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Changes in Physical and Chemical Soil Characteristics as a Result of Subsurface Tile Drainage

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Abstract

This project defined changes in soil properties after construction of subsurface tile drainage. We compared the physical and chemical properties of soil samples taken before construction of drainage and new soil samples taken from identical sites at present. The research was made for Stagnic Cambisols (Dystric) and Haplic Stagnosols. The pH value and saturation of the topsoil sorption complex of both soil types statistically increased and simultaneously the cation exchange capacity (CEC) decreased. In the topsoil of Stagnosols, the effective cation exchange capacity and porosity also decreased, and at the same time the particle density and bulk density increased. Soil organic matter and minimum air capacity increased in the topsoil of Cambisols. Porosity and minimum air capacity increased in both soils in the subsoil. In the Cambisol subsoil, the CEC and bulk density decreased. We can assume that after drainage Stagnosols are susceptible to soil compaction, especially in topsoil.

Keywords

Soil, Drainage, Soil Characteristics, Land Use Change

1. Introduction

Agricultural subsurface drainage, popularly known as tile drainage, is an essential water management practice in agricultural regions with seasonal, high water tables [1]. It is commonly used to improve the poor drainage capacities of agricultural fields [2]. In some areas of the temperate zone, drainage systems continue to be an essential tool of groundwater control [3]. This practice reduces the risk of water logging and soil erosion caused by surface runoff [2] and it ensures the most favourable development of plants and suitable conditions for tillage. Drainage stabilizes productivity by minimizing the variation in crop yields from year to year, and it results in a considerable reduction in the duration of over-wetting and over-flooding of the active soil layer [4]. The greatest drainage importance in the control of the soil water regime is in the winter and spring periods [5]. To achieve all these aims, drainage systems should be properly designed and adequately installed using appropriate materials [3].

Subsurface drainage has been practiced for thousands of years; however, rapid introduction in Europe and North America only started around 1940, when the prevailing empirical knowledge of drainage and salinity control gained a solid theoretical foundation. During the second half of the 20th century, drainage was implemented in about 150 million ha of under-producing and naturally waterlogged or saline lands. This resulted in important improvements that contributed to a considerable increase in food production. Drainage has also contributed to agricultural intensification and diversification and as such has made the agricultural sector more competitive and financially sustainable [6]. In the Czech Republic, 25% of the soil agriculture fund is drained; that is, an area of 1,084,000 ha of soil [7].

The drainage of agricultural soils was intended to improve the water and air conditions of soils. Therefore, it is very important to describe the changes in the physical and chemical properties of the soil affected by this ameliorative construction.

2. Materials and Methods

The Zelezna model area is located in the Domazlice district on the border with Germany (49˚34 - 35'N, 12˚34 - 36'E). From a geological point of view, it belongs to the crystalline or moldanubic massif of the Bohemian Forest (Cesky Les), with a predominance of cordirietic gneiss and silmanitic-biotitic migmatised paragneiss with cordierite. The area falls within the moderately cool and wet climatic region [8].

The majority of its soil cover (approx. 40%) consists of Stagnic Cambisols (Dystric), Haplic Stagnosols make up about a quarter of the soil cover, Haplic Gleysols almost one fifth, and Endogleyic Stagnosols one tenth. The remainder of the soil cover consists of Histic Gleysols, Cambisols (Dystric), and Gleyic-Stagnosol [9]. The drainage network comprises natural streams (the Nivni, Farsky, and Lesni), and man-made canals. The study area lies within the drainage basin of the Danube. In the 1970s, the area was drained systematically using subsurface tile drainage with the aim of improving the physical state of the soil and water regime of the agricultural land.

A detailed hydropedological survey was carried out in the 1970s by the State Land Reclamation Authority [10] [11] to provide a background for the drainage construction. The previous data of soil properties before drainage were found in The Comprehensive Soil Survey of Czechoslovak Soils and other soil investigations in the model area [12] [13] [14].

The systematic pipe drainage system was formed by flexible plastic perforated pipes (we obtained the original construction plans). Due to a susceptibility to silting, the pipes were covered with glassfabric. The spacing of the drains depended on the water-logging level of the soil and varies between 7.5 and 11 m, and the depth of the pipe placement was 1m. The system is still functional. After the drainage had been built, the agricultural areas were used as arable land, but since the 1990s they have been used as pasture (**Figure 1**). The fertilization of the Zelezna study area is extensive analogous to farming intensity. Carbamide is applied during spring time on the pastures (trefoil grasslands). The grasslands are fertilized by potassium with a fertilizer rate of 50 kg/ha and by phosphorous with a rate of 30kg/ha during their reclamation.

The detailed hydropedological survey was carried out in Zelezna before drainage construction in 1974 (old data). The new soil samples were taken in 2006 at the same places as the former soil pits in 1974 (new data). These two sets of data were subsequently statistically compared (T-test). We determined the same physical characteristics as in 1974 and used the same analytical procedures as in the first datasets to have two comparable sets of data. The results were processed by the MS Access database program and statistically evaluated by a paired t-test at a significance level of $\alpha_{0.05}$ or $\alpha_{0.1}$ (in this case, the index is attributed in the table) in the Unistat program. We performed this process for the topsoil and also for the subsoil for two of the most widespread soil types-Stagnic Cambisols (Dystric)-11 soil pits, and Haplic Stagnosols-6 soil pits.

Figure 1. Zelena model area (overview) (author's own photography).

From each soil pit we took a disturbed sample to evaluate the soil chemical properties, namely **Exchangeable soil reaction $\mathrm{pH_{KCl}}$** [15] the **Percentage of soil organic matter** SOM [16] [17] the **Cation exchange capacity** $\mathrm{CEC_{pH8.1}}$ [18] the **Effective cation exchange capacity** ECEC [19] and the **Saturation of sorption complex** (calculated value).

In addition, we took away 3 undisturbed soil samples from each horizon, we set aside samples that were statistically different, and then we calculated the average value from the rest of the samples. The undisturbed samples were taken by steel cylinders of 100 $\mathrm{cm^3}$ (Kopecky's rings) to determine the following soil physical properties: **Particle density** (PD)—the weight of a unit volume of soil without pores [20], **Bulk density** (BD)—the weight of a unit volume of dry soil [21] and **Maximum capillary water capacity** (θ_{CMC})—% volume of capillary soil pores which corresponds approximately to the field water capacity (θ_{FC}), determined in the laboratory using an empirical procedure according to Novak [22]. Its determination is based on the mass change after 2 h water suction from Kopecky's ring fully soaked with capillary water on dry filter paper. The last physical property is **Porosity** (P) which is defined as the volume of the sample in natural deposition not filled with solid particles, established by means of the formula:

$$P = \left(PD - BD\right)/PD * 100$$

The basic soil characteristics of the compared soils are shown in **Table 1**.

3. Results and Discussion

The statistical evaluations of data sets are shown in **Table 2** and **Table 3**.

Table 1. Basic average soil characteristics of the Zelezna model area at present.

Study area	Soil [9]	horizon	Particle size distribution <0.002 (mm)	<0.01 (mm)	0.01 - 0.05 (mm)	0.05 - 2 (mm)	SOM (%)	pH KCl	CEC ($\mathrm{mmol^{(+)}}$/100 g)
Zelezna	Stagnic Cambisol (Dystric)	Ah	11.9	22.4	15.1	62.5	2.0	5.22	13.4
		Bwg	7.1	10.0	9.1	80.9	0.3	5.25	9.7
	Haplic Stagnosols	Ah	10.7	31.1	31.4	37.5	3.6	5.45	31
		Bg	17.2	24.2	21.0	54.8	0.3	5.26	11.2

Study area	Soils [9]	horizon	Saturation of sorption complex (%)	ECEC $\mathrm{Ca^{2+}}$ ($\mathrm{mmol^{(+)}}$/100 g)	$\mathrm{Mg^{2+}}$	$\mathrm{K^{+}}$	Particle density ($\mathrm{g/cm^3}$)	Bulk density ($\mathrm{g/cm^3}$)	P (%)
Zelezna	Stagnic Cambisol (Dystric)	Ah	81	7.52	0.82	0.29	1.47	2.66	46.4
		Bwg	69	6.91	0.83	0.22	1.54	2.72	43.4
	Haplic Stagnosols	Ah	73	20	6.46	0.37	1.00	2.37	59.4
		Bg	87	4.37	5.01	0.3	1.55	2.72	43.1

Table 2. Changes of soil properties of Stagnic Cambisols (Dystric) (n = 11).

Stagnic Cambisols (Dystric)	topsoil		average old data	% change	subsoil		average old data	% change
Significance level *α*	0.05	0.1			0.05	0.1		
pH_{KCl}	▲		4.3	17.5	▲		4.1	15.7
Soil organic matter (%)	▲		2.4	46.1	ø			
Cation exchange capacity ($\text{mmol}^{(+)}$/100 g)	▼		25.8	39.7	▼		18.3	49.5
Effective cation exchange capacity ($\text{mmol}^{(+)}$/100 g)	ø				ø			
Saturation of sorption complex (%)	▲		36.9	40.2	ø			
Porosity (%)	ø				▲		40.8	12.5
Particle density (g/cm^3)	ø				ø			
Bulk density (g/cm^3)	ø				ø	▼	1.6	8.4
Minimum air capacity (%)	▲		5.3	128	▲		7.0	151.5

Explanations: Ø—statistically inconclusive; ▲—statistically conclusive increase; ▼—statistically conclusive decrease.

Table 3. Changes of soil properties of Haplic Stagnosol (n = 6).

Haplic Stagnosols	topsoil		average old data	% change	subsoil		average old data	% change
Significance level *α*	0.05	0.1			0.05	0.1		
pH_{KCl}	▲		4.0	26.6	ø			
Soil organic matter (%)	ø				ø			
Cation exchange capacity ($\text{mmol}^{(+)}$/100 g)	▼		31.3	43.0	ø			
Effective cation exchange capacity ($\text{mmol}^{(+)}$/100 g)	▼		11.5	7.3	ø			
Saturation of sorption complex (%)	▲		31.4	90.0	ø			
Porosity (%)	▼		65.4	20.4	▲		33.3	23.7
Particle density (g/cm^3)	▲		2.4	5.1	ø			
Bulk density (g/cm^3)	▲		0.8	47.3	ø			
Minimum air capacity (%)	ø				▲		1.3	513.0

Explanations: Ø—statistically inconclusive; ▲—statistically conclusive increase; ▼—statistically conclusive decrease.

3.1. Topsoil of Stagnic Cambisols (Dystric)

There was a statistically conclusive increase in the pH value in the topsoil of Cambisols during the last 30 years. Despite this increase, all soil pits in the model area were still acidic or strongly acidic. The increase in the value of soil reaction was probably caused by ameliorative liming, which was applied after the drainage construction, and by liming of the area during intensive farming. It was also caused by the decreasing of soil acidification, because there is only better humification of the soil organic matter in sufficiently aerated soils. Thus, it prevents production of fulvo acids which decrease the soil pH value.

The soil organic matter (SOM) content statistically increased in the topsoil of Cambisols. During intensive cultivation of the arable land there was a higher loss of soil organic matter compared to the areas extensively managed. The area of previous soil pits have been used as pasture during the last 15 years, so vegetation consists of grasses or a grass-legume mixture. The increase of the SOM was probably caused by the accumulation of organic matter in the topsoil (remediation of vegetation, better humification...) after the land use change. It is very interesting that there was a more significant increase of the SOM in almost all the soil pits taken during the hydropedologic survey in 1974 on the arable land compared to the other soil pits. This was caused by the already lower SOM content in these soils before drainage construction, due to losses of soil organic matter during their more intensive land use.

The value of the cation exchange capacity (CEC) characterises soil sorption ability. There was a statistically conclusive decrease in this characteristic in the topsoil of Cambisols. The change of content of the effective cation exchange capacity (ECEC) was statistically inconclusive over 30 years. We can state that, except for 2 soil pits, there was a decrease in the value of the effective cation exchange capacity, but the change was not conclusive.

The saturation of sorption complex is defined as the ratio of the value of the effective cation exchange capacity to the cation exchange capacity. There was a statistically significant increase in the value of this characteristic. According to the saturation value, most soils belonged to the same evaluated group as in 1974. The soil pits were mostly taken on the upper parts of steep terrains. The decrease in the value of the CEC could be caused by decreasing one of the content of sorption complex during intensive farming. Whereas the soil organic matter content of most of the soil pits increased, there must have been a decrease in the content of fine particles, probably washed off by erosion. Simultaneously, there should have been a decrease in the content of organic matter, which was not shown in our results. So the intensive erosion must have occurred in the period after drainage. In the nineties, the arable land was converted to permanent grassland. After stabilisation of the soil by grassing, the erosion features and accumulation of organic matter were eliminated.

Concerning the physical soil characteristics of the topsoil of Cambisols, there was only one statistically conclusive change-the increase of minimum air capacity. The increase of this value was caused by drainage, and thus it enabled air to enter the soil pores. Apart from this change, some trends and continuities were found in the physical characteristics. Four soil pits showed an increase in porosity after drainage, which was probably caused by better biological activities and the higher presence of plant roots in the topsoil. The soil structure was stabilised by the activities of soil flora and fauna, which was confirmed by an increase in the values of minimum air capacity. Along with these changes, there was also a decrease in the maximum capillary capacity. With regard to the increase in porosity, there was probably an increase in the number of macro pores. The soil pits which showed an increase in porosity value also indicated an increase in bulk density. The decrease in porosity compared to the soil samples taken in 1974 was shown in the soil pits which were significantly influenced by water. There were significant marks of pseudogleyzation by means of the frequent appearance of Fe-Mn nodules in the topsoil. The soil structure of waterlogged soils was less stable according to our conclusions and after drainage caused the disintegration of structural elements, which consequently had an influence on the decrease in porosity. This was confirmed by the increase in particle density and bulk density.

3.3. Subsoil of Stagnic Cambisols (Dystric)

There was a statistically conclusive increase in pH value in the subsoil of drained Cambisols. The pH value was also influenced by liming of the drained soils in the subsoil, where carbonates were leached from the topsoil. Moreover, the better the aerobic conditions, the better the decomposition of organic matter and suppression of production of easily movable fulvo acids, which decrease the soil pH. The change in the SOM content of the subsoil was not statistically significant, but there was a decrease in its content in most of the soil pits. The SOM content there was very low (eventually low). After drainage, mineralization was accelerated due to the development of aerobic soil microflora caused by the increasing air content in the subsoil. This confirmed the statistical increase in minimum air capacity.

There was a statistically conclusive decrease in the cation exchange capacity. The content of fine particles statistically decreased in all of the soil pits. In most of the soil pits, with a decrease in the CEC, the contents of the effective cation exchange capacity and the soil organic matter also decreased. The loss of the SOM could be caused by a change in the conditions after drainage of the Cambic Bw horizon. The soil aeration increased (an increase in the minimum air capacity) and hence the development of aerobic soil microflora was supported, and subsequently caused an increase in mineralization and a decrease in the SOM content. The losses of the effective cation exchange capacity and fine particles were explained by moving these particles throughout the soil profile; this confirmed a significant decrease in porosity in the third horizon and an otherwise inconclusive, but prevailing increase in the value of effective cation exchange capacity.

The value of porosity and the minimum air capacity statistically increased (both at significance level $\alpha_{0.05}$) during the 30years after drainage, while the value of bulk density (at significance level $\alpha_{0.1}$) statistically decreased. The reason for the increase in porosity value was better biological activity and a higher presence of plant roots in the Bw horizon, which couldn’t have been done before drainage due to waterlogging, which prevented the development of soil microflora and fauna. The statistical increase in minimum air capacity is caused by drainage water from pores, better permeability, and movement in the soil profile.

3.4. Topsoil of Haplic Stagnosols

The pH (KCl) value statistically increased in the topsoil of all Haplic Stagnosols during the 30 years after drainage. This increase was caused by several factors. The first was liming with the purpose of improving soil conditions for cultivation. Due to aeration, in the previously waterlogged soils there was faster mineralization, better conditions for humification, and soil microflora could develop. In the soils with insufficient oxygen there is imperfect decomposition of soil organic matter. During this process fulvo acids are produced which decrease the pH value.

The change in the soil organic matter content was statistically inconclusive. However, in most soil pits there was a decrease in the SOM content compared to 1974. We can explain this by the mineralization of the accumulated soil organic matter in the subsoil of previously waterlogged soil. If there is a lack of air during mineralization, it stops in intermediate products, which are accumulated till a change in the aerobic conditions in the topsoil (or can be moved throughout the soil profile). In comparison with Cambisols, the trend of Haplic Stagnosols was the opposite. Both soil types had been used since the 1990s as perennial pastures. The decreasing trend of the SOM content was caused by several factors. After the intensive management and ploughing of drained Stagnosols, there was significant mineralization of the accumulated organic matter. After the land use change (during the last 15 years), the SOM content started to increase and we can assume that this content will keep rising.

According to the physical soil characteristics (see below) there was soil compaction which influenced the growth of vegetation. This means there were not good conditions for sufficient root growth, so the roots were not able to penetrate to deeper soil depths. These features were confirmed on excavated soil pits in the terrain.

There was a statistically significant decrease in the value of the cation exchange capacity and the effective cation exchange capacity during the 30 years after drainage of Stagnosols. The value of saturation of the sorption complex statistically significantly increased compared to 1974. A decrease in the value of the CEC from a very high capacity to the values of medium capacity was observed in three soil pits. These were lighter soils than the others or these soils belonged to soils with a higher content of coarse fragment. Only these soils were situated on the terrain slopes to 3˚ (the others are in lowland). There was also a decrease in the value of the minimum air capacity in these soils. We can assume that after drainage of the pores, mineralization was performed there with the highest intensity. The decrease in the CEC value can be explained by the loss of organic matter after drainage (also partially by erosion). The increase in the ECEC was logically related to the changes in the contents of the ECEC and CEC. The slight decrease of the effective cation exchange capacity and the marked decrease of the ability of the cation sorption correspond to the statistically conclusive change in the effective cation exchange capacity.

The value of bulk density and particle density statistically increased in the topsoil of Stagnosols, while the porosity statistically decreased (by 20% on average).

The Haplic Stagnosols in our model area were greatly influenced by water, which was confirmed by the presence of pseudogleyzation features (Fe-Mn concretions, oxidizing coatings) formed in the whole soil profile. From the original soil reports we have found that there was hydrophilic vegetation, birch seeding, and springs in this model area. The pores in the topsoil were mostly filled with water for most of the year. Of course, it influenced the production of soil structure and its stability, which couldn't be formed in the acidic conditions without good quality soil organic matter and enough calcium. After the drainage, there was a lot of traversing in this area within the intensification of farming. Due to the unstable structure with heavier soil texture, technogenic soil compaction occurred. This was confirmed in our excavated soils, both in the terrain and in the lab (a statistically significant increase in the values of particle density and reduced soil volume).

3.4. Subsoil of Haplic Stagnosols

The change in pH (KCl) value was not statistically conclusive in the subsoil of Haplic Stagnosols. It was obvious that liming, which influenced the pH value of the topsoil, didn't have a significant influence on the subsoil. Most of the carbonate fertilizers were bounded by fulvo acids, which caused an increase in the pH value of the topsoil, and at the same time were not able to influence the lower soil horizons. Moreover, the subsoil was compacted, with no biological activity and low porosity. This prevents the movement of base cations and thus has a significant impact on the pH value in the subsoil.

A statistically inconclusive change was found in the soil organic matter content. The SOM content in Haplic Stagnosols was also very low 30 years after drainage. The values of particle density showed enrichment of this soil horizon by ferrum (the values are higher than 2.7 g/cm^3). This horizon was waterlogged for most of the year and showed minimal biological activity and no presence of rootage, which corresponded to the SOM content. None of the soil sorption characteristics showed significant change. The CEC value decreased in all soil pits, which corresponded to the content of fine particles fraction, specifically by the clay fraction, which moved down into the soil profile.

The values of porosity and minimum air capacity were statistically significantly increased after drainage. The value of porosity increased about 23.7%. This was caused by the development of soil flora and fauna after the drainage of Stagnosols. The subsoil horizons were waterlogged for most of the year and didn't allow roots to move down into the profile, which, together with the soil compaction (high values of particle density caused by a higher content of ferrum), didn't enable soil organisms to penetrate into the deeper parts of the soil profile. The compact subsoil structure was partly disturbed by drainage and ploughing. The increase in minimum air capacity enabled soil microflora and fauna to partly stabilize the soil structure (soil pores).

4. Conclusions

The pH value increased in the topsoil of Stagnic Cambisols (Dystric). This was influenced by ameliorative liming after the drainage construction and liming during farming. The value of the cation exchange capacity statistically decreased. The value of the saturation of sorption complex statistically increased. The change of content of the effective cation exchange capacity was statistically inconclusive over 30 years, which means one of the parts of the sorption complex decreased—probably by washing off the fine particles during the use of the land as arable land in intensive cultivation. The soil sorption capacity was statistically increased. The soil organic matter content statistically increased there. There was one statistically conclusive change in the physical soil characteristics of the topsoil of Cambisols—an increase in the minimum air capacity. The second Bw horizon of Cambisols was also influenced by intensive and frequent liming. The pH value statistically increased there. A statistically conclusive decrease in the CEC value was probably the result of erosion and movement of fine particles down the profile after drainage and deforestation. This corresponded to a decrease in the porosity value in the third horizon. The value of porosity and the minimum air capacity in the second horizon were statistically increased, while the value of bulk density statistically decreased.

In the topsoil of Haplic Stagnosols the pH value statistically increased, and the change in the SOM content was statistically inconclusive. The statistically conclusive decrease in the value of the cation exchange capacity and the effective cation exchange capacity value was probably caused by erosion (loss of the fine particle-size fraction) and by leaching and washing off during intensive farming. The value of porosity statistically decreased, while the value of bulk density and particle density statistically increased, which reflected soil compaction and was the result of the use of heavy machinery and intensive tillage. According to these conclusions we can assume that the reclaimed and drained Stagnosols are more vulnerable to such types of soil degradation. In the subsoil of Haplic Stagnosols, the change in pH value was not statistically conclusive, likewise for the SOM content. The values of porosity and minimum air capacity were statistically significantly increased after drainage.

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