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Ecosystems: Climate Change Vulnerability and Resilience †

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Abstract: Since 1976, mean annual temperature in Russia has been rising at 0.47 °C per decade (in the Arctic at 1 °C per decade). This process determines shifts in biome boundaries and large-scale ecosystem restructuring. Biome boundaries should have moved 400 to 500 km northwards in the Arctic and 200 to 300 km northwards in other climate zones and are likely to shift another 200–500 km to the north. Arctic, mountain, steppe, and the Far East ecosystems are the most vulnerable to adverse climate change. Creation of protected areas has become a priority measure for the adaptation of ecosystems. On average, protected areas (PAs) of federal significance account for 7.6 percent of a biome territory across the country. However, in five biomes no PA has been established. For the purpose of effective adaptation to climate change it is advisable to increase the total territory covered by all-category PAs to 17 percent of each biome.

Keywords: biometeorology and climate change; weather sensitivity; biomes; ecosystems; climate change adaptation

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1. Introduction

Global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99 °C (0.84–1.10 °C) higher than in 1850–1900 [1]. In Russia, mean annual temperature has grown nearly 2.5 times faster than the global average, and yet at a higher rate (3.5 times faster) in the Arctic [2]. Generalization of the data obtained from benchmark stations shows that the fastest growth is observed in the Taimyr Peninsula in the Arctic (1 °C/10 years [3]), while the average growth rate since 1976 is 0.47 °C/10 years [2]. A more careful look at the temperature evolution trends has shown, that such fast temperature growth is observed not only in the Arctic, but also in certain locations in other climate zones, for example, at the Black Sea coast of the Caucasus [4].

Such substantial change in total heat received predetermines changes in species ranges and shifts of ecosystem boundaries. A one-degree change in mean annual temperature results in an about one-degree (approximately 100 km) latitude shift of the boundaries, or in an about 50–100 m altitude shift (in the mountains) [5,6]. This means that, based on their temperature parameters, biome boundaries common for the 1970s [6] should now shift 400 to 500 km northwards in the Arctic and 200 to 300 km northwards in other climate zones, if we look at the map of mean annual temperature trends (Figure 1, [3]).

Even the best climate change scenarios and just 2 °C average global temperature rise from the pre-industrial levels, in accordance with IPCC SSP5-8.5 scenario, would bring the mean annual temperature in Russia up by 2.5 °C, and in the Arctic up by 3–5 °C, from the current levels [7]. This may drive a shift of biome ranges by another 200–500 km to the north.

Most biomes found in the territory of Russia stretch for about 500 km from north to south [6]. Simulation results obtained for RCP-8.5 GHG emission scenario using 26 CMIP5 models show that as soon as in the middle of this century climate conditions of today's biomes in the larger part of Russia will be replaced with those typical of more southerly biomes (Table 1).

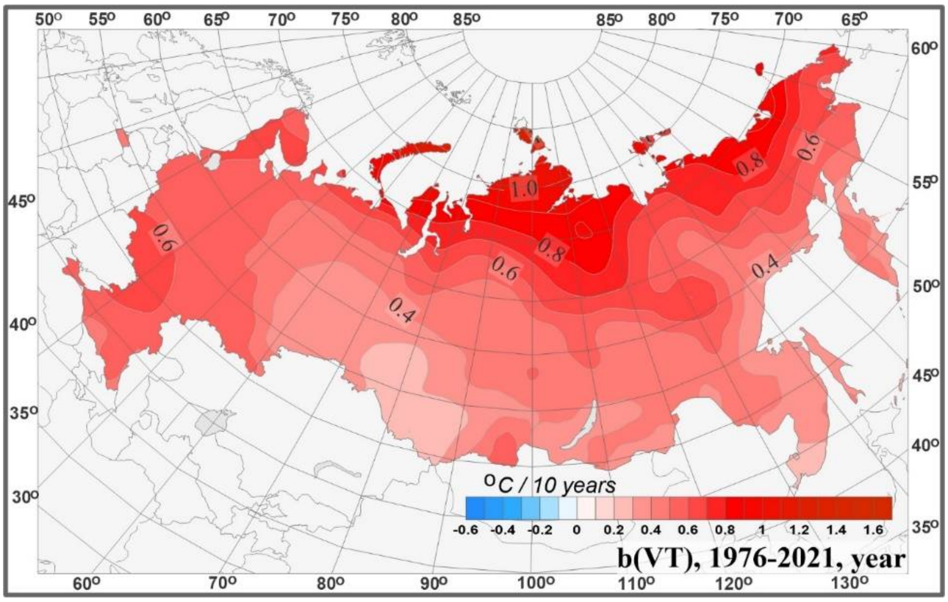

Figure 1. Linear trend coefficient for mean annual surface temperature in Russia in 1976–2021 (°C/10 years), adapted with permission from Ref. [3].

Table 1. Fractions of Russia's territories (%) where biomes are projected to change in the first quarter and mid-21st century [8].

Period	European Russia	West Siberia	East Siberia	Far East	Russian Federation
2016–2045	58	64	55	48	56
2031–2060	71	74	70	57	67

The result is that subarctic tundra and partially arctic tundra biomes are becoming fit for the development of forest vegetation [9]. In southern regions, on the contrary, forest retreat and expansion of the steppe area are projected [8]. It is expected that a warmer and drier climate will shift Siberian forests to the northeast, while forest steppe and steppe areas will expand in the south. The melting of the uppermost permafrost and active layer expansion will facilitate a northward advancement of dark coniferous taiga of cedar, fir, and spruce. However, melting will take time, and boreal forests of Dahurian larch will continue to prevail in the 21st century [10]. For RCP 2.6, 4.5, 6.0, and 8.5 scenarios it is projected that the area covered by evergreen boreal forests will substantially decrease, while not much reduction is expected for the area covered by boreal broad-leaved and larch forests. These two types of forests will be replaced mostly by broad-leaved deciduous forests and herbaceous vegetation [11].

Preservation of biodiversity, primarily of rare and endemic species, requires both exploration of climate change trends in a specific area or habitat and research on the current and potential adaptation measures. The sustainability of ecosystems is determined not only by their own potential and climate change magnitude in a certain territory, but also by a number of related factors, primarily by the type and severity of the anthropogenic pressure.

The Convention on Biological Diversity has specified that removal of anthropogenic pressure is the key measure for ecosystem adaptation to climate change [12]. Indeed, reduction in the anthropogenic impact reduces the disturbance, enables ecosystems to more smoothly adjust to the new climate conditions, and helps species to successfully migrate to areas where climate is more suitable for them [13,14]. Russia's Sixth National Report for the Convention on Biological Diversity [15] specifies that the following land categories to some extent relieve anthropogenic pressure from ecosystems and, thereby, promote adaptation to climate change: protected areas (PAs); PA buffer zones; areas of traditional nature use; fish protection areas and fishery reserves; protective forests, particularly protective forest plots, reserved forests; sanitary (mountain-sanitary) protection areas around healthcare sites and resorts; hunting grounds and sanitary zones around them; aquatic buffers and coastal protection belts. In all, PAs occupy some 238.8 million ha, and all other land categories taken together are about three times larger [15].

Protected areas of federal significance can be viewed in their entirety as the basis for ecosystem adaptation measures, because PAs ensure the strictest species and ecosystem protection regime and the greatest reduction in anthropogenic pressure (up to a total ban and elimination thereof in certain parts of PAs). They are also best suited for the monitoring of the territory, species' populations, and weather conditions [16–18].

At that, the system of protected areas is designed and developed in accordance with the administrative division of the country into administrative regions ('subjects of the Russian Federation'), whereas in the context of conservation of biodiversity and adaptation to climate change it would be practical to design the PA system based on the natural zones and biome boundaries.

The purpose of this research is to explore to what extent the removal of anthropogenic pressure (which is the priority measure for ecosystem and species adaptation to climate change) has been successful for biomes in the territory of Russia.

2. Materials and Methods

The present-day concept of climate change adaptation was formulated in the IPCC Fifth Assessment Report (Contribution of Working Group II [19]) and further developed in the Sixth Assessment cycle (2015–2022). Three key concepts determine the condition of ecosystems in the context of changing climate:

Resilience—the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

Vulnerability—the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Adaptation—the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects [19].

This paper builds on the biomes classification and boundaries as provided in "The Biomes of Russia" map [6]. This map shows 6 zonal biomes found in the territory of Russia: Tundra, Boreal Forests (taiga), Gemiboreal Forests (mixed broad-leaved and coniferous forests and small-leaved subtaiga), Broad-Leaved Forests (temperate mixed and broad-leaved forests, including forest steppes), Steppes (moderate steppes and shrub communities), and Deserts (desert steppes and northern deserts). Vegetation cover of zonal biomes is characterized by a dominant type of vegetation (climatype), which is best adapted to the zonal habitat conditions and terrain structure [20]. For mountainous regions, zonal biomes correspond to first order orobiomes, which include types of altitudinal zonation grouped by the structure of altitudinal belt spectra, the determinant component for which is the type of vegetation: tundra; boreal (taiga); nemoral coniferous-broad-leaved and broad-leaved forests; and steppe (subarid). Zonal biomes and orobiomes can be subdivided into 66 plain and mountainous biomes [6]. The territories of these biomes are the key units of analysis in this paper.

Data on the amount and total area of PAs of federal significance in the three categories under consideration were taken from Rosstat's website [21]. Up-to-date information about the areas covered by PA was taken from the corresponding section of the website of the RF Ministry of natural resources and ecology.

Data on the accurate geographical location of PAs was taken from the Research and information system "Protected natural areas of Russia" (IAS Research and Information System "Protected Natural Areas of Russia" Arctic and Antarctic Institute, St.Petersburg, Russia) [22], from the map "Russia's reserves and national parks" [23], and from The World Database on Protected Areas (WDPA) [24], and were verified using each PA's own websites, links to which are provided on the official website of the RF Ministry of natural resources and ecology.

Regrettably, the accurate location of some PAs, such as those that were established after 2017, could not be identified, because the maps of these PA territories are yet to be entered into the open-access database IAS "OOPT RF" and uploaded to their own websites. Where this was the case, the authors had to make an approximate connection of the PA areas to biome territories based on the location of such a PA's administrative premises and conspicuous natural objects.

In addition, some other methodological barriers were encountered while attempting to connect PA borders with biome boundaries:

The scale of the biome map [6] (1:7.5 mln) is too small compared to the average PA size (around 300 thousand ha), leading to potential errors and uncertainties in the PA/biome connection, especially if a PA is close to biome boundaries;
The map [6] also shows climatograms for each biome, which partially overlay the boundaries;
Biome area on the map does not correlate with the area as indicated in the explanatory note to plain biomes [20], thus further exacerbating the uncertainty. This paper builds on the values as provided in the map [6];
Some PAs include offshore areas, whereas the biome map [6] depicts only terrestrial biomes (including water bodies, if any, within the biomes). Where this was the case, the offshore part was deducted from the PA area;
In recent years, PA boundaries are being verified and the relevant information is entered into the national Land Register. Notably, the PA area might have somewhat changed, but the information on the website of the RF Ministry of natural resources or in the databases is updated with a delay.

Based on the analysis of the available information and the gaps, the following methodological approach was chosen. Where a PA was shared by several biomes, it was counted in each one of them as an individual unit of analysis. In view of the above restrictions, it was not possible to accurately determine the portion of such PAs located in each biome. Then an assumption was made that the PA area (less the offshore territory) was evenly shared between the constituent biomes. The uncertainty resulting from this formal apportioning of PA by constituent biomes seemed insignificant against the methodology barriers discussed above.

3. Results and Discussion

Projected exacerbation of climate change implications for Russia in the 21st century is supported by the results of international research [1,25] and also by the Main Geophysical Observatory's regional model runs for Russia [26,27].

Today, it is impossible to pick up a region in Russia which is not exposed to climate change or to the adverse impact thereof. However, in some regions, the warming rate is faster ($\geq$1 °C/10 years), or extreme weather events are much more frequent [3,28,29], than in others.

In terms of adverse climate change exposure and vulnerability, the Sixth National Report for the Convention on Biological Diversity [15] specifies the following ecosystems: Arctic (substantial temperature rise), mountainous (a large variety of climate-related hazards), steppe (temperature rise-driven aridization), and the Far East (additional impacts of extreme precipitation and strong winds).

In addition, there are a number of weather hazards typical of offshore and littoral areas: high wave action; storm surge; coastal erosion; icing; tornado; inundation caused by sea level rise [25,28,29].

The vulnerability and resilience of ecosystems to climate change can be characterized by the changing biome boundaries. For example, over the last 30 years the general trend towards pre-tundra woodland boundary advancement to the north has been 10 to 30 km [30]. In the European part of Russia, forest boundary advancement to the north is slower, up to 100 m/year over the last 50 years, and there are territories where no visible change can be detected. In the Asian part of Russia, the advancement rate is much slower, up to 10 m/year, and in some localities in the east the boundary is retreating [31]. In orobiomes, the advancement of woody vegetation (woodlands and shrubs) into the mountain tundra of the Khibines [32], the Urals [33], Putoran plateau [34] and other circumpolar highlands, and into the Altay was detected [35,36]. Over the last 80–90 years, the upper boundary of larch woodlands and closed forest stands has moved 35–40 m on average (and 50–80 m at the maximum) [37].

In boreal biomes, climate change and wildfires are shifting the southern taiga ecotone to the north [38]. In nemoral biomes, the eastern boundary of broad-leaved species is eventually shifting to the east [39]. In forest–steppe biomes at the southern boundary of the Siberian larch range, forest stands suffer from droughts, which slow down growth and increase tree mortality [40]. Wildfires add to the impacts of temperature rise and moisture deficit in South Siberia and facilitate forest retreat [41].

Investigation of ecosystem resilience to climate change is in progress. While degradation and/or destruction of ecosystems through increasingly frequent wildfires and hurricanes is supported by reports and satellite data and projected using simulations, ecosystem degradation as a result of changing precipitation patterns, higher seasonal temperatures, floods, or multiple adverse factors, even if documented, is not supported by spatial or quantitative estimates. Even more scarce are publications that contain projections of ecosystem recovery after disturbances in the context of the changing climate, when the environment becomes less favorable for cold-loving dominating plant species.

Each biome is characterized by a specific set of hazardous and adverse weather events and implications thereof. The location of a particular PA determines its exposure to climate-induced risks. It is by no means always the case that an extreme event, which is characteristic of the biome as a whole, massively threatens species and ecosystems. For example, landslides, mudflows, and avalanches are more or less confined to certain locations, highlands become natural shelters during floods, and rivers are natural barriers to wildfires.

If a PA is in the proximity of a sub-latitudinal boundary between biomes, or if there is a sufficient altitude gradient to develop a few vegetation belts, then substantial changes in ecosystems and species distribution can be expected. Extremely vulnerable are PAs located in ecotone zones. As a result of boundary shifts in the main biomes some of the species will no longer be able to live within the PA in place and will have to relocate or become extinct [42].

In addition, distribution of PAs by absolute altitudes also has an important role to play when it comes to vulnerability to climate change. As of 2015, more than 60% of the territory of PAs of federal significance were located between −28 and 300 m above sea level [43], which is pretty low. It is not uncommon that lowlands are more subject to anthropogenic development, than mountainous regions. However, the latter are more exposed to a number of climate-induced events, such as mudflows, landslides, avalanches, and mountain lake outburst floods. The greatest difference in altitudes within one PA, more than 4000 m, was observed in the Caucasus, namely, in Prielbrusie National Park and Sovetsky Nature Reserve [43].

According to Rosstat, as of late 2020, there were 233 PAs in Russia in the categories "wildlife reserve", "national park", and "nature reserve of federal significance", covering a total of 74,982,511.5 ha and amounting to more than 30% of the total PA area in Russia (240,159,255.6 ha) [21]. This source provides an analysis of the amount and area of PA of federal significance for each of the biomes.

Distribution of the number of PAs by biomes is not homogeneous. As of late 2021, PAs of federal significance were missing in five biomes. At the same time, PAs in the Smolensko-Privolzhsky broad-leaved and coniferous forest biome amounted to 23, and in the Dneprovsko-Privolzhsky broad-leaved forest and forest steppe biome to 27 (Figure 2).

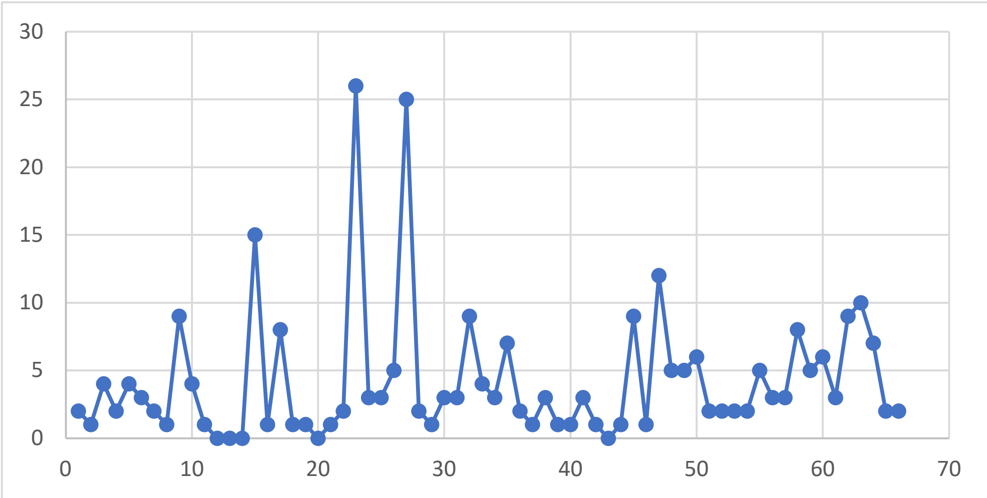

Figure 2. Distribution of PA of federal significance by biomes. The numbers on horizontal axis correspond to the numbers of biomes on the map [6]. Vertical axis is for the amount.

In terms of the number of PAs, the spatial distribution is dominated by biomes of the central part of the European part of Russia and orobiomes of the Altay-Sayan ecoregion. That said, in tundra and wooded tundra in the north of East Siberia and in the Far East PAs of federal significance are non-existent in a vast territory (Figure 3).

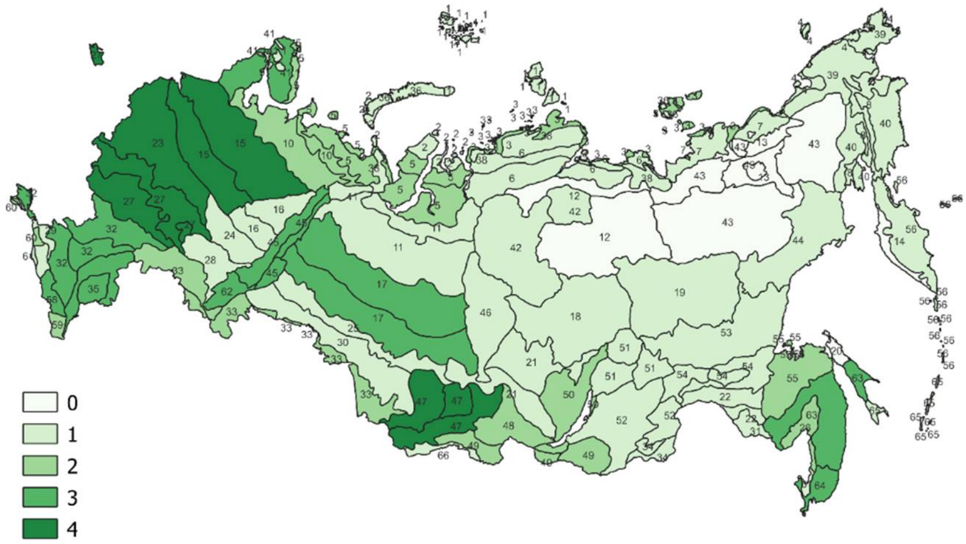

Figure 3. Distribution of PA of federal significance by biomes (ranking): the numbers correspond to the numbers of biomes on the map [6]. 0—no PA of federal significance; 1—1–3 PA; 2—4–6 PA; 3—7–10 PA; 4—more than 10 PA.

On average, most often there are (in whole or in part) 1 to 6 PAs of federal significance in the territory of one biome.

Comparison of the PA areas with the biome areas gave a somewhat different spatial distribution. On average, PAs accounted for 7.6 percent of biome territories across the country, yet in the biomes of Wrangel Island (37) and Sochi (subtropical) (61), the PA area amounted to more than 70%. A large proportion of PAs was typical of mountainous and underdeveloped Arctic regions (Figures 4 and 5).

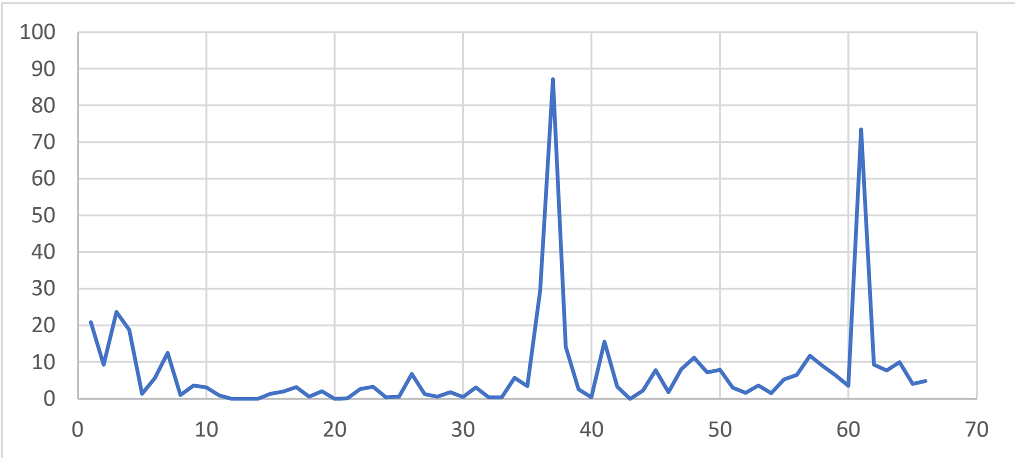

Figure 4. Distribution of fractions of PA area in total biome territory. The numbers correspond to biome numbers on the map [6].

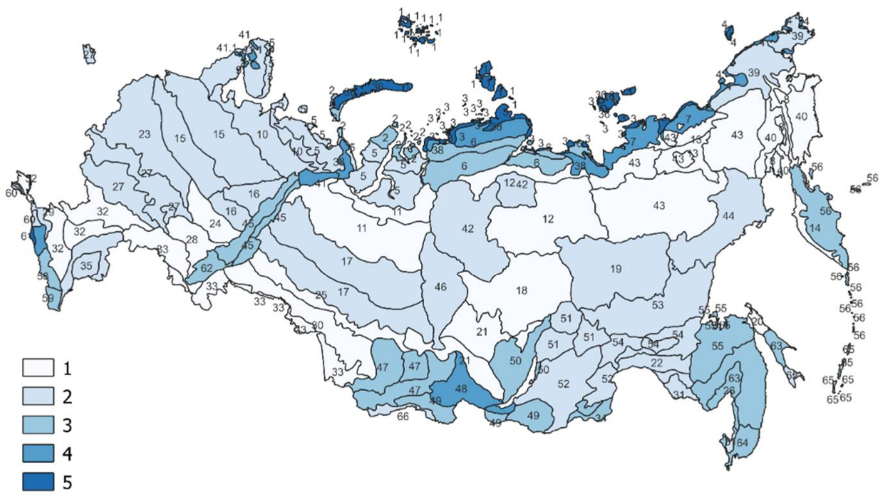

Figure 5. Distribution of fractions of PA area in total biome territory. The numbers correspond to biome numbers on the map [6]. 1—PA amount to less than 1% of a biome territory; 2—1%-up to 5%; 3—5%-up to 10%; 4—10%-up to 20%; 5—more than 20%.

4. Conclusions

There are practically no biomes in Russia which are not exposed to gradual climate change and implications thereof, as well as to hazardous weather events. The high rate (higher than the global average) of mean annual temperature rise determines their extreme vulnerability to climate change. Arctic, mountainous, steppe, and the Far East ecosystems are the least resilient.

At the same time, ecosystem boundaries are not shifting very fast as yet, and this fact can be taken for an indication of sustainability. However, based on their climate parameters, nearly half of the biome territories are already beyond the characteristics common for the late last century, and, by the end of this century, nearly all of the biomes will be beyond their climate parameters. It is practical to expect substantial ecosystem restructuring, changes in the types of vegetation, and significant changes in the ranges of individual species.

PAs of federal significance are the backbone of climate change adaptation measures for ecosystems. In terms of the amount and area, PAs of federal significance are very unevenly distributed by biomes: from a total lack to more than 20 within one biome covering more than 70% of the biome territory.

The largest PA areas are found in the most vulnerable Arctic and mountainous biomes. The Far East biomes are covered by PAs to a lesser extent, and steppe biomes are the least covered. Substantial ecosystem restructuring in the near future in response to climate change is expected in the PAs located on biome boundaries. The role of such PAs is particularly important for maintaining ecological corridors and enabling species to migrate to areas where the climate is more suitable for them.

Lack of PAs of federal significance in five biomes is an indication of the insufficiency of efforts taken to date to ensure ecosystem adaptation to climate change.

For successful conservation of species and ecosystems in a changing climate it is advisable to increase the total territory covered by all-category PAs to 17 percent of each biome in compliance with the Aichi Target 11 of the Convention on Biological Diversity [12].

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