SOIL WATER MANAGEMENT IN THE SIBERIAN KULUNDA- DRY STEPPE

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Abstract: *From 1954 to 1963, approximately 42 million ha of the Southern Russian steppe, of which 6.2 million ha are located in Western Siberia, were converted into large-scale intensive agricultural area. The affected areas are highly vulnerable to wind erosion and the presently ongoing climate change effect. The establishment of sustainable land management practices is essential to secure agricultural production and the further economic development of the region. The assessment and management of the soil water is of great importance for crop yield potentials and protection against wind erosion. The paper presents a meteorological and soil hydrological measuring network. The results showed that the No-Tillage technology gradually formed soil conditions close to the natural dry steppe background. Furthermore, the installed techniques can be used to measure the parameter "actual evapotranspiration" which is a key factor to evaluate climate change impacts.*

Keywords: ACTUAL EVAPOTRANSPIRATION, KULUNDA– RESEARCH PROJECT, LYSIMETER, MEASURING TECHNIQUE, PRECIPITATION, SOIL TILLAGE, SOIL WATER

1. Introduction

The Altai region is one of the most important grain-producing regions in Russia. Its total area of cultivated land is 5.4 million hectares, of which 3.5 million hectares are designated for grain and leguminous crops, including maize. From 1954 to 1963 approximately 42 Mio ha of the Southern Russian steppe, of which 6.2 Mio ha are located in Western Siberia, were converted into a large-scale intensive agriculture area. This area was highly vulnerable to wind erosion that results in decreased top soils thickness and humus content and therefore in decreased concentrations of carbon. The adversely influenced soil water and nutrient regime as well as the declining fertility have resulted in a decrease in crop yields. In 1963-1965, more than 1 million hectares of eroded land was set aside in Altai. In 1960-1970, a set of measures aimed at soil conservation was implemented, including the establishment of plantations and shelter belts, conservative tillage, soil-protecting crop rotation, crop lane placement, mulch with straw, etc. However, the problem of "black storms" (wind erosion) resolved in the 1960s and 1970s is currently reappearing. "Black storms" were recorded in the Altai region in the mid-1990s and in the 2000s [1].

The region is part of the Southwest Siberian Kulunda steppe lowland and located between the Central Asian steppe and the North Asian forest-steppe. In the North, the Kulunda steppe borders on the Baraba forest steppe with a vegetation mosaic composed of steppe communities and birch "kolki" (birch islets). The Western part of the Kulunda steppe borders on Eastern part of the Irtysh valley in Kazakhstan. The Kulunda depression is located at altitudes of 100-140 m asl. The lowland is covered by a 50 to 60 m thick layer of pleistocene alluvial and 0.5 - 10 m of eolian sediments. The soil cover of the Kulunda dry steppe consists of chestnut soils, meadow-chestnut soils, meadow soils, solonetz and solonchaks with different degrees of hydro-morphism. The chestnut soils significantly vary in texture as a result of the ancient limnic and eolian genesis of the territory. Sandy loams (15 - 19% clay, 11 - 20% silt, 65 - 70 % sand) are predominant; their contents of humus (2 - 4 %) and carbon (5 - 8 %) are comparatively high [2].

In the continental climate of Kulunda steppe long, cold and little-snowy winters and short, but hot and dry summers occur. Due to its open position, the steppe is often affected by cold air masses from the Kara Sea, and warm and dry ones from Kazakh and Middle Asian steppes and deserts. Thus, the temperature is highly variable: May and September often have night frost, in late snow-free autumn periods the temperature can drop to -20 °C or lower, spring sometimes has very dry periods, and dry winds are common throughout the year. The mean annual temperature is about 0 °C, the mean temperature of January (the coldest month) is -19 °C, the absolute minimum is -47 °C, the mean temperature of July (the warmest month) is +19 °C, the absolute maximum is +40 °C. The frostless period lasts 112-120 days per year from May 15-25 till September 10-15. The annual precipitation is about 250-450 mm; the precipitation in April to October is about 200 mm. The duration of a stable snow cover reaches 140-150 days (from November 10-15 to April 5-10). The mean depth of the snow cover is 15 cm (absolute maximum 35-38 cm). Such a thin snow cover does not protect the soil from frost, so in winter soil freezes down to 2 m deep (and even more). The amount of global radiation is 2-3 times higher than it is required for the evaporation of such an amount of precipitation [3].

From 2011 until 2016 the German-Russian interdisciplinary research project KULUNDA was carried out [4]. The main goal of the project was to mitigate degradation and desertification processes in the Southern Siberian agriculturally used steppe sites, to stimulate and, in the long run, to enhance carbon sequestration in soils of the Kulunda steppe. The project also aims to increase crop yields and to implement sustainable land management practices for agricultural areas and thereby to contribute to rural and regional development. The gained knowledge and the results of the KULUNDA project will largely contribute to the research on climate change, sustainable land management practices and rural and regional development.

The assessment and management of water and solute balance of soils are of great importance for crop yield potentials and sustainable development of the territory. A key factor in soil water management is the natural availability of precipitation during the vegetation period. Also in former Soviet Union research activities were started to minimize the water deficit in the region. Already in the seventies of the last century Kulunda plain was included in the national Russian economic plan of reclamation to increase the area of irrigated land. But the economic conditions have changed and present land management activities in the region showed that irrigation don't play an essential role in agriculture. Alternative methods to improve the soil water efficiency have been developed and tested. In [5] it was demonstrated that the main agricultural methods to retain soil moisture are minimum or No-Till-technologies including stubble and chopped crop residues.

An essential topic of the interdisciplinary KULUNDA-project was the impact of land management practices on the soil water and solute balance of the Kulunda steppe in Altai Krai. For this reason a pedo-hydrological measuring network was installed and measurements were carried out during the investigation period. The objectives of this paper are i) to describe the design and establishment of the monitoring system and ii) to explain some essential results regarding soil water management in the Kulunda steppe.

2. Materials and Methods

The monitoring network consists of a weather station, two soil-hydrological measuring stations and a weighable gravitation lysimeter station (Table 1). The weather station was installed in September 2012. It was equipped with a pyranometer (at height of 2.0 m) to measure the solar radiation, a multisensor "Vaisala" (Vaisala Weather Transmitter –VWT, at a height of 2.3 m), measuring wind speed and direction, air temperature and humidity, barometric pressure and rainfall. Additionally, the liquid and solid precipitation was measured by a pluviometer, which is mounted in "Hellmann" rain gauge (Hellmann tipping bucket rain gauge – HRG) on the standard height of 1 meter. The two soil hydrological measuring stations (SHMS 1 and 2 - manufacturer "Eco-Tech", Germany) were also established in September 2012. They were equipped with sensors to measure soil water content, soil temperature, osmotic pressure, and electric conductivity fitted at depths of 30 cm, 60 cm, and 120 cm in automatic mode. During June-August 2013 a containerized (Polyethylene PE-HD) lysimeter station with two weighable soil monoliths (manufacturer "UGT-Muencheberg", Germany and Helmholtz Centre for Environmental Research – UFZ, Germany) was installed at the test farm "Partner" of the KULUNDA- project in Poluyamki (dry steppe region). This site was chosen because the South-Western Kulunda steppe region is mostly affected by soil degradation processes compared with the other parts of the administrative unit Altai Krai [6].

It is well known that a weighable gravitation lysimeter is a sufficient tool to measure the relevant parameters of the soil water balance equation with high precision [7]. Such data are missing for the dry steppe conditions of Siberia but they are essential for the evaluation of the former development of this region. Especially the climate change is a main driver regarding the direction of future land use. The lysimeter measuring results will help to investigate and establish sustainable land management strategies for this region. The aim is to deepen the understanding of relevant processes concerning the interaction of land degradation and climate change, to quantify fluxes of water, nutrients, carbon, and other relevant matters. The results serve as the basis to simulate the effects of land management on soil and matter balance by using adequate models (for example the hydrological model HYDRUS). In cooperation with German and Russian project partners the soil monoliths (surface area of 1 m^2, 2 m depth) were monolithically extracted from both an arable land (lysimeter 1 – LYS 1) and a fallow site which was ploughed once in the 1950s, but since then covered with natural, nearly pristine steppe vegetation (lysimeter 2- LYS 2) for the lysimeter-based investigations. Following the FAO guidelines the soils are identified as Calcic Chernozems (Table 2). The LYS 1 consists of a 25 cm thick humic horizon including a plough layer at its bottom. It is followed by a crossing A-C-horizon with its bottom at 50 cm depth. Beneath there is a subsoil C-horizon from parent material including calcareous deposits. The grain size distribution in the upper part of the profile (0-50 cm) indicates sandy loamy silt, beneath silt loam and below 70 cm loamy sand occurs. The site was under intensive agricultural usage for 60 years.

Table 1 *Design of the pedo-hydrological monitoring network in the Kulunda steppe*

Name and coordinates	Lysimeter	Soil-hydrological measuring station		Weather station
	N 52°03.959' E 79° 42.786'	DATT[1)] (SHMS 1) N52 04.180 E79 54.014	No-Till (SHMS 2) N52 04.128 E79 54.006	N 52° 03.959' E 79° 42.786'
Parameters	Soil monolith mass for registration of various atmospheric precipitation, amount and concentration of seepage, soil temperature,	Water content and soil temperature, soil water pressure, (tension) suction, electrical conductivity		Amount of liquid precipitation (multi-sensor), equivalent of frozen precipitation (pluviometer in Hellmann rain gauge), wind power and direction, air temperature, humidity, and pressure, solar radiation
Sensor types	1. FDR- and temperature sensor, soil moisture content and temperature 2. Watermark sensor- matrix potential 3. Ceramic suction cups- sampling soil solution (nutrients, pollutants)	1. TDR-sensor: soil moisture content and temperature 2. pF-Meter: Stress meter: soil water pressure, (tension) and electrical conductivity		1. Multisensor «Vaisala»: air temperature and humidity, atmospheric pressure, wind speed and direction. 2. Radiometer: solar radiation. 3. Pluviometer in Hellmann rain gauge- measurement of frozen precipitation.
Height and depth of sensor location (cm)	-30; -50; -120	-30, -60, -120		+100 (Rain gauge) +200 (Radiometer) +230 (Multi-sensor)

Note: [1)] - Deep autumn tillage technology on 22-24 cm depth

The LYS 2 consists of a 30 cm thick humic Ah-horizon, followed by a 15 cm thick crossing A-C-horizon and by the subsoil from parent material which is interjected by calcareous deposits. The upper 30 cm consists of sandy loamy silt, below silty loam occurs, which is underlain by loamy sand beneath 70 cm.

***Table 2** Soil properties of the lysimeter extraction sites in the Kulunda steppe, Siberia.*

Name/No.	**Extraction site Lysimeter 1 (LYS 1)**			
Date	28.06.2013			
Position	N52 04.012 - E79 54.526			
Altitude	138 m			
Slope/ Exposition	>1			
Usage	Field/ Wheat			
Notice	Amazone test field; Poluyamki / Conventional tillage			
Soil Type	Calcic Chernozem			
Horizon	**Ah**	**AC**	**Ckc**	**C**
Lower boundary (cm)	25	50	70	120+
Grain size fraction	SLSi (Uls)	SLSi (Uls)	SiL (Lu)	LS (Sl4)

Name/No.	**Extraction site Lysimeter 2 (LYS 2)**			
Date	28.06.2013			
Position	N52 03.778 - E79 55.868			
Altitude	142 m			
Slope/ Exposition	>1			
Usage	Natural steppe vegetation			
Notice	No tillage for decades			
Soil Type	Calcic Chernozem			
Horizon	**Ah**	**AC**	**Ckc**	**C**
Lower boundary (cm)	30	45	70	110+
Grain size fraction	SLSi (Uls)	SiL (Lu)	LS (Sl4)	LS (Sl4)

After the extraction of the soil columns a 20 cm thick filter layer (geotextile over fine-coarse sand over gravel) was placed at the bottom of the lysimeter vessels to minimize disturbances to the natural flux. The depths of the soil columns are greater than the natural flux plane, which lies referred to the environmental and management conditions at the extraction sites between 0.9 and 1.3 m below the surface. Hence, it can be assumed that seepage flow in the lysimeters is not affected before it reaches the filter layer. The composition of the filter layer was chosen to allow free drainage of seepage water.

The vessels were transported to the Poluyamki site and positioned into the lysimeter station on load cells by using a three-legged steel frame (Fig. 1). The lysimeter station measures mass changes with sufficiently high precision (± 20 g) to enable the calculation of water fractions input (dew, rime and the water equivalent of snow) and the rates of actual evapotranspiration (ETa). The total mass of each lysimeter vessel is approximately 4 t (the mass changed in dependence on the water content of the vessel). Both lysimeter vessels are equipped at different depths (0.30 m, 0.50 m and 1.20 m) with frequency-domain reflectometry (FDR) stick probes to measure the soil moisture content and soil temperature, watermark-sensors to measure the matrix potential and suction cups to extract soil solution (cf. Fig. 1). The lysimeter is specifically adapted to the cold winter conditions in Siberia by adding an extendible cutting ring to burst bridges between the snow on lysimeter surface and adjacent snow in the surrounding.

The measured values are consolidated and stored in a data logger with a recording interval chosen by the user. It permits a very high temporal resolution (< 1 minute). The amount of seepage water is measured with a tipping bucket (values are stored by the data logger) and collected in a storage container from which water samples can be taken for chemical analysis. The installed computer software makes it possible to present all measured parameters in different ways (e.g. average, minimum, maximum or all values).

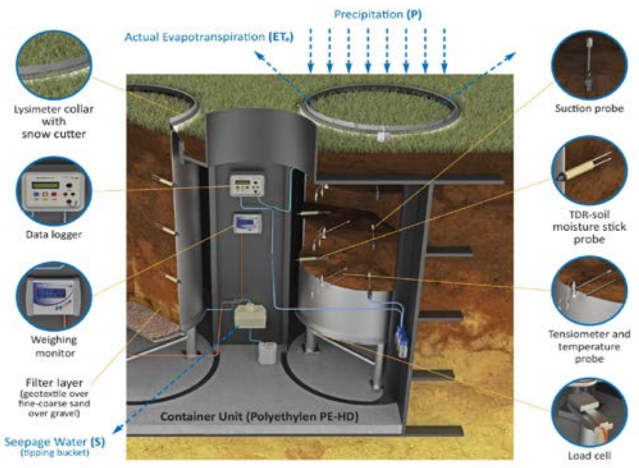

***Fig. 1** Sketch of the weighable two-fold containerized lysimeter station established at Poluyamki site, Russia, Siberia.*

3. Results and Discussion

3.1 Precipitation

As already mentioned, the annual amount of precipitation is about 250-450 mm with a tendency of declining because of global climate change effects. The available meteorological data base is rare and the above explained monitoring network should improve our knowledge regarding the soil water budget. Especially the parameter precipitation is fundamental to reach this aim. The precipitation was measured by three different methods, the HRG, the VWT and the weighable lysimeters LYS 1 and 2. The different devices used for precipitation recording have specific systematic measurement errors (wind field deformation above the gauge orifice, wetting loss at the internal wall of the container, evaporation, splashing, size of the gauge etc.) and thus deliver individual value arrays, even if they are installed in vicinity. These errors have to be detected and can be reduced for example by correction factors [8]. Due to the relative large size of a lysimeter vessel (usually 1 m^2 surface area) random errors are widely reduced. If the lysimeter vessel contains a complete soil-plant system, interception of the vegetation is part of the precipitation term. Based on the lysimeter weighing system measuring errors may occur regarding vibrations caused by wind, maintenance and field work respectively or due to animals entering the lysimeter vessel. In [8] it is demonstrated that a sophisticated weighable lysimeter can be used as a reference to compare different rain gauge devices.

Precipitation measurements by HRG, VWT, LYS 1 and LYS 2 are presented in Figure 2. LYS 1 showed in the observation period a precipitation of 121.5 mm whereas 143.4 mm were measured at LYS 2. The precipitation measured in the observation period by HRG and VWT was 100.1 mm and 136.3 mm, respectively. Precipitation measurement by lysimeters can be regarded as reliable with insignificant systematic errors. The different amounts of precipitation of LYS 1 and LYS 2 can be attributed to the different vegetation cover. The steppe vegetation of LYS 2 is characterized by higher leaf area coverage than that of LYS 1. Therefore, the precipitation measurements of both, LYS 1 and LYS 2 showed different results. The precipitation amount measured by HRG was continuously lower in comparison to VWT, LYS 1 and LYS 2. These deviations exist further on even after application of the correction factor of approximately 10 % according to [8] on HRG results to compensate effects of different measurement heights.

The results of precipitation measurements by VWT are very similar to that of LYS 2 regarding the registered precipitation events and amounts. It was already mentioned, that precipitation measurements by VWT were carried out in height of 2.3 m. The measuring height is predetermined by the manufacturer of the meteorological station. Correction factors for VWT precipitation measurement systems are not available.

In general, all devices recorded precipitation and showed analogies concerning the distribution of rain events, but the amounts are different. Referred to LYS 1, the precipitation amount measured by HRG reached only 90.6 %, whereas the amount of LYS 1 was exceeded by VWT and LYS 2 (112 % and 118 %, respectively).

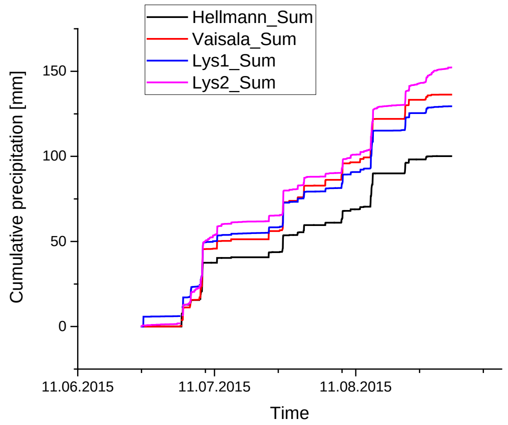

Fig. 2 *Cumulative precipitation rates of HRG, VWT, LYS 1, and LYS 2 during the investigation period.*

3.2 Soil moisture

The SHMS 1 and 2 were installed directly in the field inside the trials. The following soil tillage technologies were tested:

a) «DATT» technology with deep loosener on 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).

Additional measurements of soil moisture content were performed by LYS 1 and LYS 2 at depths 30-50-120 cm for different crop rotations LYS 1: wheat (2013) – peas (2014) – wheat (2015) – fallow (2016). LYS 2: natural feather grass (Stípa pennáta) dominated dry steppe (2013-2016).

Analysis of the soil moisture regime of SHMS 1 and 2 for 2013 - 2016 (not displayed) showed that advantages of No-Till revealed only in the third year, since 2015 (Tab. 3). The results from SHMS 2 demonstrated the advantages of No-Till at a depth of 30 cm and 60 cm in June-July 2015, when the site was seeded with spring wheat. Also in 2016, we observed the same effects, when it was seeded with peas, which had higher soil moisture consumption than spring wheat. In general, the measurements under No-Till system demonstrate the similarity dynamic of soil moisture in different depths for the vegetation season 2015-2016.

Table 3 *Monthly average soil moisture in depths 30, 60, 120 cm during the vegetation season in 2015 and 2016, SHMS 1 and 2 «Poluyamki».*

Period	Soil moisture in depth 30 cm (Vol. %)		Soil moisture in depth 60 cm (Vol. %)		Soil moisture in depth 120 cm (Vol. %)	
	DATT	No-Till	DATT	No-Till	DATT	No-Till
2015						
May	-	16.1	-	22.7	-	23.1
June[1)]	11.8	18.0	15.4	21.6	15.4	19.0
July[2)]	10.2	15.0	13.8	15.5	13.8	12.9
August	11.3	12.6	13.0	14.5	13.0	12.5
September	14.9	12.4	12.5	14.1	12.5	12.7
Average	**12.0**	**14.8**	**13.7**	**17.7**	**13.7**	**16.0**
2016						
May[3)]	21.4	17.5	21.6	22.6	20.7	23.2
June	-	17.9	-	22.6	-	20.8
July[4)]	12.7	17.5	14.5	17.4	16.2	14.3
August	11.6	16.4	13.6	15.0	16.5	12.4
September[5)]	11.2	15.5	13.3	14.8	16.9	11.8
Average	**15.6**	**17.0**	**16.8**	**18.5**	**18.2**	**16.5**

Note: [1)] data for June 25 - June 30 2015
[2)] no data from July 11 – July 15 2015
[3)] data by DAAT only for May 05 2016
[4)] data by DAAT for July 23 - July 31 2016
[5)] data for September 01 - September 25 2016.

3.3 Actual Evapotranspiration

Lysimeters are typically used to quantify rainfall, drainage and ETa [9]. According to the water balance equation, the changing masses (weights) represent the water storage within the soil monoliths. These changes can be displayed as positive or negative values. A mass gain of the soil monolith means precipitation; mass reduction must be interpreted as seepage or as a release of gaseous water from plants and soil in the form of evaporation or transpiration respectively. Hence the rising and falling masses of the soil monoliths are the basis for calculations of precipitation and ETa, which can be displayed as quantities in mm.

To demonstrate the operational reliability of the lysimeter station, Fig. 3 shows the mass of the installed lysimeter recorded over a three-day period in August 2013 based on a one-hour measurement. There was no drainage from the lysimeters in that period. While the mass of LYS 1 (arable land, spring wheat) on 2013/08/25 08:00 was 3914.1 kg, the LYS 2 mass (natural steppe vegetation) was 3707.4 kg.

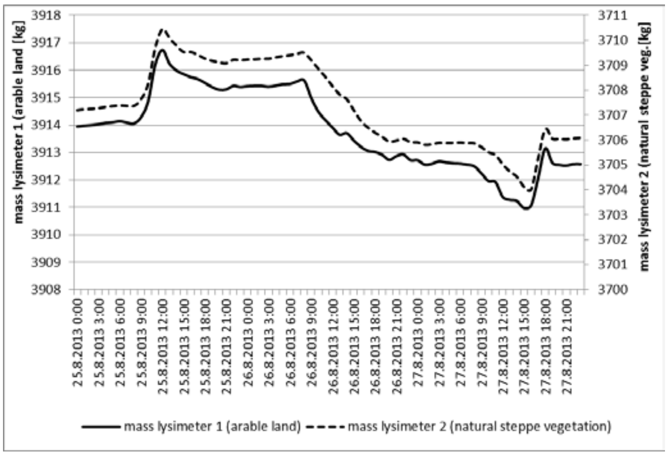

Fig.3 *Example of the diurnal mass changes of two gravitation lysimeters planted with spring wheat and a pristine plant cover.*

Both soil monoliths registered a precipitation event on 2013/08/25 08:00-12:00 resulting in mass increases about 2.7 kg (= 2.7 mm) (LYS 1) and 3.1 kg (= 3.1 mm) (LYS 2) respectively. The differences between the two monoliths are mainly based on the different vegetation covers and associated interception. Between 12:00 and 21:00 both monoliths registered a mass reduction about 1.4 kg (= 1.4 mm), which has to be interpreted as ETa. At the following day the monolith mass decreased with the rising sun; during 08:00 to 12:00 an ETa of 2.9 mm (LYS 1) and 3.6 mm respectively was measured. Also on 2013/08/27 between 08:00 and 15:00 ETa values of 1.5 mm (lysimeter 1) and 1.7 mm (LYS 2) were determined. The precipitation event after 16:00 (LYS 1: 2.2 mm, LYS 2: 2.4 mm) stopped the ongoing ETa. From 18.00 until the end of the measuring period ETa occurred and caused a small mass loss of 0.5 kg (= 0.5 mm, LYS 1) and 0.4 kg (= 0.4 mm, LYS 2) respectively. Considering the entire study period (2013/08/25 00:00 – 2013/08/27 23:00) it was seen that on LYS 1 the mass was reduced about -1.4 kg during a precipitation amount of 4.9 mm, this leads to an ETa of 6.3 mm. In comparison for LYS 2 a mass change of -1.6 kg and a precipitation amount of 5.5 mm were recorded; based on this data the calculated ETa was 7.1 mm.

Due to technical reasons, there was the problem of continuity of measurements and there are some gaps in the data, especially during winter time. The measuring system must be adapted better to the meteorological conditions of the region.

4. Conculsions

Based on the collected data, it could be shown that the precipitation measurement by HRG, VWT, LYS 1, and LYS 2 delivers plausible datasets regarding the precipitation dynamics. As expected, precipitation measurement by lysimeter resulted in a precise and reliable detection of rainfall. HRG installed at 1 m height underestimated significantly the amount of precipitation. Measuring results from VWT as integrated part of a meteorological station can be used for advanced assessments.

There are certain advantages of No-Till management compared to DATT technology due to more available soil moisture at depths of 30-60-120 cm. Moreover, the rise of moisture from the deeper soil horizons probably occurs at topsoil aridization. We suggest that No-Till technology gradually forms soil conditions close to the natural background (steppe) with respect to possible errors caused by technical measurements.

Based on sophisticated lysimeter measurements it was possible to estimate for the first time reliable data concerning the amount of ETa for the environmental conditions of the Kulunda dry steppe.

Further research is necessary to get certain information regarding precipitation measuring during the whole year in Siberia and to improve the lysimeter measuring during winter time in this region. To tackle these problems the new research project "Innovations for sustainable use of agricultural resources and climate adaptation in the arid steppes of Kazakhstan and Southwestern Siberia" (ReKKS) started in August 2017. The research is sponsored from the German Federal Ministry of Education and Research (BMBF).

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