, Polish Academy of Sciences, a database of hydrophysical properties of Polish arable soils was created [5], containing, between others, the information about physical properties of the soils, the water retention curves and the values of water conductivity coefficients under different values of soil water potential. Therefore, a possibility was created to study the impact of chosen soil physical parameters on the value of the water content and water conductivity coefficient under chosen soil water potential values.

The measurements of the water retention curve and the water conductivity coefficient in saturated and unsaturated zones are time and labor consuming and require a specific instrumentation. Therefore, a general tendency exists to evaluate those characteristics with acceptable accuracy with the use of elaborated physical, mathematical and statistical models and algorithms. The investigations, performed in this direction have resulted in creation of numerous models and algorithms, which enable to evaluate the water retention curve and the values of the coefficient of water conductivity. A large group of these models are pedotransfer functions. Therefore in the Institute of Agrophysics PAS in Lublin, the model of retention curve was elaborated, based on the following equations of multiple regression [4]:

$$\theta_p = b_0 + b_1 Y_1 + b_2 Y_2 + b_3 Y_3 \qquad (4)$$

for water potential values in the range from pF 0 to pF 2.7 (0.98-490 hPa) and

$$\theta_p = b_0 + b_1 Y_1 \qquad (5)$$

for the water potential values higher then pF 2.7 (490 hPa), where: θ_p is the predicted water content [g g^{-1}], Y_1 - the specific surface area [$m^2 g^{-1}$], Y_2 - the mean weight diameter of particles [mm], Y_3 - the bulk density [g cm^{-3}] and the parameters b_0, b_1, b_2, b_3 are the regression coefficients. Elaborated model was validated using Obtained correlation coefficient for validation of this model (Fig. 6.) is R = 0.87.

Hydraulic conductivity coefficient

The impact of chosen soil physical parameters on the value of the water conductivity coefficient under chosen soil water potential values was investigated [3]. The following values of the soil water potential were taken for the statistical analysis and the respective pF values: pF 0 (0.98 hPa); pF 1 (9.8 hPa); pF 1,5 (31 hPa); pF 2 (98 hPa); pF 2,2(155 hPa); pF 2,5 (310 hPa); pF 2,7 (490 hPa) ;pF 3 (980 hPa).

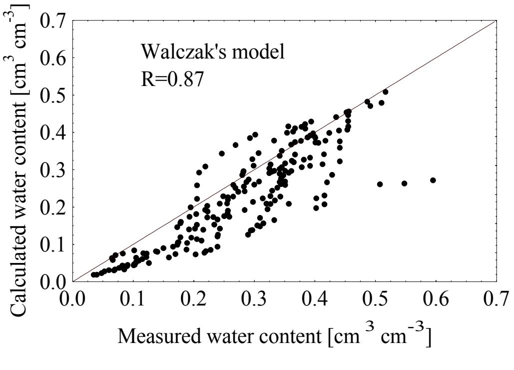

Fig. 6. *Validation of the model: measured and calculated water content*

The investigations were performed for 290 soil profiles selected from the Bank of Samples of the Mineral Arable Polish Soils.The performed analysis of the segmental regression for the logarithms of the coefficient of water conductivity showed that for the regression equations with the following set of parameters: the percentage content of clay – F_{clay}, the percentage content of sand – F_{sand}, the specific surface area- S_{BET}, the percentage content of organic carbon - C_{org}, the content of gravitational water – W_G and the water content under the potential corresponding with the field water capacity - FWC, the values of correlation coefficient $0.81 \le R \le 0.85$ were obtained. The relatively high correlation coefficients caused that this model was used for particular soil textures. The correlation coefficient values within the range $0.86 \le R \le 0.96$ were obtained for the following set of parameters: the percentage content of clay- F_{clay}, the percentage content of sand – F_{sand}, the specific surface - S_{BET}, the percentage content of organic carbon - C_{org}, the content of gravitational water – W_G and the water content under the potential corresponding with the field water capacity – FWC. The general form of this model's equation is:

$$\begin{aligned} LogK &= A(a_0 + a_1 F_{clay} + a_2 F_{sand} + a_3 S_{BET} \\ &+ a_4 C_{org} + a_5 W_G + a_6 FWC) + \\ &B(b_0 + b_1 F_{clay} + b_2 F_{sand} + b_3 S_{BET} \\ &+ b_4 C_{org} + b_5 W_G + b_6 FWC \end{aligned} \tag{6}$$

where: $A=1$and $B=0$ for $LogK \le PP$ as well as $A=0$ and $B=1$ for $LogK > PP$, PP is the point of break.

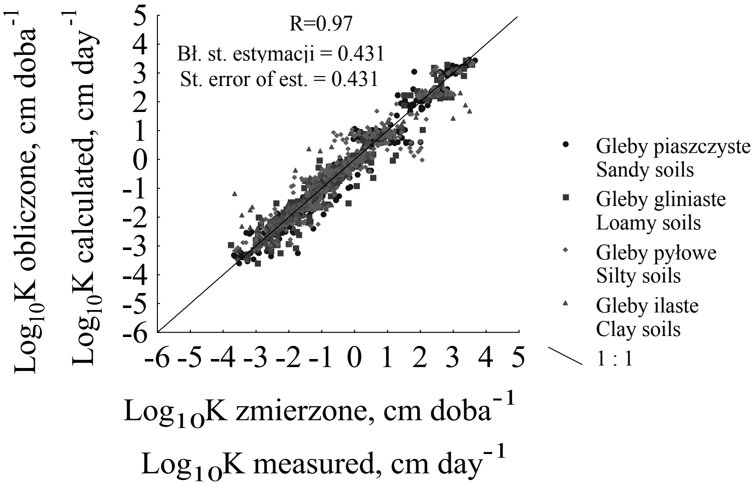

Fig. 7. *Validation of the model: measured and calculated values of logarithm of hydraulic conductivity coefficient*

Obtained correlation coefficient for validation of this model (Fig. 7.) is R = 0.97.

REFERENCES

1. Malicki M.A., Skierucha W. 1989. A manually controlled TDR soil moisture meter operating with 300ps rise-time needle pulse. Irrig Sci 10:153
2. Malicki M.A., R. Plagge, M. Renger, R. T. Walczak. 1992. Application of time-domain reflectometry (TDR) soil moisture miniprobe for the determination of unsaturated soil water characteristics from undisturbed soil cores. Irrig. Sci. 13:65-72
3. Sławiński C. 2003. The influence of soil physical parameters on values of hydraulic conductivity coefficient, Acta Agrophysica, 90, (in Polish).
4. Walczak R., Witkowska-Walczak B., Sławiński C. 2002. Comparison of correlation models for the estimation of the water retention characteristics of soil. Int. Agrophysics, 16, 79-82
5. Walczak R., Ostrowski J., Witkowska-Walczak B., Sławiński C. 2002, Hydrophysical characteristics of Polish mineral soils, Acta Agrophysica, 79, 3 (in Polish)

SOLUBILITY OF CADMIUM IN ERODED LOESS SOILS

Stępniewska Z., Gliński P., Gliński J.

INTRODUCTION

Heavy metals originated from natural (minerals and rocks) or from human activities are a potential danger for soil, air and water thus plants and further animals and humans [1, 5, 11].

To know the role of heavy metals in environment and their hazardous effects on plants it is necessary to examine conditions of their release, migration and availability in soils.

The rate of their volume and contamination can vary in place and time, as a function of sources, source densities, meteorological conditions of their solubility and plant availability.

Knowing conditions of heavy metals mobility in soils and also climatic (rainfall, temperature) and hydrological (e.g. surface and subsurface runoff in eroded areas) variations in a given place we can predict environmental hazards of this process and create prognostic models [2, 4, 10].

To show the role of these processes in cadmium transformations in a loess soil, small eroded river basin was taken into consideration.

CADMIUM IN THE ENVIRONMENT

Cadmium is an element strongly scattered in rocks where it is in the average amount of 0.03-0.22 $mg \cdot kg^{-1}$. Its concentration in soils is 0.2-1.05 $mg \cdot kg^{-1}$ and in soil solution is 0.2-6 $ug \cdot l^{-1}$. The natural Cd concentration in soils is an effect of its content in mother rocks but because of anthropogenic influences its concentration may increase to very high values even till 1 500 $mg \cdot kg^{-1}$ near metallurgic factories. High amounts of Cd are also introduced to soils with phosphorous fertilizers and urban wastes [5].

Cadmium appears mainly as divalent cation and creates various complex ions, eg. $CdOH^+$, $CdHCO_3$, $CdCl^-$, $Cd(OH)_4$ and also organic chelates.

The mobility of Cd in soils is very high at pH 4.5-5.5. In alkaline environment insoluble cadmium carbonates and phosphates are precipitated.

Cadmium is easily transported form soils to surface, subsurface or ground waters where its toxicity is very high. Cadmium is easily absorbed by plants both by their roots and overground parts, proportionally to its concentration in the soil and at acid soil reaction.

Cadmium content in plants is very often in the range of 0.05-0.2 $mg \cdot l^{-1}$ but its toxicity occurs at 5-30 $mg \cdot kg^{-1}$. The most sensitive for Cd toxicity are papilionaceous plants, oats, carrot and redish. Physiological effects of Cd excess are connected with disturbance in physiological processes, transpiration and nitrogen compounds transformations and also with changes in cell-membrane permeability and in DNA structure.

OBJECT

The object of the study was a small basin of river Ciemięga under strong erosion and intensive agricultural use (Fig. 1 and Phot. 1.) [3, 4, 6, 7, 9, 12].

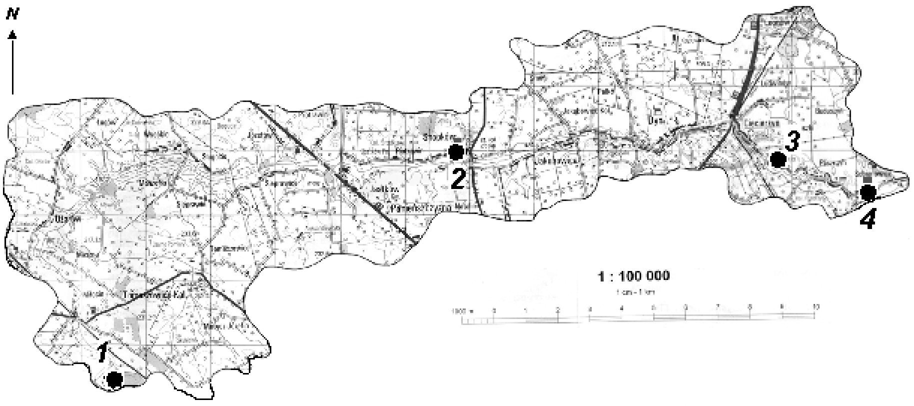

Fig. 1. Valley of Ciemięga river: 1 – Motycz, 2 – Snopoków, 3 – Baszki, 4 – Pliszczyn

Phot. 1. General view on the studied area

Ciemięga river is an affluent of Bystrzyca river. Its catchment is located on Lublin Upland on 200-230 m a.s.l. and amount of 157 km^2. Its length is 41 km. Such basins are of wide interest in Poland from the point of view of their hydrological (water retention) character especially in flood hazards caused by heavy storms [8].

For examinations four localities along the basin (Pliszczyn, Baszki, Snopków, Motycz) were taken under consideration. First two (Pliszczyn, Baszki) characterize the lower part of valley with strongly undulating relief. The two others (Snopków, and Motycz) are situated in a more gentle relief. In each of 4 localities from 3 or 4 parts of the hill-slope (upper - 1, middle – 2, and lower – 3 and 4) soils from 2 horizons (0-20 and 20-40 cm) were sampled. All together 23 soil samples were taken.

Basic properties of these samples are shown in Table 1.

Table. 1. Main soil characteristics

Locality	Stand	Depth cm	Granulometric composition (%) (fractions in mm)						Corg. %	S H_2O	S N_2	pH H_2O
			1 - 0.1	0.1 - 0.05	0.05 - 0.02	0.02 - 0.005	0.005 - 0.002	< 0.002		m^2 g^{-1}		
Pliszczyn	1.1	0-20	1	10	62	19	1	7	2.63	40.58	12.35	7.55
Pliszczyn	1.2	0-20	5	15	54	19	1	6	3.05	45.17	7.44	7.38
Pliszczyn	1.3	15-20	8	12	53	19	1	7	2.51	33.72	6.61	7.8
Pliszczyn	1.4	0-20	13	15	47	19	1	5	3.48	34.7	5.25	8.15
Pliszczyn	1.4	50-60	1	13	53	21	1	11	1.85	34	12.17	8.41
Baszki	2.1	0-20	6	9	53	21	3	8	2.28	36.78	15.31	8.11
Baszki	2.1	20-40	2	10	50	23	6	9	0.35	37.3	14.92	8.14
Baszki	2.2	0-20	4	13	50	20	5	8	1.94	40.44	10.88	7.06
Baszki	2.2	20-40	4	10	50	21	6	9	2.04	39.78	12.55	7.01
Baszki	2.3	0-20	8	14	58	13	2	5	2.72	35.36	8.97	7.6
Baszki	2.3	20-40	3	13	54	19	4	7	1.16	27.6	9.44	7.91
Baszki	2.4	0-20	6	17	58	6	17	58	2.28	34.02	6.4	7.88
Snopków	3.1	0-20	7	15	56	3	17	2	3.08	47.24	6.8	7.86
Snopków	3.1	40-60	2	10	52	14	15	7	1.8	37.54	9.89	7.93
Snopków	3.2	0-20	6	14	57	17	2	4	2.4	40.93	9.53	7.73
Snopków	3.3	20-40	4	17	57	13	5	4	2.49	33.95	9.46	8.12
Snopków	3.2	40-60	0	12	55	20	8	5	1.42	36.86	6.92	8.06
Snopków	3.3	0-20	22	18	50	7	1	2	5.08	55.69	6.65	7.94
Motycz	4.1	0-20	27	12	35	13	3	10	1.74	35.07	7.06	6.56
Motycz	4.1	20-40	29	10	33	15	4	9	0.92	30.53	9.57	6.4
Motycz	4.2	0-10	10	13	46	20	4	7	1.87	31.84	6.39	7.5
Motycz	4.2	0-20	7	11	47	21	10	4	0.49	31.12	10.26	7.76
Motycz	4.3	0-20	8	12	48	20	7	5	5.42	70.95	8.63	7.4

Air dry soil samples were flooded with distilled water (soil : water = 1:1) in glass vessels tightly covered. Then they were incubated at 5°C during 1, 10, 20, 30, 40, 50, 60 days and at 20°C during 1, 2, 3, 4, 7, 9, 11 days.

In the course of incubation, measurements of pH and Eh were made in the vessels in the solution above the soil. Analysis of Cadmium was made in the filtrates with the use of the Atomic Absorption Spectrometry.

RESUTLS

Cadmium concentration was changed during incubation. After 3 hours of the incubation of air dry soil samples flooded with water, differences in Cd concentration depended on the temperature, time of the incubation but also were visible between localities of the soils. Figure 2 shows mean values of Cd concentration for soils taken from all 4 localities and 3-4 parts of the hill-slopes after soil incubation at 5^{o}C and Figure 3 at 20^{o}C.

The Cd concentration was 0.39 ppb at 5^{o}C, and 0.7 ppb at 20^{o}C. During 60 days incubation course at 5^{o}C Cd concentration decreased till 0.26 ppb in comparison to the initial value 0.26 ppb. During the whole time of incubation Cd content was from 0.09 to 3.9 ppb (average 0.68 ppb). The increase of concentration was found at the beginning of the experiment in all samples. The maximum was in the 10th day of incubation, after which a systematic decrease of concentration appeared.

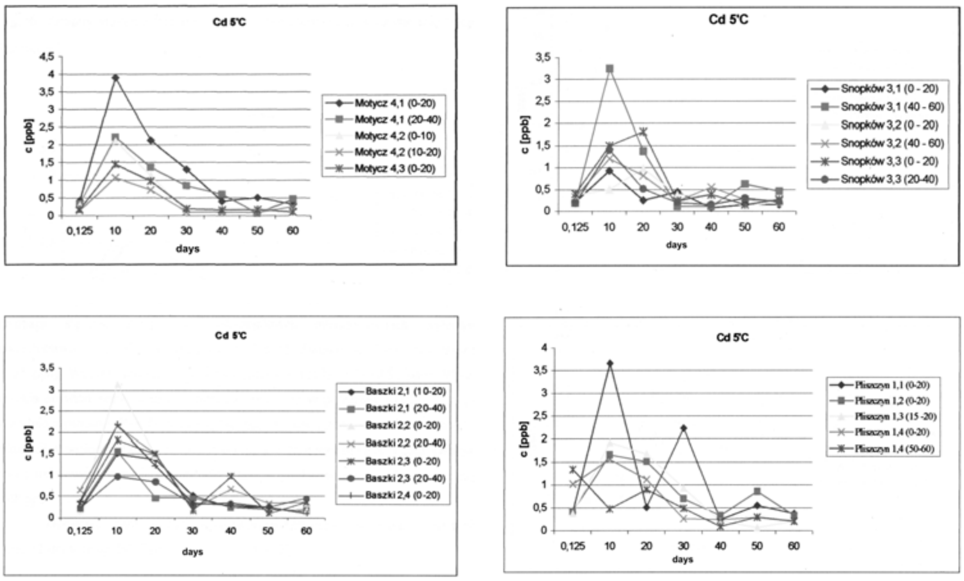

Fig.2. *Mean values of Cd concentration for the studied soils after incubation at 5^{o}C*

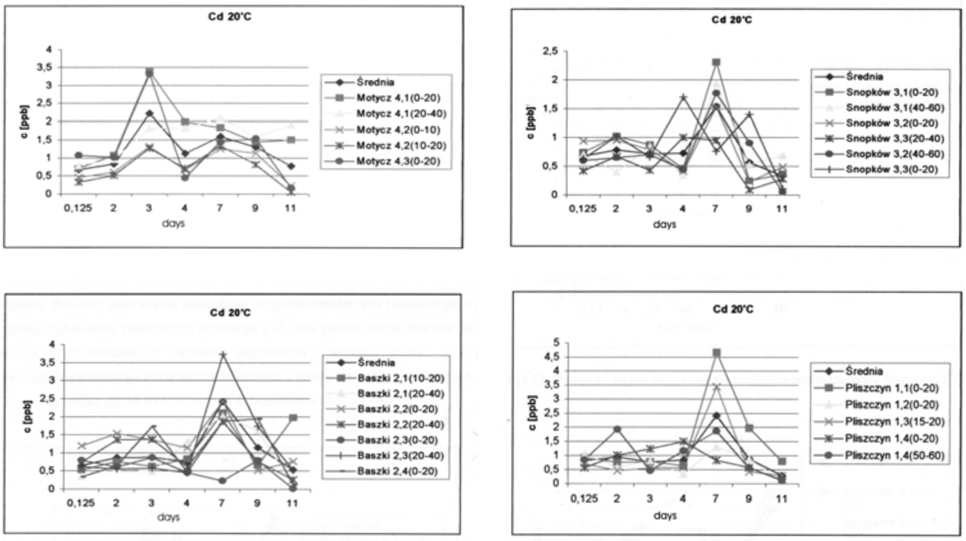

Fig.3. *Mean values of Cd concentration for the studied soils after incubation at 20°C*

At the temperature of 20°C Cadmium concentration at the beginning of the incubation showed in samples from all localities similar values as at 5°C: in Motycz 0.67ppb, Snopków 0.67 ppb, Baszki 0.65 ppb. Only at the mouth of the river (in Pliszczyn) there was a higher concentration equal to 0.81 ppb.

During 11 days of incubation course at 20°C Cadmium concentration was between 0.05 and 3.38 ppb (average 0.99 ppb). The maximum was found in the 7th day of incubation in majority of samples, except this from Motycz where peak appeared also in the 3rd day of incubation. At the end of the experiment Cd concentration was 0.48 ppb and was lower than at the beginning of the incubation.

CONCLUSION

The results obtained show the ability to passing of Cd from soil to water and conditions determining the amount of this metal in various sites of eroded homogenous loess soils. We can also predict, on the knowledge of climatic condition (when oversaturated of soils with water and increase of temperature), the appearance of toxic for plants concentrations of this metal.

Acknowledgements

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REFERENCES

1. Adriano D.C. (1992): Biogeochemistry of Trace Metals. Lewish Publication.
2. Gliński J., Stępniewska Z. (1986): An evaluation of soil resistance to reduction processes. Polish J. Soil Sci., 19, 15-19.
3. Gliński P., Dębicki R. (2000a): Degradacja gleb lessowych na przykładzie zlewni Ciemięgi. (Degradation of less soils on the example of the Ciemięga river basin). Acta Agrophysica 23, 39-46.
4. Gliński P., Dębicki R. (2000b): Ocena zagrożeń erozyjnych oraz charakterystyka jakości wód przy zastosowaniu symulacji komputerowej. (Evaluation of erosion hazard and characteristics of water quality with the use of computer simulation). Acta Agrophysica 36.
5. Kabata-Pendias A., Pendias A. (1998): Biogeochemiczne pierwiastki śladowe. (Biogeochemistry of trace elements) PWN, wyd.II, Warszawa.
6. Mazur Z., Orlik T., Pałys S. (1972): Procesy erozyjne w zlewni rzeki Ciemięgi. (Erosion processes in the Ciemięga river basin).Ann. UMCS, XVI, E, 147-168.
7. Michalczyk Z. (1998): Conditions for the formation of outflow and its characteristics in river basins of the Lublin region. Int. Agrophysics, 12, 271-276.
8. Mioduszewski W. (1998): Reconstruction of retention capacity of small river basin of the Lublin region. Int. Agrophysics, 12, 259-270.
9. Orlik T. (1979): Szybkość infiltracji wody w nalessowym terenie falistym (Infiltration velocity in the loessial undulating terrain).Zesz. Probl. Post. Nauk Roln., 222, 79-89.
10. Patrick W.H.Jr. (1981): The role of inorganic redox systems in controlling reduction of paddy soils. Proc. Symp. Paddy Soils, Nanjing, China, 1980, Science Press Bejing-Springer Verlag, Berlin, 107-115.
11. Terelak H., Stuczyński T., Piotrowska M. (1997): Heavy metals in agricultural soils in Poland. Pol.J.Soil Sci. 30/2
12. Turski R., Uziak S. Zawadzki S. (1993): Środowisko przyrodnicze Lubelszczyzny (Natural Environment of the Lublin Region). Wyd. LTN, Lublin.

EFFECT OF PLANT GROWTH AND MACHINERY TRAFFIC ON SOIL THERMAL CONDUCTIVITY IN VINEYARD

Usowicz B., Lipiec J., Ferrero A.

ABSTRACT

The paper presents the results of thermal conductivity and its alterations induced by vine plants and passes of crawler tractor and associated machinery along the vine interrows situated crosswise the slope. The experiment was conducted on vineyard silt loam soil that was under controlled grass cover or bare fallow (conventionally cultivated). The results showed that the soil thermal conductivity under grass covers was considerably higher under lower than upper crawler track. However, in the bare fallow vineyard the thermal conductivity under both tracks and in the inter-track area was rather smoothed with tendency to increase along the slope. Soil bulk density was greatest under lower crawler track and successively decreased under upper track and inter-track area. Such distribution was associated with different tractor's loading and soil water content along the slope. Under comparable tracks, bulk density was greater in grass covered than bare fallow tilled soil. The highest soil water content was between the tracks in conventionally tilled and under the lower track in grass covered vineyard soil. The least soil water content was found upper crawler track in both treatments.

Key words: bulk density, soil water content, thermal conductivity, slope

INTRODUCTION

Maintenance of suitable conditions for vine growth requires numerous operations associated with soil tillage and application of chemicals [2,3,4,]. These operations result in soil loosening or compaction and affect soil structure, root growth and yield. Local discontinuities in spatial distribution of soil compactness influence soil structure, root growth and crop yield [6,7,13].

Increasing soil bulk density under tractor wheels or tracks alter soil water, heat and air conditions that determine heat and energy transfer in soil medium, and as a consequence conditions for plant growth [1,5,8]. These effects depend on that whether soil was with or without grass cover.

The aim of the paper was to determine the effect of grass cover and passes of crawler tractor in the vine interrows crosswise the slope on distribution of thermal conductivity and bulk density. The study was conducted on grass covered and cultivated bare fallow vineyard soil.

MATERIALS AND METHODS

The study was conducted at a Piedmont,s hillside viticulture in north-west Italy (Fig.1). The soil was silt loam with 33% of sand, 58% of silt and 9% of clay. Organic matter was on average 3 % and particle density of soil 2.6 Mg m^{-3}. Solid phase of organic matter was taken as 1.3 Mg m^{-3}. The measurements were done in the vineyard inter-row of 2.7 m width in four transects (10 m apart) situated on slope of 20%. The crawler tractor of 2.82 Mg weight and 1.31 m width was for tillage and chemical operations. The measuring points of soil bulk density and water content were in places corresponding to upper, inter-rut and lower rut areas (Fig. 2). They were distributed uniformly around the circle of 20-cm radius. To determine bulk density and water content the soil cores of 100 cm^3 were taken at 3 depths: 1-8, 9-16 and 17-25 cm in 4 replicates from each depth. The measurements were done in autumn 2001.

Two treatments that are permanent grass cover and cultivated bare fallow were applied. Rut depth in the bare fallow soil was more than twice greater under the lower than upper crawler track. The difference in the grass covered soil was lower.

Soil thermal conductivity λ (W m^{-1} K^{-1}) was calculated using physical-statistical model described by the following equations [9,11,12]:

$$\lambda = \frac{4\pi}{u\sum_{j=1}^{L}\frac{P(x_{1j},\dots,x_{kj})}{x_{1j}\lambda_1(T)r_1+\dots+x_{kj}\lambda_k(T)r_k}} \tag{1}$$

where u is the number parallel connections of soil particles treated as thermal resistors, L is the number of all possible combinations of particle configuration, x_1, x_2 ,..., x_k – a number of particles of individual particles of a soil with thermal conductivity λ_1, λ_2 ,..., λ_k and particle radii r_1, r_2 ,..., r_k, where $\sum_{i=1}^{k} x_{ij} = u$, $j=1,2,\dots,L$, $P(x_{ij})$ – probability of occurrence of a given soil particle configuration calculated from the polynomial distribution:

$$P(x_{1j},\dots,x_{kj}) = \frac{u!}{x_{1j}!\dots x_{kj}!} f_1^{x_{1j}} \dots f_k^{x_{kj}} \,. \tag{2}$$

The condition: $\sum_{j=1}^{L} P\left(X = x_j\right) = 1$ must also be fulfilled. The probability of selecting a given soil constituent (particle) f_i, $i = s, c, g$, in a single trial was determined based on fundamental physical soil properties. In this case f_s , f_c , and f_g are the content of individual minerals and organic matter – $f_s = 1-\phi$, liquid – $f_c = \theta_v$ and air – $f_g = \phi - \theta_v$ in a unit of volume, ϕ – soil porosity.

The basic soil data used to calculate thermal conductivity with the statistical-physical model were measured in the experimental vineyard. The data on texture, organic matter content and solid phase densities of soil and organic matter were used to determine probability of occurrence of given soil component. It was assumed that sand fraction consists mainly of quartz; however other minerals are contained in majority silt and clay fractions [14]. Based on the soil textural composition and solid phase density, content of quartz and other minerals and organic matter per unit volume was calculated [10].

Fig. 1. *General viewed of vineyard in Italy, at Piedmont district*

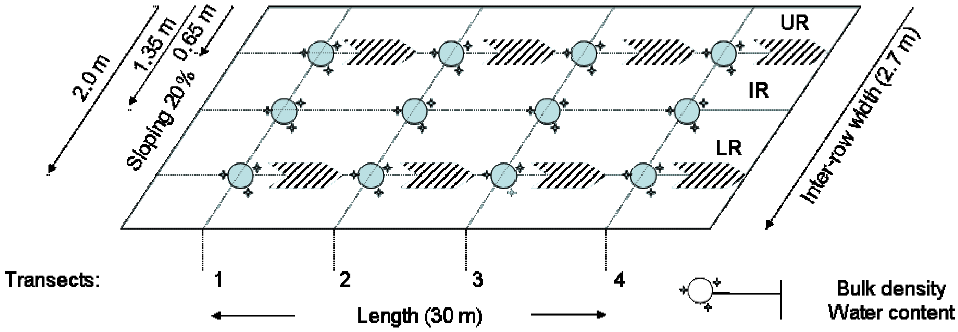


Fig. 2. *The location of measurements points in the study object (UR – upper rut, IR – Inter rut, LR – lower rut)*

RESULTS

The figures 3-5 present distribution of soil bulk density, water content and thermal conductivity with depth in vineyard with basic statistics that is mean value, standard error, minimum and maximum values and coefficient of variation for the bare fallow and grass cover treatments. Statistical analysis in each treatment was conducted separately for all data (a) and from upper track (b), inter-track and lower track (c) areas.

Mean value is an important measure of main tendency and its certainty is increasing with increasing number of sample data. Therefore, statistical parameters for all data set were analyzed first. It was found that thermal conductivity of surface soil was greater under the grass cover than bare fallow (Fig. 3a) and similar in both treatments in deeper soil. Soil bulk density increased with depth to somewhat higher extent under grass cover than bare fallow. However, mean bulk density in both treatments was not much different (Fig 4a). Soil water content increased with depth under the grass cover whereas under the bare fallow the opposite was true (Fig. 5a). The range of values of all properties was greater under grass cover than bare fallow soil (Fig. 3-5a). Such distribution of the thermal conductivity can be associated with distribution of soil water content, which in turn was modified by plant cover in the vineyard. Soil under grass cover was somewhat wetter than under bare fallow.

The differences in thermal conductivity between the upper and lower tracks were relatively high under the grass cover in contrast to the bare fallow where they were much smaller. Dispersion of the thermal conductivity was similar under both tracks in grass covered soil whereas under the bare fallow soil it was substantially greater under lower track. In the inter-track area the soil thermal conductivity was similar in both grass covered and bare fallow soil but dispersion of the conductivity values was greater under the grass cover. Analyzing distributions of soil bulk density and water content at the same locations one can conclude that course of the thermal conductivity was mainly affected by soil water content and to much lower extent by soil compaction (Fig. 3 b-d). Relatively low bulk density at surface soil and somewhat greater and stabilized deeper was only slightly reflected in distribution of the thermal conductivity, in particular under crawler ruts. Similar effect of bulk density on the thermal conductivity was observed under bare fallow (Fig. 3 b-d). However, the distribution of soil water content with depth and along the slope was somewhat different (Fig. 4 b-d). In grass covered vineyard the soil water content was low in upper part and higher in lower part of the slope. However, under bare fallow it was smoothed not only in soil profile but also along the slope. The distributions indicate that soil water content had a dominant effect on distribution of thermal conductivity in soil profile.

Variability of the thermal conductivity, as indicated by coefficient of variation, was associated with status of soil wetness, compaction level and plant cover (Figs. 3-5). The variability of all the properties was in general greater in the inter-track than under track area (Figs. 3-5 b,d). Variation coefficient values for the thermal conductivity and water content with depth and along slope were similar. The variability of soil bulk (Fig. 3) density was noticeably lower than that of soil water content and thermal conductivity (Figs. 4,5).

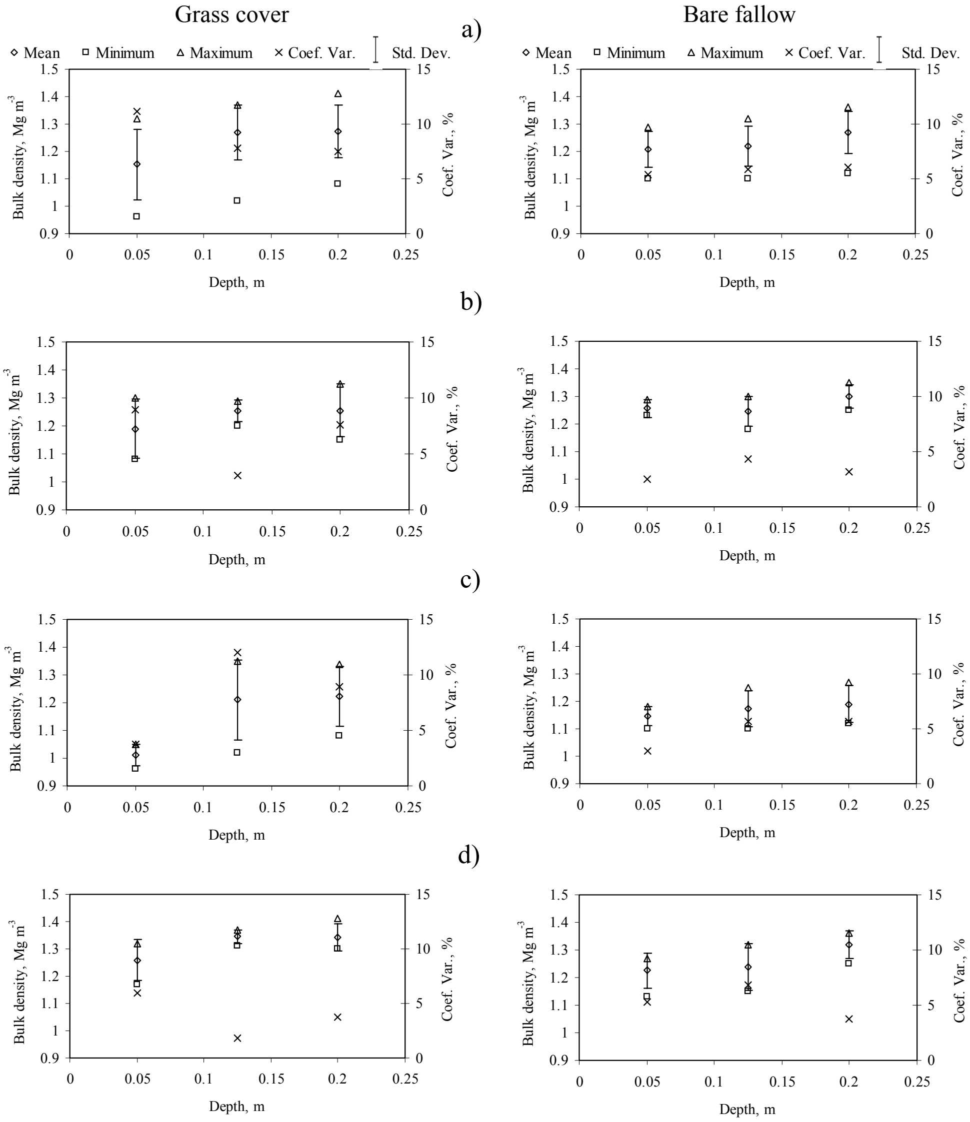


Fig. 3. *Bulk density of soil in soil profile on grass and cultivated field, a) all data, b) data from upper rut, c) inter rut and d) lower rut*

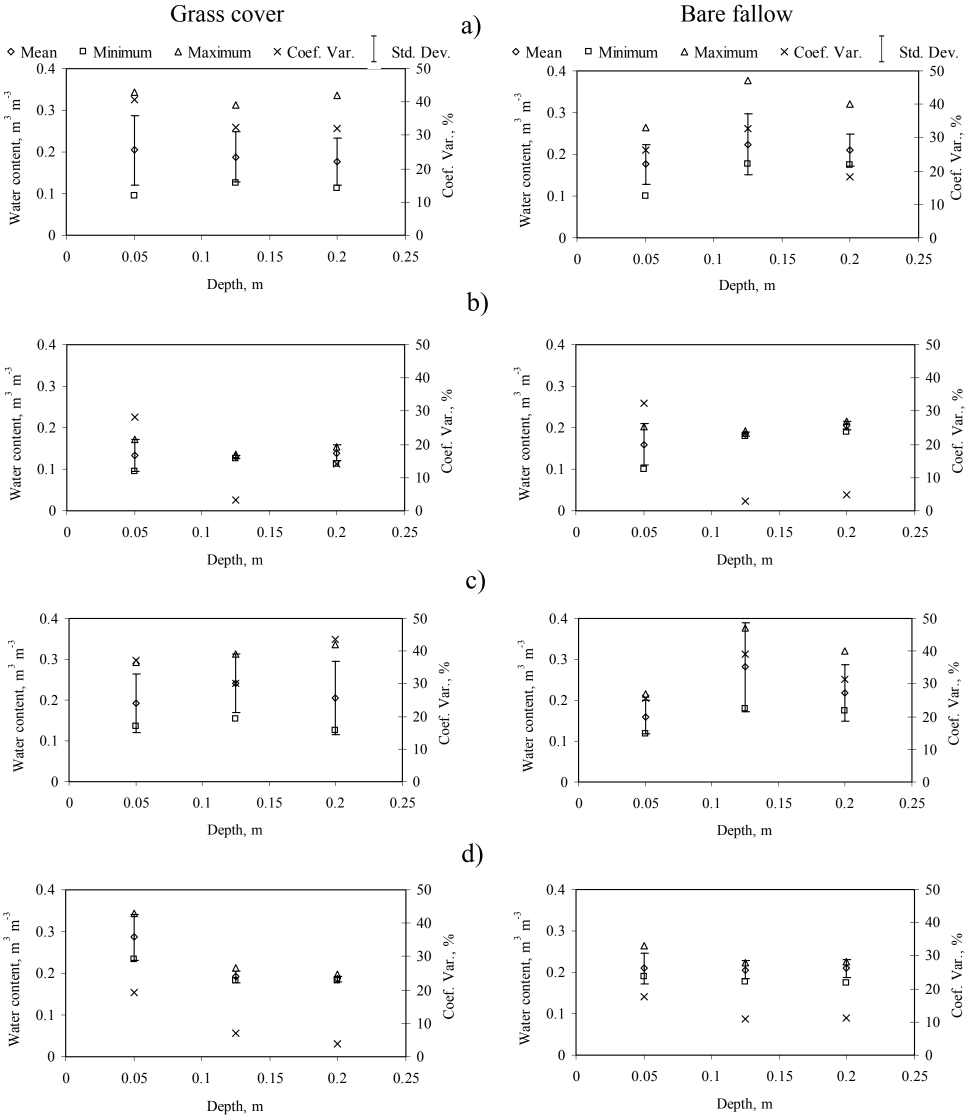


Fig. 4. *Water content of soil in soil profile on grass and cultivated field, a) all data, b) data from upper rut, c) inter rut and d) lower rut*

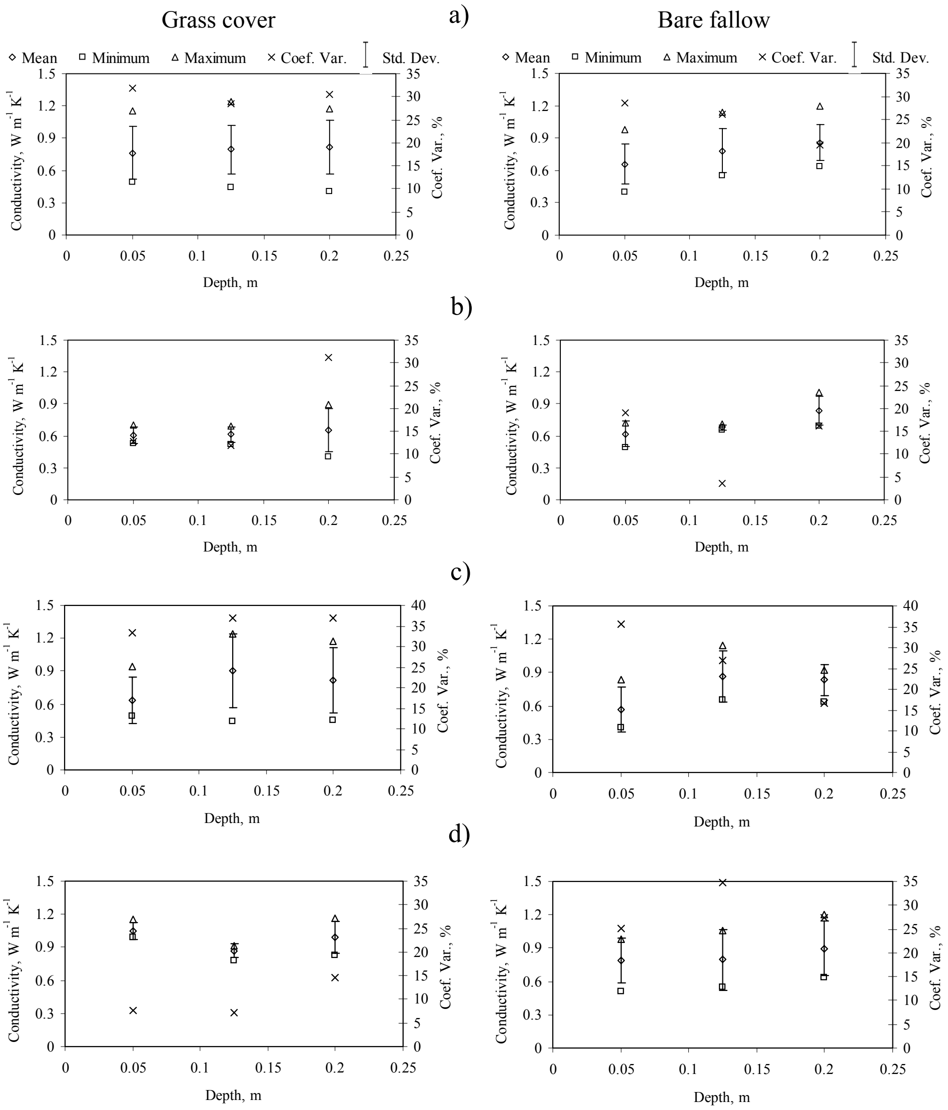


Fig. 5. *Thermal conductivity of soil in soil profile on grass and cultivated field, a) all data, b) data from upper rut, c) inter rut and d) lower rut*

CONCLUSIONS

This research showed that distribution of the thermal conductivity in vineyard soil was more related with distribution of water content than of bulk density. Effect of plant cover on the thermal conductivity was mostly through the soil water content. Protective effect of grass cover on water evaporation from surface soil layer was observed.

In grass covered soil the thermal conductivity in the interrow was considerably greater under lower crawler rut than lower rut and inter-track areas. Under bare fallow the differentiation along the slope and between the crawler ruts were substantially lower.

REFERENCES

1. Bachmann J., Horton R., Ren T. and Van der Ploge R.R. (2001). Comparison of the thermal properties of four wettable and four water-repellent soils. Soil Sci. Soc. Am. J., 65, 1675-1679.
2. Ferrero A., Lipiec J. 2000. Determining the effect of trampling on soils in hillslope - woodlands. Int. Agrophysics, 14, 9-16.
3. Ferrero, A., Sudiro, L., Nosalewicz, A. Lipiec, J. 2004. Effects of grass cover and tillage on temperature of soil in sloping vineyard. Int. Agrophysics 18(2), 121-126.
4. Ferrero A., Usowicz B. Lipiec J. 2004. Effects of tractor traffic on spatial variability of soil strength and water content in grass covered and cultivated sloping vineyard (accepted to Soil and Tillage Research).
5. Hopmans J.W. and Dane J.H. (1986). Thermal conductivity of two porous media as a function of water content, temperature and density. Soil Sci., 142 (4), 187-195.
6. Lipiec J., Hatano R. 2003. Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116, (issues 1-2), 107-136.
7. Lisa L., Parena S., Laura Lisa. 1995. Working times and production cost of grapes in grass covered or tilled vineyards of Piedmont. GESCO, Proc. 8th Meeting, 3-5 July 2000, Vairão (Portugal), 325-330.
8. Ochsner T.E., Horton R. and Ren T. (2001). A new perspective on soil thermal properties. Soil Sci. Soc. Am. J., 65, 1641-1647.
9. Usowicz B. 1992. Statistical-physical model of thermal conductivity in soil. Polish J. Soil Sci., XXV/1, 27–34.
10. Usowicz B. 1995. Evaluation of methods for soil thermal conductivity calculations. Int. Agrophysics, 9(2), 109–113.
11. Usowicz B. 1998. Soil thermal properties software package 2.0. Copyright: Institute of Agrophysics PAS, Lublin.
12. Usowicz B. 2000. Statystyczno-fizyczne modele przepływu masy i energii w ośrodku porowatym. Acta Agrophysica, 29, s.112.
13. Van Dijck S.J.E., van Asch Th.W.J. 2002. Compaction of loamy soils due to tractor traffic in vineyards and orchards and its effect on infiltration in southern France. Soil Till. Res. 63, 141-153.
14. Vries de. D.A. (1963). Thermal properties of soils. In: Physics of Plant Environment. (Ed.) van Wijk W.R. North-Holland Publ. Co., Amsterdam, pp. 210–235.

MODELLING OF ACTUAL EVAPOTRANSPIRATION WITH THE USE OF CROP COVER RADIATION TEMPERATURE AND SOIL DATA

Walczak R.T., Baranowski P., Mazurek W.

INTRODUCTION

The modelling of actual evapotranspiration is a complex research problem due to majority of physiological and physical processes which influence the rate of water transported from the soil, through the rooting system and plant tissue into the atmosphere [11].

The theoretical bases of evapotranspiration determination were given by Penman. His papers analysed the transport processes of water and energy from an evaporating surface on the ground of semiempirical equations [19,20]. The author states that the transport of water vapour from the evaporating surface is determined by the gradient of water vapour pressure between the surface and the air above it, and is strongly modified by the wind speed. On the other hand, the transport of energy from the evaporating surface, which analysis requires taking into account the heat balance on the surface, includes the process of energy supply for the water transition from the liquid phase into gaseous phase in the form of the latent heat.

The equations, formulated by Penman, describing both kinds of transport contained the parameter of surface temperature or/and the water vapour pressure on the evaporating surface, which according to the author could not be measured during the routine measurements in agro-meteorological stations at that time. Therefore, the author made a modification of the heat balance equation, including an aerodynamic component to eliminate the necessity of measurements of these parameters.

Penman equations for calculation of the evapotranspiration rate, which revealed the importance of the temperature of evaporating surface, made many researchers look for possibilities of measuring this quantity. First measurements of plant cover temperature were conducted with the use of contact thermometers [17]. However, the accuracy of this method was very small. In nineteen fifties Stoll and Hardy [22] elaborated a radiometer working in the infrared range for the temperature measurement of the natural environment. Gates [10] successfully used this device for the measurement of the plant cover temperature.

A rapid development of the infrared sensors in nineteen sixties and seventies caused increased production of hand-held thermal radiometers and first thermographic systems which enabled to measure the surface temperature with accuracy of 0,5-0.1 ^{0}C.

Monteith and Szeicz [18], Wiegand and Namken [26] were among the first who used the infrared thermometry in the studies of plant temperature in the context of its relation to the soil water conditions. Further studies of plant temperature under different soil water content values made it possible to state that plant temperature increase occurs for limited availability of water for plants, therefore it can be an indicator of plant water stress [2-5, 13-15].

The intensive studies of radiation temperature of the bare soil and plant cover for determination of actual evapotranspiration were initiated in nineteen seventies. Airborne and satellite level thermal images became available from multispectral scanners containing thermal channels and temperature distribution of large agricultural areas were analyzed to create new models of actual evapotranspiration.

Remote sensing methods of soil and plant cover temperature measurements of large areas replaced point measurements and a new perspective was created to determine actual evapotranspiration in regional scale. It was a milestone in the analysis of the water balance of large areas. Fundamental studies on this topic were performed by Bartholic et al. [6], Brown [7], Stone and Horton [23] as well as Heilman et al. [12]. They analyzed the physical relations between radiation temperature of plant cover measured from different levels and intensity of evapotranspiration [9, 21].

In nineteen eighties and nineties the studies were continued to apply thermal images of plant cover from different levels for calculation of actual evapotranspiration [1, 8, 16]. The main assumptions of the models created as the results of these studies were [24, 25]:

- radiation temperature of plant cover is determined by the processes of water and heat transport in the soil-plant-atmosphere system;
- energy exchange on the plant surface is expressed by the heat balance equation;
- plant temperature can be used for determination of actual evapotranspiration by connecting the heat balance equation of the active surface with the equations of vertical transport of latent and sensible heat fluxes.

In this paper a scheme of determination of actual E_a to potential E_p evapotranspiration relation, enabling the calculation of crop water stress index *CWSI* is presented. In the lysimetric study the actual evapotranspiration was calculated from the energy balance equation in which radiation temperature of plant cover measured with the use of thermographic device is a component of sensible heat flux expressing the transport of heat energy from evaporating surface to the atmosphere.

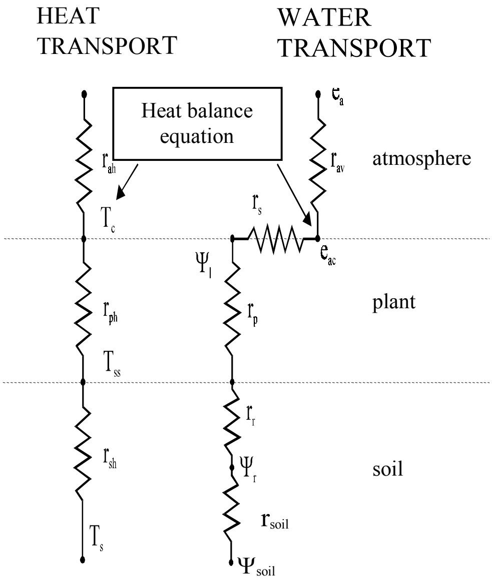
HEAT AND WATER TRANSPORT MODEL IN THE SOIL-PLANT-ATMOSPHERE SYSTEM

Heat and water transport in the soil-plant-atmosphere system can be described using a resistance model constructed as an analog of the electrical circuit. The scheme of such a model is presented in Fig. 1.

The energy balance equation describes the process of energy exchange at the evaporating surface (e.g. crop surface). The most frequently used form of this equation is as follows:

$$L \cdot E + H + R_n + G = 0 \tag{1}$$

where: L· E - the latent heat flux [W·m^{-2}] (energetic equivalent of the evapotranspiration flux); L - the latent heat of vaporisation of water per unit mass (L=2,45· 10^{6} J· kg^{-1}); E - evapotranspiration flux [kg· m^{-2}· s^{-1}]; H -the sensible heat flux [W· m^{-2}]; R$_n$ -the net radiation flux [W· m^{-2}]; G - the heat flux into the soil [W· m^{-2}]. In this equation fluxes towards the crop surface are given the positive value and the fluxes out of the surface are given the negative value.



r_{ah}, r_{av} - aerodynamic resistance for heat and water vapour transport;

r_s - plant resistance for water vapour transport (stomatal resistance);

r_{soil}, r_p, r_r - water transport resistance in soil, in above-ground plant part and in root;

r_{ph}, r_{sh} - heat transport resistance in plant and in soil;

T_a, T_c, T_{ss}, T_s - temperature at reference level, on active area surface, on the soil surface and in soil;

e_a, e_{ac} - water vapour pressure at reference level and on the active surface;

ψ_l, ψ_r, ψ_{soil} - water potential in leaf, root and soil

Fig. 1. *Simplified resistance model of water and heat transport in soil-plant-atmosphere system [5].*

Heat and energy transport in soil-plant-atmosphere system can be described using resistance model built as an analogue of electric circuit. The transport equations for sensible heat H and latent heat L· E in this case can be expressed as:

$$H = \rho \cdot c_p \frac{T_c - T_a}{r_{ah}} \tag{2}$$

$$L \cdot E = \frac{\rho \cdot c_p}{\gamma} \frac{e_c^* - e_a}{r_{av} + r_s} \tag{3}$$

where: T_c - crop surface temperature [K]; T_a - air temperature [K] measured at reference height z_a; e_c^* - saturated vapour pressure [Pa] at the apparent crop temperature T_c; e_a - water vapour pressure of the air [Pa] measured at reference level z_a; r_{ah} , r_{av} - diffusion resistance respectively for transport of heat and water vapour [s· m^{-1}]; r_s - stomatal resistance of the crop [s· m^{-1}]; ρ- density of air [kg· m^{-3}]; γ - psychrometric constant; c_p - air specific heat [J· kg^{-1}· K^{-1}].

Aerodynamic resistance for heat transport r_{ah} is a function of wind velocity, stability of the atmosphere over the plant cover and the roughness of the surface. As a good approximation it can be assumed that $r_{ah}= r_{av}=r_a$ (turbulent diffusion resistance for heat and water vapour transport). Combining equations (1), (2) and (3) we obtain the relation between actual value of radiation temperature of evaporating crop surface and agrometeorological parameters in the atmospheric boundary layer and soil:

$$T_c = T_a + \frac{r_a\left(R_n - G\right)}{\rho c_p} \cdot \frac{\gamma\left(1+\frac{r_c}{r_a}\right)}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)} - \frac{e_a^* - e_a}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)} \tag{4}$$

It results from this equation that the difference between crop surface temperature and air temperature is linearly dependent on vapour pressure deficit in the air VPD (e^*_a - e_a). This relation was used by Jackson et al. [13]. They created crop water stress index (CWSI). This index bases on relation of the actual evapotranspiration to potential evapotranspiration and is expressed as:

$$CWSI = 1 - \frac{E_a}{E_p} = \frac{\gamma\left(1+\frac{r_c}{r_a}\right) - \gamma\left(1+\frac{r_{cp}}{r_a}\right)}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)} \tag{5}$$

where: E_a - actual evapotranspiration flux [kg·m^{-2}·s^{-1}];, E_p - potential evapotranspiration flux [kg·m^{-2}·s^{-1}];, r_{cp} - the canopy resistance at potential evapotranspiration [s·m^{-1}], Δ - slope of saturated water vapour pressure curve versus temperature [kPa·K^{-1}], the other symbols as in previous equation.

MODEL STUDIES OF ACTUAL EVAPOTRANSPIRATION DETERMINATION

In the Institute of Agrophysics PAS a several years series of investigation was realised on determination of plant water stress as a factor limiting biomass production and actual evapotranspiration, i.e. a component of water balance with the use of remote sensing thermography methods. The aim of these studies was to elaborate the method of water conditions measurement of grasslands and cultivated fields in the aspect of the control of melioration systems of arable lands. The investigations were directed towards the possibility of the use of thermographic method for determination of the influence of soil water availability for the rooting system on evapotranspiration intensity, thus on leaf temperature distribution. It is especially important to determine the moment of stress water conditions occurrence.

The experiment was performed in lysimetric station of the Institute for Land Reclamation and Grassland Farming in Sosnowica (51°31'30''N, 23°04'48''E). The station is situated in the central part of Wieprz-Krzna Canal district, 164 m above sea level. The object of the study was natural grass cover growing in lysimeters of the area 1700 cm^2 and height 120 cm. (Lysimeters with different ground water levels of sandy and peat soil). In initial stage of the experiment the optimal water level of 60 cm was kept in all the lysimeters. Soil water content in lysimeters was differentiated. The pairs of lysimeters were created and in each pair there was one lysimeter with gravitational water completely carried away and the other with soil water level representing the comfort water conditions for plants.

Thermal images of plant cover in lysimeters were taken with AGEMA 880 LWB. One minute sequences were taken every hour during daily hours and every two hour at night. The measurements of radiation temperature of each pair of lysimeters were done from the distance of 4,3 m and height of 2,2m with the angle 60° between optical axis of the camera and the perpendicular. The whole day registration of meteorological data was performed with the use of automatic data acquisition system elaborated in IA PAS Lublin. The subsystem referring to the soil was composed of TDR (Time Domain Reflectometry) water content measuring device and thermoelectric sensors of soil temperature. The subsystem referring to the atmosphere was composed of thermoelectric sensors of air temperature, anemometers, psychrometers and sensors for direct and reflected short and long wave solar radiation. Water potential in plants was measured with Wescor device using dew point method.

On the base of temperature differences between crop surface and the air, the stability conditions in boundary layer of the atmosphere were determined. Using the appropriate equations for calculation of the components of the heat balance equation, the hourly and daily values of actual evapotranspiration were obtained. High differences in the course of sensible (Hs and Hc) and latent (Les and Lec) heat fluxes for lysimeters with different soil moisture levels were noticed (Fig. 2).

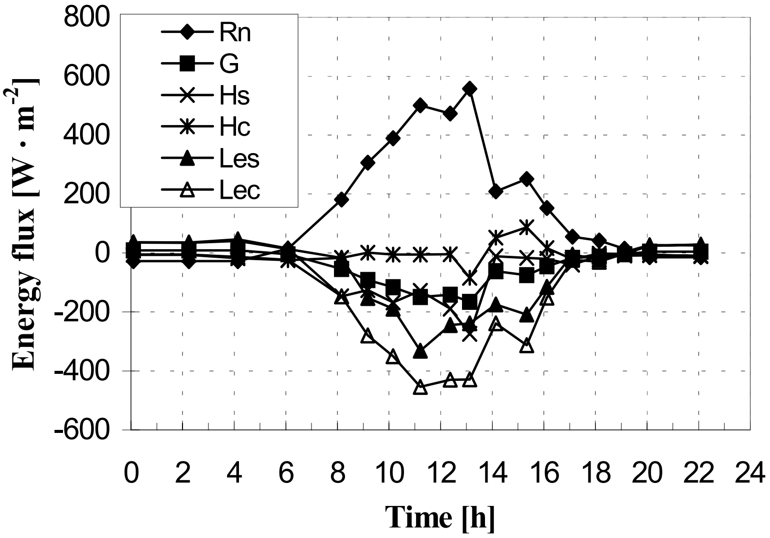


Fig.2. *Daily courses of components of heat balance equation; comfort water conditions - Hc and Lec, stress water conditions - Hs and Les [5]*

Daily courses of potential evapotranspiration calculated with different methods were compared with actual evapotranspiration under comfort soil water conditions. It was stated that the hourly values of actual evapotranspiration in lysimeters with comfortable water conditions (Ec) follow best the evapotranspiration calculated according to the 63-Penman (63Pn) and Kimberly-Penman (KPen) formulae (Fig.3). Considering daily values of potential and actual evapotranspiration the meaningful differences were noticed between lysimeters with stress and comfort conditions and between lysimeters with organic and mineral soils.

Basing on eq. 4 the upper limit of crop-air temperature difference was found representing the complete restrain of evapotranspiration ($r_c \to \infty$) and the lower limit which corresponds to the case of wet plants acting as free water surface ($r_c=0$) (Fig. 4). The regression line for well watered plants is close to the lower limit line and the regression line for stressed plants is close to the upper limit. Upper and lower limits in Fig. 4 were calculated for net radiation higher than 500 W/m^2, turbulent aerodynamic resistance 90 s/m for stressed plant cover and 68 s/m for plants in comfortable water conditions and air temperature 30^{o}C.

High dispersion of measuring data for the lysimeters with stress water conditions was noticed (R^2=0,10) comparing with the data for the lysimeters with comfort soil water conditions (R^2=0,75).

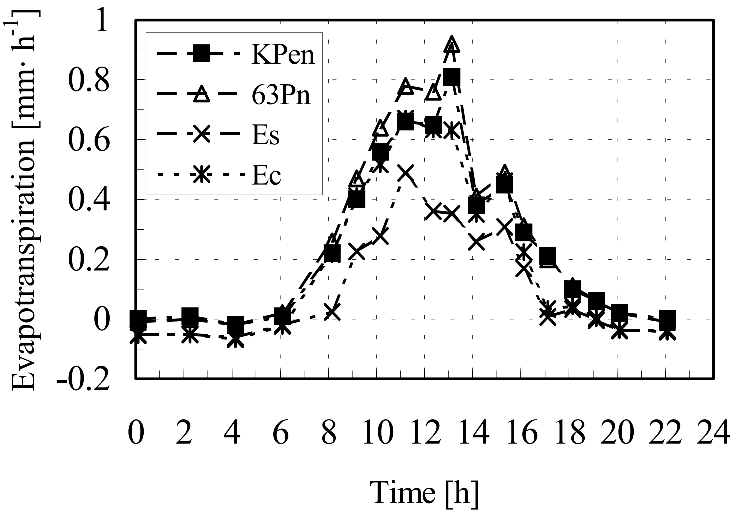


Fig.3. *Daily courses of actual and potential evapotranspiration calculated using different methods [3, 5].*

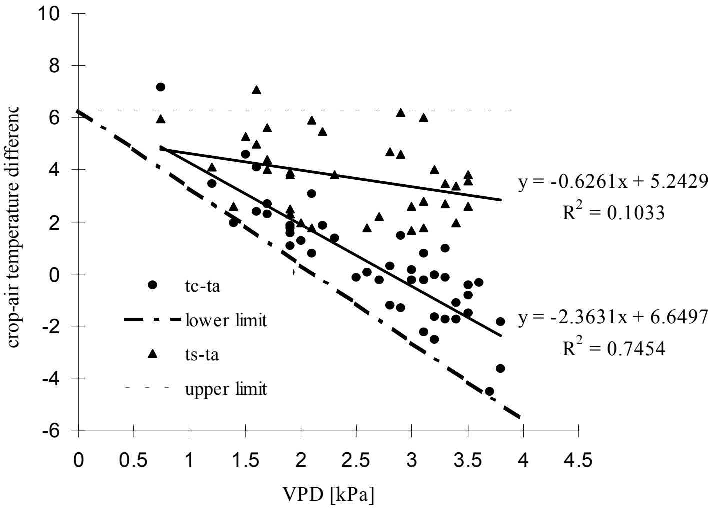


Fig. 4. *The relation between crop-air temperature difference for stressed ts-ta and non-stressed tc-ta plants and vapour pressure deficit*

Hourly values of CWSI and crop temperature are presented in Fig. 5 for plant cover in lysimeters of one pair. CWSI was calculated from equation 5. Potential evapotranspiration was calculated from Penman-Monteith formula and actual evapotranspiration using heat balance method.

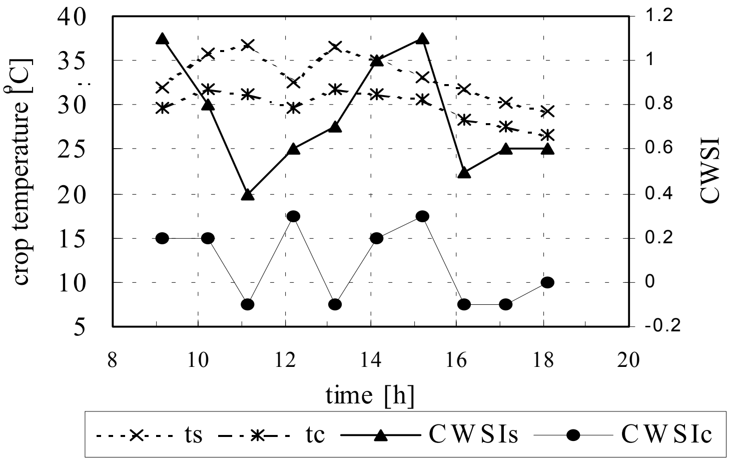


Fig. 5. The changes of CWSI during daily hours for water stressed(CWSI$_s$) and non-stressed (CWSI$_c$) plants against a background of crop temperature courses: (t_s -stressed plants, t_c - comfort water conditions)

During daily hours significant differences in crop cover temperature correspond with high differences in evapotranspiration rates and at the same time CWSI values.

Evapotranspiration intensity is mainly determined by availability of soil water for plants. High differences of water potential exist in soil-plant-atmosphere system. Under high atmospheric evaporative demand (high water pressure deficit) the differences of soil water potential lead to considerable differences of plant water potential and evapotranspiration rate.

REFERENCES

1. Allen R.G., Jensen M.E., Wright J.L., Burman R.D., 1989, Operational estimates of reference evapotranspiration. Agronomy Journal, 81:650-662.
2. Baranowski P., Lamorski K., Mazurek W., Walczak R.T., 2004, Determination of energetic status and evaporation from porous bodies on the base of infrared imaging. In Soil-plant-atmosphere aeration and environmental problems edited by Jan Gliński, Grzegorz Józefaciuk, Karl Stahr, Lublin - Stuttgart.
3. Baranowski P., Mazurek W., Walczak R.T., 1998, The investigation of actual evapotranspiration with the use of thermography. Quantitative Infrared Thermography QIRT'98, Politechnika Łódzka, 7-10.09.
4. Baranowski P., Mazurek W., Walczak R.T., 2001, The relation of actual to potential evapotranspiration as an indicator of plant water stress for meadow plant cover. Acta Agrophysica nr 53, 17-28.
5. Baranowski P., Mazurek W., Walczak R.T., 1999, Zastosowanie termografii do badania stresu wodnego roślin i ewapotranspiracji rzeczywistej. Monografia. Acta Agrophysica 21.

6. Bartholic J., Namken L., Wiegand C. 1972, Aerial thermal scanner to determine temperatures of soils and of crop canapies differing in water stress. Agron. J. 64:603-608.
7. Brown K.W., 1974, Calculation of ewapotranspiration from crop surface temperature. Agric. Meteorol. 14:199-209.
8. Brutseart W., 1982, Evaporation into the atmosphere. Kulwer Academic Publishers.
9. Businger J.A., Wyngaard J.C, Izumi Y., Bradley E.F., 1971, Flux profile relationships in the atmospheric surface layer. J. Atmos. Sci. 28, 181-189.
10. Gates D.M., Tantraporn W., 1952, The reflectivity of deciduous trees and herbaceous plants in the infrared to 25 microns. Science, 115:613-616.
11. Gliński J., Lipiec J., 1990, Soil physical conditions and plant roots. CRC Press, Boca Raton, FL.
12. Heilman J.L., Kanemasu E.T., Rosenberg N.J., Blad B.L., 1976, Thermal scaner measurement of canopy temperature to estimate evapotranspiration. Remote Sens. of Environm. 5:137-145.
13. Jackson R.D., Idso S.B., Reginato R.J., Pinter P.J., 1981, Canopy temperature as a crop water stress indicator. Water Resour. Res., 17, 4, 1133-1138.
14. Jackson R.D., Moran M.S., Gay L.W., Raymond L.E., 1987, Evaluating evaporation from field crops using airborne radiometry and ground based meteorological data. Irrigation Sci. 8, 324-332.
15. Łabędzki L., 1995, Evaluating crop water stress using infrared thermometry. Zesz. Probl. Post. Nauk Roln., 419, 69-73.
16. Mazurek W, Walczak R.T., Sobczuk H.A., Baranowski P., 1996, The model investigation of soil water content and soil water potential impact on radiation temperature of meadow plant cover. Zesz. Probl. Post. Nauk Rol. z.436:93-100.
17. Miller E.C., Saunders A.R., 1923, Some observation on the temperature of the leaves of crop plants. J. Agric. Res. 26:15-43.
18. Monteith J.L., Szeicz G., 1962, Radiative temperature in the heat balance of natural surfaces. Q. J. R. Meteorol. Soc., 88:496-507.
19. Penman H.L., 1956, Evaporation: An introductory survey. Neth. J. Agr. Sci., 9:9-29.
20. Penman H.L., 1948, Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London, A 193: 120-146.
21. Soer G.J.R., 1977, The TERGRA model - a mathematical model for the simulation of the daily behaviour of crop surface temperature and actual evapotranspiration. NIWARS publ. 46, Delft.
22. Stoll A.M., Hardy J.D., 1952, A method for measuring radiant temperatures of the environment. J. Appl. Physiol. 5:117-124.
23. Stone L.R., Horton M.L., 1974, Estimating ewapotranspiration using canapy temperatures: Field evaluation. Agron. J. 66:450-454.
24. Walczak R.T., Baranowski P., Mazurek W., Lamorski K., 2003, The analysis of infrared images to evaluate energetic status of agricultural porous media. 2nd International Workshop Applied Physics in Life ScienceCzech University of Agriculture Prague, Technical faculty, Department of Physics, Prague, 25th September.
25. Walczak R.T., Baranowski P., Mazurek W., 2003, Application of thermography in agrophysics. Materials of training course for young research workers "Physicochemical and physical methods of studies of soil and plant materials. Theory and practice" Centre of excellence AGROPHYSICS, IA PAS 27th November-2nd December.
26. Wiegand C.L., Namken L.N., 1966, Influence of plant moisture stress, solar radiation, and air temperature on cotton leaf temperatures. Agron. J., 58, 582-586.

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