The Application of Digital Monitoring in Studying Soil Water Holding Capacity and Implications for Conservation Agriculture in the South-Western Siberia

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Abstract. The Kulunda Steppe is an example of soil degradation resulting from the intensive agricultural land use in the South Siberia. In this region, water is a limiting factor for crop production. Soil cultivation affects the soil’s physical properties, thus its water retention capacity. The study presents and discusses the results of measurements of the volume and availability of soil moisture at depths of 30cm, 60cm, and 120cm of loamy, low humus southern chernozems in the south of Western Siberia in the dry Kulunda Steppe during the 2013 and 2016 vegetation periods. We revealed some advantages of soil moisture conservation in the No-Tillage [NT] system compared with the system of deep tillage [DT]. At depths of up to 30 cm, there was a lower volume moisture level. Nevertheless, at depths of 60 cm, there was a higher moisture level in the NT system that could be considered a potential stock for individual crops during drought. Further measurements are needed to identify additional features of the NT soil conservation system.

Keywords: Soil water regime · Water supply · Soil hydrological station · Kulunda Steppe · Russia

1. Introduction

More than 78% of Russian arable lands are concentrated in the arid zone. They produced an essential bulk of agriculture crops [27, p. 195]. The Kulunda Steppe (South-Western Siberia) is a unique territory covering 5.3 million ha [16]. It is essential for the development of Russian AIC. Economic activity in the Kulunda Steppe is mainly hampered by the specific climatic and soil conditions and requires adaptation to the global climate changes [10, 19]. The abundance of light and heat with the sum of active temperatures of 2000–2600 °C and limited precipitation during the vegetation period (230–350 mm per year) are specific features of the Kulunda Steppe. The distribution of precipitation across the area during the seasons is uneven [35]. The Kulunda Steppe developed on Mesozoic-Cenozoic sediments (sandy-sabulous and layered sediments). Chestnut and dark chestnut soils are changing to the southern low-humus, low power, and medium-power chernozems of the East Kulunda subprovince. The soils of the Kulunda Steppe have variable mechanical composition. Crop production is also limited by the halogen soils (solonetz, solonchaks, solodi) generally used for grazing [15, 33]. In such conditions, it is particularly important to study the soil water regime and provide scientific support for conservation
agriculture technologies [CA] in an unstable climate, considering environmental and economic factors [4].

CA is typically defined as a sustainable agricultural practice comprising three core principles: minimal soil disturbance, permanent soil cover using green crops or crop residues, and crop rotation [17]. CA considerably changes soil properties and soil processes compared to conventional agriculture. These changes can affect the ecosystem services, including climate regulation through carbon sequestration and greenhouse gas emissions, water regulation, and supply through soil physical, chemical, and biological properties. Thus, the conservation of agriculture can also affect global biodiversity [30].

Initially, dust storms occurred in the steppe zone of North America, forced to reconsider the existing soil cultivation system in the 1930s [10, 23]. Just minimum tillage (Minimum Tillage, [MT]) was applied in the USA and Canada in the late 1930s and early 1940s [14]. In the USSR, annual plowing was unnecessary or even harmful [3, p. 21]. CA has not been displacing the stockpile plowing with tillage depth up to 25–30 cm for a long time, firstly due to farmers’ inertia, and secondly, because the stockpile plowing was often more effective than deflation-free plowing, especially in combating against weeds. Dust storms in the US and the USSR gave a new impulse for conservation technologies and an overall reduction in intensity and number of treatments in the 1950s. A. I. Barayev developed a new soil cultivation system to a depth of 18 cm to preserve stubble [3, p. 21] for the dry steppe soils in northern Kazakhstan and western Siberia in the late 1950s.

Subsequently, the farmers and agriculture researchers came up with the idea of “direct sowing” (No-Tillage [NT]), “zero sowing” (Zero-Tillage [ZT]), and sowing in sliced strips (Strip-Till [ST]) [5, 18, 20, 21].

The main requirements for mastering ZT technologies were:

- the conservation of plant residues and their quality distribution;
- the application of crop rotation with cost-effective crops for improving soil fertility;
- integrated management to control the weeds, diseases, and pests;
- qualitative seeds;
- the application of complex mineral and organic fertilizers and their flexible application;
- the equipment ensuring high-quality sowing [2, p. 8].

Later, the concept of water holding capacity of soils [WHC] was developed and described towards two measurable parameters – soil moisture [SM] (%) and matrix potential [MP] (pF) [9, 31]. A similar concept of “thermodynamic potential” was also developed in Russia. This potential has a negative value, defined as “the pressure of the soil moisture” [11]. The pressure measured in the water column’s height is 1,000 cm of water column (1,000 hPa). Considered that the assessment scope is ranged from 0 to 10,000,000 hPa, it was proposed to convert these values into negative decimal logarithm as the value of pF (p – potential, F – “free energy” of water) – (pF=log [-hPa/cm]). As a result, pF ranged from 1 to 7, which characterizes SM’s condition from saturated to dry [7, 8].

There is a strong correlation between the SM (%) and MP (pF), which describes soil water holding capacity [9, 31]. The WHC is connected with the mechanical structure and porosity of soils. In general, if the pores of any soil type are filled with water, when the value of pF=0, the water is mobile and percolates through the coarse pores. Decreasing the SM can increase the MP because the water could move only by capillary forces of the average and small pores that slow soil moisture movement. Infiltration decreases, and the capillary moisture prevails. In general, the decrease in SM leads to an increase in MP regardless of the soil type. The MP is as higher as smaller the pore size is. In this case, the pF equal to 4.2 marks the limit of water availability to the plants and the area of permanent wilting point [PWP], where the plant roots cannot create the proper osmotic pressure against the water tension and caused the turgor lost [14]. Four MP bands determine the moisture availability:

1) 0 to 1.8 pF – moisture is unavailable, quick water movement and infiltration;
2) 1.8–2.5 – field capacity (FC), moisture is available, slow water movement;
3) 2.5–4.2 pF – available water capacity (AWC), moisture is available optimally;
4) 4.2–7 pF – moisture is unavailable (PWP) because of “soil suction,” which exceeds the osmotic pressure of plant roots [7].

2. Materials and Methods

One weather station [WS] and two soil-hydrological measure stations [SHMS] (manufacturer “Eco-Tech,” Germany) were installed (Coordinates WS: E 79° 42.786’ N 52° 03.959’; SHMS 1: N52° 04.180 E79°54.014; SHMS 2: N52°04.128 E79° 54.006) in the Kulunda Dry Steppe in September 2012.

WS was equipped with a pyranometer (at the height of 2 m) to measure the solar radiation. Multisensor “Vaisala” (at the height of 2.30 m) was used to measure the wind speed and direction, air temperature, humidity, barometric pressure, and rainfall. Additionally, the liquid and solid precipitation were measured by a pluviometer, which is mounted in “Hellmann” rain gauges on the standard height of one meter. SHMS equipped with sensors measured soil water content (SM), soil temperature, availability of soil moisture to plants (MP), and electric conductivity fitted at depths of 30, 60, and 120 cm in automatic mode [37].

The analysis of meteorological parameters during the 2013–2016 vegetation periods for WS was discussed by G. Schmidt et al. [32] and R. Meissner et al. [26]. The hydrothermal moisture coefficient was calculated to assess the aridity’s degree, as suggested by V. I. Belyaev et al. [6]. According to the moisture gradation proposed by G. T. Selyaninov, the periods of 2013 and 2015 can be described as “dry,” and 2014 and 2016 as “provided moistening” [26].

Our study aimed to analyze WS’s regional climate and compare the soil moisture regime at the CT and the NT technologies by in situ measurements with soil-hydrological measuring stations (SHMS).

We tested the following technologies:

a) “Conventional technology” with deep loosener (PG-3-5 – “Ploskorez Glubokorihlitel”) at 22-24 cm depth (SHMS 1). Crop rotation: wheat (2013) – fallow (2014) – wheat (2015) – wheat (2016);
b) “No-Till” technology, without autumn tillage (SHMS 2). Crop rotation: wheat (2013) – rape (2014) – wheat (2015) – peas (2016).

We used the data from vegetation periods (May-September) in 2013–2016.

3. Results and Discussion

A slightly higher volume of SM for CT was revealed in 2013, the first year of our experiment. SM was available during the growing season. In both variants, it did not reach the permanent wilting point (PWP, pF=4.2.). The comparison of variants was interesting because CT and NT cultivated spring wheat (figures 1, 2).
Figure 1. Soil moisture (%, average daily values) and standard errors, 2013. Source: Compiled by the authors. Note: 1) – data CT and NT for May 3, 2013 – September 30, 2013, Obs. of data for each depth – 153.

Figure 2. Matrix potential (pF, average daily values) and standard errors, 2013. Source: Compiled by the authors. Note: 1) – data CT and NT for May 3, 2013 – September 30, 2013, Obs. of data for each depth – 153.

We managed to get the CT data in 2014 only for September (“secured moistening” period). At the same time, we observed the moisture reserve at the end of the growing season. The CT system had mechanical steam, while the NT system had rape in 2014. The SM and MP diagrams clearly show that “fallowing” was generally a rather effective way of keeping soil moisture (figures 3, 4). For CT, the SM was 20% at all depths, while for the SM – 11.9% (30 cm depth), 14.5% for – 60 cm, and 11.8% – 120 cm. The NT depth of 30 cm demonstrate the transition across plants’ moisture availability boundary (PWP, pF=4.2). We believe that the decrease in moisture and its availability was caused by increased water consumption of rapeseed (600–700 l/kg dry weight), which was 100 l/kg more than its spring wheat predecessor [12].
Figure 3. Daily average soil moisture (%) and standard errors, September 2014. Source: Compiled by the authors. 
Note: 1) – data CT and NT for September 9 - September 30, 2014; Obs. of data for each depth – 18.

Figure 4. The daily average of matrix potential (pF) and standard errors, September 2014. Source: Compiled by the authors. 
Note: 1) – data CT and NT for September 9 – September 30, 2014; Obs. of data for each depth – 18.

The same wheat crops and worst starting conditions for moisture become apparent in 2015 (“dry” period). The main advantages of SM by NT became apparent at depths of 30 and 60 cm. Nor was a 12.0% humidity drop observed for NT, as was a 30 cm drop for CT. For NT at the depths of 30 and 60 cm, we observe a tendency of MP movement towards the permanent wilting point (PWP) (pF=4.2). It is important to note that SM on NT will be challenging to reach at the end of the growing season.
We performed the analysis for CT only for July 23 – September 10, 2016 (“secured moistening”) due to the limited row. Moreover, the NT system had higher volume and lower water availability at 30–60 cm compared to CT.

NT was cultivated for peas, which have the same water consumption level as rape [12] and higher level than wheat cultivated according to CT. We assumed that four years of the experiment created soil conditions providing higher NT system moisture content than CT that were also registered in Canada [21].
Figure 7. Daily average soil moisture (%) and standard errors, 2016. Source: Compiled by the authors. 
Note: 1) – data CT and NT for July 7 – September 10, 2016; Obs. of data for each depth – 50.

Figure 8. Daily average matrix potential and standard errors, 2016. Source: Compiled by the authors. 
Note: 1) – data CT and NT for July 7 – September 10, 2016; Obs. of data for each depth – 50.

It is still disputable which system could improve the soil water holding capacity [WHC]. Studies conducted in semi-arid areas reported positive effects of NT on agrophysical soil parameters [18, 20, 21, 22, 29, 34]. NT also negatively impacted soil compaction [1]. Recently, farmers expanded the NT usage in High Plains arid areas (the USA). The trend towards minimum tillage (Min-Till) is observed. Every five years, the soil is treated, and steam is used (using mechanical tillage) [5]. Some studies did not reveal any changes, or these differences in the dynamics of physical soil parameters were rather insignificant [25, 28, 36].

4. Conclusion
The principal advantage of the NT system compared to CT was identified with respect to the moisture content for the vegetation periods in 2013-2016. These differences were most significant in the third and fourth years of the experiment at 30 and 60 cm. It is essential that the NT experiment was initially based on the parameters that objectively reduced the soil water holding capacity. In 2014 and 2016, rape and peas were cultivated in NT crop rotation, which had higher water consumption than wheat in CT.
crop rotation. Additionally, in 2014, “fallowing” was carried out using CT, which is one of the most effective methods for soil moisture conservation.

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