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STUDIES ON THE EFFECT OF FREEZING ON STRUCTURE OF COMPACTED SOIL

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Summary. The influence of freezing processes on the structure of a compacted Haplic Luvisol, Mollic Leptosol, and Mollic Gleysol with use of morphological analysis was investigated. The freezing processes caused the evident alteration in the structure of the studied soils. The magnitude and tendency of the changes resulting from the low temperature effect depended on the soil type, the soil water potential prior to freezing, and the number of freezing-thawing cycles.

Keywords: soil, structure, compaction, freezing.

INTRODUCTION

Tilled soils are physically degraded to a high extent due to a compaction by wheels of agricultural machines and equipment. The degradation is manifested by an increase of the compactness of an arable layer and an impairment of soil structure, which cause in consequence alterations of soil physical properties, influencing substantially crop growth and yield and conditions of soil organism's life [6,16].

An intense tillage improves the macrostructure of the arable layer for a short time, but in a longer perspective it is a factor of degradation. The aggregates-fragments, which come into being by disintegration of bulk soil, are not water-resistant and disappear rapidly. For that reason a continuous loosening of the soil is required, and in consequence – the movement of heavy machinery over the soil surface [14]. Moreover, in the layer unaffected by the action of cultivation tools, the cumulating of stresses takes place, which induces the increase of the subsoil bulk density.

In order to find means of preventing such unfavourable phenomena, the comprehensive research had been performed, which regards among others the novel solutions of constructions of agricultural machinery or the introduction of the structure-stabilising substances into the soil. These projects demand however large financial support. In the climatic zone, where Poland is located, there exist a natural process, which requires no economical effort, and which improves the soil structure. That process is associated with periods of the frost during wintertime. The favourable effect of the freezing on the capability of soil mass for breaking up into aggregates after winter is observed in the agricultural practice for a long time [2,8,12,17]. Farmers attempt to encourage the action of the frost by deep tillage operations prior to winter. In that manner between the turned arable layer and the underlying soil an isolating layer of air is formed. By reason of the isolation, for a certain period of time, the temperatures below 0°C are present only in the arable layer, which freezes completely and during the spring ploughing easily falls apart into aggregates. It is during the winter season when the most pronounced changes in the soil structure, besides those influenced by tillage, occur [1].

The nature of the low temperature effect on the soil is not recognised thoroughly. In the present paper an attempt was made to evaluate the influence of freezing processes on the structure of typologically different and compacted soils in relation to the number of freezing-thawing cycles and the potential of the soil water prior to freezing.

MATERIALS AND METHODS

The investigation was performed on three typologically different soils:

- Haplic Luvisol, LVha [19] (a typical soil lessivé) derived from loess (Huta Turobińska 50°48′ N – 22°41′ E, West Roztocze, cultivated field);
- Mollic Leptosol, LPmo [19] (a chernozemic rendzina) derived from chalk (Sielec 51°02′ N – 23°32′ E, Chełm Hills, cultivated field);
- Mollic Gleysol, GLmo [19] (a mud-gley soil) derived from clay (Tarnawka 50°55′ N – 22°36′ E, Zamość Valley, meadow).

The samples of a partially disturbed structure were taken from the superficial seasoned soil layer of 0–10 cm. The soil was poured into rectangular metal boxes of 8×9×4 cm in size (12 for each soil) and compacted in the tri-axial compression apparatus with a pressure of 200 kPa for 2 seconds. By this method the soil samples were obtained, which characterised with a bulk density of 1.37 $Mg \cdot m^{-3}$ for Haplic Luvisol, 1.28 $Mg \cdot m^{-3}$ for Mollic Leptosol, and 0.88 $Mg \cdot m^{-3}$ for Mollic

Gleysol. The soils were compacted at the actual moisture (the moisture during sampling) that for Haplic Luvisol and Mollic Leptosol corresponded to $\Psi = -49.03$ kPa (water content 0.30 $kg \cdot kg^{-1}$ for both of the soils), and for Mollic Gleysol corresponded to $\Psi = -15.54$ kPa (water content 0.40 $kg \cdot kg^{-1}$). The next step was to stabilise the moisture of the compacted samples in the low-pressure chambers, at the two selected final soil water potentials. There were obtained 6 samples for each soil, characterised with the moisture content equivalent to the soil water potential of –0.98 kPa (pF 1.0) and –15.54 kPa (pF 2.2), respectively. Each two samples for each soil for each of the two soil water potentials were subjected to the single and triple freezing, and two samples for each soil were left as a reference (control without freezing). The freezing of the soil samples at the two moistures was performed in a refrigerator for 72 hours at the temperature –15°C. The temperature of the freezing was selected on the ground of the average temperatures recorded in the long term in the region of Lublin Upland, taking into account the lowest temperature occurring every year. The thawing took place at the room temperature during 48 hours.

Subsequently, the samples were dried at the room temperature and impregnated with a solution of polyester resin, according to the method described earlier [13,15]. After hardening, the blocks were cut in the vertical plane into plates of 8×9 cm and 1 cm thick. Their faces were polished, obtaining the opaque soil plates, which were then subjected to a morphological analysis.

As regards Haplic Luvisol, the pressure used during the preparation of the compacted samples caused the development of the regions of a very high bulk density, and thus the complete impregnation of those soil samples with the resin was impossible. Consequently, for each moisture value of these samples only one image of the soil structure was achieved.

From the polished opaque block faces the maximum differently sized regions of the best quality were chosen and scanned with the resolution of 600 dpi. The digitised photographs in 256 shades of grey were subjected to a thresholding with use of the program "Aphelion" (ADCIS SA, AAI Inc.). The threshold level was chosen on the basis of the brightness histogram and the comparison with the opaque soil blocks. The binary images were obtained, where the white colour corresponded to the soil phase and black – to the pores filled with the resin. Afterwards the binary images underwent a sequence of morphological and logical operations: opening (with square element of size 1) → not → opening → not. In that manner from the images the smallest objects of a cross-sectional area less than 6 $pixel^2$ (0.011 mm^2) – the noise – were removed. In consequence, in the images only the objects of an equivalent diameter of at least 117 μm were visible. In the current paper the selected binary images, representative for each state, were presented.

Moreover, in order to obtain the more detailed characterisation of soils, the following properties were determined: the granulometric composition by areometrical method of Bouyoucos and Casagrande with modifications of Prószyński; the soil particle density by pycnometric method; the total carbon content by Tiurin method with modifications of Simakov; the calcium carbonate content by Scheibler method.

RESULTS

The basic characteristics of the examined soils are given in Table 1.

Table 1. Basic characteristics of examined soils

Properties		Haplic Luvisol	Mollic Leptosol	Mollic Gleysol
Granulometric composition ($kg \cdot kg^{-1}$)	1–0.1 mm	0.01	0.17	0.01
	0.1–0.02 mm	0.58	0.18	0.22
	< 0.02 mm	0.41	0.65	0.77
	< 0.002 mm	0.09	0.35	0.46
Soil particle density ($Mg \cdot m^{-3}$)		2.61	2.45	2.31
Total organic carbon ($g \cdot kg^{-1}$)		8.00	21.50	45.20
Calcium carbonate ($g \cdot kg^{-1}$)		0	190	0

The compacted unfrozen samples of Haplic Luvisol had a massive, microporous structure (Fig. 1a, 1d). On account of the freezing, changes were observed exclusively in the structure of soils of the higher soil water potential, $\Psi = -0.98$ kPa (water content 0.35 $kg \cdot kg^{-1}$).

The changes regarded particularly the soil frozen once (Fig. 1b), although were also visible in the soil frozen three times (Fig. 1c), and included the development of many linear or curved, smooth-walled fissures of a varied direction. In the samples of Haplic Luvisol, frozen at the lower soil water potential, $\Psi = -15.54$ kPa (water content 0.30 $kg \cdot kg^{-1}$), the massive, monolith structure dominated, with a minor number of tiny pores, frequently of a round cross-section, Fig. 1e, 1f. In comparison with the unfrozen soil, no evident differences between the latter and the frozen soil were detected.

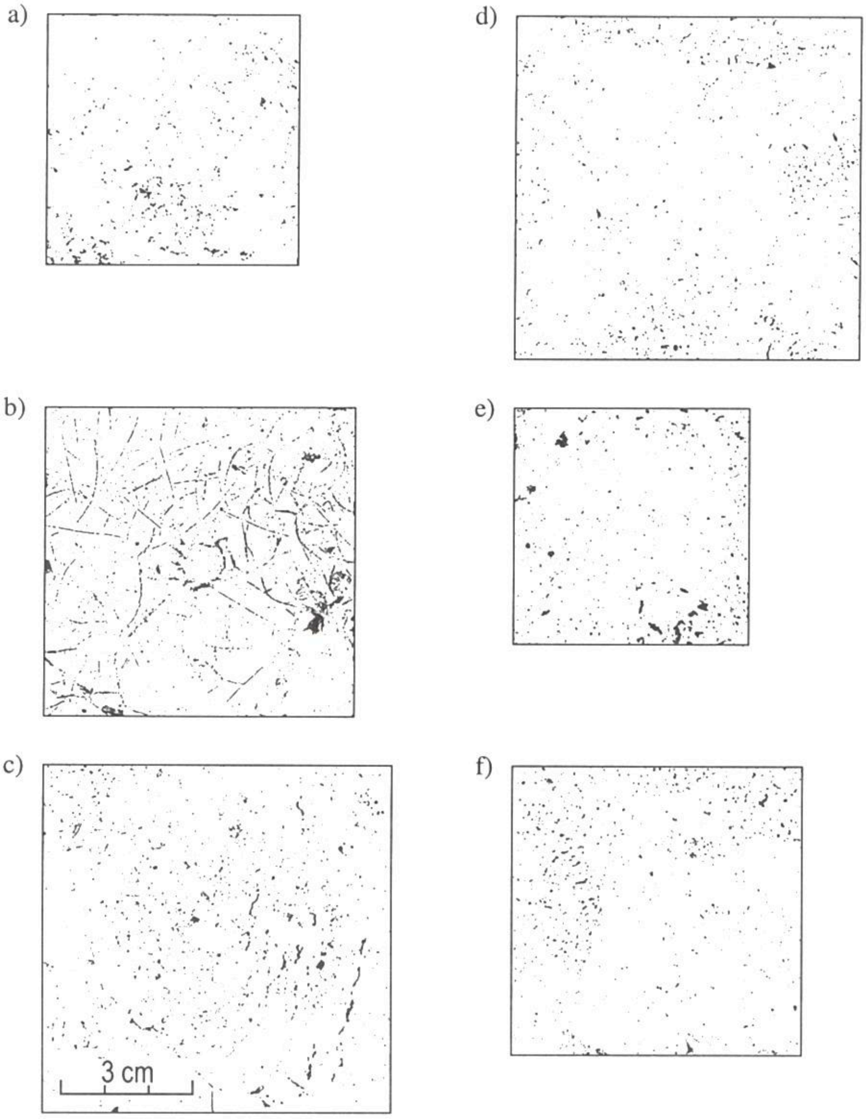

Fig. 1. Binary images of Haplic Luvisol structure. Left panel: the soil at the moisture equivalent to $\Psi = -0.98$ kPa: (a) unfrozen; (b) frozen once; (c) frozen three times. Right panel: the soil at the moisture equivalent to $\Psi = -15.54$ kPa: (d) unfrozen; (e) frozen once; (f) frozen three times. White colour – solid, black – pores.

The compacted unfrozen Mollic Leptosol was characterised with a consolidated massive structure, many second-order pores, however, were discernible as well, Fig. 2a, 2d. The single freezing caused the creation of numerous fissures, which quantity and size depended on the soil water potential during the freezing process. The best-formed smooth-walled fissures appeared in the soil frozen at the field water potential ($\Psi = -15.54$ kPa), that is at the water content of 0.31 $kg \cdot kg^{-1}$, Fig. 2e. It ought to be mentioned however, that between the fissures the soil mass revealed a compacted structure. In the soil samples frozen at the higher water potential, $\Psi = -0.98$ kPa (water content 0.34 $kg \cdot kg^{-1}$), no such a visible net of fissures developed, but abundant minor pores were formed, which were evenly distributed in the whole soil volume, Fig. 2b.

In the Mollic Leptosol frozen three times the differentiation of soil structure on account of the value of the soil water potential during freezing was even more apparent. Both in the soil frozen at the water potential –15.54 kPa (Fig. 2c), and –0.98 kPa (Fig. f), there were formed large cavity-type pores, which characterised with irregular shapes and unaccommodating opposite walls. However, the number of such pores was considerably higher in the samples frozen at the lower water potential. Consequently, in some areas of those samples a semi-aggregate to aggregate structure evolved.

The unfrozen Mollic Gleysol (Fig. 3a, 3d) was characterised, in spite of compacting, with an aggregate or semi-aggregate structure with an abundance of irregular, mostly interconnected, inter-aggregate pores. The intra-aggregate porosity was however low. The single freezing of the soil (Fig. 3b, 3e), both at the higher, $\Psi = -0.98$ kPa (water content 0.55 $kg \cdot kg^{-1}$), and at the lower water potential, $\Psi = -15.54$ kPa (water content 0.47 $kg \cdot kg^{-1}$), caused the reorganisation of soil structure. It consisted in the partial disappearance of aggregates and the development of many short and narrow pores-fissures. In addition, an insignificant number of irregular and elongated fissures was detected. After the triple freezing of Mollic Gleysol at the higher water potential (Fig. 3c) the soil characterised with an aggregate structure, similarly to the control (unfrozen) soil, but the aggregates were smaller and revealed a higher internal porosity. As a consequence of the triple soil freezing at the lower water potential, a structure appeared, which was comparable to the structure resulted from the single freezing, although in the former some areas of an evident aggregate structure emerged additionally, Fig. 3f.

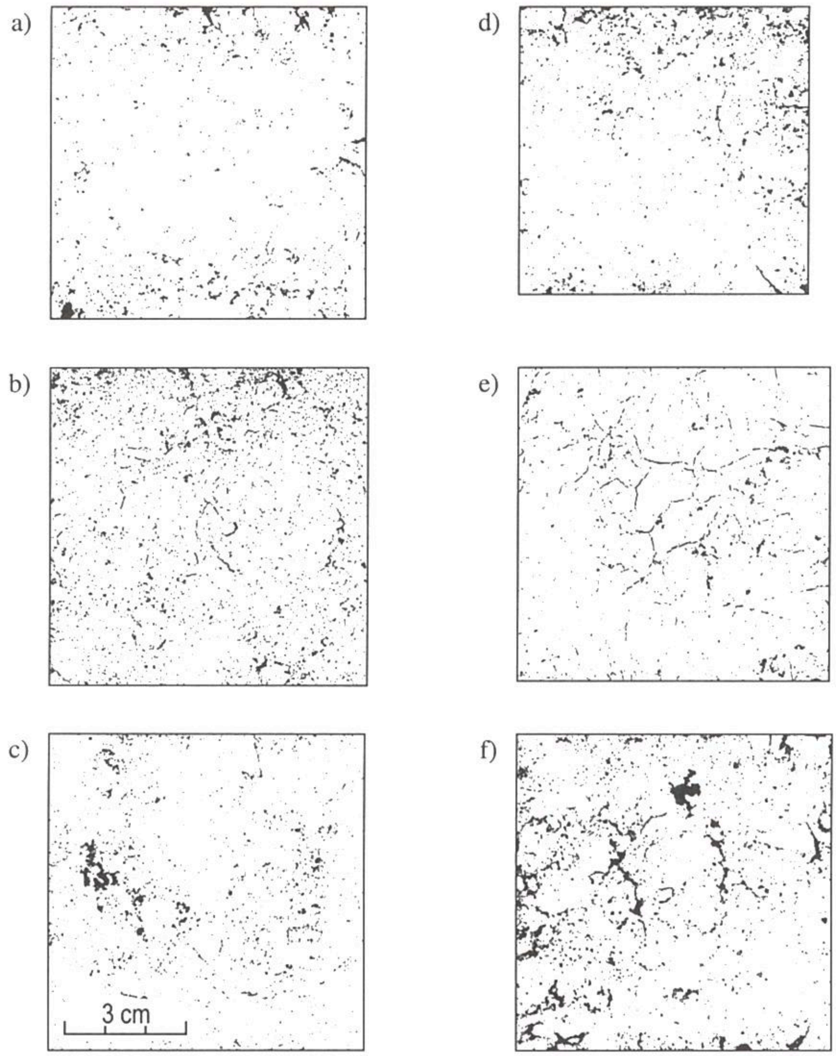

Fig. 2. Binary images of Mollic Leptosol structure. Left panel: the soil at the moisture equivalent to $\Psi = -0.98$ kPa: (a) unfrozen; (b) frozen once; (c) frozen three times. Right panel: the soil at the moisture equivalent to $\Psi = -15.54$ kPa: (d) unfrozen; (e) frozen once; (f) frozen three times. White colour – solid, black – pores.

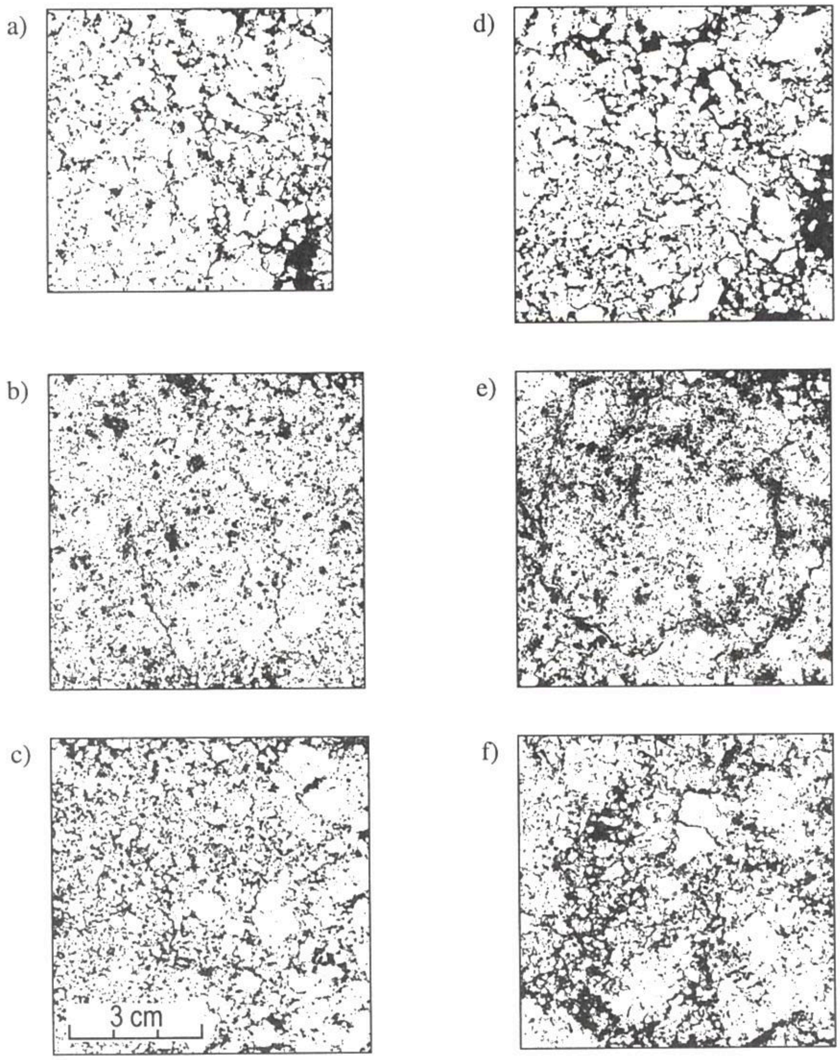

Fig. 3. Binary images of Mollic Gleysol structure. Left panel: the soil at the moisture equivalent to $\Psi = -0.98$ kPa: (a) unfrozen; (b) frozen once; (c) frozen three times. Right panel: the soil at the moisture equivalent to $\Psi = -15.54$ kPa: (d) unfrozen; (e) frozen once; (f) frozen three times. White colour – solid, black – pores.

DISCUSSION

The obtained results enable to state that both the emergence of soil structure alteration caused by the freezing and the direction of that alternation were diverse and depended on the soil type, the soil water potential prior to the freezing and the intensity of the freezing process.

Mollic Leptosol revealed the most pronounced reaction to the freezing. As early as at the moment of freezing of the soil samples a noticeable lifting of the soil mass was observed, which proved the segregation of ice. Despite the return of the soil mass to the state preceding the freezing process, and even the slight decrease of the sample volume, the fissures in which the lenticularly shaped ice crystals were formed were clearly visible in the opaque Mollic Leptosol blocks. The morphological analysis revealed that the greatest changes took place in the soil samples frozen at the field water capacity.

The strong alternations caused by the freezing in Mollic Leptosol could be with no doubt related to the three advantageous factors. The first of them was the loamy granulometric composition of the soil material, allowing for the high retention of water and the presence of reasonably large pores favouring an initiation of ice lens formation. Van Vliet-Lanoë [18] stated that the optimum conditions for the process of ice segregation existed in the loamy soils. The other factor were the presence of calcium carbonate and the saturation of the sorptive complex with Ca^{2+} ions, which are characteristic for calcareous soils. The increase of structure stability of the frozen soils in the presence of exchangeable cations was confirmed by many researchers [4,10,11]. The third factor, that definitely strengthened the influence of the frost, was a high value of total carbon ($21.5\ g \cdot kg^{-1}$). The freezing led to dehydration and coagulation of soil colloids and consequently intra-aggregate bonds reinforced.

The morphological analysis of Haplic Luvisol samples revealed that by reason of the single freezing a net of fissures was formed in the samples of the higher soil water potential. Other authors investigating the influence of freezing on the soils of similar granulometric composition obtained diversified results. Florkeimeier et al. [3] exploring the effect of the frost on loess soils stated, that multiply freezing-thawing cycles at miscellaneous temperatures failed to increase the porosity. The frost action in a compacted soil resulted in the loosening of the soil due to a growth of the macropore number, but caused no improvement of a compacted first-order structure. Konrad [9], on the other hand, determined that the freezing cycles increased the porosity of clayey silt, regardless on its degree of compaction, and consequently that soil after thawing was characterised with an increased vertical water permeability. These changes occurred after three cycles of freezing.

The third of the investigated soils, Mollic Gleysol, was characterised with the finest granulometric composition (clay) and a relatively large total carbon content. These factors determined to a high degree the structure and physical status of the soil and, moreover, its reaction to the freezing. It is worth mentioning that, on the contrary to Haplic Luvisol and Mollic Leptosol, the compacting of Mollic Gleysol samples did not destroy their aggregate structure. The morphological analysis of Mollic Gleysol structure after the single freezing revealed a reorganisation of the soil material constitution associated with a partial consolidation of the soil mass and a simultaneous formation of large irregular fissures. The observed phenomenon might be related to the described in the literature [5,7] frost-dehydration of pores and dehydration of soil colloids.

CONCLUSIONS

The freezing processes caused the evident alteration in the structure of the studied soils. The magnitude and tendency of the changes resulted from the low temperature effect depended on the soil type, the soil water potential during freezing, and the number of freezing-thawing cycles.

The soil most susceptible to the freezing was Mollic Leptosol, where the majority of advantageous changes occurred, particularly in the samples frozen at the field water capacity.

As concerns Haplic Luvisol, the beneficial changes took place only in the samples of the high water potential and consisted in the formation of the pores of a fissure type.

In Mollic Gleysol, in reaction to the freezing, the evident reorganisation of soil material occurred, which was associated with a consolidation of selected sections, nevertheless the fundamental soil structure type did not change.

REFERENCES

1. **Bullock M.S., Kemper W.D., Nelson S.D.:** Soil cohesion as affected by freezing, water content, time and tillage. Soil Sci. Soc. Am. J., 52, 770–776, 1988.
2. **Fitz Patrick E.A.:** An indurated soil horizon formed by permafrost. J. Soil Sci., 7, 248–257, 1956.
3. **Florkemeier H., Frede H.G., Meyer B.:** Lockerung dichter Aggregate loessgebürtiger Boden durch Frost. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft, 59, 145–150, 1989.
4. **Gardner R.:** Some effects of freezing and thawing on the aggregation and permeability of dispersed soils. Soil Sci., 60, 437–443, 1945.
5. **Hartge K.H., Horn R.:** Einführung in die Bodenphysik. Ferdinand Enke Verlag, Stuttgart, 303, 1991.
6. **Horn R., Domżał H., Słowińska-Jurkiewicz A., van Ouwerkerk C.:** Soil compaction

processes and their effects on the structure of arable soils and the environment. Soil Tillage Res., 35, 23–36, 1995.
7. **Kay B.D.:** Rates of change of soil structure under different cropping systems. Adv. in Soil Sci., 12, 1990.
8. **Kokkonen P.:** Beobachtungen über die Struktur des Bodenfrostes. Acta Forest. Fennica, 30, 1–55, 1927.
9. **Konrad J.M.** Physical processes during freeze–thaw cycles in clayey silts. Cold Regions Science and Technology, 16, 291–303, 1989.
10. **Norrish K., Raussell-Colom J.A.:** Effects of freezing on the swelling of clay minerals. Clay Miner. Bull., 5, 9–16, 1962.
11. **Perfect E., van Loon W.K.P., Kay B.D., Groenevelt P.H.:** Influence of ice segregation and solutes on soil structural stability. Can. J Soil. Sci., 70, 571–581, 1990.
12. **Sharp R.P.:** Periglacial involutions in Northeast Illinois. Journal of Geology, 50, 113–133, 1942.
13. **Słowińska-Jurkiewicz A.:** Structure and water and air properties of soils developed from loess (in Polish). Rocz., Nauk Roln., D218, 1989.
14. **Słowińska-Jurkiewicz A.:** Changes in the structure and physical properties of soil during spring tillage operations. Soil & Tillage Research, 29, 397–407, 1994.
15. **Słowińska-Jurkiewicz A., Domżał H.:** The influence of cultivation tools on the structure of soil arable layer (in Polish). Soil Science Annual, 35, 165–175, 1984.
16. **Soane B.D., van Ouwerkerk C.:** Soil compaction problems in world agriculture. [In] Soil Compaction in Crop Production (Eds B.D. Soane and C. van Ouwerkerk). Elsevier, Amsterdam, 1–21, 1994.
17. **Taber S.:** Frost heaving. J. Geol. 37, 428–461, 1929.
18. **Van Vliet-Lanoë B.:** Frost effects in soils. [In] Soils and Quaternary Landcape Evolution. (Ed. J. Boardman), Wiley, Chichester, 115–156, 1985.
19. **World Reference Base for Soil Resources**, FAO, ISRIC & ISSS, Rome, 1998.

BADANIA WPŁYWU PROCESÓW MROZOWYCH NA STRUKTURĘ GLEB UGNIATANYCH

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Streszczenie. Za pomocą analizy morfologicznej badano wpływ procesów mrozowych na strukturę ugniatanych gleb: gleby płowej, rędziny i gleby mułowo-glejowej. Procesy mrozowe spowodowały znaczące przeobrażenia w strukturze badanych gleb. Wielkość i kierunek wywołanych działaniem niskich temperatur zmian uzależnione były od typu gleby, potencjału wody glebowej przed mrożeniem i liczby cykli zamarzania-rozmarzania.

Słowa kluczowe: gleba, struktura, ugniatanie, procesy mrozowe.