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# Assessment of the Spatial and Temporal Variability of Arid Ecosystems in the Republic of Buryatia

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**Abstract**—Climate change and anthropogenic activity in the Republic of Buryatia aggravate the processes of desertification and land degradation. The territory of Buryatia was zoned according to the aridity index based on ENVIREM climate data with a high spatial resolution. Long-term changes in the vegetation cover in arid and humid zones are quantitatively assessed based on a combined study of the time series of the normalized-difference vegetation index (NDVI) with the Advanced Very High Radiation Radiometer (AVHRR), meteorological series of the NCEP/NCAR Reanalysis data set, and field studies. Maps of the spatial distribution of NDVI linear trends and precipitation for 1982–2015 (with the differentiation of the wet (1982–1999) and dry periods (2000–2015)) have been constructed. During the wet period, positive NDVI trends are observed for almost the entire republic, while the dry period is characterized by a significant increase in negative trends of the vegetation index. A positive correlation between the Selyaninov hydrothermal coefficient and NDVI is observed for intermountain steppe basins, while it is negative for forest landscapes. The dynamics of the NDVI for steppe vegetation is more dependent on precipitation, while the dynamics of the NDVI for forests is more significantly correlated with temperature. Reforestation, postpyrogenic succession, the bushing of fallow lands, and other factors determine the growth in the NDVI. Negative NDVI trends are characteristic of steppe ecosystems with low precipitation and forest ecosystems exposed to felling and fires.

*Keywords:* Buryatia, arid areas, vegetation, NDVI, HTC, precipitation, trend, reanalysis, dendrochronology

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## INTRODUCTION

In recent decades, the climate dynamics in Russia has resulted in more frequent extreme events, such as droughts, forest and steppe fires, floods, and mudflows (*Vtoroi otsenochnyi doklad*..., 2014). Along with these natural phenomena, desertification is also influenced by human activities, which are manifested by deforestation, overgrazing, soil contamination due to technogenic accidents, etc. The vegetation cover is an indicator of ongoing climatic shifts, and it is currently important to study its changes for both the assessment and prediction of the resource potential of Russian regions. The cartographic representation of these changes is a necessary information base for the planning and implementation of measures to mitigate the negative impact of climate changes on vegetation.

Although there are many publications on desertification problems, there are an insufficient number of studies that quantitatively assess landscape degradation processes using Earth remote sensing methods and data. A number of studies use high time resolution satellite data to assess the long-term dynamics of vegetation cover. The most widespread indices are vegetation indices obtained from MODIS, SPOT Vegetation, and AVHRR sensors with a survey frequency of at least one time per day. Although images from these systems have a low spatial resolution, they are suitable for the construction of continuous time series, as opposed to other satellites, e.g., Landsat satellites, which have much higher spatial resolution higher spatial resolution but a very low survey frequency (once per 16 days)). These time series are used to calculate trends in the normalized-difference vegetation index (NDVI), determine phenological dates, detect fires and forest felling, etc. Global NDVI-based estimates of vegetation cover trends and their relationships with climate factors are given in many studies (Zolotokrylin, 2003; De Jong et al., 2011; Fensholt and Proud, 2012; Zhao et al., 2018; Pan et al., 2018). The geographical coverage of regional studies is also wide (Tulokhonov et al., 2014; Mandakh et al., 2016). There are also many Russian studies analyzing NDVI time series. For example, multidirectional trends significantly correlated with surface temperature have been revealed for mountain taiga and coniferous forests in Krasnoyarsk krai (Shevyrnogov et al., 2012). The dynamics of tundra vegetation is also highly related to air temperature and is determined by local physical and geographical conditions (Varlamova and Solov'ev, 2014; Elsakov, 2017). The state of steppe communities in Russian arid zones is primarily determined by moisture variations and anthropogenic factors (Zolotokrylin et al., 2015; Zharnikova et al., 2016; Tel'nova, 2017).

Aridity and climate severity and continentality with high annual and diurnal temperature amplitudes and uneven wind and precipitation patterns by season, as well as the mainly light granulometric composition of soils and underlying rocks in many areas of the region, high relief roughness, large areas of bare lands and lands poorly fixed by vegetation, etc., contribute to the negative transformation of terrestrial geosystems of the Republic of Buryatia (RB). The climate aridity in the study area, combined with the unsustainable use of natural resources, makes terrestrial ecosystems significantly vulnerable to negative natural and anthropogenic processes, such as land degradation, soil erosion and deflation, and secondary salinization. Negative processes are intensified due to periodic aridization trends in the climate system, which causes not only unfavorable changes in moisture conditions but also a reduction in the productivity of arable lands and pastures, which, in turn, affects the already rather weak economy of the republic.

Research on the negative response of land ecosystems, expressed as the deterioration of their state, as well as the determination of causes of droughts, desertification, and land degradation and their mapping, are an important resource in the planning, implementation, and assessment to combat desertification.

The *purpose of this research* is to assess and analyze long-term changes in the vegetation cover of the Republic of Buryatia based on the NDVI vegetation index and field studies.

## MATERIALS AND METHODS

**Study area.** The Republic of Buryatia is located deep in the Asian continent. It is elevated significantly above sea level and has a heterogeneous relief and a long historical development of contemporary geosystems. The climate continentality and severity are much more extreme in Buryatia than in other Russian areas at the same latitude and neighboring areas (except Zabaikalsky krai). Buryatia is characterized by harsh, long winters and short but warm summers. It is a permafrost region. The complex orography and sharply differentiated regimes and types of local climates determine the maximum density and concentration of the borders between many provinces (Fig. 1) and sectors of botanical and geographical zoning, while the zoning of natural systems is smoothed.

Vegetation is a key element in the landscape organization of Buryatia; it represents a complex system that formed over a long historical development. Long-term climate fluctuations (towards either warming or cooling) led to changes in the forest and steppe ratio: the increase in the extremeness of natural conditions caused a reduction of forest areas. Treeless steppe natural complexes alternating with forest areas in the conditions of dissected relief predominate in hollows, on their bottoms and insulated slopes. Intermountain depressions formed from loose quaternary deposits are influenced by semidesert arid conditions. All of the main ecosystems of the Northern Hemisphere occur there: communities of steppes, forests, bogs, meadows, alpine tundra ecosystems, and alpine heaths with unique floral complexes. The greater part of the area in the republic is occupied mainly by light coniferous forests; dark coniferous fir and cedar forests are widespread in areas with a highly humid climate. There are steppe communities in the basins of large rivers and along their valleys; although these communities occupy small areas, they are interesting in terms of their composition and genesis. The most remarkable communities are true (forb, bunchgrass, and dry bunchgrass), cryoxerophytic high-mountain, meadow, desert, sas, and psammophytic steppes, which are various in their composition and structure (Dambiev and Valova, 2015).

The growth rates of the surface air temperature are much higher (by 2.5 times) in Transbaikalia (the Republic of Buryatia and Zabaikalsky krai) than in the Northern Hemisphere (Obyazov, 2015). The long-term variations in precipitation are highly cyclical (Andreev et al., 2016), while the latest arid phase began in 1999 (Obyazov and Smakhtin, 2012). Climate changes aggravate the processes of land degradation, which are widespread in the steppe landscapes of Buryatia (Dambiev and Valova, 2015), where the anthropogenic component of desertification is more pronounced due to a higher economic development of the areas. Forest ecosystems are also exposed to natural and anthropogenic effects. There is a high frequency of forest fires in the region; along with com-

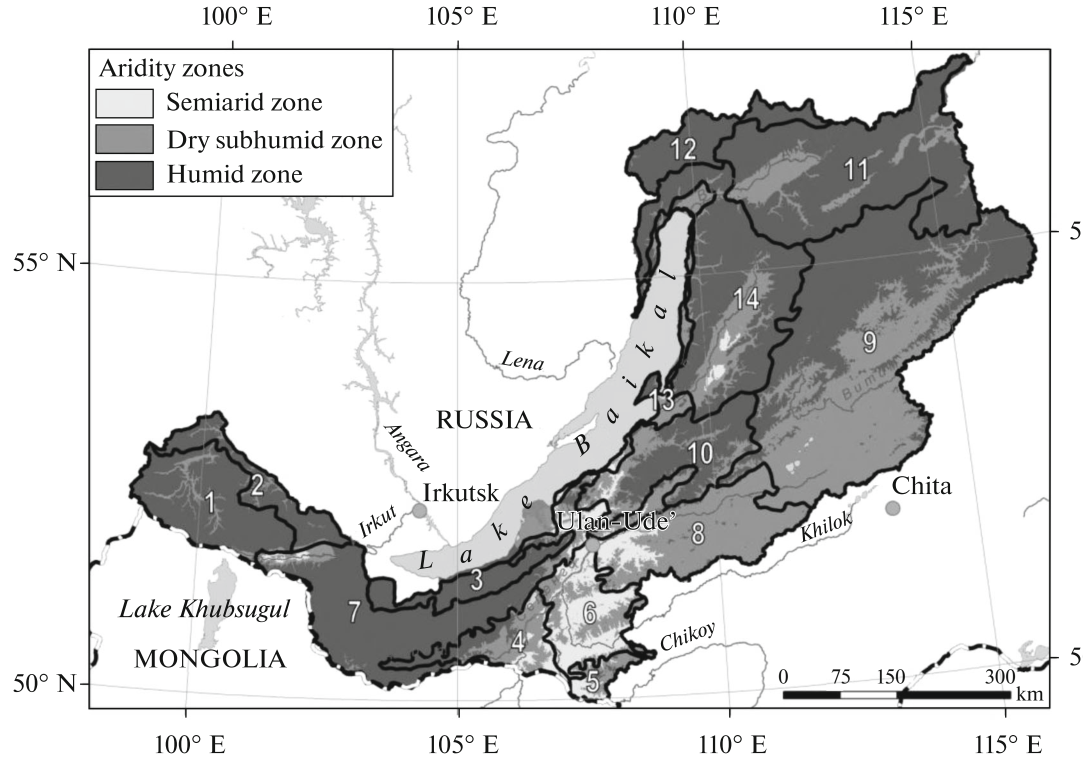

**Fig. 1.** Map of RB climatic zones according to the aridity index and of provinces of physical and geographical areas in the RB. Notations: the dashed line indicates the state border and the solid line indicates the borders of the provinces. Provinces of the South Siberian mountain area: (1) Okinsko-Tunkinskaya mountain-taiga—alpine-tundra province, (2) Okinsko—Kitoyskaya alpine-tundra—mountain-taiga province, (3) Khamar-Daban alpine-tundra—mountain-taiga province, (4) Selenga—Orkhon steppe—mid-mountain province, (5) Chikoy—Ingoda basin—mountain-taiga province, (6) Selenga—Khilok steppe—mid-mountain province, (7) Dzhida—Lower-Selenga basin—mountain-taiga province, and (8) Khilok—Uda steppe—mid-mountain province. Provinces of the Baikal-Dzhugdzhur mountain-taiga area: (9) Vitim taiga-plateau province, (10) Ulan-Burgas mountain-taiga province, (11) western Transbaikal mountain-taiga—alpine-tundra province, (12) northern Baikal taiga-mountain province, (13) Baikal lake basin, and (14) Baikal alpine-tundra—mountain-taiga province (Mikheev and Ryashin, 1977).

mercial activities, forests are illegally logged here. It should be noted that the aforementioned factors (in particular, the drought in recent years) led to disturbance of the level regime of Lake Baikal, a UNESCO World Heritage Site (Garmaev et al., 2017; Dabaeva et al., 2016).

**Remote sensing data.** This study is based on an analysis of the well-known NDVI vegetation index, which characterizes the amount of green phytomass and is calculated as the ratio of the difference between reflections in the near infrared and red regions of the spectrum to their sum. NDVI time series from a spectroradiometer, the Advanced Very High Radiation Radiometer (AVHRR) (NOAA satellite series), served as the initial data (Tucker et al., 2005). The low spatial and high time resolutions make it possible to cover large areas and extract the maximum information for analysis of the dynamics of the vegetation cover. The product is formed from the maximum values of the vegetation index for a 15-day period: this made it possible to minimize the effect of the atmosphere on the image quality. The spatial resolution of the images is formed 8 km. Our research used images obtained during the growing period of the vegetation cover from 1982 to 2015.

**Climatic and meteorological data.** The NDVI trends and meteorological parameters were spatially compared based on NCEP/NCAR reanalysis data (Kalnay et al., 1996). The boundaries of arid lands were determined with a widely recognized index of aridity known as the moisture index (the ratio of annual precipitation to potential evapotranspiration) (Zolotokrylin, 2002). The calculations used an ENVIREM set of meteorological data with a spatial resolution of 1 km$^2$ that were averaged for the period from 1961 to 1990 (Title and Bemmels, 2018).

We determined the Selyaninov hydrothermal coefficient (HTC), an integrated index of moisture supply for the study area; it was calculated as the ratio of the 10-fold precipitation amount in mm for the period with temperatures above 10°C to the sum of temperatures (°C) for the same period. The temperature and precipitation data were provided by the NOAA/Climate Prediction Center (Physical Sciences Division, 2019). These data are part of the Global Telecommu-

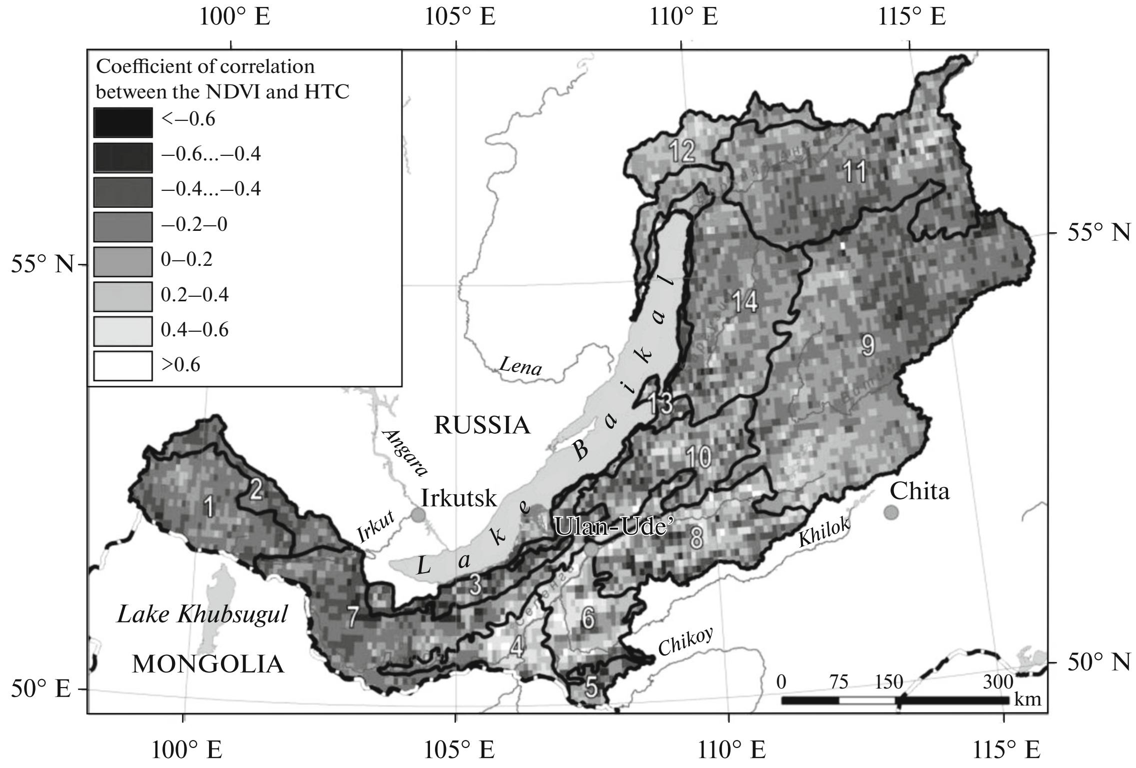

**Fig. 2.** Correlation between the average annual HTC and NDVI.

nication System and are linked to the regular network with a cell size of 0.5 angular degrees. The annual HTC values were calculated for the period from 1982 to 2015; a correlation analysis of the time series of annual HTC and maximum values of annual NDVIs was carried out (Fig. 2).

**Data processing.** The data were preprocessed to restore the missing values and to smooth the NDVI time series (Sodnomov et al., 2018). Incorrect values of the NDVI were replaced by its average value for the entire period. The time series were smoothed with the Savitsky–Golay filter. The seasonal component was removed from the time series with the moving average method. The preprocessed data were used to build a linear regression model and to calculate the trend. The precipitation and NDVI trends were calculated for two periods: the wet period (from 1982 to 1999) and the dry period (from 2000 to 2015). We chose this differentiation, since it is at the turn of the millennium when the wet moisture phase changed to the dry phase in Transbaikalia (Obyazov and Smakhtin, 2012).

**Validation of satellite data.** Changes in the vegetation cover were assessed based on data from field geobotanical and dendrochronological studies, as well as high resolution Google Earth images and aerial survey data.

## RESULTS AND DISCUSSION

Figure 1 presents our map of RB climatic zones for the current base climate period. It was revealed that the total area of arid zones was 128 358 km$^2$, or 38.6% of the RB area (without Lake Baikal). The area of the semiarid zone is 19 823 km$^2$ (6%) and that of the dry subhumid zone is 108 535 km$^2$ (32.6%). The semiarid area is widespread in the Selenga–Khilok, Khilok–Uda, and Selenga–Orkhon steppe mid-mountain provinces and is slightly distributed in the Dzhida–Lower-Selenga basin–mountain-taiga, Ulan-Burgas mountain-taiga, and Pribaikalskaya alpine-tundra (goltsy) mountain-taiga provinces, and within intermountain basins in the river valleys. A dry subhumid zone is also widespread in these areas, as well as in the Vitim taiga-plateau, western Transbaikal mountain taiga–alpine-tundra provinces, and the Baikal lake basin on the border of the eastern and northern shores of the lake. At the same time, even the presence of a large water body does not significantly influence the climate of the region: being orographically isolated, Lake Baikal loses its marine climate features even at a distance of several kilometers from the shore (Fig. 1).

Analysis of the spatial distribution of NDVI trends in the RB revealed that positive trend values (up to 98%) prevailed both in humid and arid zones during the wet period (Fig. 3a). During the dry period, high growth rates of negative NDVI trends were recorded in

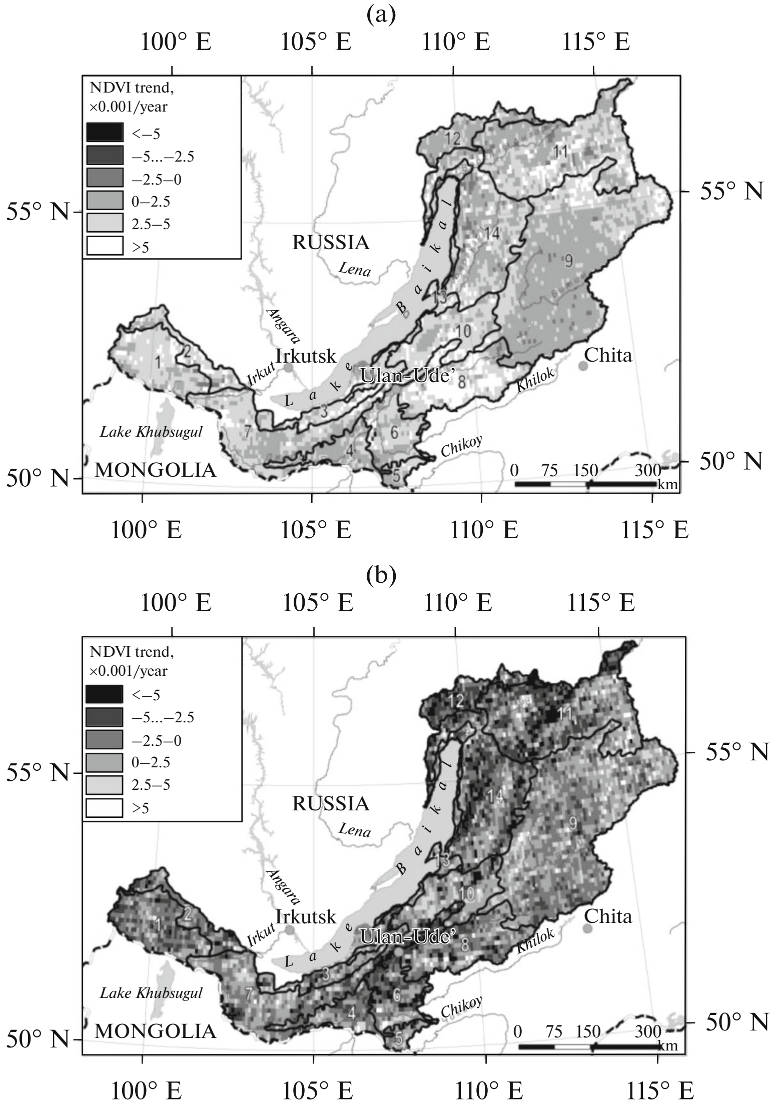

**Fig. 3.** NDVI trends in the Republic of Buryatia: (a) wet period (1982–1999), (b) dry period (2000–2015).

the semiarid and dry subhumid zones (up to 35 times), which shows their highest sensitivity to the moisture regime. The most significant negative transformations of the vegetation cover throughout the study period (from 1982 to 2015) are characteristic of the semiarid zone (40.6%), while this indicator is 26.3% for the humid zone. Zero trends are characteristic of the Earth's surface without vegetation, i.e., water bodies and the goltsy altitudinal belt (Table 1).

Precipitation trends are unevenly distributed in the RB: the wet period is characterized by an increase in precipitation in the arid areas of the RB, except for the greater part of the Vitim taiga-plateau province, as well as in the western Transbaikal, Pribaikalskaya, Okinsko-Tunkinskaya, and Okinsko-Kitoyskaya alpine-tundra–taiga provinces (Fig. 4a); the picture is opposite during the dry period (Fig. 4b). Precipitation decreases in the Ulan-Burgas mountain-taiga and northern Baikal taiga-mountain provinces, reaching the minimum on the border of the Selenga–Khilok and Khilok–Uda steppe–mid-mountain provinces. The Khamar-Daban Range is an area with the highest and lowest values of precipitation trends at average annual levels of 800–1000 mm. The moisture regime of this mountain system, which is located near the main arid zones of the RB, is a type of indicator of precipitation changes in the region.

One should take the interpolated reanalysis data with precaution, since there are few weather stations in the RB and they are located mainly in river valleys, while the precipitation in the mountains remain unrecorded. This is confirmed by the fact that no stable relationship was found between precipitation and the river runoff formed in mountain areas (Garmaev, 2010).

**Table 1.** Proportion of positive and negative NDVI trends in the dry and humid lands of the Republic of Buryatia, %

| Periods | NDVI trend | Semiarid zone | Dry subhumid zone | Humid zone |
|---|---|---|---|---|
| Wet period (1982–1999) | Positive | 98.1 | 97.8 | 96.8 |
| | Negative | 1.9 | 1.6 | 2.4 |
| | Zero | 0 | 0.6 | 0.8 |
| Dry period (2000–2015) | Positive | 42.2 | 43.9 | 40.6 |
| | Negative | 57.8 | 55.5 | 58.9 |
| | Zero | 0 | 0.6 | 0.5 |
| Entire period (1982–2015) | Positive | 59.4 | 67.0 | 72.9 |
| | Negative | 40.6 | 32.4 | 26.3 |
| | Zero | 0 | 0.6 | 0.8 |

The wet period was marked by the almost general NDVI growth. A less-intensive growth in the vegetation index is observed in the dry subhumid zone of the Vitim taiga-plateau province, where the precipitation trend has a weak negative slope. In the dry period, solid zones with a negative NDVI trend are characteristic of semiarid and dry subhumid steppe landscapes in the intermountain basins: these are the valleys of the Selenga, Upper Angara, Barguzin, Uda, and Dzhida rivers. In addition to forest vegetation, negative NDVI trends in the Vitim taiga-plateau province are also observed in grass–moss bogs and reedgrass meadows (Fig. 3b).

It is noteworthy that the Baikal upland (northern Baikal taiga-mountain province) with humid climate is also characterized by negative NDVI trends. The precipitation reduction and large-scale fires (in 1998 and 2006), combined with prospecting activities, have stabilized the negative trend. Despite the weak positive precipitation trends in the Pribaikalskaya alpine-tundra–mountain-taiga province, the NDVI trends have negative values in most of the mountain range. The bidirectionality of NDVI and precipitation trends is also more characteristic of forest vegetation. Here, the NDVI dynamics is influenced by temperature. Analysis of the spatial correlation between the series of average annual HTC and NDVI values revealed a positive relationship for intermountain basins with widespread steppe communities and a negative correlation for forest landscapes (Fig. 2). Therefore, precipitation has a greater effect on the NDVI for steppe vegetation, while temperature has a greater influence on the NDVI for forest vegetation. Our dendrochronological studies on the Hamar-Daban range revealed that the correlation between the NDVI and radial growth index of coniferous species is higher on the “dry” southern macroslope (up to 0.78) than on the moisture-rich northern one. The correlation relationship decreases with altitude on the southern macroslope of the range, while the picture is opposite on the northern slope. On the southern slope, the proportion of representatives of dark coniferous taiga increases with altitude, while the northern macroslope is naturally represented by dark coniferous taiga. One should further take into account the spectral reflectivity of light coniferous and dark coniferous taiga.

Field studies show that the development of positive NDVI values is determined by the succession of native pine forests for secondary small-leaved forests, as well as by reforestation, intensive bushing of steppe sites, and overgrowth of agricultural arable lands. Agricultural lands that were abandoned at different times and are dominated by cinquefoil populations have positive values; the same values are observed for fallow lands during their overgrowth and bushing with elm grove. A succession of communities for secondary ruderal species is observed less frequently. Fallow lands in the last stages of succession (i.e., that are close to regeneration of the primary communities) have weakly negative trends.

Negative trend values are widespread mainly on rocky, cold-sagebrush–cinquefoil, cleistogenes, and bluegrass–hardish-sedge communities on medium-gentle slopes that lack moisture (perennial drought, groundwater reduction, cessation of ameliorative activities, etc.) or suffer anthropogenic impact (spring–autumn burning or overgrazing). A short-term increase in the aboveground phytomass after pyrogenic effects is observed in some areas; however, this does not contribute to any changes in the direction of the trend. Analysis of the postpyrogenic processes should take into account the pattern and duration of fires, which determine the rate of succession processes.

In turn, the impact of forest fires on landscapes is more significant and often accompanied by a cascade effect. Woodlands exposed to fires before the 2000s are characterized by positive trend values due to their postpyrogenic recovery successions at late stages. Fires from the 2000s to the present time usually result in negative trend values, since early stages of secondary successions (weeds and bushing) are common in these areas. The distinctive feature of the spatial distribution of NDVI trends is their maximum and mini-

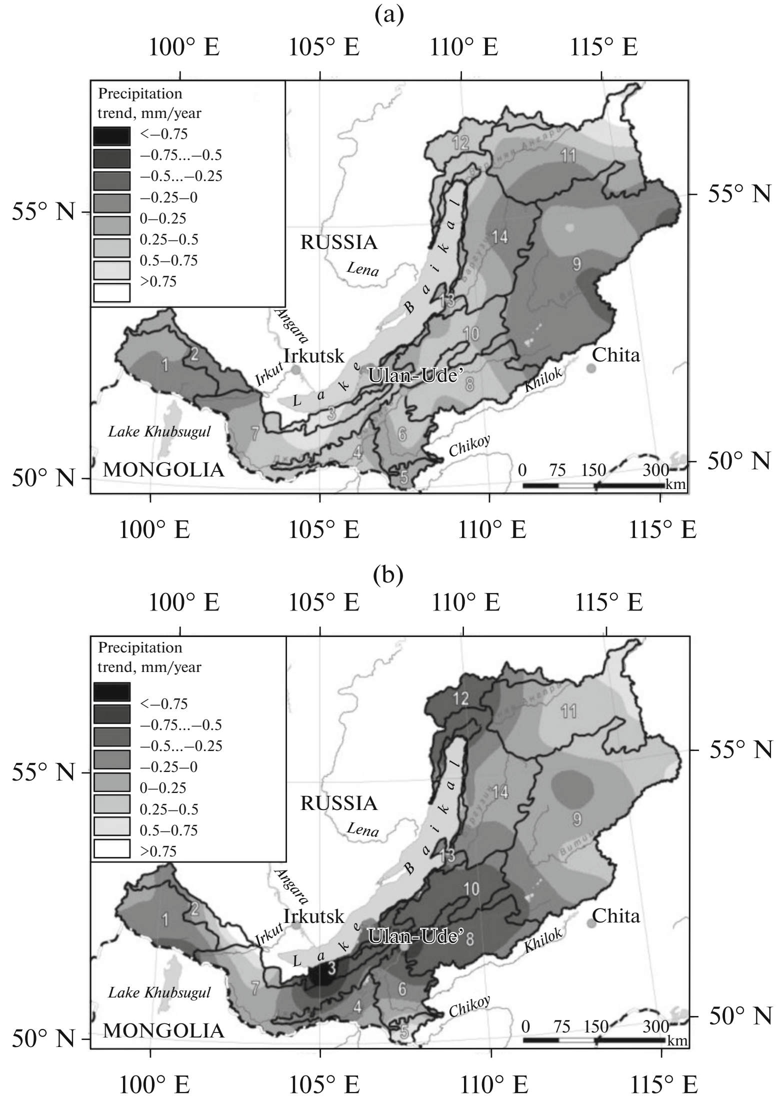

Fig. 4. Precipitation trends in the Republic of Buryatia: (a) wet period (1982–1999), (b) dry period (2000–2015).

mum values in afforestation and deforestation areas, respectively.

## CONCLUSIONS

Arid zones are widespread in almost all physical and geographical provinces in the RB. Their total area is 128 358 km$^2$, or 38.6% of the RB area (without Lake Baikal). Among them, the semiarid and dry subhumid zones occupy 6 and 32.6% of the RB area, respectively.

Precipitation and NDVI trends were calculated for the wet period (1982–1999) and dry period (2000–2015). It is noteworthy that the precipitation trends reversed their direction almost throughout the RB in the selected time intervals. Thus, while the amount of precipitation in arid zones increased during the wet period, it decreased in the dry period.

Positive NDVI trends, which reached 90%, were observed throughout the republic in the wet period (1982–1999). The dry period is characterized by a more than 30-fold increase in negative NDVI trends in arid zones as compared to the wet period; this shows the high sensitivity of these zones to the moisture regime. The entire period was marked by the dominance of positive NDVI trends in the humid zone (72.9% of the area); this index is 59.4 and 67.0% for the semiarid and dry subhumid zones, respectively.

Positive NDVI trends are confined to fallow lands and wild lands used for haying and pasturing, as well as postpyrogenic woodlands and reforestation sites. Negative NDVI trends are characteristic of steppe ecosystems and forest vegetation exposed to deforestation and fires. The climate-related NDVI dynamics is more dependent on precipitation in steppe vegetation, while the forest-related NDVI dynamics is more dependent on temperature.

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## COMPLIANCE WITH ETHICAL STANDARDS

*Conflict of interests*. The authors declare that they have no conflicts 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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