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Climatogenic Restrictions of Arid Forestry

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Abstract—The creation of protective forests is especially difficult in arid regions of Russia, and global warming can further affect their ability to persist. In this study climatogenic changes in forest growing conditions are examined in the Northern Caspian region, taking into account that the functioning of forest stands is limited on historically treeless lands: authomorphic meliorated solonetz soils and calcisoles (by the extra moisture of winter snowfalls and the humidity levels during the vegetational period), as well as intrazonal hydromorphic gleyic kastanozems of the local relief depressions (by the inexhaustibility of freshwater lenses in salty subterranean waters based on its periodic resupply by the spring surface flow every 2–4 years). For forest stands established on automorphic soils, a prolonged period of annual draughts and mild winters with little snow deposit in forest lands has proven to be the most dangerous. During such periods, the large-scale death of trees is observed and many forest stands are ruined. For forest stands on hydromorphic soils, such periods prove to be just as dangerous because of the 15-year-long absence of spring surface flow. Such a climatogenic scenario of long-termed deterioration of forest growing conditions in the Northern Caspian region is similar to the southernmost regions of Russia that are currently totally unable to sustain forests, with unstable snow cover and frequent draughts.

Keywords: forest stands, climate warming, humidity index, snowfall deposits, surface water flow

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Afforestation in primordially treeless areas has more than a century of experience. The most ambitious and unsurpassed-in-scale forestry work was carried out in the 1950s as part of the so-called Plan for the Transformation of Nature. Millions of hectares of forest crops were created, a significant part of which died in the very first years of cultivation due to errors in planting technologies.

The most stable were protective plantations created on hydromorphic intrazonal soil types with available groundwater. At the same time, there is no doubt about the enormous benefits of silvicultural work in primordially treeless areas (Koldanov, 1967; *Instruktivnye ukazaniya*... 1983; Kulik et al., 2017).

For most of the existing protective afforestation, especially in the arid regions of Russia, restoration and renewal measures are required, since the crops are in an unsatisfactory condition, subject to further drying out and decay. The deterioration of the state of forest stands is associated not only with an increase in age, but also with climate change, the effect of which on artificially created stands is still poorly understood. In this regard, let us consider the features of the functioning of protective afforestation created in the early 1950s in the arid conditions of the clay semidesert of the Northern Caspian region, where the climate warmed by more than 2°C over a half-century (Sapanov, 2018b).

MATERIALS AND METHODS

The time variation of the influence of limiting environmental factors caused by climate fluctuations has been studied. The work was carried out at the Dzhanybek station of the Institute of Forest Science of the Russian Academy of Sciences, located in the interfluve of the Volga and the Urals, 30 km north of Elton Lake. Annual observations of the general condition and developmental characteristics of trees and shrubs planted in the early 1950s were carried out on different soil types. On automorphic reclaimed solonetzes and light chestnut soils, observations were made of the drought-resistant species grown here: squat elm, Pennsylvanian ash, Tatar honeysuckle, etc. One distinctive feature of these habitat conditions is the presence of a salt screen at a depth of 1.5–2.0 m, formed due to the reclamation leaching of readily soluble salts from the upper soil horizons (Sizemskaya, 2013). Therefore, trees and shrubs here have a superficial root system and do not use groundwater.

On intrazonal hydromorphic meadow–chestnut soils of local relief depressions, high-stemmed stands were studied, which include pedunculate oak, various types of poplars, apple trees, pears, etc. Here, the soil–ground layer is washed from readily soluble salts and, at a depth of 5–7 m, there is a fresh lens formed due to the periodic infiltration of spring meltwater. It can be considered that this lens is “pressed” into the mirror of regional saline waters and has a common level with it. Trees use water from fresh lenses for desuction (Kissis, 1963; Olovyannikova, 1977; Sapanov, 2000, 2003).

Since 1951, at a station under the main elements of the landscape, 10-day observations of the groundwater level have been carried out, an annual survey of the snow cover is carried out during the period of its maximum thickness (before the spring snowmelt), and years of surface meltwater runoff are noted. Weather conditions (since 1951) are analyzed according to the data of the Dzhanybek meteorological station of Kazhydromet. Evaporation is calculated according to Ivanov (1962). The materials were processed using the Excel.

RESULTS AND DISCUSSION

The variability of natural and climatic conditions is considered within the framework of its influence on the state and development of forest plantations with their geographical and ecological discrepancy. It is generally known that the functioning of plant ecosystems largely depends on the level of tension in the hydrothermal conditions of the growing season. To characterize it, we use the moisture coefficient calculated by dividing the amount of precipitation for the hydrological year (starting from October 1) by the evaporation rate for the growing season (April to August). The biological meaning of this coefficient is to determine the true amount of water available to plants and the conditions for its consumption through the potentially possible evapotranspiration by the amount of evaporation (Ivanov, 1962; Sapanov, 2003).

Precipitation of the cold period is most important for plants, as it forms the soil reserve of available moisture. For example, it is on this moisture that the entire biomass of a tree is formed due to the dissolution and conversion into mobile forms of nutrients present in the soil (Larher, 1978; Sapanov, 2006a). Precipitation of the growing season is involved in the functioning of forest stands to a large extent indirectly—relieving tension by a decrease in temperature and an increase in the relative humidity of the air, and, consequently, a decrease in evaporation, thereby reducing the risk of atmospheric drought. Note that the frequency, instability, and intensity of spring–summer precipitation cannot guarantee the long-term survival of trees. For example, most of them fall out at about 1 mm and do not even wet the soil (Sapanov, 2006a).

The functioning of afforestation on automorphic soil types depends entirely on the spring moisture recharge of the root-inhabited soil horizons. On a flat territory, to ensure the conditions for the functioning of trees until autumn, an additional amount of water is needed, which can only be obtained here due to snow accumulation (Sapanov, 2018a). In this regard, in climatic terms, it is important to know the change in snow accumulation conditions over time.

Forest plantations on hydromorphic soils of local depressions can be created by small multirow clumps. Such stands are very stable and survive any climatic fluctuations due to the constant use of water from fresh lenses, the desuctive discharge of which can reach 45–70% of the total evapotranspiration (more than 400 mm) (Kissis, 1963; Olovyannikova, 1977; Sapanov, 2003). Unfortunately, these lenses under large depressions have a low thickness and are consumed by massive plantations for several decades with simultaneous replacement by saline waters from the sandy interstratal horizon. This process can cause the death of forest stands (Sapanov, 2005). Only in a small area near the cannon (about 10 m) does the lens remain constantly freshened due to the lateral inflow of water from under the virgin depression. As you can see, here it is possible to optimize the planting areas by creating small clumps or narrow strips. Such small stands can survive for a long time (more than 100 years). At the same time, an inexhaustible water regime in fresh lenses in such a depression should be provided by a periodic spring surface runoff of meltwater into these closed relief depressions (Sapanov, 2003). Runoff occurs only under a certain combination of weather factors, which can change with climate warming. Obviously, a fresh lens will deplete if there is no such refill for a long time.

Thus, in order to identify the influence of climate on artificial forest ecosystems in the Northern Caspian region, first and foremost, it is necessary to consider the change in time of the factors that pose the greatest threat to their survival: the degree of moisture content of the growing seasons, conditions of additional snow accumulation in forest belts, and spring water runoff in the lower relief.

First, we note a steady increase in the temperature regime of the air during the hydrological year (Fig. 1). The temperature regime of the warm period for many years remained in a dynamically equilibrium state, and only since 2005 a tendency towards a positive trend has been outlined, thereby increasing the likelihood of atmospheric droughts. The air temperature steadily increased during the cold period of the year, and since 2000 for several years it has fluctuated near zero. Warm winters continued until 2006, and then a tendency towards a gradual cooling was observed. The revealed multidirectionality of the trends in the temperature regime of the air in warm and cold periods in 2005–2006 indicates an increase in the continentality of the climate against the background of ongoing general warming (Sapanov, 2018b).

Interesting features were also revealed in the annual dynamics of the amount of atmospheric precipitation (Fig. 2). For example, there is a slight positive trend in precipitation, mainly due to the excess of their average annual level in the warm period of 1985–

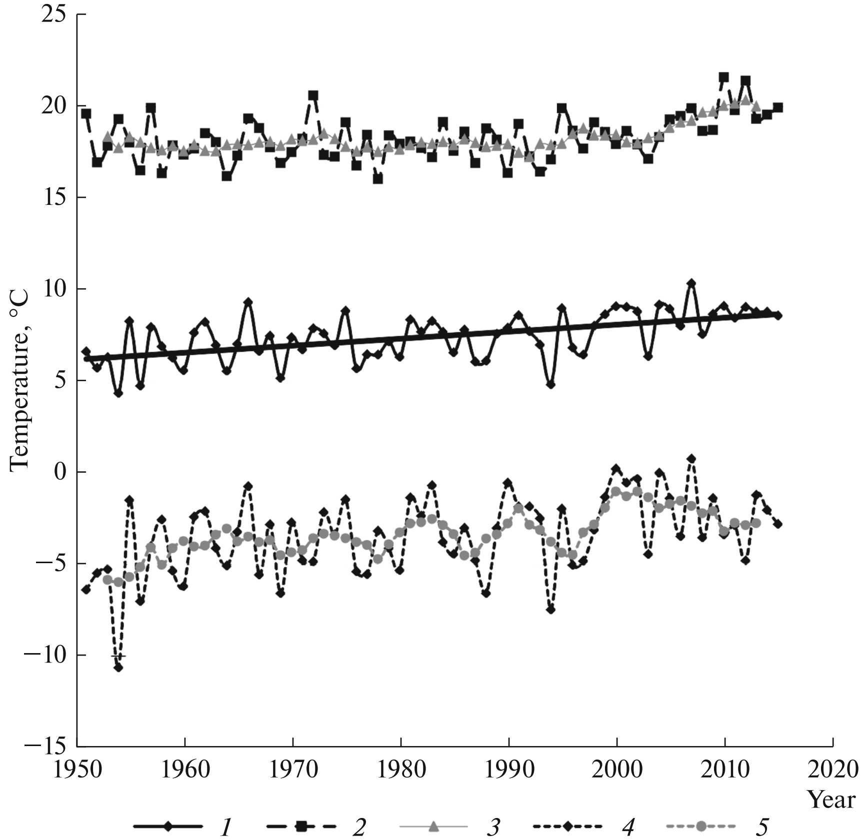

Fig. 1. Dynamics of the annual air temperature: (*1*) for the hydrological year and its linear trend, (*2*, *3*) for the warm half-year and its 5-year sliding, and (*4*, *5*) for the cold half-year and its 5-year sliding.

1994. There is also a period of decrease in the amount of annual precipitation over several years since 2006 due to autumn–winter precipitation.

An analysis of the cumulative variability of hydrothermal conditions by the dynamics of the moisture coefficient showed that, over the 65-year period of research, periods of different moisture content were distinguished which significantly influenced the preservation of forest stands on automorphic soil types (Fig. 3). During the period of increased moisture (1980–1994), the state of plantations steadily improved; the death of trees was insignificant and not systemic (Sapanov, 2006b). Conversely, in the period of low moisture content (2006–2010) with a high level of evaporation, there was a widespread drying out of trees and shrubs, right up to the complete decay of stands. It should be noted that recurrent droughts from year to year are the most dangerous for forest species. The mechanism of this phenomenon is obviously associated with the fact that trees consume during these years the reserve substances accumulated earlier and do not have the opportunity to replenish them due to the rapid end of seasonal development during a drought (Sapanov, 2006a). This is especially true for plantations grown on automorphic soil types, while on hydromorphic soils they function until autumn and, obviously, have time to accumulate reserve substances for the respiration of trunks and a successful start of the growing season the next year.

As was noted above, the safety and condition of forest crops on soils with inaccessible groundwater depends mainly on additional snow accumulation. At the same time, the accumulation of snow mass is regulated not only by the total amount and condition of the falling snow, but also by the snow collection area from which it is transferred to the obstacle, since the horizontal movement of one snowflake does not exceed 200–500 m (Grishin, 1962). For example, the average amount of water due to additional snow accumulation for a given area from 1953 to 1970 was 14000 mm linear m^{-1} (Sapanov, 2003). With such an amount of water, it is possible to create forest crops only according to the so-called “garden type,” with the obligatory annual agrotechnical maintenance near the plants to eliminate competition with grass vegetation (Godnev, 1973; *Rekomendatsii*..., 1988).

Subsequently, changes in the total amount of snow and the mechanics of its snowstorm transport due to the general warming of the climate significantly changed the moisture supply of forest stands. The

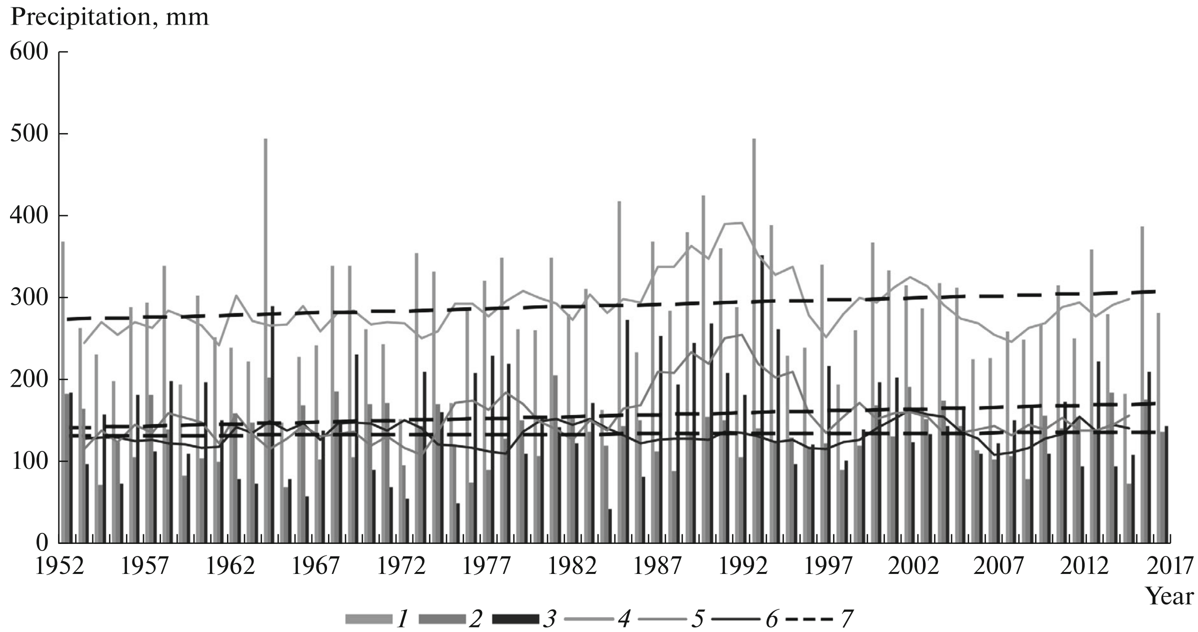

Fig. 2. Dynamics of precipitation amounts in the Northern Caspian region: (*1–3*) for a hydrological year, warm and cold periods, respectively; (*4–6*) the same values adjusted by the 5-year moving average; and (*7*) straight-line trends of these values.

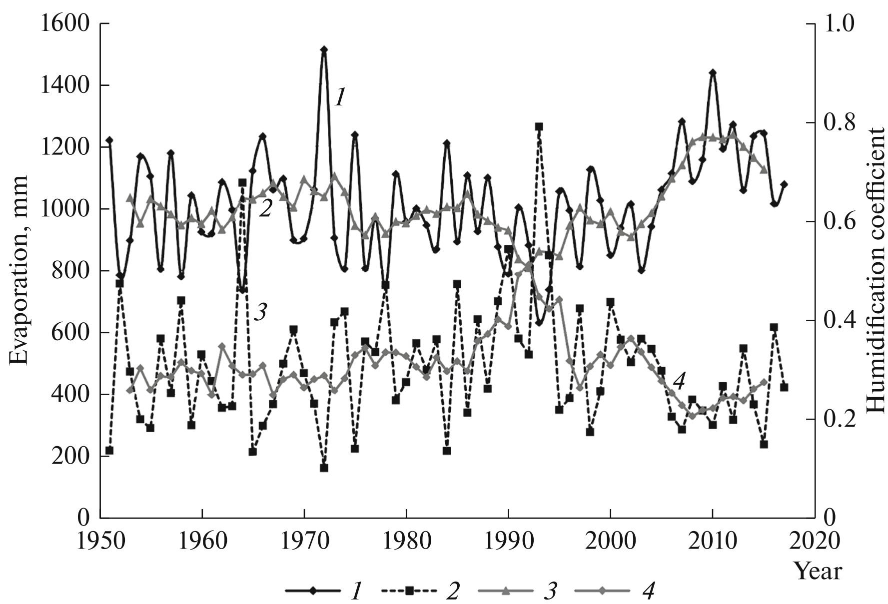

Fig. 3. Evaporation dynamics from an open water surface (*1*), moisture factor (*3*), and their 5-year sliding (*2*, *4*).

most remarkable increase in the thickness of the snow cover in 1985–1997 apparently, along with the general increase in moisture content in this period, contributed to the best preservation of forest stands due to the additional snow accumulation in forest belts (Fig. 4). Then, in the warmest winters since the early 2000s, the amount of solid precipitation has greatly decreased. Obviously, during this period, a significant part of the precipitation fell in the form of rain and sleet, which excluded a significant snow drift.

As we can see, in the dynamics of the climate there is a long unfavorable period since 2000 for the normal functioning of artificial forest ecosystems on automorphic soil types, since they are not adapted to the simultaneous deterioration of the annual moisture content

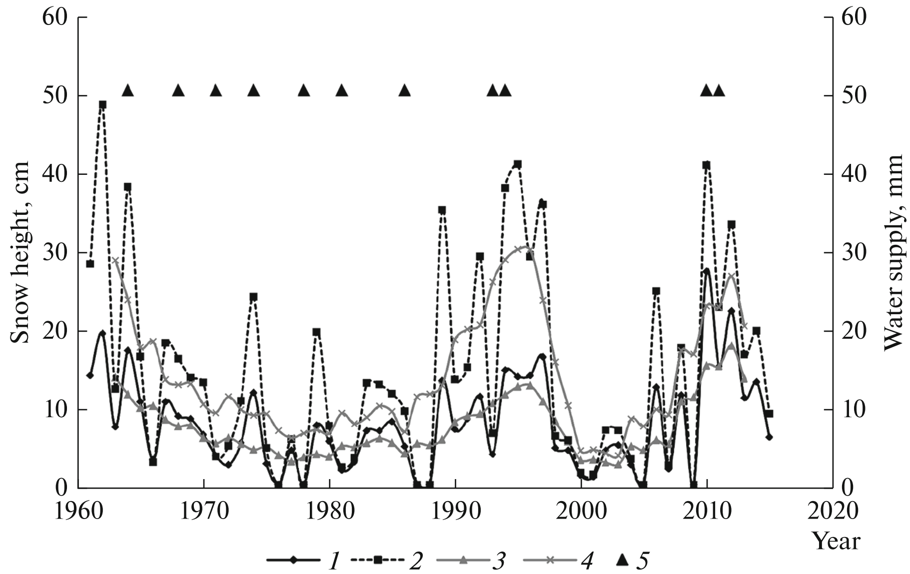

Fig. 4. Maximum height of snow cover before melting, water reserve in snow (*1*, *2*) and their values, aligned by 5-year sliding (*3*, *4*), and years of flooding of relief depressions (*5*).

of the territory (see above) against the background of the absence of additional snow accumulation.

Let us consider the conditions for the moisture supply of forest plantations on hydromorphic soils, where the inexhaustibility of the fresh lens is the key to the preservation of forest stands. In Fig. 4 it can be seen that the runoff of meltwater in the relief depressions in 1960–1994 happened every few years. Apparently, just such a periodicity in the water runoff can exclude the secondary salinization of a fresh lens (at optimal areas and species composition of plantations). However, due to the warming of the climate, there was no spring runoff into the large depressions in the next 15 years (1995–2009). This is due to the fact that surface runoff occurs only with a sufficient amount of snow, the presence of frozen soil, and a rapid increase in average daily positive air temperatures (Sapanov, 2003). Obviously, in years with warm winters, the likelihood of such conditions was extremely low.

The situation changed only in 2010, when there was a favorable combination of all natural factors contributing to the surface runoff of meltwater (Fig. 5). Low autumn–winter temperatures (–3.4°C) froze the soil to a depth of 110 cm, a lot of snow fell, and spring was late with slow soil thawing until March 27. The main melting of snow took place from March 21 on the still-frozen soil as a result of a sharp transition of the average daily air temperature through 0°C. As we can see, the inexhaustible water regime of the fresh lenses of the valleys occupied by forest plantations can be disturbed as a result of periodic warming of the autumn–winter period and restored during a cold snap.

Thus, the climatogenic threat to the preservation of artificial forest ecosystems in the Northern Caspian region against the background of general warming is largely due to recurring droughts from year to year, the occurrence of long periods of absence of snow transfer into plantations, and surface runoff of meltwater in the relief depression. Optimal weather and climatic conditions for the functioning of forest plantations developed in 1980–1994 due to an increase in moisture in the growing season and an increase in the amount of snow in the autumn–winter period. The deterioration of forest growing conditions was noted in 2000–2009 due to warm winters, repeated droughts, a decrease in the total amount of snow and deterioration of the conditions for its transfer to forest belts, and a long absence of surface meltwater runoff. According to our observations, in the years under consideration, there was a massive drying out of forest cultures not only within the Northern Caspian region, but also in the entire south of European Russia.

CONCLUSIONS

The conditions of functioning and the state of protective forest plantations in the clay semidesert of the Northern Caspian region in connection with climate warming were studied. On this primordially treeless territory, only herbal phytocenoses can grow in their natural form, which are maximally adapted to the seasonal moisture deficit and summer droughts. For forest plantations, in order to extend the growing season, an additional amount of water is needed, which can only be obtained here by redistributing snow. It is snow that is the main source of additional moisture, both in the form of snowstorm accumulation in forest belts and and surface-water runoff in the lowering of the relief during snow melting.

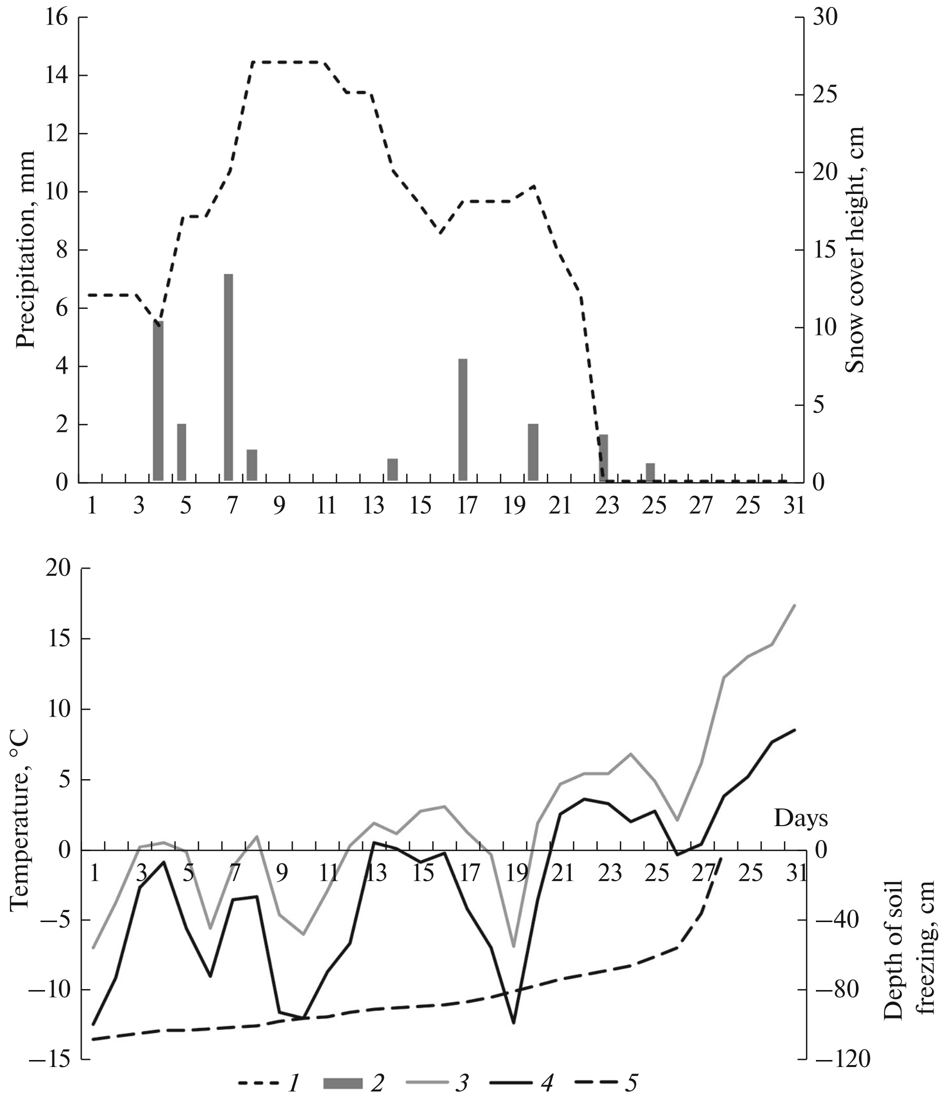

Fig. 5. Meteorological conditions during the meltwater runoff in the relief depression (2010): thickness of the snow cover (*1*), precipitation (*2*), daily maximum and average air temperatures (*3*, *4*), and soil thawing rate (*5*).

The occurrence of a period of warm winters with an insignificant amount of snow and its weak snow drift was most dangerous, as well as the absence of spring surface runoff of meltwater in the relief depression (2000–2009). This period coincided with atmospheric droughts recurring from year to year (since 2006), which caused the widespread drying out and decay of forest plantations on zonal automorphic reclaimed solonetz soils and light chestnut types of soils. In the same years, the inexhaustible water regime of forest plantations was disturbed, which were created on intrazonal hydromorphic meadow–chestnut soils of local relief depressions due to the lack of periodic replenishment of fresh lenses with meltwater. The surface runoff of meltwater has recovered with the cooling of the autumn–winter period since 2010. Thus, climate warming can significantly limit the creation of forest plantations due to a decrease in the degree of moisture in the growing seasons, worsening conditions for additional snow accumulation in forest belts, and spring water runoff in the lower relief.

The revealed scenario of climate warming in the Northern Caspian region, caused by a periodic long-term decrease in the degree of moisture in the growing seasons, worsening conditions for additional snow accumulation in forest belts, and spring meltwater runoff in lowering the relief, explains the reasons for a significant deterioration in the state and safety of forest cultures in such years. The prolonged deterioration of the conditions of their habitat brings the natural features of the Northern Caspian closer to the unsuitable territories of the more southern regions of Russia with initially unstable snow cover and annual droughts.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interest.

Statement on the welfare of animals. This article does not contain any studies involving animals performed by any of the authors.

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