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Comparative Analysis of Soil Temperature-Moisture Regime and Hydrothermal Potential (HTP) in Different Ecosystems

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Abstract. *In the brown mountain-forest soils of the Greater Caucasus, the formation features of the hydrothermal potential of the soil environment under different ecosystems (forest, xerophytic forest, and meadow) were studied. The research was aimed at determining the regularities of temperature and moisture changes along the profile in the 0–20 cm soil layer. The impact of vegetation cover on the dynamics of soil temperature and moisture, and consequently on the formation of hydrothermal potential, was evaluated. The purpose of the study was to identify the influence of vegetation cover on the formation of the hydrothermal potential of the soil environment and to assess the functional characteristics of soil cover under various ecological conditions. The obtained results are significant for the study of soil processes in mountain-forest ecosystems, the evaluation of soil fertility, and the improvement of ecological monitoring systems.*

Keywords: *hydrothermal potential (HTP), temperature regime, moisture regime, brown mountain-forest soils, forest ecosystem, meadow, xerophytic forest*

Introduction

The diversity of hydrothermal regimes in ecosystems composed of different plant formations is undeniable, since the moisture requirements of herbaceous, shrub, and tree species are closely related to their biomass, the shape of leaves, and the size and structure of the evaporative surface of their vegetative organs. Therefore, the coexistence of different ecosystems is possible under conditions where soil environments with varying degrees of moisture supply exist within the annual cycle. In other words, within the hydrothermal limits of the soil environment, the theoretical basis for the formation of any ecosystem with specific vegetation cover is the natural harmony between the hydrothermal regime and the plant's requirements.

Daily, seasonal, and global fluctuations of temperature indicate that the inflow of energy into the soil occurs in a variable regime. This requires evaluating processes according to the potential and duration of energy entering the soil. Since the rise in temperature during the day is accompanied by the loss of soil surface moisture, the opposite process—soil moistening—is asynchronously related to cooling (Suleymanov et al., 2011). It should be noted that these processes manifest more sharply in areas with high continentality, while in other regions they are observed on a relatively smaller scale. In mountainous areas, these features are permanent due to differences in vegetation cover across relief exposures, making their study and explanation scientifically significant and relevant.

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Thus, 95–99.5% of the energy spent on soil formation is used for evaporation and total transpiration. Consequently, the efficiency of energy entering the soil directly depends on the degree of soil moistening; in other words, the soil's thermal regime is closely linked to its moisture regime. The most general regularities of soil distribution on Earth are determined by the combined influence of moisture and temperature. Recently, the main direction in the development of soil science and soil physics has been the study of elementary areas and polypedons using methods based on quantitative indicators (Shikhalibeyli, 1956).

In nature, without fundamental changes in the hydrothermal regime, which is a limiting factor in soil formation, there cannot be a change of vegetation (reforestation, afforestation, desertification), processes that occur continuously, in close correlation with the first (Hasanov, 1979, 1981; Suleymanov, 2009). To determine the dependence of soil cover on hydrothermal conditions, various coefficients have been used. This was done to identify correlations between the thermal and moisture regimes of different soil types. The coefficients expressing these relationships are called hydrothermal coefficients (Alizade, 2025; Dobrovolsky & Urusevskaya, 2004). From the above, it can be concluded that all processes occurring under the influence of climatic factors are limited by soil moisture and temperature indicators. In this case, the use of soil moisture and temperature as limiting factors is theoretically acceptable. Studying the relationship between soil moisture and temperature and the elementary soil processes and microprocesses involved in soil formation is one of the main problems facing modern soil science (Suleymanov, 2009a, 2009b). In the soil–plant system, water plays a regulatory role. The volume of water and the energetic state of moisture in the soil environment determine the rate of soil–biological processes, soil development, and phyto-climatic ratios (Suleymanov, 2009).

The formation of the soil temperature regime is influenced by many factors: vegetation cover, snow cover, lithological composition, humus content, etc. Since the amount of solar radiation flux depends on slope exposure, the structure and density of the vegetation layer and the length of the growing season determine the living conditions of soil fauna (Shulgin, 1957; Elizbarashvili et al., 2010; Eyubova, 2010). The aim of the study is to determine and provide a comparative characterization of the hydrothermal potential (HTP) of soil profiles in different ecosystems and landscape elements of the brown mountain forest soils of the southern slope of the Greater Caucasus, using modern digital mobile devices.

Methods

The object of research is selected from the southern slope of the Big Caucasus, an area with brown mountain-forest soils. Administratively, the territory is subject to the Ismayilli region. The area is situated at an altitude of 700–850 m and above. The location terrain is favorable for the development of deciduous relict forests and grass and trees and shrubs, and is closely correlated with the distribution of hydrothermal resources and the spatial and temporal position of the relief elements. The characteristics of the areas where mountain-forest brown soils are received in separate areas, the development of herbaceous, xerophytes, deciduous, and mesophyll's forests (Fig. 1). To identify existing differences, it is necessary to use a parameter, giving the opportunity to evaluate digital local deviations from the statistical indicators and exceptions. From the point of view of the above, an acceptable option is the hydrothermal potential of the soil medium-HTP, proposed by the author, expressing the dialectical integrity of natural processes, or reversible processes occurring in the soil environment in native under different ecosystems in the space-time format.

Figure 1
General view of systems and elements of the landscape mountain-forest brown soils

Theoretically, it is possible to redistribute climatic factors under the effective influence of local requirements (Suleymanov et al., 2010; Suleymanov, 2012). HTP provides an overview of reversible processes in the soil environment, but the genetic function of the parameter does not allow a clearer differentiation of reference for studies of meso-level terrain.

Results

The hydrothermal potential (HTP) of brown mountain forest soils varied considerably among the three investigated ecosystems, reflecting differences in vegetation cover, soil temperature, and moisture regimes. The obtained results demonstrate that vegetation significantly modifies the redistribution of heat and moisture within the soil profile, resulting in distinct hydrothermal conditions. In the mesophytic forest ecosystem, soil temperature increased gradually with depth from 10.21°C at 5 cm to 25.41°C at 20 cm. Soil moisture also showed a consistent increase from 20.33% to 43.76% along the profile. Consequently, HTP values increased from 58 snr in the upper layer to 548 snr at 20 cm depth, with a weighted average value of 385 snr for the 0–20 cm soil layer. The structural coefficient (Kst) remained relatively stable, varying between 0.6 and 0.8.

In the xerophytic forest ecosystem, the soil temperature exhibited an opposite pattern, decreasing with depth from 39.3°C in the upper layer to 21.2°C at 30 cm. In contrast, soil moisture increased substantially, reaching 58.4% at 20 cm depth. Water reserves also increased markedly below 10 cm, indicating the accumulation of subsurface moisture. The hydrothermal potential ranged from 187 to 742 snr within the 0–20 cm profile, while the average HTP reached 485 snr, representing the highest value among the investigated ecosystems. Under meadow vegetation, soil temperature gradually decreased from 27.73°C to 22.00°C with increasing depth, whereas soil moisture increased from 18.14% to 38.64%. The maximum HTP value (465 snr) occurred at a depth of 10–15 cm rather than at 20 cm, indicating a different vertical distribution of hydrothermal resources compared with forest ecosystems. The weighted average HTP for the meadow ecosystem was 362 snr. Comparison of the three ecosystems revealed clear differences in the distribution of hydrothermal potential throughout the soil profile. The annual average HTP values followed the order:

Xerophytic forest (485 snr) > Mesophytic forest (385 snr) > Meadow (362 snr)

The amplitude of HTP variation also differed among ecosystems, amounting to 555 snr in xerophytic forest soils, 490 snr in mesophytic forest soils, and 298 snr in meadow soils. These differences indicate that vegetation cover strongly regulates the redistribution of soil heat and moisture and consequently controls the formation of hydrothermal potential. Polynomial regression analysis showed that the HTP curves of all ecosystems had similar sinusoidal patterns despite differences in absolute values. The regression models demonstrated excellent agreement with the observed data (R^2

≈ 1.0), confirming the reliability of the calculated hydrothermal potential and its suitability for describing the hydrothermal state of brown mountain forest soils under different vegetation covers.

Discussion

The results of the study on the role of vegetation cover in the formation of hydrothermal potential show that the HTP formed in the forest understory brown mountain forest soils differs from the potential existing in other landscape elements. Distinguishing features include the rate, character, direction, and stages of soil-forming processes, which depend on the vegetation cover shading the soil in arid regions, the slope of the relief, and its exposure—local factors that must be taken into account. Table 1 presents the three-year average statistical indicators of fertility, moisture, and HTP elements that form the forest understory brown mountain forest soil type. The main indicator of the landscape is the slope direction, which is north and northwest, with an inclination of ≥ 19.4°. Research carried out in the experimental area (directly measured in field conditions using digital devices) shows that forests are distributed on slopes with an inclination greater than 19°, starting from elevations of 780–800 m.

Table 1

Annual average statistical indicators of HTP and K_{st} formed in forest-understory brown mountain-forest soils

Depth, cm	Soil temperature, °C	Moisture, %	Water content, mm	HTP, snr	K_{st}	Humus, %
3	11,73	20,33	6,46	76	0,6	7,53
5	10,21	22,93	5,64	58	0,6	7,53
10	22,77	38,31	18,64	424	0,8	4,84
15	24,50	41,12	20,33	498	0,8	-
20	25,41	43,76	21,59	548	0,8	-
0-20 cm	20,95	36,1	16,67	385	0,8	4,30

The average statistical value of soil temperature (at the 20 cm layer) fluctuates between 10.21–25.41 °C. In general, it shows an increasing tendency and is synchronous with moisture. Other soil parameters and indicators along the profile have the character of an increasing function, with the only exception observed in the distribution of humus, which corresponds to the general theory of fertility. The HTP formed in forest understory brown mountain forest soils has a fluctuating interval of 58–548 snr across the calculated layers, with the maximum value at a depth of 20 cm and the minimum at a depth of 5 cm. The average statistical limit of the ecosystem is equal to 385 snr. Table 2 presents the three-year average statistical indicators of fertility, moisture, and HTP elements that form the forest understory brown mountain forest soil type.

From the table, it is clear that, unlike the forest ecosystem, under xerophytic forest cover the soil temperature decreases along the profile from top to bottom. This decrease is slightly more than 18 °C. The temperature range is 21.2–39.3 °C. In the 0–20 cm layer, the average statistical temperature determined by the weighted average method is equal to 30.2 °C. Moisture along the profile has the character of an increasing function, varying within the interval of 23.4–58.4%. Moisture reserves are very small in the upper layers; below 10 cm they amount to 15–20 mm, while at depths of 20 cm a sharp increase is observed. This situation indicates the occurrence of “verxovodka” (near-surface intra-soil flow), which causes transformation and sliding in the landscape.

Table 2

Annual average statistical indicators of HTP and K_{st} formed in xerophytic forest soils

Depth, cm	Soil temperature, °C	Moisture, %	Water content, mm	HTP, snr	K_{st}	Humus, %
3	39.3	23,4	7.43	292	0.2	-
5	34.9	25,3	5.36	187	0.2	4.84
10	31.8	28,4	15.04	478	0.5	3.76
15	27.6	32,2	17.05	471	0.6	-
20	24.0	58,4	30.92	742	1.3	-
30	21.2	58,1	61.53	1304	2.9	-
0-20 cm	30.2	35,8	17,40	485	0,6	4,30

Under xerophytic forest cover, the HTP formed in brown mountain-forest soils fluctuates within the boundaries of 187–742 snr across calculated layers, with the maximum value at a depth of 20 cm (742 snr) and the minimum at a depth of 5 cm (187 snr). The average statistical limit of the ecosystem is equal to 485 snr. Compared to forest-understory brown mountain-forest soils, the HTP formed in this landscape element is 100 snr higher. This means that the forest ecosystem assimilates HTP more rapidly within a shorter time interval, so the residual potential is fixed at a lower level.

Table 3 presents the distribution by depth of HTP and soil indicators formed under mixed grass (belonging to the wormwood-ephemeral family) vegetation cover. As seen from the table, the three-year average statistical indicators of soil temperature and moisture respectively have decreasing and increasing functional characteristics. The fluctuation of soil temperature in the 20 cm soil layer has a lower boundary of 22.0 °C, amounting to 5.7 °C, while the dynamics of moisture have an upper boundary of 38.64%, amounting to 20.5%. Moisture reserves below the 10 cm soil layer increase threefold compared to the upper layer. The reason for the low moisture in the upper layer is that the root system of herbaceous plants is mainly distributed at this depth and uses the incoming water reserves. The average statistical limit of the ecosystem is equal to 362 snr. The interval of HTP variation is 146–465 snr, with the lowest value observed in the upper layers and the highest value at a depth of 15 cm. As can be seen, the HTP formed in the meadow-understory soil environment differs from forest and xerophytic forest ecosystems mainly in terms of the depth at which the maximum potential is located. While in other areas the maximum HTP was located at a depth of 20 cm, under meadow cover it is established at a different point.

Table 3

Annual average statistical indicators (3-year) of HTP and K_{st} formed in meadow-understory brown mountain-forest soils

Depth, cm	Soil temperature, °C	Moisture, %	Water content, mm	HTP, Snr	K_{st}	Humus, %
3	27,73	18,14	5,76	160	0,2	3,85
5	26,02	23,78	5,62	146	0,2	3,23
10	24,34	38,47	19,09	465	0,8	-
15	23,21	38,64	19,13	444	0,8	-
20	22,00	35,43	17,46	384	0,8	-
0-20 cm	24,15	33,2	15,35	362	0,7	3,32

In Figure 2, the HTP curves formed in the soil environment of different ecosystems constituting the landscape are presented. Analytical analysis of the quantitative indicators of the HTP parameter shows that the annual average value of brown mountain-forest soils, determined by the weighted average method, fluctuates within the closed interval [362÷485]. The HTP value for meadow ecosystems varies within [146÷465 snr], in xerophytic forests within [187÷742 snr], and in mesophytic forests within [58÷548 snr]. The fluctuation amplitude is respectively equal to 298, 555, and 490 snr.

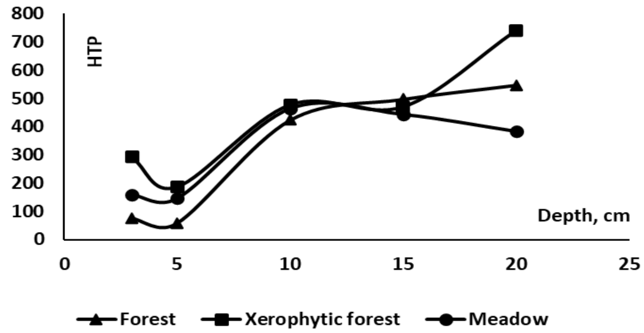

Figure 2
Comparison of HTP curves formed in the soil environment of different brown mountain-forest ecosystems

The general comparison shows that the curves have an arbitrary form with a sinusoidal character. The fact that the regression equations of the curves, which possess three maxima and two minima, have approximation coefficients at the maximum level indicates that the adequacy of the equations carries functional significance.

The following equations respectively express the polynomial curves characterizing the soil environments (0–20 cm) of meadow, xerophytic forest, and mesophytic forest ecosystems:

$$y = 0{,}1849x^4 - 8.5113x^3 + 127{,}49x^2 - 652{,}87x + 1148{,}6 \qquad (1)$$

$$y = 0{,}1522x^4 - 6{,}8408x^3 + 104{,}1x^2 - 591{,}62x + 1302{,}4 \qquad (2)$$

$$y = 0{,}1013x^4 - 4{,}8981x^3 + 79{,}01x^2 - 437{,}83x + 838{,}46 \qquad (3)$$

In the brown mountain-forest soil type, the approximation coefficient of the equations being equal to one indicates that the adequacy of the mathematical models is at the maximum level. The synchronicity of the polynomial curves, their having the same amplitude, and the close correlation of quantitative indicators show that they fall within the HTP limits of the brown mountain-forest soil type. As a conclusion of the research, it should be noted that the determination of HTP makes it possible to record and monitor, in a point-based multiparametric format, the dynamics of the potential existing in the soil—namely, the sum of moisture and temperature—within any arbitrary soil layer and genetic horizon in space and time, through a digital parameter that meets the requirements of the "soil-moment" principles. According to N.R. Suleymanova, HTP represents a methodological approach that is "fair both to the natural world, to the interactions between humans and nature, and in general to the process of understanding," in line with V.R. Volobuyev's emphasis on a systematic approach in comprehending natural processes (Volobuev, 1981).

Conclusion

1. In different landscape elements of the Greater Caucasus brown mountain-forest soils, under various vegetation covers (mesophytic and xerophytic forests, meadow), the elements of the soil hydrothermal potential (HTP) and the structural coefficient of the potential (Kst) have been determined at the elementary area level in a micro-caten format.

2. It has been established that the annual average statistical natural hydrothermal potential (HTP) limits of brown mountain-forest soils fluctuate within the closed interval of 362–485 snr, and the HTP formed in brown mountain-forest soil environments developed under meadow, mesophytic, and xerophytic forest ecosystems has been determined respectively at 362, 385, and 485 snr.
3. The differences in HTP under various vegetation covers (23, 123, 100 snr) are regulated by the water demand of the plants forming the ecosystem, the density of vegetation cover, the level of transpiration, the slope of the relief, and finally the exposure, thereby identifying local features that correct the influence of abiotic factors.
4. As a conclusion of the research, it should be noted that the determination of HTP provides the opportunity to record and monitor, in a point-based multiparametric format, the dynamics of soil moisture within any arbitrary soil layer in space and time, through a digital parameter that meets the requirements of the "soil-moment" principles.

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