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Air temperature changes due to altitude above sea level in the Northern Ural Mountains

Nikolai V. Tantsyrev, Natalya S. Ivanova ✉, Irina V. Petrova

Institute Botanic Garden Ural Branch of Russian Academy of Sciences, Yekaterinburg, Russian Federation

✉i.n.s@bk.ru

Abstract. The research is devoted to an urgent modern problem: the identification of temperature factors that limit the distribution and survival of plants in the mountainous conditions of the Northern Urals. The article's aim is to determine the air temperature in four altitudinal zones of the southern part of the Northern Urals (Sverdlovsk region 59º30´N, 59º15´E) and to identify regression relationships of the obtained temperature data with control temperature data from the nearest meteorological station. Registration of air temperatures was carried out from May to September 2019 around the clock, every two hours in the mountain forest zone (at an altitude of 460 and 640 m above sea level) under the canopy of Siberian stone pine forests, in the zone of subalpine woodlands with elements of mountain forest tundra (820 m above sea level) and on a plateau in the mountain tundra zone (1030 m above sea level). It has been established that the change in air temperature at different altitude levels and at the nearest meteorological station (far from 60 km, at an altitude of 202 m above sea level) occurs relatively synchronously. Difference between average daily temperatures at altitudes of 460, 640, 820 and 1030 m above sea level and the control data of the meteorological station is 2.2, 3.0, 4.7 and 5.1ºC respectively. For all altitude levels, a reliable close straight-line relationship between average daily air temperatures and meteorological station data has been established. The altitudes of 460, 640, 820 and 1030 m above sea level correspond to the coefficients of determination (R^2) equal to 0.96, 0.95, 0.92 and 0.88. The relationship of the minimum temperatures of the corresponding altitude levels with the control data is also quite high (R^2 is not lower than 0.7). With the help of the identified relationships and the obtained regression equations, it is possible to retrospectively restore the dynamics of the thermal regime according to the meteorological station data for mountain habitats of different altitudes in the southern part of the Northern Urals over a long period. Including extreme critical temperatures, which act as factors limiting the resettlement and survival of plants and determine the ecosystem biodiversity.

Keywords: Northern Urals, mountain ecosystems, altitude zones, air temperature, plant communities

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Изменения температуры воздуха в зависимости от высоты над уровнем моря в горах Северного Урала

Н.В. Танцырев, Н.С. Иванова✉, И.В. Петрова

Ботанический сад УрО РАН, г. Екатеринбург, Российская Федерация
✉i.n.s@bk.ru

Аннотация. Исследование посвящено актуальной проблеме – выявлению температурных факторов, лимитирующих распространение и выживаемость растений в горных условиях Северного Урала. Цель – определение температуры воздуха в четырех высотных поясах южной части Северного Урала (Свердловская область 59º30´ с.ш., 59º15´ в.д.) и выявление регрессионных связей, полученных температурных данных с контрольными данными ближайшей метеостанции. Регистрация температур воздуха проводилась с мая по сентябрь 2019 г. круглосуточно, через каждые два часа в горно-лесной зоне (на высоте 460 и 640 м над уровнем моря) под пологом кедровых лесов, в зоне подгольцовых редколесий с элементами горной лесотундры (820 м над ур. м.) и на плато в зоне горной тундры (1030 м над ур. м.). Установлено, что изменение температуры воздуха на разных высотных уровнях и на ближайшей метеостанции (на расстоянии 60 км, на высоте 202 м над ур. м.) происходит относительно синхронно. Разность среднесуточных температур на высотах 460, 640, 820 и 1030 м над уровнем моря от контрольных данных метеостанции составляет 2,2, 3,0, 4,7 и 5,1 ºС соответственно. Для всех высотных уровней установлена достоверная тесная прямолинейная связь между среднесуточной температурой воздуха и данными метеостанции. Для высот 460, 640, 820 и 1030 м над уровнем моря соответствуют коэффициенты детерминации (R^2), равные 0,96, 0,95, 0,92 и 0,88. Связь минимальных температур с контрольными данными на соответствующих высотах также достаточно высока (R^2 не ниже 0,7). С помощью выявленных связей и полученных уравнений регрессии появляется возможность ретроспективного восстановления динамики термического режима по данным метеостанций для разных горных высот в южной части Северного Урала за длительный период. В том числе экстремально критические температуры, которые выступают факторами, ограничивающими расселение и выживание растений и определяющими биоразнообразие экосистем.

Ключевые слова: Северный Урал, горные экосистемы, высотные пояса, температура воздуха, растительные сообщества

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Introduction

The importance of the biospheric role of mountain ecosystems is recognized by many researchers [1; 2]. Distinguished by significant biological diversity, they also perform water-regulating functions, on which half of the world's population depends [3]. At the same time, mountain ecosystems are most sensitive to external influences, including climate change [1; 3–5]. Therefore, since the second half of the 20th century, due to progressive climate change, the problem of vegetation dynamics in extreme mountainous conditions has been one of the priority areas of modern environmental research [2; 6–8]. Numerous studies confirm that climate change can go beyond the adaptive capacity of natural vegetation [9–12] and there will be a threat of catastrophic changes in biodiversity, loss of stability of both local ecosystems and the biosphere as a whole [4; 10; 13; 14]. For the Urals, which performs the water-regulating functions of two large water basins (Volga-Kama and Ob), this problem is especially acute.

Presumably due to climatic changes, in the last 30–50 years, intensive settlement and survival of forest-forming woody plants above the existing mountain treeline ecotone have been observed in the Northern Urals [15; 16]. To retrospect climate changes and their impact on the growth and development of woody plants under extreme conditions of the upper treeline ecotone, mainly dendrochronological analysis is used in combination with temperature data from regional meteorological stations [17–19]. Despite the fact that this analysis has proven itself well, it cannot be used to obtain complete information on the initial stage of the formation of dendrocenoses. Data of weather stations, sometimes located at a considerable distance, do not always make it possible to identify regional and landscape features of climatic conditions for mountain systems. Therefore, the necessary information for developing predictive models of ecosystem dynamics is sometimes not enough. Reliable long-term multi-altitude data on mountain climate, which allow checking regional climate models, exist only for very few areas, such as the European Alps [3; 20]. Therefore, the problem of identifying factors that limit the survival and distribution of plants and animals in mountainous conditions remains unresolved.

The article's aim is to establish regression relationships between the data of thermal data loggers installed in four altitudinal zones of the Northern Urals, including in the conditions of mountain tundra above the treeline ecotone, with the temperature data of the nearest weather station. In the future, the justification of the methodology reconstructed on the basis of these relationships for studying the dynamics of Siberian stone pine (*Pinus sibirica* Du Tour) and related species renewal above the existing upper treeline ecotone, in connection with the annual dynamics of air and the upper soil horizon temperature.

Objects

The studies were carried out for four years (2016–2019) from May to October in the southern part of the main watershed of the Northern Urals (Sverdlovsk region) at four altitudinal levels (Table 1) of Mount "Tri Bugra" (altitude 1060 m above sea level (a.s.l.) 59º30 ´N, 59º15´E): in the mountain-taiga zone under the canopy of Siberian stone pine forest at altitudes of 460 m a.s.l. (P1) and 640 m a.s.l. (P2); in the zone of subalpine woodlands with elements of mountain forest tundra at an altitude of 820 m a.s.l. (P3); on a plateau in the mountain tundra zone at an altitude of 1030 m a.s.l. (P4). The nearest control meteorological station is located at a distance of 60 km from the objects of study in Karpinsk town (59º46´N, 60º00´E at an altitude of 202 m a.s.l.).

In the low-mountain zone in the grass-green-moss forest type, the forest stand is represented by *Picea obovata* Ledeb. 30%, *Pinus sibirica* 20%, *Pinus sylvestris* L. 20%, *Abies sibirica* Ledeb. 10%, *Populus tremula* L. 20%. In the mid-mountain zone, also in the grass-green-moss forest type, the forest stand is represented by *Pinus sibirica* 60%, *Picea obovata* 30%, *Abies sibirica* 10% and slightly *Betula pendula* Roth. Subalpine woodlands of grass-stony forest type are represented by *Pinus sibirica* 70%, *Picea obovata* 20%, *Betula pendula* 10%. In the zone of mountain stony shrub-moss-lichen tundra in the last 30–50 years, there has been an abundant renewal of *Pinus sibirica* [16]. The total number of its undergrowth not older than 55 years with an average height of 27 cm is 6.0 thousand ind./ha. The undergrowth of other woody forest-forming species is single.

Table 1. Characteristics of research objects

№	Altitude, m above sea level (a.s.l.)	Mountain zone	Average forest stand parameters			
			H, m	D, cm	S, m^2	C, %
P1	460	Low-mountain taiga	24	28	39.5	75
P2	640	Mid-mountain taiga	18	32	22.4	60
P3	820	Subalpine taiga	6.5	20	11	28
P4	1030	Mountain tundra	-	-	-	-

Notes. H, m – average stand height, m; D, cm – average stem diameter at a height of 1.3 m, cm; S, m_2 – basal area, m^2; C, % – crown projective cower of the forest canopy, %.

Methods

Altitude above sea level (a.s.l.) was determined using a GPS navigator. Recording of air temperatures at a height of 2 m (with microclimatic sun protection) from the soil surface and soil at a depth of 5 cm was carried out by thermal data loggers installed at the corresponding altitude levels around the clock every two hours. Based on the obtained time series of temperature dynamics, the following indicators were calculated: average daily temperature; the number of days with an average daily temperature above 5 and 10ºC and below 0ºC; the sum of positive average daily temperatures; average temperature for the summer observation period (from May 21 to August 31); difference of average daily temperatures at altitude levels with the control data of the weather station. On the basis of regression analysis, a study was made of the relationship between air temperatures at high-altitude levels and weather stations. The article presents the results of research in 2019.

Results

Table 2 summarizes the results of observations from May 21 to August 31, 2019. As the location of measurements increases, there is a decrease in average daily air temperatures and, accordingly, an increase in the difference with the weather station data.

Table 2. The main temperature parameters in the studied altitude zones for the period from May 21 to August 31 in 2019

Mountain zone Altitude, m above sea level	M 202	P1 460	P2 640	P3 820	P4 1030
Nd with t° > 5°C	100	98	96	88	85
Nd with t° > 10°C	86	73	67	57	50
Nd with t° < 0°C	-	-	-	3	3
∑ (+t°C)	1479.1	1249.2	1170.6	1004.2	962.1
t°C average for the summer period	14.8	12.5	11.8	10.1	9.8
t°C min	-2.0	-2.5	-3.0	-5.0	-6.0
t°C max	+31.4	+25.5	+24.5	+23.5	+23.0
The difference between average daily temperatures in high-altitude zones (P) with weather station data (M)	-	2.2±0.09	3.0±0.01	4.7±0.12	5.1±0.15

Notes. M – control date of the meteorological station; Nd – days number of the average daily temperature; t° – temperature, degrees C°; ∑ (+t°C) – the sum of the positive average daily temperature.

Possible impact on temperature data at 460 and 640 m a.s.l. renders the insolating surface of the tree canopy (crown projective cower is about 70%). In subalpine woodlands at an altitude of 820 m a.s.l., crowns of sparse trees do not form a continuous closed canopy (crown projective cower is not more than 30%), and there are no trees in the mountain tundra (1030 m a.s.l.). Nevertheless, the change in air temperature at different altitude levels occurs relatively synchronously (Figure 1).

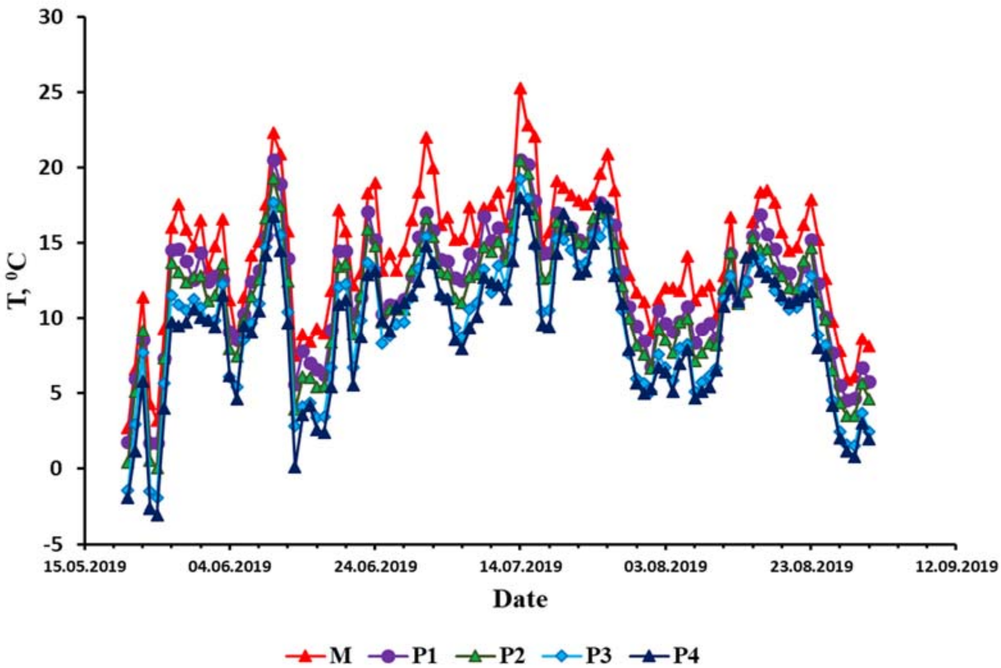

Figure 1. Dynamics of the average daily temperature (T, °C) in the corresponding altitude zone: P1 – 460 m a.s.l.; P2 – 640 m a.s.l.; P3 – 820 m a.s.l.; P4 – 1030 m a.s.l.; M – control date of meteorological station

The warmest period (about 40 days long) is observed from June 21 to July 31. In addition, two short (no more than 10 days) warm periods were observed (including in the mountain tundra at an altitude of 1030 m a.s.l.) in early June (June 1–10) and in mid-August (August 11–20). At the same time, for all high-altitude levels, a reliable close straight-line relationship was established between the average daily air temperatures recorded by thermal data loggers and the weather station data (Figure 2 a, c, e, g). For altitudes of 460, 640 and 820 m a.s.l., the coefficient of determination (R^2) is 0.96, 0.95 and 0.92, respectively, for an altitude of 1030 m a.s.l. already only 0.88.

The resulting regression equations for average daily temperatures (Figure 2 a, c, e, g) indicate the following facts. Firstly, with an increase in altitude above sea level, the coefficients “a” at the value of x increase from 0.91 at an altitude of 460 m a.s.l. to 0.99 at an altitude of 1030 m a.s.l. At the same time, they are close to one for all studied altitudinal zones. Secondly, the coefficient “b” in the equation increases from 0.87 at altitude 460 m a.s.l. to 4.93 at an altitude of 1030 m a.s.l., i.e. more than 5.5 times. This indicates that the differences in temperature with the weather station data are characterized mainly by the free term of the equation “b”. Thirdly, the tightness of the revealed dependencies remains quite high for all the studied altitudinal zones. Despite the manifestation of sudden temperature changes with an increase in the terrain altitude, which reduce the tightness of established connections.

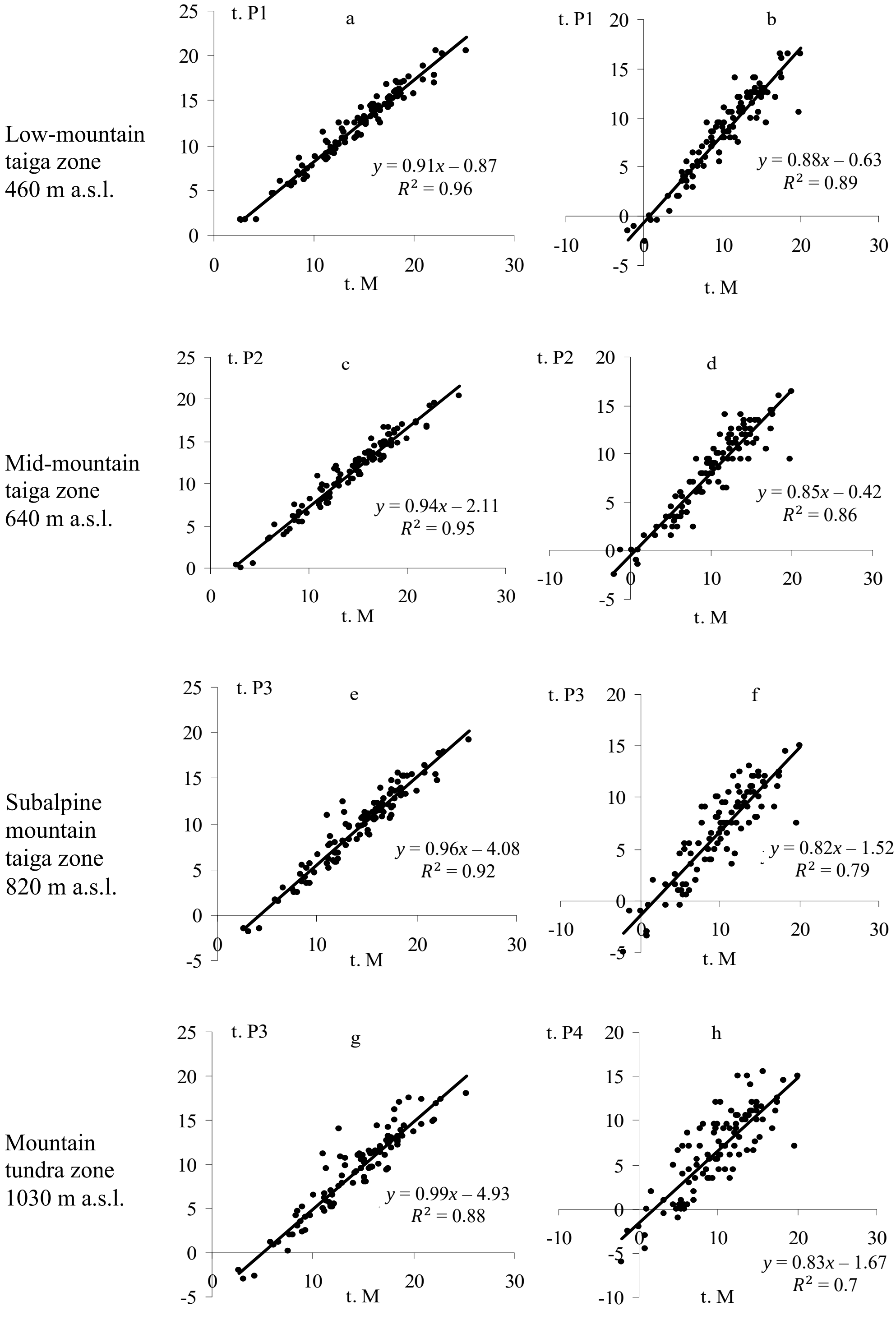

Figure 2. Dependence of the average and minimum daily air temperatures (t) in the corresponding altitudinal zones (P) on the temperature at the weather station (M)

Additionally, we investigated the relationship of the minimum daily temperatures depending on the altitude above sea level (Figure 2 b, d, f, h) with the control data of the weather station. The indicators under study are important for understanding the expansion and contraction of the ranges of plant species, their survival and differentiation of vegetation into altitudinal zones. For the average daily minimum (Figure 2 b, d, f, h), there was a tendency for the values of the coefficients "a" to decrease at the value of x with an increase in altitude above sea level (from 0.88 at an altitude of 460 m a.s.l. to 0.83 at an altitude of 1030 m a.s.l.). In general, the tightness of the relationship between the minimum temperatures of all the studied altitudinal zones and the weather station data also remains high (R^2 does not fall below 0.7).

A more detailed analysis of frosts showed that during the measurement period from May 21 to August 31, 2019 (103 days) in the zone of subalpine woodlands (P3) at an altitude of 820 m a.s.l. and in the mountain tundra zone (P4) at an altitude of 1030 m a.s.l. three days were observed (May 21, 24, and 25) with average daily negative temperatures. At the lower altitudes (460 m a.s.l. (P1) and 640 m a.s.l. (P2)) these days, the average daily air temperature remained positive (0.5–1.7ºC), but at night it dropped to –3.0ºC. In addition, at altitudes of 820 (P3) and 1030 m a.s.l. (P4) two summer night frosts were revealed: June 13 (up to –2.0ºC) and June 15 (up to –0.5ºC).

Conclusion

As a result of summer-season observations, close linear relationships of air temperatures on four mountain high-altitude zones of the Northern Urals (including the mountain tundra zone) with the control temperature data of the meteorological station in Karpinsk town were established. Regression equations are obtained. With the help of the identified relationships, it is possible to retrospectively restore the dynamics of the thermal regime according to the data of a weather station for mountain habitats of different altitudes in the southern part of the Northern Urals over a long period. Among other things, they make it possible to identify the minimum temperatures that act as factors limiting the distribution and survival of plants, determine the species composition and biodiversity of ecosystems. Thus, the long-standing methodological problem of quantitative analysis of the influence of climate dynamics on many population-biological processes, in particular, on the dynamics of the upper mountain treeline ecotone, can be solved to some extent.

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Bio notes:

Nikolay V. Tantsyrev, Candidate of Biological Science, Researcher of Laboratory of Population Biology of Woody Plants and Forest Dynamics, Institute Botanic Garden Ural Branch of Russian Academy of Sciences, 202a, 8 Marta St, Yekaterinburg, Russian Federation, 620144, Scopus Author ID: 23995967800, ResearcherID: AAW-6195-2021, ORCID: 0000-0003-1904-4751, Elibrary AuthorID: 1005870. E-mail: 89502076608@mail.ru.

Natalya S. Ivanova, Doctor of Biological Sciences, Leading Researcher, Institute Botanic Garden Ural Branch of Russian Academy of Sciences, 202a, 8 Marta St, Yekaterinburg, Russian Federation, 620144, Scopus Author ID: 56443439900, ResearcherID: Q-3292-2017, ORCID: 0000-0003-0845-9433, Elibrary AuthorID: 140717. E-mail: i.n.s@bk.ru

Irina V. Petrova, Doctor of Biological Sciences, Director, Institute Botanic Garden Ural Branch of Russian Academy of Sciences, 202a, 8 Marta St, Yekaterinburg, Russian Federation, 620144, Scopus Author ID: 55935284300, ResearcherID: N-6695-2018, ORCID: 0000-0001-5689-8452, Elibrary AuthorID: 89842. E-mail: irina.petrova@botgard.uran.ru

Сведения об авторах:

Танцырев Николай Владимирович, кандидат биологических наук, научный сотрудник, Ботанический сад УрО РАН, ул. 8 Марта, 202а, г. Екатеринбург, 620144, Россия, Scopus Author ID: 23995967800, ResearcherID: AAW-6195-2021, ORCID: 0000-0003-1904-4751, Elibrary AuthorID: 1005870. E-mail: 89502076608@mail.ru

Иванова Наталья Сергеевна, доктор биологических наук, ведущий научный сотрудник, Ботанический сад УрО РАН, ул. 8 Марта, 202а, г. Екатеринбург, 620144, Россия, Scopus Author ID: 56443439900, ResearcherID: Q-3292-2017, ORCID: 0000-0003-0845-9433, Elibrary AuthorID: 140717. E-mail: i.n.s@bk.ru

Петрова Ирина Владимировна, доктор биологических наук, директор, Ботанический сад УрО РАН, ул. 8 марта 202а, г. Екатеринбург, 620144, Россия, Scopus Author ID: 55935284300, ResearcherID: N-6695-2018, ORCID: 0000-0001-5689-8452, Elibrary AuthorID: 89842. E-mail: irina.petrova@botgard.uran.ru