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THE SIMULATION OF THE THERMAL REGIME OF SODDY-PODZOLIC SOILS OF BELARUSIAN POLESIE

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Abstract

This article presents the results of a comprehensive modeling study aimed at predicting heat transfer dynamics in soddy-podzolic soils in the Belarusian Polesie region. The study covers a time horizon up to 2035 and takes into account two key factors:

1) various land drainage standards, varying in intensity and technological parameters;

2) global climate change, expressed in a persistent trend of increasing average surface air temperature.

To achieve this goal, an original methodological framework based on mathematical modeling methods was developed. The proposed approach allows:

• for reproducing the spatiotemporal dynamics of the temperature field in a soil profile;
• comparing the thermal regimes of natural (unamendied) and drained soils;
• assessing the impact of atmospheric temperature anomalies on the thermal state of the soil cover.

The computational experiments resulted in the generation of a predictive data set, including:

• detailed soil temperature profiles for various drainage scenarios;
• quantitative assessments of temperature gradients across the depth of the soil profile;
• time series of temperature readings with a step corresponding to climatic seasonality.

The practical significance of the obtained results lies in their potential for application in reclamation agriculture. In particular, the developed predictive models can be used:

• in designing water management systems in reclaimed areas;
• optimizing water supply schedules and drainage measures;
• developing adaptive strategies for managing agricultural landscapes in a changing climate;
• assessing the risks of overheating or overcooling of the root zone under various drainage scenarios.

Thus, the conducted study creates a scientifically sound basis for making management decisions in the field of reclamation, allowing for consideration of both local hydrological conditions and macro-scale climate trends.

Keywords: Belarusian Polesie, modelling, soddy-podzolic soil, melioration, temperature, heat capacity, amount of heat.

МОДЕЛИРОВАНИЕ ТЕПЛОВОГО РЕЖИМА ОСУШЕННЫХ ДЕРНОВО-ПОДЗОЛИСТЫХ ПОЧВ БЕЛОРУССКОГО ПОЛЕСЬЯ

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Реферат

В настоящей статье представлены результаты комплексного моделирования, направленного на прогнозирование динамики теплопереноса в дерново подзолистых почвах региона Белорусского Полесья. Исследование охватывает временной горизонт до 2035 года и учитывает два ключевых фактора:

1) различные нормативы осушения земель, варьирующие по интенсивности и технологическим параметрам;

2) глобальные климатические изменения, выражающиеся в устойчивом тренде повышения средней температуры приземного слоя воздуха.

Для достижения поставленной цели разработана оригинальная методическая база, основанная на методах математического моделирования. Предложенный подход позволяет:

• воспроизводить пространственно временную динамику температурного поля в почвенном профиле;
• сравнивать термические режимы естественных (немелиорированных) и осушенных почв;
• оценивать влияние атмосферных температурных аномалий на тепловое состояние почвенного покрова.

В результате вычислительных экспериментов сформирован массив прогнозных данных, включающий:

• детализированные температурные профили почв для различных сценариев осушения;
• количественные оценки градиентов температуры по глубине почвенного профиля;
• временные ряды температурных показателей с шагом, соответствующим климатической сезонности.

Практическая значимость полученных результатов заключается в их прикладном потенциале для сферы мелиоративного земледелия. В частности, разработанные прогнозные модели могут быть использованы:

• при проектировании систем регулирования водного режима на мелиорированных территориях;
• оптимизации графиков водоподачи и дренажных мероприятий;
• разработке адаптивных стратегий управления агроландшафтами в условиях изменяющегося климата;
• оценке рисков перегрева или переохлаждения корнеобитаемого слоя при различных сценариях осушения.

Таким образом, проведенное исследование создает научно обоснованную базу для принятия управленческих решений в области мелиорации, позволяя учитывать как локальные гидрологические условия, так и макромасштабные климатические тренды.

Ключевые слова: Белорусское Полесье, моделирование, дерново-подзолистая почва, мелиорация, температура, теплоемкость, количество теплоты.

Introduction

The country's food security is linked to an increase in gross agricultural production. Its implementation is associated with the inclusion of more land in agricultural trade and increased crop yields. The solution to the first question is problematic. In addition to seed quality and fertilizer application, the maintenance of optimal water-air and heat regimes in agricultural soils is a major factor in improving crop yields. Soil thermal and water-air regimes are factors that often largely determine the agricultural productivity of land. Land productivity is primarily associated with the application of necessary fertilizers, use of new varieties, control of plant weeds etc [1–3]. Less attention is paid to the microclimate of dry areas. According to the theory of V. R. Williams, dewatering should reduce excessive soil moisture to such a size that provides the necessary water, air, heat, microbiological and nutritional regime of the soil. The climate change occurring in the territory of Belarus, as well as in Europe as a whole, in recent decades is expressed in increasing air temperature in all months of the year. Changes in agro-climatic indicators during the growing season are of particular importance for agricultural production efficiency. These changes are most noticeable in the territory of Belarusian Polesie, which, due to its geographical location, is characterized by the highest heat availability and length of the growing season in Belarus.

The decrease in the amount of precipitation over the past decades at the Poleskaya station, located on the territory of the Luninets swamp massif, and at nearby stations allows us to conclude that the implementation of reclamation work on large areas (Luninets swamp massif, Poleskaya station), which has led to a decrease in forest cover and roughness of the underlying surface, leads to an increase in wind speed and a decrease in the amount of precipitation, especially during the cold period [4].

The observed increase in atmospheric moisture runoff in the absence of a compensating increase in precipitation leads to a decrease in the resilience of the soil cover of the Belarusian Polesie to extreme temperature conditions and moisture deficit, with the most pronounced negative consequences recorded on the arable lands of the region in question.

Establishing patterns of microclimate change in land reclamation, and predicting its changes is one of the important tasks of agriculture.

The aim of this study is to investigate the patterns of formation of the thermal regime of meliorated bottom-soddy-podzolic soils of Belarusian Polesie under current conditions and estimate its change in the period until 2035 due to climate warming, which is one of the important tasks of agriculture.

The Research methods and raw data.

The thermal conductivity equation [5, 6, 7, 8] is used to describe the pattern of formation of the soil temperature profile

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \quad (1)$$

where ρ – density, kg/m3; Cp – heat capacity, J/(mol K); k – thermal conductivity, W/mK; T – temperature, ^{0}K; ∇ – hamiltonian.

Solar radiation is the primary energy source responsible for the thermal regime of the Earth's surface. When interacting with the soil cover, radiant energy is converted into thermal energy, after which it is redistributed in two directions: conductive transfer to the underlying soil layers or emission into the atmosphere through thermal radiation and reflection [9]. The balance between absorbed and emitted energy represents the amount expended on heating the Earth's surface. An increased temperature gradient between the upper and lower soil horizons leads to an increase in the proportion of thermal energy migrating into the depths of the soil profile [10].

The numerical modelling of the thermal regime of soils [11] is reduced to computations of their temperature profiles [12].

For this purpose, a mathematical modelling method is used which allows, using the initial climatic conditions, to calculate the dynamics of the soil temperature profile and calculate the amount of accumulated heat [13].

To quantify the change in soil heat capacity, a numerical experiment was carried out according to the following scheme: 5 m^3 of soil with dimensions 1 m – width, 1 m – length and 5 m – depth, were taken as a conditional volume; the selected depth value corresponds to the level, at which the temperature fluctuations associated with the degree of heating of the air by solar rays [14, 15] cease.

The study considered the soddy-podzolic model as the most common in Belarusian Polesie and occupying more than 35 % of the territory [16]. The soil structure was chosen as follows: the top layer of sand 1 m deep, and the bottom layer of coarse-grained sand 4 m deep. Calculations were made for different ground water levels (WWS): 0 m, 0,4 m, 0,8 m and 1 m [17].

On the basis of specialized software, a model of heat transfer in soil has been created and the dynamics of its heating under natural and anthropogenic conditions have been studied [18]. The numerical solution of the mathematical model is obtained by the method of finite elements [19].

Based on meteorological information from the Poleska Weather Station, located in the Luninetsky Swamp and representative of the region [20]. The air temperature was assumed to be equal to the multi-year average value for that day at 7 pm, which corresponds approximately to the average value of the temperature on the day in question.

The projected values of the increase in average air temperature for warm months, given in table 1, are taken from one of the possible climate scenarios for the period up to 2035 [21, 22].

Table 1 – Projected increase in monthly average air temperature, °C

Month	April	May	June	July	August	September	October
Temperature difference	1,71	1,49	1,7	2,08	1,97	1,77	1,61

Using the above method, a numerical experiment was carried out to simulate the temperature profile of soils for the following boundary conditions:

- on the surface of the model soil, a heat flux equal to the average monthly flow of solar radiation falling on one area of the horizontal surface was applied;
- at the lower boundary of the modular soil, temperature stabilization conditions were set at 9.1 °C [23], equal to the average annual surface air temperature [24];
- on the surface of the soil was given the condition of convective heat exchange $-\nabla(-k\nabla T) = 0$ [25];
- heat insulation conditions were applied on the lateral borders of the allocated volume;
- evaporation from the surface of the soil was defined as the change in the internal energy of water during evaporation by the formula [26]

$$Q = Lm - vRT, \quad (2)$$

where L – the specific heat of vapour formation, J/kg; m – the mass of evaporated water, kg; v – the amount of substance evaporated water, mol; T – the air temperature, °K; R – the molar gas constant, J/mol °K

Results and their discussion

As a result of the numerical experiment, the distribution of soil temperature over the entire thickness of the simulated profile was obtained with an interval of radiance for a day from May to October including, on the basis of the year-long average value of air temperature and its prognosis until 2035 [27, 28]. As an example, figure 1 shows graphs of the temperature dependence on the depth of soddy-podzolic soil without dewatering for June 3 with a dewatering rate of 0,4 m for current climatic conditions [29] and a projected temperature change up to 2035.

As the numerical experiment showed, the soil temperature dynamics is synchronized with the air temperature when the climate warms. However, the nature of the change in the heat regime of dried and undried areas has a different structure and is determined both by climatic factors and the degree of melioration [30, 31].

Depending on the degree of moisture content, soil systems exhibit significant variability in their thermophysical properties, primarily specific heat capacity. This phenomenon is due to the dramatically different heat capacities of the two main components of soil pore space – air and water.

According to experimental data, the specific heat capacity of dry air is c_{air} = 1020 J/(kg·K), while the specific heat capacity of water reaches c_{water} = 4200 J/(kg·K). Thus, the heat capacity of water is approximately four times greater than that of air. Since water displaces air in soil pores, the presence of moisture in the soil proportionally increases its overall heat capacity – also approximately four times greater than that of completely dry soil.

A similar pattern is observed with respect to thermal conductivity: moist soil is characterized by significantly higher thermal conductivity than dry soil. This is of fundamental importance for heat transfer processes in the soil profile. Due to the increased thermal conductivity of a moist substrate, solar radiation absorbed by the soil surface is more effectively distributed into the lower horizons. This results in uniform heating of the root zone, which is critical for the vital functions of plants and soil biota.

The difference in the heat capacity and thermal conductivity of dry and moist soils leads to two important thermodynamic consequences:

1) heating moist soil requires significantly more thermal energy than dry soil of the same mass and volume. This is due to the high heat capacity of the water filling the pores;

2) moist soil has greater thermal inertia: as the ambient temperature decreases, it releases accumulated heat more slowly. This effect is explained by both the high heat capacity and the improved thermal conductivity of a moist soil profile, which ensures a more uniform heat distribution across the depth.

Thus, moisture content is a key factor regulating the thermophysical properties of the soil and determining the dynamics of heat exchange between the earth's surface and the ground layer of the atmosphere.

From the graphs shown in Figure 1, it follows that the nature of the temperature change as it approaches the surface does not change. Due to the increase in air temperature, the soil temperature changes accordingly. These changes are most significant from the depth of 2 m on undrained soils. When water is discharged during the drying process, the temperature change rate changes abruptly at the depth of the upper groundwater level.

From the diagrams shown in Figure 2, it can be seen that the amount of energy accumulated per month increases with increasing air temperature.

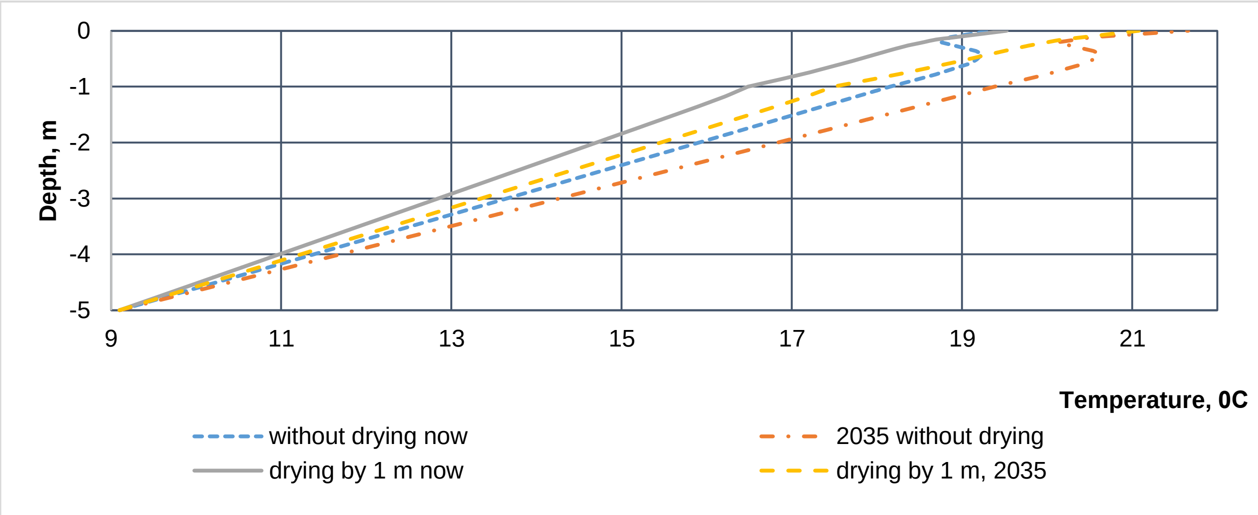
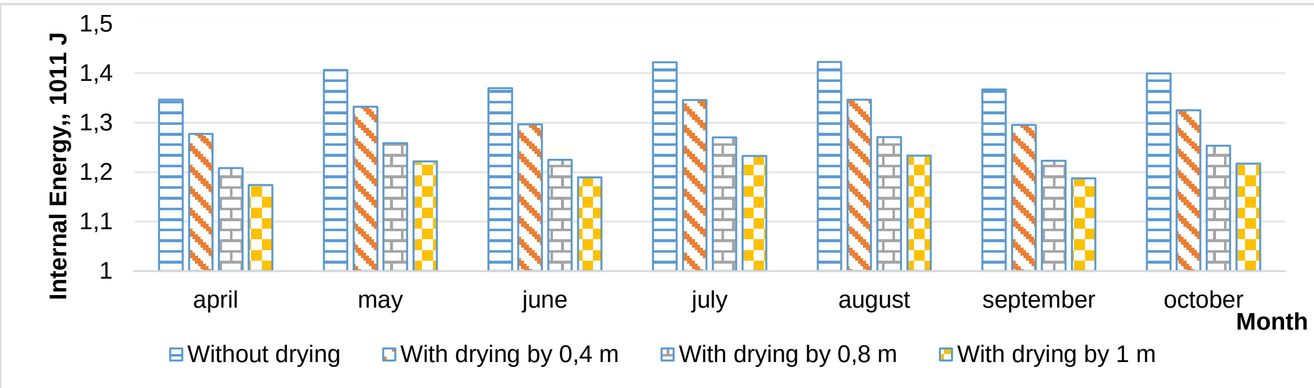
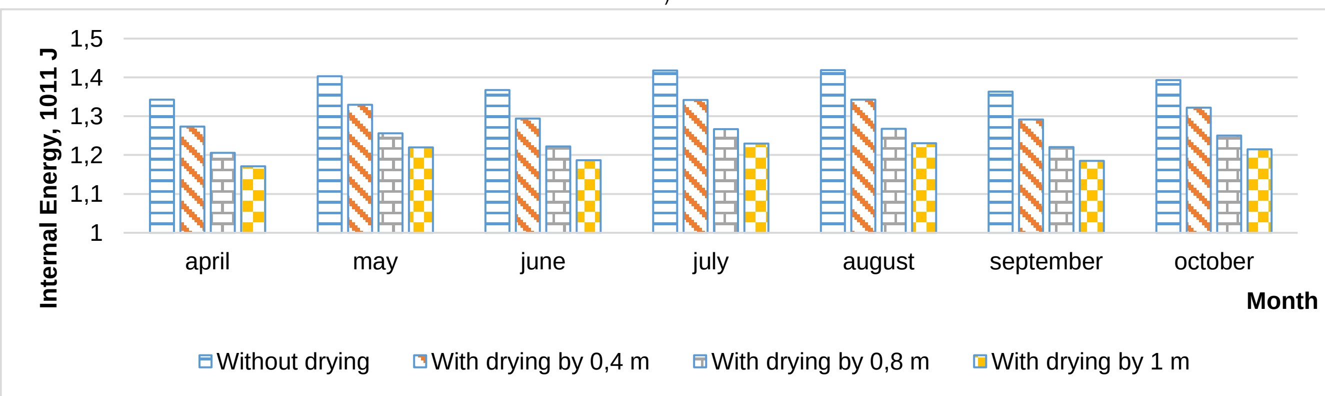


Figure 1 – Depth distribution of the temperature of soddy-podzolic soil for June 3 without drying and with normal drying 1 m



a)



b)

a) the forecast to 2035; b) current status

Figure 2 – The energy stored by bottom-seeded soils

The results shown in table 2 show that the most significant changes in the energy accumulated occur in soil without drying, since water in the soil has a greater heat capacity than air filling the soil pores. On drained soils, these changes are not as noticeable. The natural soil accumulates more heat energy and distributes it more evenly along its profile. In the process of prolonged negative temperatures during winter, at the depth of 150 cm, even by the end of the cold season, soil temperature was positive and was 2...2.1 °C. This phenomenon has been called «thermal inertia» [32, 33]. Water in the top layer of soil is more inert to changes in ambient air temperature, which helps plants to cope with late frosts in the spring and generally raises the temperature of the nutrient layer of soil and improves conditions for crop production, characteristic of more southern areas.

As it can be seen from table 2, the higher the rate of soil drying, the smaller the changes in the energy stored in the soil, therefore the soils dried out are less susceptible to climate change.

Table 2 – Change in accumulated energy of soil, 10^8 J

	April	May	June	July	August	September	October
Without drying	3,90	3,96	2,64	4,56	4,20	3,67	5,99
Drying by 0,4m	3,14	2,60	2,51	3,74	3,52	3,37	2,91
Drying by 0,8m	2,10	1,99	2,09	3,11	2,90	2,28	2,45
With drying by 1m	2,40	1,83	2,23	2,43	2,24	2,49	1,94

Depending on the heat capacity, only a certain amount of heat can be absorbed by the soil. Because the heat transfer from top to bottom is quite slow, excess energy will be added to the environment. And as a result, the ground air heats up more, resulting in its displacement to the lower pressure area. Thus, these air masses carry heat energy away from the drained areas [34].

Air with lower heat capacity accumulates less energy, therefore, as the temperature rises, the *energy* accumulated by the soil will change to a lesser extent. As a consequence, Table 2 does not show for all months the dependence of the increase in energy change at different rates of drying.

Conclusion

Based on the results of modelling the thermal regime of soil at a temperature change up to 2035, the energy, accumulated by the soddy-podzolic, soil is calculated. The most noticeable energy increase is for swamp soil. The change in accumulated energy was greatest for the undrenched soil in October and amounted to about 5,99 10^8 J, which corresponds to an increase of 0,43 % compared with the initial values. The minimum energy increase was in May for soil with a drying norm of 1 meter and amounted to 1,83 10^8 J, which corresponds to an increase of 0,15 %.

Thus, land reclamation accelerates the process of modification of the substrate surface and thermophysical properties of soddy-podzolic soils of Belarusian Polesie.

Climate warming and the resulting rise in soil temperature may lead to favourable conditions for crops grown in warmer regions. However, more extreme conditions for the cultivation of crops remain on meliorated soddy-podzolic soils, which is reflected in significant soil heating during the day and cooling at night. As a result, the number of frosts increases and the heating of the arable layer in the spring slows down, which can lead to partial crop loss.

In the system of adaptation measures to climate transformations in the Belarusian Polesie, revalidation (re-wetting) of previously drained lands occupies a key position as a method that allows for the effective regulation of heat and water balance and the increase of biological productivity of land resources [35].

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