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Diversity of thermal conditions within the paleocryogenic soil complexes of the East European Plain: The discussion of key factors and mathematical modeling

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ABSTRACT

Spatial distribution of soil temperature was modeled for paleocryogenic complexes of the East European Plain. The purpose of the research was to answer the following question: Can lateral temperature differentiation within studied complexes be explained by lateral differentiation of soil properties? Lateral distribution of soil temperature was modeled for the case of laterally uniform surface conditions and laterally variable soil properties. Simulations were performed for two plots with bare soils. In both cases the dynamics of upper boundary conditions was set by weather data and was the same for the whole plot. The spatial distribution of soil thermal diffusivity was set in two ways. For the first plot the input data on spatial arrangement of soil horizons and laboratory data on thermal diffusivity vs. moisture content dependencies for different horizons were used. For the second plot field data on spatial distribution of soil bulk density, organic carbon content and soil moisture content were used as input data for earlier derived pedotransfer functions, allowing to estimate soil thermal diffusivity. For both plots modeled temperature was underestimated as compared to field data with RMSE of 1.0–1.5 °C, but the pattern of temperature spatial differentiation was similar to that observed in the field. Lowest temperatures corresponded to areas with low bulk density and high organic carbon content, that is, areas occupied by soils with the second humus horizon. Thus, mathematical modeling has confirmed that the observed heterogeneity of soil properties is sufficient to explain the formation of a laterally heterogeneous thermal field within the studied soils. It also confirmed that we may use suggested pedotransfer functions to estimate lateral temperature variability in loamy soils from data on bulk density, organic carbon content and soil moisture content.

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1. Introduction

Soil temperature is an important factor of soil functioning, including physical, chemical and microbiological processes. Soil temperature is related to weather conditions, but this relationship is not universal. Kostychev (1886) and later Neustruev (1930) noted that soil climate is the result of “refraction of external climate” in soil strata, and this “refraction” is determined by internal soil properties, which may vary in space and time. At the same weather and surface conditions including topography and vegetation, the temperatures of soils with different properties are different (Arkhangel'skaya et al., 2005a,b, 2007; Arkhipova, 1958; Shulgin, 1972).

Spatially linked soils may have distinctly different temperature regimes. Lateral temperature differences were registered for semi-desert soil complexes (Bolshakov, 1941; Dimo, 1907; Keller, 1913), tundra and cryogenic soil complexes (Dimo, 1972; Kulikov, 1997; Vasil'yevskaya et al., 1994), and paleocryogenic soil complexes of the East European Plain (Arkhangel'skaya et al., 2005a,b, 2007). Dimo (1907) wrote about lateral differences of 2.8 °C at 20 cm depth and 2.7 °C at 200 cm depth for soils of solonetzic complexes in Volgograd region. Bolshakov (1941) also noted that temperature regimes of semi-desert soil complexes differ laterally, and reported the differences in the depth of winter freezing of studied soils. Dimo (1972) described 5 °C temperature differences and 10–12 cm differences in the depth of zero isotherm for soils of cryogenic complexes in Chita region. Kulikov (1997) worked with cryogenic complexes of Vitim plateau and registered 20–40 cm differences in the depth of permafrost and lateral temperature differences up to 4.9 °C; statistically significant temperature differences for the depth of 20 cm were 1.4–2.6 °C. We registered lateral differences in soil temperature up to 3.5, 2.1 and 1.9 °C at 50, 70 and 100 cm depths and more than 10 cm differences in the depth of zero isotherm for arable paleocryogenic soil complexes in Vladimir region (Arkhangel'skaya et al., 2005a; Arkhangelskaya et al., 2008).

Keller (1913) stressed that even small, but permanent differences in soil temperatures may have significant cumulative effect on energetics of laterally coupled soils. Vasil'yevskaya et al. (1994) noted that different rates of heating and cooling of geochemically linked tundra soils result in lateral temperature and moisture gradients. These gradients determine the direction and intensity of water flows and resulting substance transfers between the elements of soil complex and beyond.

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Most authors explain the reported differences in soil temperature by the combined effect of topography, vegetation and soil properties. But for the case of very poor semi-desert vegetation Dimo (1907) stressed the leading role of soil thermal properties for lateral differentiation of soil temperature. We assumed that for flattened arable soils with bare surface or under homogeneous agricultural vegetation soil thermal properties are also the main factor of temperature differentiation (Arkhangel'skaya et al., 2005a,b, 2007).

The spatial interrelations between soil properties, topography, vegetation, soil moisture and soil temperature are also discussed in recent articles (Savva et al., 2013; Zhu and Lin, 2011). Zhu and Lin (2011) found that in relatively flat areas soil properties dominated over topography in controlling soil moisture variation regardless of season and soil wetness. Savva et al. (2013) pointed that spatial structure of soil moisture was relatively stable under changing soil temperature and moisture conditions.

Mathematical models of soil temperature regime (Campbell, 1985; Elias et al., 2004; Karam, 2000; Liu et al., 2002; Novak, 1993; Shao et al., 1998) are based on the heat equation suggested by Fourier (1822). In accordance with Fourier's theory, the temperature of deep soil layers is determined both by the surface temperature conditions and the soil thermal diffusivity. The higher the soil thermal diffusivity is, the faster soil is warmed in spring and summer and cooled in the fall and winter.

When modeling soil temperature regime, the surface conditions are often specified as boundary conditions of the first kind, i.e. the dynamics of surface temperature (Elias et al., 2004; Gupta et al., 1982, 1984; Hanks et al., 1971; Horton et al., 1984; Liu et al., 2002; Shao et al., 1998; Wierenga and de Wit, 1970). The necessary data on soil thermal diffusivity may be determined experimentally, derived from data on thermal conductivity and heat capacity, or calculated from data on basic soil properties, using pedotransfer approach. Most models of soil thermal conductivity and diffusivity use data on soil moisture content, bulk density and organic carbon content; sometimes data on soil texture and mineralogical composition are also taken into account (Campbell, 1985; Campbell et al., 1994; Côte and Konrad, 2005; de Vries, 1963; Eitzinger et al., 2000; Johansen, 1975; Lu et al., 2007; Tarnawski and Gori, 2002; Tarnawski and Wagner, 1992).

The accuracy of modeling soil thermal properties is rather low. Farouki (1986) and Tarnawski et al. (2009) tested the model of soil thermal conductivity of Johansen (1975) and considered its results to be good, though Farouki obtained relatively low RMSE of 35% only for the case of not too dry soils with normalized moisture contents of more than 20%. For dry soils Johansen's model sometimes worked well, but in some cases it overestimated soil thermal conductivity by 4 times, i.e. up to 200% (Côte and Konrad, 2005). Peters-Lidard et al. (1998) compared the results of two models with experimental data; Johansen's model gave RMSE of 70%, and it was much better than RMSE of the model of McCumber and Pielke (1981), which were 21–333% for sand and 31–257% for clay. Usowicz and Usowicz (2004) calculated soil thermal conductivity using the model of de Vries (1963) and compared it with experimental data, which resulted in RMSE of 22–70.5%. Calculating thermal diffusivity of the East European Plain soils using the model of Campbell (1985) gave RMSE of 66% (Arkhangel'skaya, 2009), and using the model of Lu et al. (2007), which is an upgrade of the model of Johansen (1975), gave 90.8% (Arkhangelskaya and Luk'yashchenko, 2009). The author's model developed for loamy luvisols and phaeozems gave RMSE of 9–32% when applied to independent samples of similar texture and genesis, and 38–158% for solonetzic soils and chernozemic vertisols (Arkhangel'skaya, 2009).

The goal of this paper is to show that pedotransfer approach, though giving not very precise estimates of soil thermal diffusivity, is still suitable for predicting qualitative heterogeneity of soil temperature from generally available input data.

The question to be answered is: Can lateral temperature differentiation within the paleocryogenic complexes of arable soils in relatively flat area be explained only by lateral differentiation of soil morphology and corresponding differentiation of soil thermal diffusivity without referring to topography? To answer this question, a series of model experiments was carried out. Lateral distribution of soil temperature was modeled for the case of laterally uniform surface conditions and laterally variable soil properties.

2. Material and methods

2.1. Objects

Arable soils of the paleocryogenic complexes of the East European Plain were studied in Vladimir region (56°23′ N, 40°25′ E, 126 m AMSL) and in Moscow region (54°20′ N, 37°37′ E, 177 m AMSL). The regular structure of studied soil complexes was determined by the late Pleistocene peryglacial period. The intersections of former frost-contraction cracks, that is, former microdepressions, are now filled with the material of the second humus horizon, consisting of Ah and/or AE horizons, with upper part included into the arable horizon. In the middle parts of paleopolygons, that is, at the former microelevations, there developed soils with the B horizon lying immediately under the arable one. The relic soil mantle is now passing through the agrogenic stage of its evolution that resulted in almost complete smoothing of soil surface and transition of the relic topography into a buried form. The modern soil profiles include the Ap-(Ah)-AE-BEg′-EB-(B)-C horizons in former depressions, the Ap-B-Bca-Cca horizons at former interfluves, and the Ap-EB-(B)-C-(Cca) horizons in transient positions. The hypotheses on the genesis of studied soils and detailed description of their morphology, properties and spatial regularities can be found in Dmitriev (2000), Dmitriev et al. (2000), Makeev (2009), and Velichko et al. (1996). Many authors point out that paleocryogenic soil complexes are widespread in the central part of the East European Plain (Fridland, 1984; Makeev, 2009; Velichko, 1990).

At the experimental plot in Vladimir region the bulk density of studied soils varied from 1250 to 1610 kg m^{-3} in the plow horizon and from 1100 to 1610 kg m^{-3} in the subsurface layer; the organic carbon content varied from 1.45 to 3.55% in the plow horizon and from 0.40 to 4.65% in the subsurface horizons. Sand, silt and clay contents were 8–54, 30–75 and 14–35% (Fig. 1). Spatial heterogeneity of bulk density, texture and organic carbon content was accompanied by a pronounced lateral heterogeneity of soil thermal diffusivity (Arhangelskaya, 2004). The highest values of thermal diffusivity were obtained for EB horizons and the lowest ones for Ah horizons. The topographic position of soils with different morphological profiles was quite similar (Arkhangel'skaya et al., 2005a, 2007), and it means that there were no regular differences in insulation of soil surface.

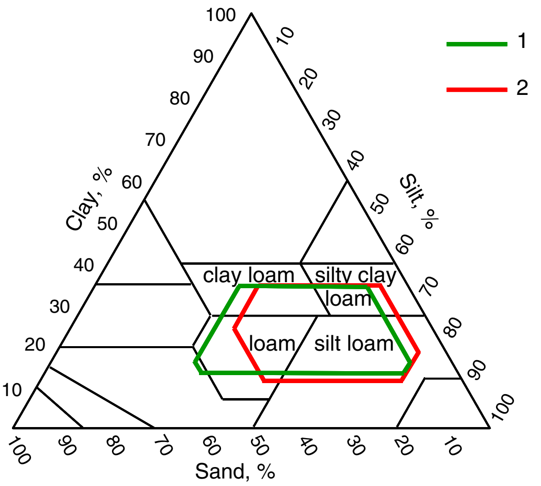

Fig. 1. Texture ranges of studied soils for Vladimir plot (1) and Moscow plot (2).

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