Geosystems-indicators of climate change and cultural landscape recovery in Tigireksky Reserve and its protective zone (Altai Krai, Russia)

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Abstract: The paper deals with major trends of landscape dynamics in the northern part of the Tigireksky Reserve. The global warming impact on the study area is confirmed by the ERA5, NCEP-NCAR and CRU TS reanalyses data for 1979–2018. It manifests in decreased atmospheric humidification during the growing season and worsening conditions for forest recovery. We discuss the possibilities of identifying geosystems-indicators for monitoring of climate change and cultural landscape recovery based on the analysis of the author's large-scale landscape map.

Keywords: Russian Altai; Altai Mountains; climate change; landscape mapping; anthropogenic transformation; recovery potential; indicativeness; forest/treeless area ratio; Russia.

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1 Introduction

Changes in climate and land use/land cover are the main drivers of landscape dynamics. It is essential to understand the ecosystem responses to such changes and the underlying processes regulating the responses (Dahlgren, 2006). The human and climate-induced changes in disturbance regimes are currently acting in concert to force ecosystems to move more quickly towards a new equilibrium with the climate (Soja et al., 2007).

The sustainable use of landscapes implies a balance between their protection and exploitation. Available measures for ecosystem management are to reduce the local and regional stressors, and designate the protected areas as refuges (Okey et al., 2015). Indeed, the protected areas are a cornerstone of global conservation efforts (Rodrigues et al., 2004).

Adaptation to climate change is becoming a prominent issue in both landscape research and land-use planning (Koomen et al., 2012). Adapting landscapes to climate change is organised around the process-pattern relationship across a range of spatial scales (Opdam et al., 2009). Many models have been developed and used to study various effects of climate change. Monier et al. (2017) provide an overview of the recent and ongoing modelling studies over Northern Eurasia and identify many ecological and geophysical processes comprising the Earth system dynamics and human dimensions.

Current global climate changes are fully relevant for the southern regions of the West Siberian plain. Several studies based on both weather station data and climate reanalysis show significant positive trends in the surface air temperature (Groisman et al., 2013; Kharlamova, 2020). Precipitation trends are not so obvious because of sparse observational networks and time-dependent systematic bias in precipitation records (Groisman et al., 2013).

It is necessary to identify geosystems acting as clear indicators of climate change under a long-term monitoring. Hereinafter, we understand geosystems in the classical definition of this term by Sochava (1978) that allows to apply a systematic approach in studying landscape dynamics: “Geosystem is the Earth’s space of all dimensions where individual components of nature are in systemic connection with each other and interact with the cosmic sphere and human society as a certain integrity.” Of particular interest in this regard are mountain regions located at equal distance from the oceans, which along with recording the effects of changes in the regional environment allow us to fully trace the regional response to global climate change.

In the Russian tradition, landscape maps play a leading role in providing the information on landscapes. One more peculiarity of the Russian landscape school is giving much attention to classification. The landscape classification is based on some principles, the observance of which is obligatory. Among them is a simultaneous consideration of a landscape as a unique phenomenon and as a type, i.e., a set of landscapes having some common features. The origin and development of the Russian landscape science are related with the strict nature reserves establishment and concurrent elaboration of methods for field landscape mapping. Russia is an important global supplier of ecosystem services. It is also the particularly interesting country for investigating the effects of landscape changes on the protected areas due to its exceptionally rich biodiversity and the well-established extensive network of protected areas (Sieber et al., 2013). More than 100 of such areas are zapovedniks (i.e., strictly protected areas, scientific state nature reserves, IUCN category Ia) established solely for conservation and scientific monitoring.

Monitoring of landscape and biological diversity is one of the main tasks of strict nature reserves in Russia. Our study demonstrates that landscape mapping has a number of systemic advantages at scientific grounding of the establishment of special protected natural areas, the change of their boundaries, the environmental monitoring, the management and other related activities. It is also important that natural reserves often include anthropogenically transformed areas (cultural landscapes). The foregoing makes feasible the observation of their recovery and the study of its mechanisms.

We chose the Tigireksky Reserve as the study area because its landscapes are representative for North-West Russian Altai. Despite its small area, the territory of the reserve is distinguished by a great landscape diversity due to its location in the mountains, and therefore, rapid change in environmental conditions with the altitude shift. All this makes it possible to trace natural and recovery dynamics at different altitudinal levels. Such investigations in the Russian Altai have not been carried out to date. In addition, this reserve is most convenient for complex monitoring because its rather small area represents both virgin natural and cultural landscapes as well as transitional altitudinal belts [forest-steppe and subgolets-subalpinetype (analogue of the subalpine one)], which are most indicative for studying landscape dynamics dependent on climate changes. Therefore, the main goal of this paper is to understand and assess the causes and probable consequences of landscape changes in the Tigireksky Reserve. Our study has raised the following questions:

1 Does climate change really occur in the study region? If so, then what is its direction and scope?

2 What are the spatial patterns of anthropogenic transformation, recovery potential and indicativeness of landscapes in the northern part of the Tigireksky Reserve?

3 Which geosystems are most promising in terms of long-term monitoring of climate and human-induced landscape dynamics?

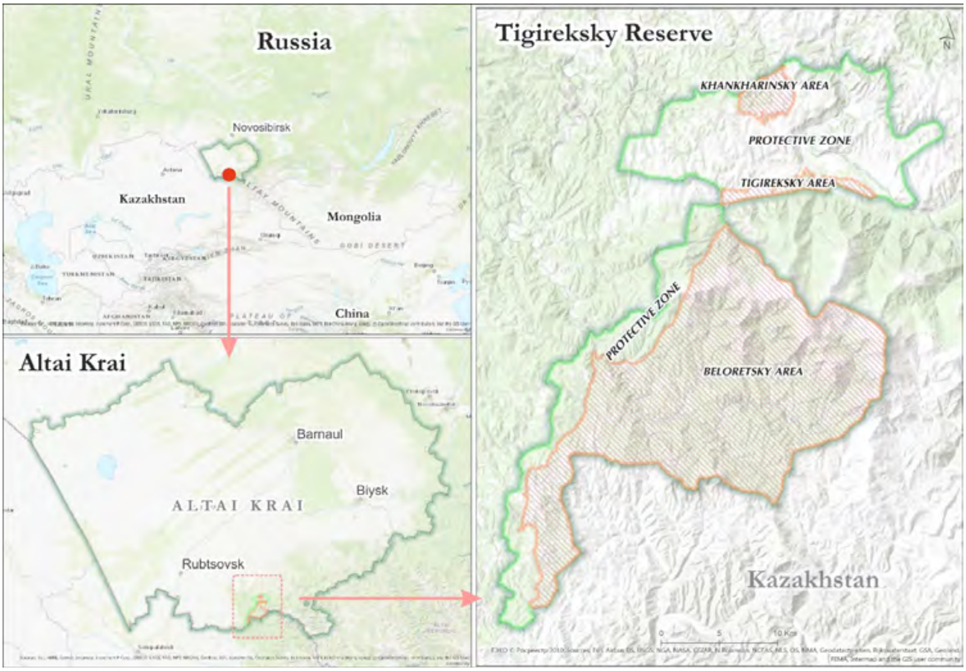
2 Materials and methods

2.1 Study area

Some Russian strict nature reserves have existed for over 100 years. The Tigireksky State Nature Reserve was founded in 1999. Its establishment has contributed to recovery processes in damaged landscapes due to economic activity restriction and population reduction. Prior to becoming the nature reserve, this area was used for agriculture, forestry and mining purposes. Currently, only village Tigirek with a population of 35 people is located within the protective zone of the reserve. The economic development of the territory began in the 18th century; logging, fires and plowing significantly reduced the forest areas. In this regard, the Tigireksky Reserve is of great interest for studying landscape recovery (primarily reforestation) under climate change conditions because of widespread abandoned farmlands.

The area of the Tigireksky State Nature Reserve is 41,505 ha with a protective zone of 26,257 ha (Figure 1). There are steppes, small-leaved, mixed and coniferous forests, meadows and wetlands. The entire territory of the Tigireksky Reserve can be conditionally divided into the northern (the Khankharinsky and Tigireksky areas and their protective zone) and southern (the Beloretsky area and its protective zone) parts.

Figure 1 Geographical position of the Tigireksky Reserve in Altai Krai (Russia) (see online version for colours)



The flora and vegetation of the reserve as well as its landscape structure are quite well studied. This raises the problem of identification of geosystems, which are most promising for monitoring major directional changes in the nature of the Tigireksky Reserve. We assume two major trends in landscape dynamics of the study area, i.e.:

1 climate change driving the altitudinal belts shift

2 cultural landscape recovery after anthropogenic load reduction.

2.2 *Analysis of climate and landscape changes in northern part of the Tigireksky Reserve*

In the Tigireksky Reserve, there are no meteorological stations with a long series of observation data. Since 2011, only one weather station in village Tigirek does exist. Note that winter precipitation measurements are not undertaken there. Because of the lack of weather stations with stable records near the study area, some researchers suggest effective use of various datasets and reanalysis for assessing regional climate changes, including ones in Western Siberia. As compared to the NCEP/DOE AMIP II, NCEP/NCAR, and ERA-Interim reanalysis data of European Centre for Medium-Range Weather Forecasts are the closest to in situ observations in Siberia.

In this situation, we employ climatic data from the atmospheric reanalysis. Firstly, it is the ERA5 reanalysis, which provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The ERA5 replaces the ERA-Interim reanalysis ceased on August 31, 2019. Being available from January 1, 1979, the ERA5 reanalysis combines vast historical observations into global estimates using advanced modelling and data assimilation systems (ECMWF, 2017). Secondly, this is the original reanalysis effort of the NCEP-NCAR (R1). It uses a frozen global state-of-the-art global data assimilation system (as of 11 January 1995). The original database was enhanced by additional quality checked datasets from the NCAR's Data Support Section (NCEP/NCAR, n.d.). Thirdly, it is a series of datasets Climatic Research Unit Time-series (CRU TS) containing monthly time-series of precipitation, daily maximum and minimum temperatures, cloud cover, and other variables covering the Earth's land areas for 1901–2018 (CRU TS4.03) (Climatic Research Unit Time-series, n.d.). Since we use the data of three reanalyses obtained from different sources, it is necessary to assess the reliability of the ERA5, NCEP-NCAR and CRU TS data. Based on these three datasets, we calculated the Spearman correlation coefficients reflecting the synchronicity of temperature and precipitation changes. To assess the climate change directions and scopes, we next calculated temperature and precipitation trends using the Mann-Kendall trend test (statistical software for Excel – XLSTAT). Then, the hydro-thermal coefficient of Selyaninov (HTC) (IDMP, n.d.) by the ERA5, NCEP-NCAR, and CRU TS data was computed. The HTC approved by the World Meteorological Organization (WMO) and Global Water Partnership (GWP) (2016) is calculated by the formula: $\mathrm{HTC} = \sum \mathrm{P} \Big/ (\mathrm{T} > 10°\mathrm{C})$ where P – sum of precipitation in mm for the period with average daily air temperatures above +10°C (t > 10°C), and T – the amount of heat (the sum of daily temperatures) during the same period. This coefficient uses the temperature and precipitation values and shows the moisture/heat ratio during the growing season. Because of the HTC sensitivity to dry conditions specific to the monitored climate regime, we also calculated its mean values and trends.

Most investigations devoted to vegetation dynamics under climate fluctuations (recovery, northern and upper forest line shifts) are based on the Landsat data available on http://glovis.usgs.gov/ (Baral et al., 2018; Yang et al., 2019). This is due to the need for satellite images with an interval of the last few decades made by the same satellite imaging systems. Among the available stock of satellite images, only the Landsat data meet these conditions. They have a large number of spectral channels, high spatial resolution, wide time coverage and free access to the database. Unfortunately, in our case, their spatial resolution (30–60 m) is not enough to fix the boundaries of small forests in the forest-steppe belt and on tops of ridges and slopes in the forest belt in the northern part of the Tigireksky Reserve. In view of this, we have to apply the ultra-high spatial resolution data (IKONOS, QuickBird, WorldView, GeoEye, etc.) to ensure the vegetation cover study in high detail suitable for the identification of individual trees (Kharuk et al., 2017). The use of these data enables study of the land cover dynamics at high spatial resolution. However, we face some 'drawbacks' such as the high costs of the product, the small size of the scene, the narrow time coverage by the data, etc.

Our study was based on the fieldwork (2013–2019), which allowed us to identify the current state of landscapes. As the landscape mapping technique, we used the combined GIS-based analysis of satellite imagery, the digital elevation model, and the ground observation data. The information on types and growing conditions of vegetation was compiled due to the expert knowledge. The proposed methodology was tested at sites throughout the study area. The landscape map of the northern part of the Tigireksky

Reserve (Chernykh and Zolotov, 2015) was constructed at the level of species of simple and compound urochishches. A total of 67 urochishches were identified, including heavily anthropogenically transformed ones (settlements and forest cultures). Urochishches are usually formed on the basis of any relief mesoform.

We apply the analysis of the landscape map of the northern part of the Tigireksky Reserve for the selection of the contours, most promising for monitoring of climate changes and cultural landscape recovery. We expect to receive rather small in area specific types of contours with manifested changes in forest/treeless area ratio able to serve as geosystems-indicators.

Based on the expert judgements, we rank all geosystems of the study area by three levels of three criteria: anthropogenic transformation – slightly transformed (Ts); medium transformed (Tm), heavily transformed (Th); recovery potential – high recovery potential (Rh), medium recovery potential (Rm), low recovery potential (Rl); and indicativeness – high indicative (Ih), medium indicative (Im), low indicative (Il).

Anthropogenic transformation is closely related to disturbance. Disturbances can be determined as directly measurable changes in the ecosystem independent of statistical distribution, a recurrence period or predictability that would define a relative disturbance (Weißhuhn et al., 2018). Slightly transformed (Ts) geosystems are virgin and weakly disturbed landscapes subject mainly to indirect impacts (sporadic grazing, visits by tourists, etc.) if the primary factor of transformation is impossible to identify. In the territory under consideration, medium transformation (Tm) is usually associated with forestry activities (logging of different intensity) and partly with grazing. Heavily transformation (Th) is caused by residential and agricultural (plowing, intensive pasture use) loads as well as planting of forest cultures (man-made stands).

By recovery potential is meant the ability of geosystems to self-recovery under natural and anthropogenic factors, which currently impede full natural recovery of landscapes. Adaptive capacity and recovery potential are rather close concepts. Adaptive capacity characterises the ability to cope with the hazard and its consequences (Weißhuhn et al., 2018).

High recovery potential (Rh) is characteristic to slightly and medium transformed landscapes located in the reserve and the protective zone parts free from current economic activities. These are primarily forest sites recovering after logging as well as pastures re-growing by forests and shrubs. Medium recovery potential (Rm) is typical for medium and heavily transformed landscapes, which are either partially involved in modern economic activity, or specific transformation calls for a long recovery time even in the absence of anthropogenic press as in case of plowing. Low recovery potential (Rl) is intrinsic to heavily transformed landscapes of the protective zone, which are currently involved in economic activities or very deeply transformed, e.g., settlements, intensively used arable lands, pastures, and vegetable gardens, forest cultures.

We consider indicativeness as the landscape ability of evident physiognomic manifestation of changes associated with natural and anthropogenic dynamics. As for the northern part of the Tigirek Reserve, this is mainly a change in the ratio of forests, shrubs, and grass communities within the analysed contours. It can be observed both using remote sensing data and ground-based field studies. Indicativeness to natural and anthropogenic dynamics may contradict. First and foremost, we evaluate indicativeness to climate changes.

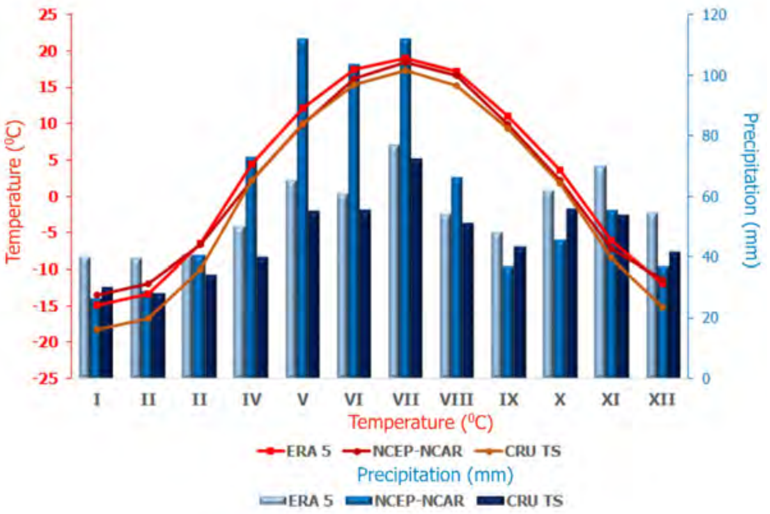
The landscape mapping and further analysis could indicate anthropogenic transformation (disturbance), recovery potential and indicativeness hotspots that may require specific intervention of protection and a long-term monitoring.

3 Results and discussion

3.1 Climate changes in northern part of the Tigireksky Reserve

Mean monthly temperatures, calculated due to the ERA5, NCEP-NCAR and CRU TS data (1979–2018), suggest that July is the warmest and January – the coldest months in the Tigireksky Reserve. In line with the ERA5 and CRU TS, the precipitation maximum falls on July, whereas the minimum – on February. However, pursuant to the NCEP-NCAR, the precipitation peak is marked not only in July, but also in May and June with precipitation amount only ≈ 10 mm less than in the months mentioned first. In May–July, precipitation is 40 mm higher according to the NCEP-NCAR as compared with the ERA5 and CRU TS reanalysis data (Figure 2).

Figure 2 Mean annual temperature and precipitation for the study area according to the ERA5, NCEP-NCAR and CRU TS (1979–2018) (see online version for colours)



To analyse the interannual variability of temperature and precipitation with the use of the ERA5, NCEP-NCAR and CRU TS data, we calculated the correlation coefficients for these reanalyses (Table 1). This was done both for the whole year and for its two periods. Since we considered the vegetation cover as the major indicator of the geosystem state, the warm and cold periods were identified. The warm period lasted from April to October and the cold one – from November to March. According to the data of all three reanalyses (ERA5, NCEP-NCAR and CRU TS), the derived correlation coefficients for temperatures show high consistency (above 0.7) as for the year as for the two selected periods. Hence, there is a consistent interannual and interseasonal temperature variability according to all three datasets. As for precipitation, the ERA5 and CRU TS data are evidence of the most consistent interannual changes for the whole year and the warm period, while the NCEP-NCAR and CRU TS – for the cold period. This is confirmed by the correlation coefficients (above 0.7) reflecting the consistency of changes in precipitation (Table 1). The results received from three reanalyses allow us to use the ERA5, NCEP-NCAR, and CRU TS data for analysing temperature changes in the Tigireksky Reserve, whereas the CRU TS – mostly for studying precipitation because it has the highest correlation coefficients with other reanalyses (Table 1).

Table 1 The Spearman correlation coefficients of interannual variability of temperature and precipitation in the northern part of the Tigireksky Reserve according to the ERA5, NCEP-NCAR and CRU TS (1979–2018)

Significance level (p < 0.001)	*Temperature*			*Precipitation*		
	ERA5	*NCEP-NCAR*	*CRU TS*	*ERA5*	*NCEP-NCAR*	*CRU TS*
Year						
ERA5	1			1		
NCEP-NCAR	0.89	1		0.47	1	
CRU TS	0.96	0.83	1	0.88	0.56	1
Warm period						
ERA5	1			1		
NCEP-NCAR	0.82	1		0.56	1	
CRU TS	0.95	0.77	1	0.90	0.53	1
Cold period						
ERA5	1			1		
NCEP-NCAR	0.94	1		0.56	1	
CRU TS	0.92	0.90	1	0.53	0.81	1

The resultant trends in annual temperature changes show the increase by 0.18°C/10 yr. and 0.28°C/10 yr. when using the ERA5 and CRU TS data, respectively (Table 2). Moreover, these reanalyses data record a temperature rise during the cold period and a more tangible one in the warm period (0.31°C/10 yr. and 0.38°C/10 yr.). However, the NCEP-NCAR data for the annual period demonstrate negative trends (–0.13°C/10 yr.). It is mainly due to the cold period (–0.23°C/10 yr.), which can be hardly compensated by a slight increase in summer temperatures (0.08°C/10 yr.). According to all three reanalyses data, a temperature rise is observed during the warm period; it exceeds 0.3°C/10 yr. by the ERA5 and CRU TS. It should be noted that the temperature of the warm period is more important for vegetation cover and forest, in particular.

According to the ERA5 and CRU TS, annual precipitation shows a slight increase (less than 3.0 mm/10 yr.). By the NCEP-NCAR data, it is greater than 6 mm/10 yr. A similar pattern (i.e., the significant growth according to the NCEP-NCAR) is observed for the warm and cold periods. An important point that this reanalysis, unlike the rest two, indicates the increased precipitation amount during the cold period (2.5 mm/10 yr.) thereby exceeding the trend values for the warm period (2.0 mm/10 yr.).

Table 2 Mann-Kendall trends of temperature (°C/10 yr.) and precipitation (mm/10 yr.) changes in the northern part of the Tigireksky Reserve according to the ERA5, NCEP-NCAR and CRU TS (1979–2018)

	Temperature (°C/10 yr.)	*Precipitation (mm/10 yr.)*
Year		
ERA5	*0.18**	*1.2*
NCEP-NCAR	–0.13	6.2
CRU TS	0.28	*2.9*
Warm period		
ERA5	0.31	*0.5*
NCEP-NCAR	0.08	2.0
CRU TS	*0.38*	*0.9*
Cold period		
ERA5	*0.10*	*0.3*
NCEP-NCAR	–0.23	2.5
CRU TS	*0.13*	1.2

Note: *Significant at the $p < 0.05$ level marked by italic font.

The ERA5, NCEP-NCAR and CRU TS data are evidence of an essential rise in temperature for the whole year and the warm period as well as of a slight increase in precipitation amount in the northern part of the Tigireksky Reserve (1979–2018). All this can negatively affect the development of vegetation (forests) in the forest-steppe altitudinal belt and in locations of the forest belt with soil moisture deficiency.

In support of this fact, HTC was calculated by the reanalyses data (ERA5, NCEP-NCAR and CRU TS). Over the study period, the HTC decrease proved by three reanalyses (0.025–0.030/10 yr.) was related with insufficient moisture (slight increase in precipitation amount) along with a significant rise in temperature (and evapotranspiration). As mentioned in Paragraph 1.2, a similar situation was registered in the south of the West Siberian plain and the Altai Mountains. It means that climate becomes drier and the forest-steppe belt shift in the northern part of the Tigireksky Reserve is expected.

3.2 Geosystems-indicators of climate change and cultural landscape recovery

In regard of anthropogenic transformation in the northern part of the Tigireksky Reserve, slightly transformed (Ts) geosystems occupy 33.3% of the area, medium transformed (Tm) – 59.3%, and heavily transformed (Th) – 7.4% (Figure 3). Geosystems with high recovery potential (Rh) cover 72.5% of the area, with medium recovery potential (Rm) – 25.3%, low recovery potential (Rl) – 2.2% (Figure 4). Indicativeness ranging shows that high indicative (Ih) geosystems hold 8.8% of the area, medium indicative (Im) – 46.7%, and low indicative (Il) – 44.5% (Figure 5).

Figure 3 Anthropogenic transformation (T) of landscapes in the northern part of the Tigireksky Reserve (see online version for colours)

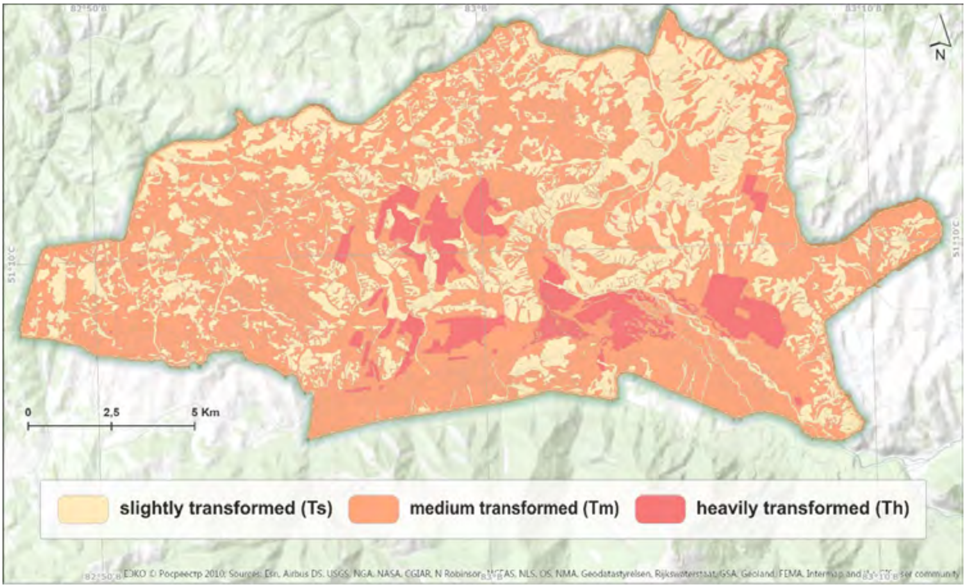


Figure 4 Recovery potential (R) of landscapes in the northern part of the Tigireksky Reserve (see online version for colours)

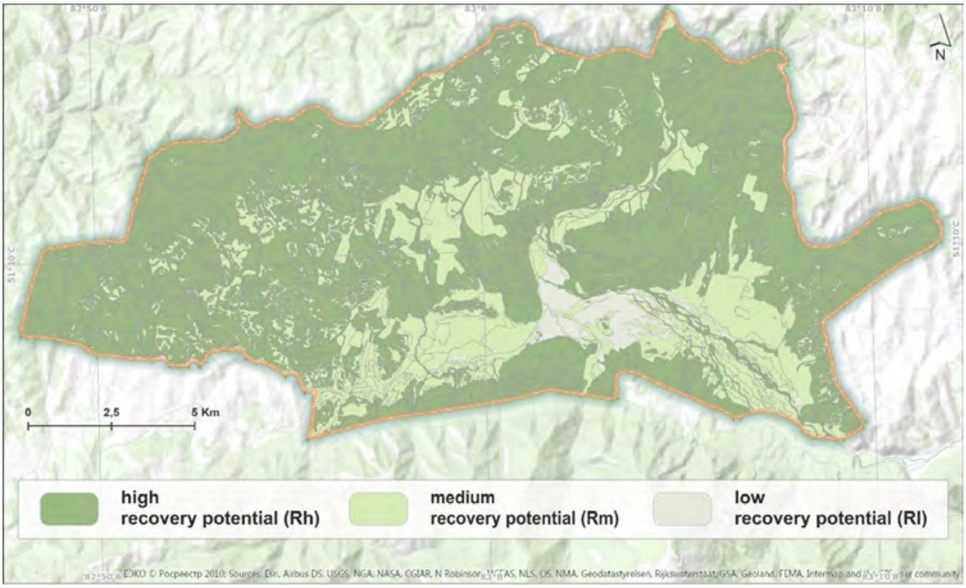
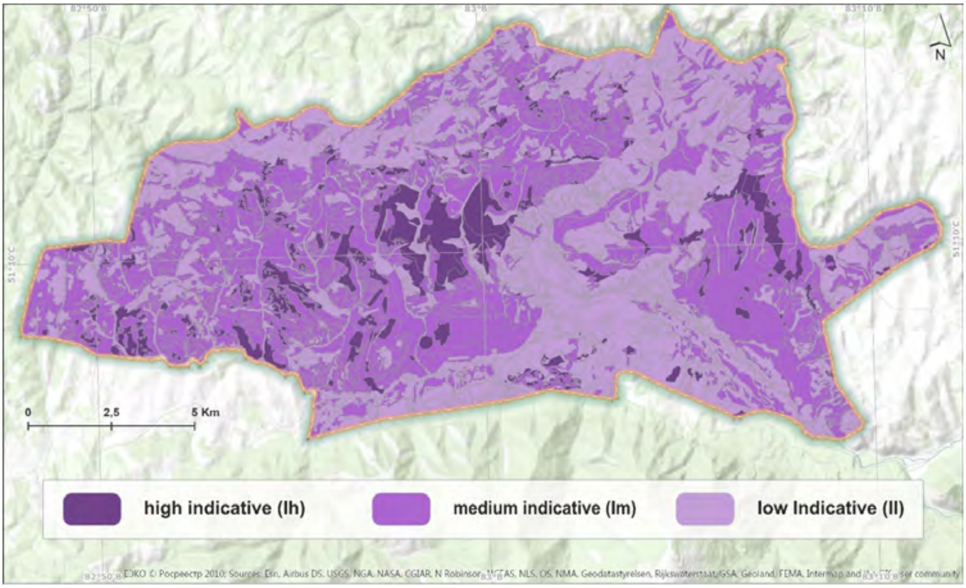


Figure 5 Indicativeness (I) of landscapes in the northern part of the Tigireksky Reserve (see online version for colours)



Understanding the spatial patterns of anthropogenic transformation, recovery potential and indicativeness are important for a long-term monitoring and assessing the contribution of these lands to carbon sequestration. Climate and human-induced changes in terrestrial ecosystems transform valuable ecosystems and their services, which in turn, require an adjustment in business planning, nature conservation, forest management, agricultural practices, and regional economic policies to mitigate or adapt to these changes (Groisman et al., 2013). Adaptation measures are also appropriate in upstream parts of river catchments to increase the potential of the landscape for water retention and runoff regulation (Begum et al., 2007). In the northern part of the Tigireksky Reserve, medium transformed geosystems with high recovery potential (Tm-Rh) predominate; they occupy 39.2% (82.76 km^2) of the area. This makes it possible to predict the significant contribution of their recovery as a result of forest re-growing to carbon sequestration, runoff regulation and other ecosystem functions and services.

The combination of anthropogenic transformation (T), recovery potential (R) and indicativeness (I) of landscapes in the northern part of the Tigireksky Reserve (Figures 6 and 7) presents the data for selecting most promising geosystems-indicators for monitoring of climate changes and cultural landscape recovery.

In our opinion, the monitoring of climate changes (Figure 8) and cultural landscape recovery can be separated dealing with practically virgin geosystems characterised by high and medium indicativeness. To monitor only climate changes, it is advisable to consider slightly anthropogenically transformed geosystems with high recovery potential and high indicativeness (Ts-Rh-Ih: 0.2 km^2, 0.1% of the northern part of the Tigireksky Reserve) and slightly transformed geosystems with high recovery potential and medium indicativeness (Ts-Rh-Im: 18.9 km^2, 9.0% of the area). In total, this group of geosystems-indicators occupies 9.1% of the study area.

Figure 6 The combination map of anthropogenic transformation (T), recovery potential (R) and indicativeness (I) of landscapes in the northern part of the Tigireksky Reserve (see online version for colours)

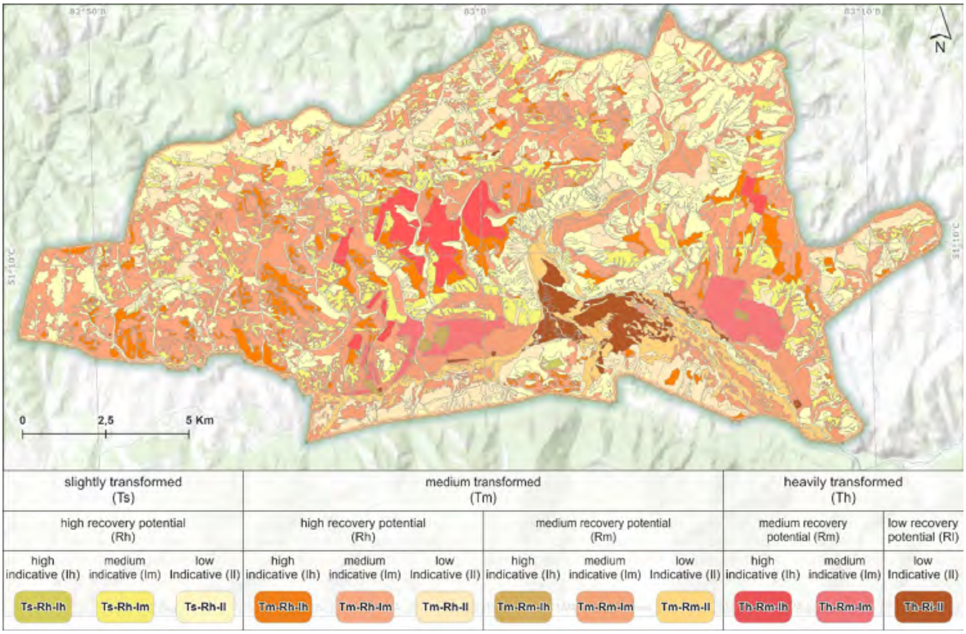
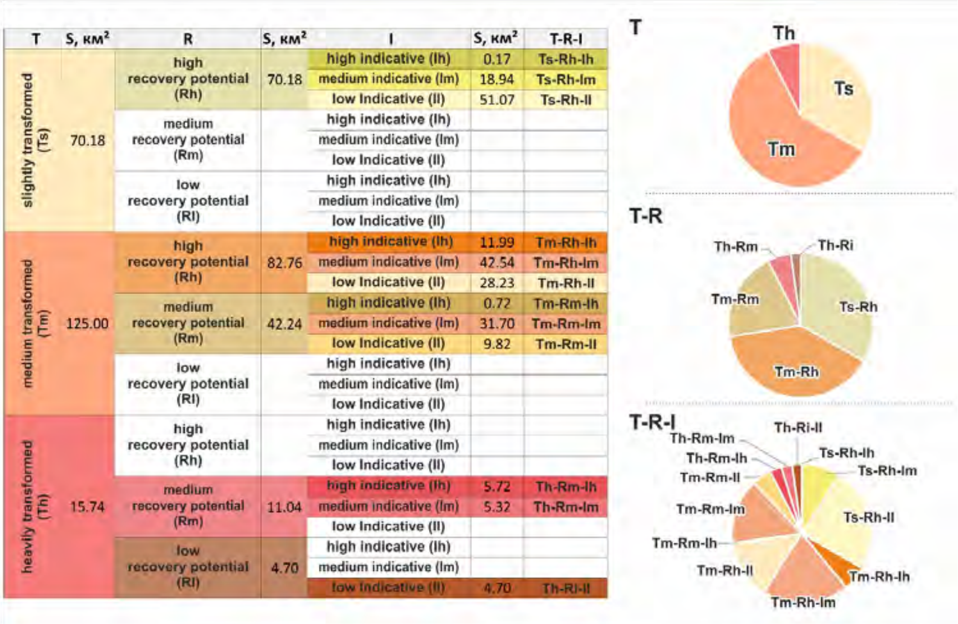


Figure 7 The combination matrix of anthropogenic transformation (T), recovery potential (R) and indicativeness (I) of landscapes in the northern part of the Tigireksky Reserve (see online version for colours)



T	S, км²	R	S, км²	I	S, км²	T-R-I
slightly transformed (Ts)	70.18	high recovery potential (Rh)	70.18	high indicative (Ih)	0.17	Ts-Rh-Ih
				medium indicative (Im)	18.94	Ts-Rh-Im
				low Indicative (Il)	51.07	Ts-Rh-Il
		medium recovery potential (Rm)		high indicative (Ih)		
				medium indicative (Im)		
				low Indicative (Il)		
		low recovery potential (Rl)		high indicative (Ih)		
				medium indicative (Im)		
				low Indicative (Il)		
medium transformed (Tm)	125.00	high recovery potential (Rh)	82.76	high indicative (Ih)	11.99	Tm-Rh-Ih
				medium indicative (Im)	42.54	Tm-Rh-Im
				low Indicative (Il)	28.23	Tm-Rh-Il
		medium recovery potential (Rm)	42.24	high indicative (Ih)	0.72	Tm-Rm-Ih
				medium indicative (Im)	31.70	Tm-Rm-Im
				low Indicative (Il)	9.82	Tm-Rm-Il
		low recovery potential (Rl)		high indicative (Ih)		
				medium indicative (Im)		
				low Indicative (Il)		
heavily transformed (Th)	15.74	high recovery potential (Rh)		high indicative (Ih)		
				medium indicative (Im)		
				low Indicative (Il)		
		medium recovery potential (Rm)	11.04	high indicative (Ih)	5.72	Th-Rm-Ih
				medium indicative (Im)	5.32	Th-Rm-Im
				low Indicative (Il)		
		low recovery potential (Rl)	4.70	high indicative (Ih)		
				medium indicative (Im)		
				low Indicative (Il)	4.70	Th-Rl-Il

Figure 8 Most promising landscapes for monitoring of climate changes in the northern part of the Tigireksky Reserve (see online version for colours)

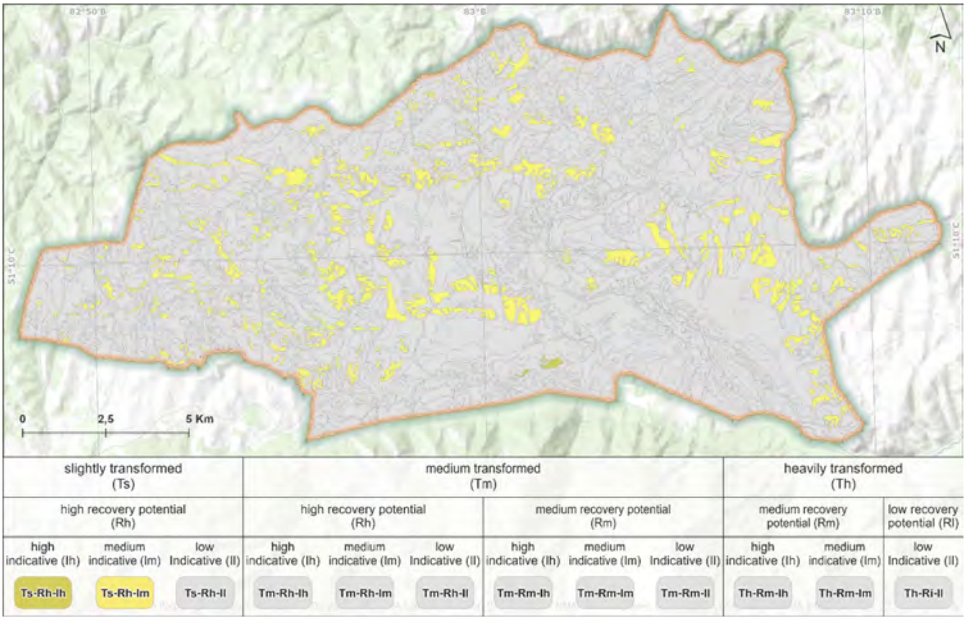
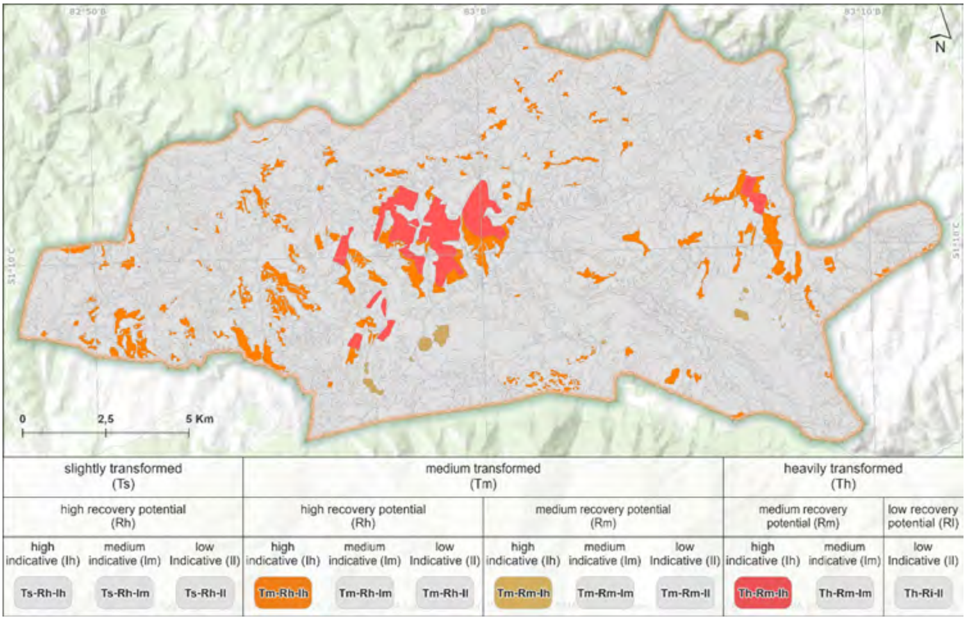


Figure 9 Most promising landscapes for the complex monitoring of climate changes and recovery processes in the northern part of the Tigireksky Reserve (see online version for colours)



On the other hand, we can hardly isolate the monitoring of cultural landscape recovery and climate changes because the latter influences on all geosystems of the study area.

That is why in the second case we deal with a complex monitoring (Figure 9) using high indicative geosystems. For the complex monitoring of climatic changes and recovery processes, the most promising landscapes are medium transformed geosystems with high recovery potential and high indicativeness (Tm-Rh-Ih: 12.0 km^2, 5.7% of the area), medium transformed geosystems with medium recovery potential and high indicativeness (Tm-Rm-Ih: 0.7 km^2, 0.3% of the area), and heavily transformed geosystems with medium recovery potential and high indicativeness (Th-Rm-Ih: 5.7 km^2, 2.7% of the area). In total, this group of geosystems-indicators covers 8.7% of the area of the northern part of the Tigireksky Reserve.

We have not found complete analogues of our research in the available literature. The use of large-scale landscape mapping and geosystems-indicators for monitoring studies is predominantly characteristic for the Post-Soviet territory, where the Russian landscape approach is common. In order to study climate-induced landscape dynamics in high mountains based on the large-scale map analysis combined with remote sensing data, the specific nival-glacial geosystems-indicators are usually employed. These studies report about the warming in the mountains of Southern Siberia (Russia) and shifting up of altitudinal belts (Kitov et al., 2015). To date, the landscape maps are used:

1. to assess the productivity of geosystems in the southern taiga of Western Siberia
2. to predict changes in the Siberia geosystems based on the factored-dynamic series model and to evaluate stability of geosystems of the Southern East Siberia and their expected state in the future.

Some researchers consider a landscape indicator as an index calculated on the basis of expert judgements on landscape criteria (Weinstoerffer and Girardin, 2000). The use of remote sensing data becomes popular under monitoring the special protected natural areas and their surroundings for studying climate changes, anthropogenic impact, and control of conservation effectiveness of habitats and biodiversity (Nagendra et al., 2013). The novelty of the study is in identifying the set of specific geosystems-indicators due to the criteria-based complex analysis of the large-scale landscape map and the use of the forest-steppe belt as well as some locations of the forest belt instead of high mountains.

4 Conclusions

1. In 1979–2018, the ERA5, NCEP-NCAR and CRU TS reanalyses data in the northern part of the Tigireksky Reserve show a rise both in mean annual and warm period (growing season) temperatures along with minor increase in precipitation amount. This leads to a decrease in the HTC. Thus, the climatic conditions in the growing season become drier that should cause a shift up of the forest-steppe belt and negatively affect forest recovery.
2. We identify spatial patterns and hotspots of anthropogenic transformation, recovery potential and indicativeness of geosystems in the northern part of the Tigireksky Reserve as a case study. The possibility of using the landscape analysis to assess the ecological state of the territory as well as ecosystem functions and services is discussed. The methodology used can be transferred to any territory covered by large-scale landscape mapping.

3 The spatial analysis of landscapes with the use of the detailed large-scale landscape maps makes it possible to identify small in area geosystems-indicators as the most promising in studying major trends of landscape dynamics. We propose specific geosystems-indicators for implementation of a long-term monitoring of climate and human-induced landscape changes using remote sensing data of ultra-high spatial resolution and ground-based field studies.

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References

Baral, P., Wen, Y. and Urriola, N.N. (2018) ‘Forest cover changes and trajectories in a typical middle mountain watershed of Western Nepal’, *Land*, Vol. 7, No. 2, p.72 [online] https://doi.org/10.3390/land7020072.

Begum, S., Stive, M.J.F. and Hall, J.W. (Eds.) (2007) *Flood Risk Management in Europe. Innovation in Policy and Practice. Advances in Natural and Technological Hazards Research*, Springer Netherlands, 534pp.

Chernykh, D.V. and Zolotov, D.V. (2015) ‘Landscape structure of Khankharinsky and Tigireksky areas and buffer zone of Tigirek strict nature reserve’, *Bulletin AB RGS (Izvestiya AO RGO)*, in Russian with abstract in English, Vol. 2, No. 37, pp.16–28 [online] https://doi.org/10.24411/2410-1192-2015-13703.

Climatic Research Unit Time-series (n.d.) *CRU TS Version 4.03* [online] https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.03/ (accessed 18 January 2018).

Dahlgren, R.A. (2006) ‘Biogeochemical processes in soils and ecosystems: from landscape to molecular scale’, *J. Geochem. Explor.*, Vol. 88, No. 1, pp.186–189.

European Centre for Medium-Range Weather Forecasts (ECMWF) (2017) *ERA-Interim* [online] https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim (accessed 18 January 2018).

Groisman, P.Y., Blyakharchuk, T.A., Chernokulsky, A.V., Arzhanov, M.M., Marchesini, L.B., Bogdanova, E.G., Borzenkova, I.I., Bulygina, O.N., Karpenko, A.A., Karpenko, L.V., Knight, R.W., Khon, V.C., Korovin, G.N., Meshcherskaya, A.V., Mokhov, I.I., Parfenova, E.I., Razuvaev, V.N., Speranskaya, N.A., Tchebakova, N.M. and Vygodskaya, N.N. (2013) ‘Climate changes in Siberia’, in Groisman, P.Y. and Gutman, G. (Eds.): *Regional Environmental Changes in Siberia and Their Global Consequences*, pp.57–109, Springer Environmental Science and Engineering, Dordrecht.

Integrated Drought Management Programme (IDMP) (n.d.) *Hydro-thermal Coefficient of Selyaninov (HTC)* [online] https://www.droughtmanagement.info/hydro-thermal-coefficient-of-selyaninov-htc/ (accessed 18 January 2018).

Kharlamova, N.F. (2020) ‘Climatic variability of the Kulunda steppe’, in Frühauf, M., Guggenberger, G., Meinel, T., Theesfeld, I. and Lentz, S. (Eds.): *KULUNDA: Climate Smart Agriculture. South Siberian Agro-steppe as Pioneering Region for Sustainable Land Use*, pp.19–32, Springer, Cham [online] https://doi.org/10.1007/978-3-030-15927-6.

Kharuk, V.I., Im, S.T., Dvinskaya, M.L., Ranson, K.J. and Petrov, I.A. (2017) ‘Tree wave migration across an elevation gradient in the Altai Mountains, Siberia’, *Journal of Mountain Science*, Vol. 14, No. 3, pp.442–452.

Kitov, A.D., Kovalenko, S.N., Plyusnin, V.M. and Suvorov, E.G. (2015) 'Modern changes of the high-mountain landscapes and glaciation in Southern Siberia (Russia) by the example of the Eastern Sayan mountains', *Environmental Earth Sciences*, Vol. 74, No. 3, pp.1931–1946 [online] https://doi.org/10.1007/s12665-015-4455-y.

Koomen, E., Opdam, P. and Steingröver, E. (2012) 'Adapting complex multi-level landscape systems to climate change', *Landscape Ecol.*, Vol. 27, pp.469–471 [online] https://doi.org/10.1007/s10980-012-9721-8.

Monier, E., Kicklighter, D., Sokolov, A., Zhuang, Q., Sokolik, I., Lawford, R., Kappas, M., Paltsev, S. and Groisman, P. (2017) 'A review of and perspectives on global change modeling for northern Eurasia', *Environ. Res. Lett.*, Vol. 12, No. 8, p.083001.

Nagendra, H., Lucas, R., Honrado, J.P., Jongman, R.H.G., Tarantino, C., Adamo, M. and Mairota, P. (2013) 'Remote sensing for conservation monitoring: assessing protected areas, habitat extent, habitat condition, species diversity, and threats', *Ecological Indicators*, Vol. 33, pp.45–59 [online] https://doi.org/10.1016/j.ecolind.2012.09.014.

NCEP/NCAR (n.d.) *Reanalysis 1: Summary* [online] https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html (accessed 18 January 2018).

Okey, T.A., Agbayani, S. and Alidina, H.M. (2015) 'Mapping ecological vulnerability to recent climate change in Canada's Pacific marine ecosystems', *Ocean Coast. Manage.*, Vol. 106, pp.35–48 [online] https://doi.org/10.1016/j.ocecoaman.2015.01.009.

Opdam, P., Luque, S. and Jones, K.B. (2009) 'Changing landscapes to accommodate for climate change impacts: a call for landscape ecology', *Landscape Ecol.*, Vol. 24, pp.715–721 [online] https://doi.org/10.1007/s10980-009-9377-1.

Rodrigues, A.S.L., Andelman, S.J., Bakarr, M.I., Boitani, L., Brooks, T.M., Cowling, R.M., Fishpool, L.D.C., Da Fonseca, G.A.B., Gaston, K.J., Hoffmann, M., Long, J.S., Marquet, P.A., Pilgrim, J.D., Pressey, R.L., Schipper, J., Sechrest, W., Stuart, S.N., Underhill, L.G., Waller, R.W., Yan, X. et al. (2004) 'Effectiveness of the global protected area network in representing species diversity', *Nature*, Vol. 428, pp.640–643.

Sieber, A., Kuemmerle, T., Prishchepov, A.V., Wendland, K.J., Baumann, M., Radeloff, V.C., Baskin, L.M. and Hostert, P. (2013) 'Landsat-based mapping of post-Soviet land-use change to assess the effectiveness of the Oksky and Mordovsky protected areas in European Russia'. *Remote Sensing of Environment*, Vol. 133, No. 2, pp.38–51 [online] https://doi.org/10.1016/j.rse.2013.01.021.

Sochava, V.B. (1978) *Introduction to the Doctrine of Geosystems (Vvedenie v uchenie o geosistemakh)*, in Russian, Nauka, Novosibirsk.

Soja, A.J., Tchebakova, N.M., French, N.H.F., Flannigan, M.D., Shugart, H.H., Stocks, B.J., Sukhinin, A.I., Parfenova, E.I., Chapin III, F.S. and Stackhouse Jr., P.W. (2007) 'Climate-induced boreal forest change: predictions versus current observations', *Glob. and Planet Change*, Vol. 56, Nos. 3–4, pp.274–296 [online] https://doi.org/10.1016/j.gloplacha.2006.07.028.

Weinstoerffer, J. and Girardin, P. (2000) 'Assessment of the contribution of land use pattern and intensity to landscape quality: use of a landscape indicator', *Ecological Modelling*, Vol. 130, pp.95–109 [online] https://doi.org/10.1016/S0304-3800(00)00209-X.

Weißhuhn, P., Müller, F. and Wiggering, H. (2018) 'Ecosystem vulnerability review: proposal of an interdisciplinary ecosystem assessment approach', *Environmental Management*, Vol. 61, No. 6, pp.904–915 [online] https://doi.org/10.1007/s00267-018-1023-8.

World Meteorological Organization (WMO) and Global Water Partnership (GWP) (2016) *Handbook of Drought Indicators and Indices*, *Integrated Drought Management Tools and Guidelines Series 2*, Svoboda, M. and Fuchs, B.A. (Eds.), WMO-No. 1173, p.19, Integrated Drought Management Programme (IDMP), Geneva [online] https://library.wmo.int/doc_num.php?explnum_id=3057.

Yang, R., Luo, Y., Yang, K., Hong, L. and Zhou, X. (2019) 'Analysis of forest deforestation and its driving factors in Myanmar from 1988 to 2017', *Sustainability*, Vol. 11, p.3047.

Yang, X. and Liu, Z.P. (2005) 'Using satellite imagery and GIS for land-use and land-cover change mapping in an estuarine watershed', *Int. J. Remote Sens.*, Vol. 26, pp.5275–5296.