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Annual dynamics of hydrothermal conditions of natural and anthropogenically transformed soils

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Abstract. Soil temperature is a key factor controlling many biotic and abiotic processes in soils. It is important to perform temperature monitoring of peat and mineral soils. An atmosphere-soil monitoring system is used to study the hydrothermal regime of soil at two sites (abandoned cropland and spruce forest) with different vegetation covers, top soil structures, and moisture regimes. The observations were carried out from 1 July 2013 to 30 June 2017 in soil profiles from the surface to a depth of 320 cm. In the early 20th century, the present abandoned cropland site was occupied by spruce forest, but later it was used as cropland. The trees were cut down and the top soil was used for croplands. Now the croplands are abandoned and covered with steppe grasses. Differences in vegetation covers lead to differences in soil thermal regimes. The abandoned cropland site soil is better warmed up than the spruce forest soil. The zero isotherm at the spruce forest site reaches a depth of 120-130 cm, while at the abandoned cropland site the zero isotherm is observed deeper than 320 cm. Negative soil temperatures exist at the spruce forest site at depths from 130 to 320 and deeper reaching permafrost soil.

1. Introduction

In the existing numerous definitions of climate, soil is considered as an active surface, under the influence of which the climate of the atmosphere is formed. Thus, soil is understood as an integral part of the physical and geographical environment, which is in interaction with climate, but not as a special medium of its manifestation. Soil climate is a combination of intra soil physical phenomena of annual and daily cyclicity, affecting the life and productivity of the soil and depending on the external climate, soil physicochemical properties, and effects on the soil and its cover [1]. While atmospheric climate is a physical phenomenon occurring in the air shell of the earth, i.e. in a mixture of gases, soil climate is formed in soil, which, unlike the atmosphere, is a bio-organo-mineral system that has its own laws of development.

The atmosphere as a whole is more or less homogeneous over large areas of the earth. Soil is heterogeneous in its composition and properties, even in relatively small areas. Because of this, physical phenomena occurring directly in the soil are less homogeneous than in the atmosphere [2].

The thermophysical state of soils is determined by vegetation and snow cover, atmospheric climatic characteristics, physical and chemical properties of soils, as well as human economic activity. Forest cutting, plowing affect not only the water-air, food, and biological regimes of soils, but also their thermophysical state. The study of the thermophysical state of soils, in conjunction with their genetic characteristics, nature and degree of natural moistening, compaction and aeration of the soil profile, is necessary both for the genetic characterization of soils and for calculating, estimating, and predicting changes in the hydrothermal regimes of soil horizons under anthropogenic influences [3].

The formation of temperature fields in soil is determined by its thermophysical properties: heat capacity, thermal and heat diffusivity, which, in turn, are functions of a number of soil-physical factors, such as moisture, granulometric composition, density, porosity, organic matter content, and temperature. All this causes the heterogeneity of soils in terms of thermophysical parameters.

2. Models and Methods

Our investigations were carried out at a site called the Tunkinskiy field station, Sochava Institute of Geography, SB RAS in the territory of the Tunkinskaya depression (south-western Pribaikalye, Republic of Buryatia) [4-6]. The object of investigation is humus-coarse-humus soils on sandy lacustrine-alluvial sediments. Two key areas were selected for an intense study of the soil thermal regime (Figure 1). The first section is represented by a 20-year reservoir on humus-coarse-humus soil (reservoir), the second one, by spruce forest on humus-coarse-humus soil (spruce). According to cartographic data, at the end of the 19th century both sites were under forest. Since the beginning of the twentieth century the first site began to be used as arable land. The crisis of the agricultural production complex at the end of the 20th century led to the fact that most of the arable land on the territory of the Tunkinskaya depression was abandoned and is currently at various post-aggressive stages of soil and vegetation restoration [7].

a b

Figure 1. Investigation sites: (a) abandoned cropland, (b) spruce forest.

The study of the intra-annual dynamics of temperature of humus-coarse-humic soils under spruce forest and the abandoned cropland was carried out on the basis of measurement data of 2013-2017 obtained with the help of a vandal proof atmosphere-soil measuring systems (ASMSs) [8]. The vandal proof ASMS designed for hidden installation which determines the inability to use masking structures: soil temperature and humidity sensors, controller with ultra-low power consumption (battery power) was developed with large internal non-volatile memory for data recording and USB interface, using a special cable with a sealed connector to connect to the logger, and maximum degree of protection of the enclosure IP68 (possible operation below the groundwater level). The microcontroller is used in the logger, which through the digital interface interrogates temperature sensors, analog inputs and stores data in non-volatile memory with reference to the measurement time using a clock. The USB interface allows the ASMS to communicate with the computer to configure its operation and read data.

The temperature sensors were located on the soil surface and at the following depths: 2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 80, 120, 160, 240, and 320 cm below the surface [9]. The humidity sensor (TRIME-PICO32) was located at a depth of 15 cm. The measurement period is 1 hour. The physicochemical properties of soils and underlying soils were studied by methods generally accepted in soil science.

The use of ASMS in these areas is conditioned by the need for year-round monitoring and the possibility of flexible installation of sensors.

In turn, at meteorological stations measurements are made using standard meteorological instruments (extracting deep soil thermometers, Savinov’s crank thermometers) [10]. The extracting soil-depth thermometer is a glass mercury thermometer with a cylindrical reservoir and a glass scale. A thermometer fused into an outer protecting glass shield is used for measurements at greater depths. Wax was inserted between the bulb and the shield to increase the time constant. To obtain a measurement, the instrument is extracted from a plastic tube that has been driven into the soil to the desired depth.

Observations using extracting soil-depth thermometers at depths of 80, 120, 160, 240, and 320 cm are produced all year round once a day on time, the closest to 14 hours of the belt-time (winter) time. Observations at depths of 20 and 40 cm in the warm half of the year are made in a single synchronous time (8 times a day). Savinov’s crank thermometers are a set of four glass mercury thermometers with cylindrical tanks the ends of which are rounded. Savinov's crank thermometers are installed at depths of 5, 10, 15, and 20 cm in a row along the line from east to west in the middle of the site. Observations by the Savinov’s cranked thermometers are made only in the warm season (at positive temperatures) in a single synchronous time (8 times a day).

Earlier a comparison was made between the data of standard meteorological instruments and ASMS data [11]. Correlation coefficients have a high value at all depths for each month (from 0.9 and above). But for the entire period under investigation, several anomalies are observed when the correlation coefficient is below 0.9. Low values of the correlation coefficient were recorded in September at a depth of 240 cm - 0.66 (2014), 0.69 (2013), and 0.83 (2015). In September, the soil temperature measured with ASMS at a depth of 240 cm is higher by an average of 0.5°C. Such differences were observed in all years. In addition, low values of the correlation coefficient are also found at a depth of 320 cm in April-May. The values of the correlation coefficient in these months vary from 0.55 in April 2015 to -0.06 in April 2014. Comparison of the temperature at these depths during these periods shows a difference of 0.1-0.2°C. Such differences in the values may be caused by a mechanical error in the measurement of the extracting soil thermometers (error: 0.2°C).

The greatest deviations in the average daily temperature of the soil are observed in the cold season at a depth of 20 cm, and with an increase in depth they are smoothed out. During this period, the value of soil temperature according to ASMS is higher by 1.8-2.0°C than the soil temperature from the data of extracting soil thermometers. Differences in soil temperature values decrease with the transition from the cold period to the warm one, in summer they are minimal on the average, 0.5-0.8°C. At the beginning of summer, the soil temperature, according to the atmospheric-soil measurement system, is higher, and at the end of summer it is lower.

With increasing depth, there is a decrease in deviations between ASMS and extracting soil thermometers. Analysis of the temperature distribution at a depth of 160 cm shows that the soil temperature values obtained from ASMS data are greater in winter-spring by 1.0-1.5°C and less in summer-autumn by 0.1-0.3°C.

3. Results and discussion

Average daily, average monthly, and annual values of soil temperature in the profile of 0-320 cm and soil moisture at a depth of 15 cm were calculated. The volumetric soil moisture over the period with a temperature above 0°C for the abandoned cropland was 18%, and for the spruce forest it was 37% on average.

The distribution of soil temperature along the profile in the sections under study differs significantly. Two clearly defined periods can be identified on the abandoned cropland: cold when the soil temperature throughout the profile is below 0°C and warm when the soil temperature is above 0°C. In the winter of 2013/2014 and 2014/2015 the lower boundary of the seasonally frozen layer was below 320 cm, while in the winter of 2016/2017 the lower boundary of the seasonally frozen layer was recorded at a depth of about 300 cm. At the same time, the area in which the spruce forest is located is seasonally thawed. The maximum depth of the zero isotherm in the warm period is 120-130 cm (Figure 2), below this mark there is permafrost with a temperature from 0 to -2°C. In the cold period, the isotherm depth of -2°C is also about 120-130 cm during all years of observation.

Such large differences in the features of the temperature regime were manifested against the background of a change in the landscape structure of one of the sites. At the same time, the soil climate formation factors at these sites are the same: the atmospheric climate, the shape of the relief, the proximity of rivers, irrigation or drainage systems, and the altitude above sea level. Thus, the removing of vegetation cover (forest) and plowing of the upper soil horizons on the abandoned croplands led not only to a decrease in soil moisture, but also to a change in the warming-up regime of the soil in the warm period and freezing into the cold. Also, at the site of the abandoned cropland, compared to the spruce forest, the character of soil moisture has changed. In the summer period, the site covered by the crowns of trees receives less moisture in the form of precipitation than the open ones. In this case, the soil in the spruce forest is more humid than on the abandoned cropland. In the cold season, the ground freeze depth is greatly affected by maximum snow cover depth and temperatures during the winter months [12].

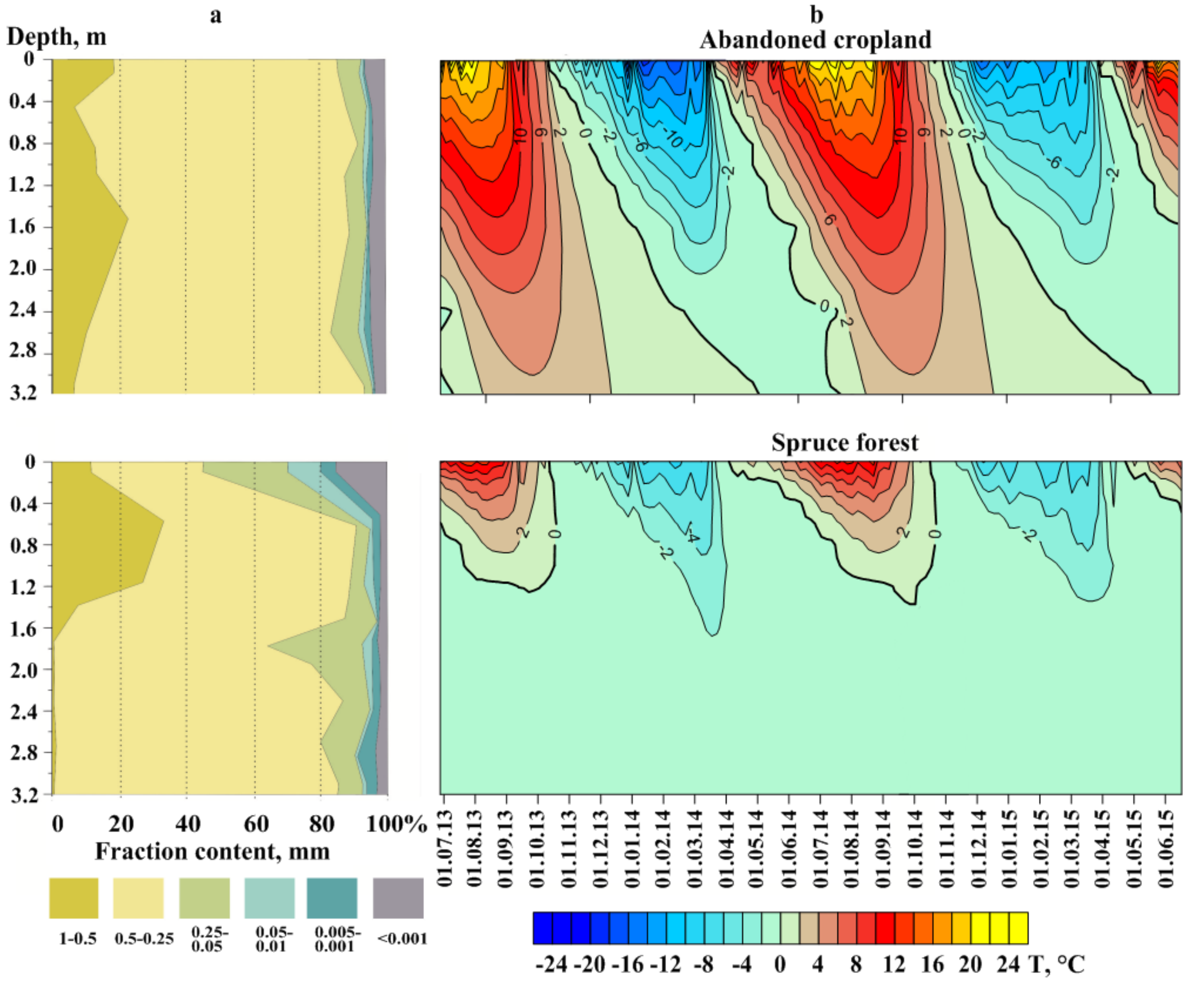

Figure 2. Soil granulometric composition (a) and temperature profile (b).

The spruce forest site has a relatively less uniform distribution of fractions of the granulometric composition along the profile: from the surface to 130 cm the soil consists of coarse sand (the size of fractions is 0.5-1.0 mm) and its amount is from 10 to 35%, with a maximum of 30-35% in the 50-110 cm layer. The rest of the soil consists mainly of medium sand (size of fractions: 0.25-0.5 mm). While on the abandoned cropland the proportion of coarse sand throughout the soil profile varies from 8-10 to 20%, the rest of the soil also predominantly consists of medium sand (Figure 3).

a b

Figure 3. Soil profiles (a) abandoned cropland, (b) spruce forest.

The above-listed factors contribute a relatively small role to changes in the temperature regime, but with a complex effect of all factors the temperature regime changes significantly. First of all, this affects the rate of warming up and freezing of the soil.

The warmest period during the study was the summer of 2016, the maximum temperature in the annual course of the profile in the profile from the surface to 320 cm varied from 30.9°C to 4.9°C. This year in the spruce forest the maximum soil temperature varied from 20.4°C on the surface to -0.2°C to a depth of 320 cm. The coldest period during the study was the winter of 2016/2017. On the abandoned cropland the minimum temperature in the profile during the annual course varied from 4.1°C on the surface to -0.1°C at a depth of 320 cm. In the winter of the same year, in the spruce forest the minimum soil temperature varied from -11.3°C on the surface to -1.2°C at a depth of 320 cm.

The transition of daily soil temperature through 0°C, which corresponds to the beginning of stable freezing of the soil, occurs on the soil surface in both areas in November. However, in the spruce forest in most cases it is observed earlier, thus, in the autumn of 2014 the difference was 14 days, 2015 - 10 days, 2016 - 3 days. An exception was 2013, when the soil temperature transition through 0°C in the spruce forest was fixed later by 2 days than on the abandoned cropland. Thawing of the soil and, consequently, a stable temperature transition through 0°C towards positive temperatures is observed on the abandoned croplands in March, and in the spruce forest, in April. Thus, during the onset of meteorological spring, the abandoned cropland begins thawing much earlier: in 2014, this difference was 15 days, in 2015 - 25 days, in 2016 - 22 days, and in 2017, 6 days. Such a difference in the dates of the onset of freezing and thawing of the soil surface is mainly due to differences in the vegetation cover. When freezing, the daily amplitude of temperature on the surface of the soil in the spruce forest is less than that of the abandoned cropland, and the warming up of the surface is not so intense that it promotes active freezing of the soil. In spring, in the spruce forest vegetation also absorbs some of the incoming solar radiation, thereby reducing the rate of snow melting, and this leads to an increase in the lifetime of the frozen layer.

With increasing depth, the differences in soil temperature between sites increase. Thus, on the abandoned cropland at a depth of 120 cm the temperature transition through 0°C in the direction of negative temperatures is observed in December. Whereas in the spruce forest it occurs mainly in November. Transition through 0°C in the direction of positive temperatures at a depth of 120 cm on the abandoned croplands is fixed in May, and in the spruce forest, in September.

On abandoned croplands the duration of the period with positive soil temperatures on the surface is greater, it varies from 198 to 215 days, whereas in the spruce forest it varies from 176 to 193 days. On abandoned croplands with increasing depth the duration of the period with a temperature above 0°C remains almost unchanged and at 120 cm in different years it is from 204 to 219 days. While in the spruce forest this period is greatly reduced and varies from 22 to 80 days, depending on the conditions of a particular year, and deeper than 130 cm there is perennial frozen ground.

4. Conclusions

As a result of the information of the forest on the plots chosen for arable land at the beginning of the 20th century, humus-coarse-humic soil underwent homogenization of the humus horizon and facilitation of its granulometric composition due to partial tilling of the underlying sandy horizon. Agrogenic use led to a change in the chemical (partial mineralization of organic matter, depletion of organic matter and nitrogen) and physical (grain size distribution, density) characteristics of the humus horizon of the soil, which led to a change in such characteristics as thermal conductivity and moisture capacity.

In addition, the obtained data show that vegetation removing has a great influence on thawing of the soils, which prevents the entry of solar radiation onto the surface and, consequently, warming of the soil stratum. There are clear differences in heating / freezing and the difference in temperatures in the areas under study. Thus, in 2016 on the anthropogenically disturbed section the maximum temperature in the annual course is 30.9°C, while in the undisturbed forest massif it is 20.4°C. The minimum temperature in the annual course is in winter 2016/17 on the surface: -4.1°C and -11.3°C, respectively.

On an anthropogenically disturbed site, the duration of the period with positive soil temperatures on the surface is greater by an average of 22 days than in the undisturbed forest. With increasing depth, the differences in the temperature regime are preserved.

Thus, for the period from 2013 to 2017, it was found that anthropogenically disturbed areas in the upper 300 cm layer are seasonally frozen. The lower boundary of the seasonally frozen layer in these areas is below 300 cm, while the undisturbed areas are seasonally thawed. In the warm period the maximum depth of the zero isotherm is 120-130 cm.

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