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CASE STUDY

Soil use practices for sustainable agricultural land and water management

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Abstract – This paper presents experimental results focused on measures increasing water infiltration into the soil profile and higher water holding capacity of the land. It is important from soil and land protection point of view against both drought and floods.

Keywords – soil use, subsoiling, water infiltration, soil water holding capacity

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Introduction

Soil is the most important water storage in nature. It means that water content in soil is a very significant parameter of the water regime of the country which depends on soil area acreage and quality of the soil. Lower acreage of soil and lower soil quality lead to less water content in the country and vice versa. Because both, acreage and quality of soil, still depend more and more on human activities (agriculture, forest management, soil sealing) those influences are still more important factors of water regimes of land. Mainly agriculture has a leading position in the soil water regime from positive and/or negative points of view. It is due to permanent influences of agriculture on soil by many used operations inside the realized farming systems. Because not only soil degradation but also soil improvement could be observed as a result of soil use by agriculture it can be a good motivation of looking for relevant farming systems which can bring positive effects on water regime of the country.

During the past decades, several approaches have been used in agricultural practices which brought a decrease of water infiltration intensities into the soil profile and lower water quantities accumulated by soil. Harmful is mainly soil compaction. It is the result of heavy machine use, lack of organic matter application into the soil and not enough deep root plants share in the structure of agricultural crop rotation. As a result of this situation, less water in the soil is offered for agriculture and for many essential needs of nature as well. Simply, drought is a more and more dangerous phenomenon of agricultural land. Moreover, in case of heavy rainfalls in areas of compacted soil frequencies and flooding accidents are more often observed.

All can be presented by existing data published in several key documents. For example, in Slovakia, about 600 thousand ha of agricultural land (at least 30 % of the total area) is compacted which decreases the total water infiltration into the soil on level 100 mill. of m^3 (Bielek 2014). It is about 10 % in comparison to the total volume of all Slovakian artificial water reservoirs (54 reservoirs, www.sazp.sk). It means that loss of water due to lower soil water holding capacity of compacted soils in Slovakia is relevant to about 5 existing Slovakian artificial national water reservoirs. Total average potential of water infiltration into the whole Slovakian soil cover is about 11 billion m^3 per year (Šútor 2003). The decrease of yields due to soil compaction and water deficiency in Slovakia is estimated to 10 - 40 % depending on the degree of compaction (Houškova 1999). The relatively high share of light soils in Poland (60.8 % in comparison to 31.8 % in EU), and low level of precipitation yields are also decreasing due to low water retention in soils (Kedziora 2015). WOFOST method of evaluation declared that potential yields in

Poland are limited due to soil moisture shortage by 46.9 % for winter wheat, 42.9 % for spring barley, 60 % for winter rape and 58.9 % for potatoes. A significant decrease in water content in soil has simultaneously another negative impact on nature and society. On the other hand, lower soil water holding capacity can contribute to more often flood appearance. As far as water content, the special situation is in Slovenia (Mihelič 2015). There is high precipitation (1567 mm per annum) but soil drought is also a problem in this country, mainly in Sava, Savinja, Drava and Mura river basins. It is due to shallow soils, higher skeleton, and sand contents, and low soil organic matter content as well. Simply, water is not only "blue gold" for nature and society (Barlow and Clark 2002) but also dangerous medium against both. "Fighting for water saving and against water threats" started to be the fundamental principle of water management theory and practices in many countries and soil has a critical position in this philosophy.

Theoretical background

Regulation of water regime in soil is required by farmers mainly. Both, draining and irrigation technologies have been significantly developed and implemented into agriculture at the beginning of the past century. In the middle of this century, a new so-called "industrial agriculture" started to be well known using new farming systems and heavy machines in soil cultivation. Both have brought new progressive and effective practices in agriculture but at the same time led to soil degradation as well. Now, mainly soil compaction as physical degradation of soil is observed. Besides of negative influences of soil compaction on cultivated plants also soil water regimes have been deteriorated (especially heavy soils). Compacted soils are suffering from lower water infiltration into the soil profile, lower soil and country moisture, higher surface water removal from the soil cover and increased intensity of floods. It is more dangerous under climate change conditions when heavy rains are more observed in nature.

For mitigation of these problems both agriculture and water management practices must be concerned. Mainly after "EU Water Directive" adoption, those problems started to be more sensitive. EU Recommendation for Soil Protection (R/92/8, 1992) also emphasizes the needs to save the soil as a water reservoir in nature.

Technical and technological solutions of those problems have several approaches and have been developed as a concern of agriculture mainly. For the future, subsoiling could be accepted from soil and country water regime improvement point of view. Besides reduced tillage methods (digging to 10 cm depth), tied-ridge tillage, minimal soil cultivation (para plough, chisel, rotary grape), no-tillage, appropriate plant cover, organic matter application into the soil, all could be a good way to achieve higher water infiltration into the soil profile (Reynolds et al. 2007; Moraru and Rusu, 2010; Hartmann et al. 2012; Alliaume et al. 2013; Bielek et al. 2015; Hladik et al. 2015).

Several studies of this problem have been presented during the past 30 years. Most of those studies have been focused on problems of farming production decrease due to soil compaction. There was identified that high axle loads can cause compaction zones developed below a depth of 30 cm and may be extended to 50 cm or deeper (Voorhees et al. 1986, Lowery et Schuler 1991, Gameda et al. 1985). Axle loads range from 8 to 20 Mg is not excessive when a modern four-wheel drive tractor may weigh 12-16 Mg. Large harvesting combine can have a loaded weight 24 Mg with 75 % of the weight on the front axle, and large grain carts can carry loads of 20-36 Mg on a single axle. The increase of soil bulk density due to heavy machines are only slowly ameliorated by natural forces such as soil freezing and thawing or wetting and drying (Voorhees et al., 1986).

New knowledge about it brings new ideas. Information was accepted that subsoiling is a technique commonly used to alleviate the adverse effects of soil compaction and improve soil physical conditions, in both cropping and pastoral agriculture. Under ideal conditions, subsoiling should break the soil at depth and produce vertical cracks through the soil profile. Subsoiling has been reported to increase the total volume of pores and increase the proportion of macropores (Harrison et al. 1994). The macroporosity volume could be increased up to 30 % of total soil volume which is a good message for higher yields and for higher water holding of soil. It is also affecting the yields because of reducing crop water stress during dry conditions. Yield increases for up to three years have been observed where soil has been effectively subsoiled, but where soil disturbance was minimal, the effect of subsoiling was less persistent. Results from New Zealand show, that subsoiling increased macroporosity by up to 39 % and increased saturated hydraulic conductivity and air permeability by up to two orders of magnitude. Improvements in soil physical conditions have been proved for two years after subsoiling (Drewry et al. 2000).

From several results received it is possible to say, that it was not necessary to conduct subsoiling every year, mostly it is recommended to use it every 2-4 years. In agriculture under intensified technologies (used in developed countries), subsoiling is an important procedure to eliminate areas (at least temporary) of degraded soils by compaction and loss of soil structure. This is too important also in relation to soil water holding capacity increase not only for agriculture but also in favor of better water regime of the country. Mainly in rain-feed water regimes and under influence of climate change, it could be a strategy to more sustainable agriculture and quality of the environment.

Subsoiling is a green technology effective for both agriculture and water management. This is a technology for large areas of land and brings success for a large population and for nature. It is because the share of agricultural land in total areas of the countries is about 40 % in OECD countries, about 50 % of EU-15 and almost 60 % in the Central European countries.

2.1 Water holding capacity of soil

Soil water holding capacity is defined as the water retained between field capacity and wilting point. Simply it is the water that remains in the soil after draining held by a force greater than gravity. Many studies dealt with the effect of soil cultivation on its water content, water holding capacity or other characteristics connected with infiltration. Guzha (2004) states the highest soil water content of soil profile of Dystric Regosols (FAO soil classification) during the seasons under the cover of sorghum by topsoil ridging, then it is followed by reduced tillage method – digging to 10 cm depth with a hand hoe to form a strip in which planting of the seed was done and a three-furrow disc plough, pulled by a 50 HP tractor ploughing at a depth of 15 cm. In the spring the highest soil water content was found in uncultivated soils, then it was followed by flat cultivation with a hand hoe which involved digging across the slope to a depth of 10 cm, the use of a hand hoe in a row and three-furrow disc plough. According to Josa and Hereter (2005), the soil water content of upper 20 cm of soil is according to the observation in Mediterranean climate for Calcic Cambisol in this order: no tillage > limited cultivation > conventional soil cultivation. The highest contents of water were presented at tied-ridge tillage and lower values for ox-ploughing and subsoiling-ripping, which weren't mutually statistically different. Moraru and Rusu (2012) found out higher soil water content at Argic-Stagnic Faeoziom (Romanian System of Soil Taxonomy) under the cover of wheat, corn, and soybeans at direct sowing or minimal soil cultivation (para plough, chisel, rotatory grape) than at conventional cultivation. There was also described higher soil water retention using minimal soil cultivation (para plough, chisel plough, rotary harrow) than the conventional method, for Haplic Luvisols by 1–6 %, for Mollic Fluvisols and Cambic Chernozems by 11–15 %.

Bescansa et al. (2006) state that water holding capacity of soil was higher for no-tillage than for reduced or conventional cultivation, where the change was related only to retention in potential -33 till -50 kPa. Similar conclusions are presented in the study of Shukla et al. (2003) who compared mouldboard ploughing, chisel ploughing, and no-tillage. Statistically conclusive changes were displayed only in the upper 10 cm of soil; water content at full saturation was the highest for soil with no-tillage. Retention is higher at different potentials using chisel plough than plough, the values of volume density of no-tillage soils are usually within their range. Farkas et al. (2009) found out an increase in soil water holding capacity using intercrops. Abid and Lal (2009) found out that no-tillage soil in comparison with conventional cultivation had not statistically influenced the values of water holding capacity in the uppermost 10 cm of soil.

2.2 Saturated hydraulic conductivity of the soil

In theoretical terms, saturated hydraulic conductivity is a measure of how easily water can pass through soil. Hartmann et al. (2012) describe differences in hydraulic characteristics of soil at conventional and conservational cultivated areas. In Ap soil horizon saturated hydraulic conductivity is bigger at conventionally cultivated soil than at soil cultivated by the protective way, while in Eg (gleic) soil horizon it was not. Bell et al. (2005) state, that the decrease of hydraulic conductivity by the impact of conventional cultivation is set in the cultivated layer (ca upper 30cm); this characteristic is not influenced in higher depths. Shukla et al. (2003) proved the impact of agrotechnology only in topsoil, where saturated hydraulic conductivity was higher in soils with no-tillage than in soils cultivated by chisel plough and mouldboard plough. Shukla et al. (2003) proved the impact of agrotechnology only at the uppermost soil layer, where saturated hydraulic conductivity was higher for soils with no-tillage than for soils cultivated by chisel plough and moldboard plough. Moraru and Rusu (2010) found higher values of saturated hydraulic conductivity for minimally cultivated soils (para plough, chisel plough) in comparison with soil cultivated conventionally. Osunbitan et al. (2005) found the highest saturated hydraulic conductivity for soils with no-tillage and the lowest value for soils twice ploughed by plough-plough tillage; moreover, the conductivity of soils with manual tillage (hoe) did not differ from the ploughed soils too much. Pagliai et al. (2004) found out that topsoil with conventional ploughing has due to more developed surface crust significantly lower saturated hydraulic conductivity than soil cultivated alternatively. In a depth of 10-20 cm, it has significantly lower values of saturated conductivity than minimally cultivated soil. Jiang et al. (2007) did not find any significant differences in saturated hydraulic conductivity at the cultivation of soil by different protective technologies.

Reynolds et al. (2007) point out to a decrease in saturated hydraulic conductivity at the changes of cultivation from permanent grassland or uncultivated soil into arable land, which happens right in the first year of change and during the following three years there are no more significant changes. The rate of infiltration is significantly influenced by tillage. Abid and Lal (2009) and Shukla et al. (2003) state, that arable land has a lower infiltration rate than no-tillage soils. On the contrary, Guzha (2004) found, that water infiltrates faster on cultivated soil. McConkey et al. (1997) mention an increasing amount and depth of water infiltrated for subsoiled land if rainfall during November - April was average. At lower rainfall, the increase was not expressed. On the contrary, Moroke et al. (2009) did not record statistically significant changes in infiltration rate of various soil types and of different soil textures in dependence on the way of cultivation (conventional ploughing, double ploughing, deep ripping).

State of practices and perspectives

Saving water in the country is not enough implemented into the agricultural practices in moderate climate zones. Even in areas where water deficiency for agriculture is occurring most preferable actions are not for water saving in soil but only for soil and plant irrigation. On the contrary, wetland areas are drained which is against water saving in soil or those areas are not used by agriculture. Also, in official agricultural policies (EU, nationals) some efficient measures for higher water saving by soil are missing and/or are not inside as subsidiary items. It is because of the low-level implementation of the EU Water Directive into agricultural practices and mainly because of not enough accepted roles of soil and agriculture led to ineffective national water management policies in the countries. The result is that the water saving in nature are not required and the multi-sectorial approach with soil and agriculture are ignored. Activities focused on that can bring some motivation for change in this situation.

In the frame of soil science, research and agricultural practice activities focused on so-called conservation agriculture are becoming more and more popular. There are several new farming systems (no-till, mulch-till, ridge till, low input, precision farming, eco-farming, and others) saving the soil and soil properties. In conservation agriculture, currently, so-called water-saving farming systems are the most promising: these can save water in agriculture including soil. This is a good space for many activities of the research and development both related to global water management (plans and implementation) in the country.

Real water-saving farming systems are mainly the following operations:

No-till or zero tillage refers to a system where a crop is planted directly into the soil with no primary or secondary tillage. It is an extreme form of conservation tillage in which soil remains undisturbed at all times except during planting. Water infiltration rates and saturated hydraulic conductivity tend to be higher under no-till than in ploughed soils because of abundant macropores. Macropores remain intact in no-till soils.

Subsoiling is used to break up compacted subsurface layers that are formed between 25 and 40 cm below the soil surface from natural consolidation or machinery traffic. This compacted layer, also called ploughpan, restricts seedling emergence, root growth, and down- and up-ward water and air movement. In some cases, the soil may be saturated with water above the ploughpan and unsaturated below due to the virtual impermeability of the ploughpan. Plant roots often concentrate above the ploughpans with reduced access to subsurface available water and often wilt when the supply of surface water is limited.

Reduced tillage refers to any conservation system that minimizes the total number of tillage primary and secondary operations for seed planting from that normally used on a field under conventional tillage. It is also called minimum tillage because it reduces the use of tillage to minimum enough to meet the requirements of crop growth.

Mulch tillage is a practice where at least 30% of the soil surface remains covered with crop residues after tillage. Tillage under this system is performed in a way that leaves or maintains crop residues stay on the soil surface. Mulch tillage is an extension of reduced tillage and is also called mulch farming or stubble mulch tillage.

Strip tillage. This system is also called partial-width tillage and consists of performing tillage in isolated bands while leaving undisturbed strips throughout the field. By doing so, strip tillage combines the benefits of no-till and tillage. Strip tillage loosens the tilled strip and temporarily improves drainage and reduces soil compaction. The strip tillage can be an alternative to no-till farming in poorly drained and clayey soils. Where no-till has not maintained or improved corn production, strip tillage is a recommended option.

Field experiments

Field experiments have been set up on the territory of Agricultural cooperative in Kolíňany, nearby Nitra city (Slovakia). Fields belong to Experimental Research Station of the Slovak University of Agriculture in Nitra. Soil subtype is Haplic Luvisols (HMa, according to WRB 2006). Organic carbon content (C_{ox}) is in the range from 0.96 % to 1.31 %.

In September 2012, the whole experimental area was fertilized by P and K fertilizers (P60 and K40 kg per ha) and ploughed. In April 2013 first 2 experimental plots (each 200 m^2) were set up as (1) not subsoiled field and (2) subsoiled field. Subsoiling was provided into the depth of 0.6 m by a special agricultural machine (Artiglio Moschra, see Fig 1). On May 3rd, 2013 the maize was sown by traditional operations. Nitrogen fertilizers were applied before sowing (60 kg N per ha, Urea form of Nitrogen) and an additional 60 kg N/ha

(Urea) at the end of August on both experimental fields. During the future growing season 2013 - 2014 winter barley was cultivated on both fields by no-till technology (no applied subsoiling treatment again).

In autumn 2013 new additional experimental fields were set up close to the first experiments with the following plots: (3) new not subsoiled soil, (4) new singly subsoiled soil and (5) crossly subsoiled soil. The depth of subsoiling was 60 cm. Phosphorus and Potassium were applied (80 P and 30 K per ha) before subsoiling. During the growing season (2014) nitrogen (Urea form) were applied in rate 60 kg N/ha at the beginning of April and an additional 60 kg N/ha in the end of May. In July 2014 the yields of all cultivated plants (fields 1,2,3,4 and 5) were harvested.

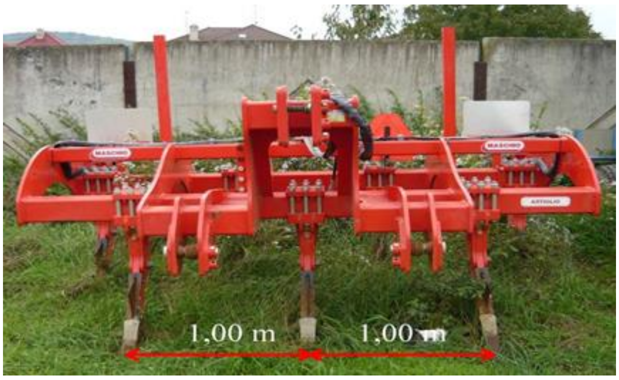

Fig. 1. The subsoiling machine used during the field experiments.

Finalized inventory of the field experiments structure is as follows:
2013: 1. Not subsoiled field (with maize). 2. Singly subsoiled field (with maize).
2014: 1. Not subsoiled field continued from spring 2013 (with winter barley). 2. Singly subsoiled field continued from spring 2013 (with winter barley). 3. New not subsoiled field in autumn 2013 (with winter wheat). 4. New singly subsoiled field in autumn 2013 (with winter wheat). 5. New crossly (#) subsoiled field in autumn 2013 (with winter wheat).

All experimental fields were set up with the following ideas:
- To verify the influence of subsoiling on water infiltration into the soil profile (single and cross subsoiling);
- To identify the influence of verified subsoiling approaches on yields of maize, winter barley and winter wheat (because farmers want to know this information);
- To identify the influence of subsoiling on water regime of soil after one and two years of treatment (to answer to the persistence of subsoiling operation);
- To receive practical key information for future agricultural practice;
- To generalize results of field observations for soil conditions of Slovakia;
- To bring some ideas for water management regulations by correction of the farming system;
- To propose some ideas for the Code of Good Water Management Practices in Agriculture;
- To summarize some recommendations for agriculture and water management sectors.

Observations and results

The penetrometric study was the first most important experimental activity for the determination of soil profile resistance against water infiltration into the soil profile (Fig.2).


Fig. 2. Penetrometer for indirect determination of soil resistance against water infiltration.

This study brought detailed electronic records about the resistance of soil profile against penetration of penetrometric stick into the soil. Results of the records are presented in Fig. 3, 4, and 5.

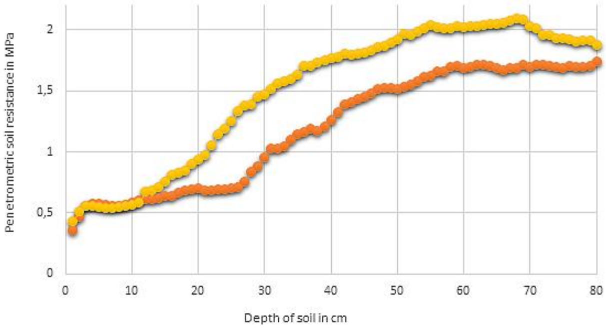

Fig. 3. Penetrometric records of not subsoiled (yellow curve) and subsoiled (orange curve) soils (June 2013, fields 1 and 2).

Fig. 3 presents that subsoiling destroys the soil profile (lower numbers of penetrometric resistance) that simultaneously improves conditions for water infiltration deeper into the soil profile. In the second year after the treatment, it is not very effective (Fig.4). More effective is cross-subsoiling in comparison to singly subsoiled soil (Fig.5).

Water infiltration experiment (see Fig. 6) shows real information about the ability of the soil to transmit the water deeper into the soil profile. Double ring infiltrometer is a widely used method of infiltration test used in many applications. The infiltrometer consists of two concentric metal rings which are driven into the soil, and two nail points of different lengths are fixed to the metal plate. These nail points are used for observation of decreasing water level during the infiltration. Water is poured into both cylinders. The stopwatch starts and the time needed for the water level to drop from the upper nail point to the lower nail point is measured and recorded. When the water level reaches the lower nail point, the time is recorded and the same amount of water is poured back. A special calculation is provided for water infiltration determination.

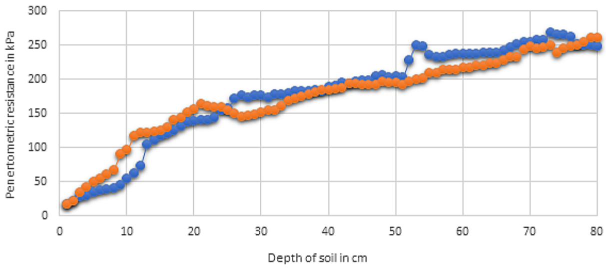

Fig. 4. Penetrometric records as a comparison between not subsoiled (blue curve) and singly subsoiled soil (orange curve) in the second vegetation period after the treatments (May 2014, fields 1 and 2).

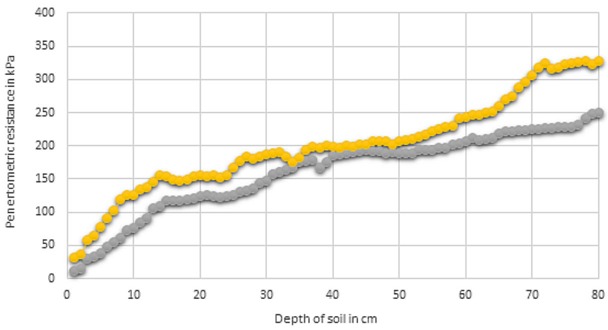

Fig. 5. Penetrometric records as a comparison between singly subsoiled (yellow curve) and crossly subsoiled (gray curve) soils (2014, fields 4 and 5).

Fig. 6. Infiltrometer installed on the experimental field.

Soil moisture has been determined as an additional argument for water infiltration increase after the subsoiling operation. Gravimetric method of soil moisture determination was used. Soil samples from different depths were taken and moisture content (%) was determined from samples weights before and after drying (105 ºC).

In our experiment, the water infiltration into the subsoiled soil profile was significantly higher (results of infiltrometer observations) and higher soil moisture was observed in every layer of subsoiled soil profile in comparison to not subsoiled soil (Table 1). Here we can emphasize that 1 % of the moisture is relevant to 10 l of water per 1 ton of soil matter that is relevant to 30 thousand liters of water per 1 ha of soil (to the depth of 30 cm). Simply, this experiment confirmed that subsoiling could be a significantly effective measure for higher water accumulation in the soil and land as well.

Table 1. Soil moisture (in %) before and after infiltration experiment (May 2013, variant 1 and 2). S: subsoiled. NS: not subsoiled.

	Before infiltration		**After infiltration**	
Depth, cm	**S**	**NS**	**S**	**NS**
0-15	15.98	15.11	29.78	25.07
15-30	17.42	17.88	20.52	19.87
30-45	17.49	18.71	20.81	19.44
45-60	18.98	17.98	19.42	19.01
60-75	19.70	18.90	19.48	18.00

Fig. 7. Maize cultivated on subsoiled field (right side of picture) in comparison to not subsoiled soil (left side of picture).

Table 2. Average yield parameters of maize (after harvesting in October 2013) cultivated on subsoiled and not subsoiled soils.

Yields parameters	**S**	**NS**
Plant height (m)	2.27	1.64
Plant weight (kg/m^2)	2.43	1.51
Grain moisture (%)	47.38	46.30
Grain yield (t. ha^{-1})	9.25	8.28

Table 3. Grain yields (t ha^{-1}) in 2014. Fields: 1– no subsoiled in spring 2013; 2 – subsoiled in spring 2013; 3 – no subsoiled in autumn 2013; 4 – singly subsoiled in autumn 2013; 5 – crossly subsoiled in autumn 2013.

Fields	**Winter barley**	**Winter wheat**
1	4.38	
2	4.54	
3		7.96
4		8.20
5		8.91

Conclusions

Field research was carried out during the period 2012 - 2014 with the aim to determine how subsoiling can improve water penetration into the soil profile and how it can increase water saving of land by soil. It is important from drought and flood reducing point of view. From the results the following conclusions can be summarized:
1. Subsoiling decreased the resistance of soil profile against root growth and water penetration into the soil profile (penetrometric experiments) that increases water infiltration into the soil profile (infiltration experiments), mainly when cross subsoiling was applied;
2. Subsoiling increased the yields of maize, winter barley, and winter wheat, but in the second year it was not very effective;
3. Subsoiling is a realistic approach to improving the water regime of land.

Proposals for practical use of results

In relation to the results of this project, we can use the Geographical Soil Information System focused on identification of all fields on the territory of Slovakia which are suffering from soil compaction and simultaneously have decreased the water infiltration potential of soil and of the land as a whole. All those fields are primarily suitable for subsoiling. Using the web site every farmer in Slovakia has the information about every field farmed available.

Policy development for recommendations of subsoiling use

Each member state of the European Union has subsidized agriculture. It is due to the EU and member states concerns for food sufficiency with the acceptable economic situation and ecological functions of agriculture. Because subsoiling is in principle better than traditional tillage approach and still not such a cheap procedure a supporting policy could be fruitful in the frame of Common Agricultural Policy (CAP EU). In this case, the farmers could be more accepted as participants of the water management practices inside the EU territory.

Acknowledgments

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