Spatiotemporal changes in the boreal forest in Siberia over the period 1985–2015 against the background of climate change

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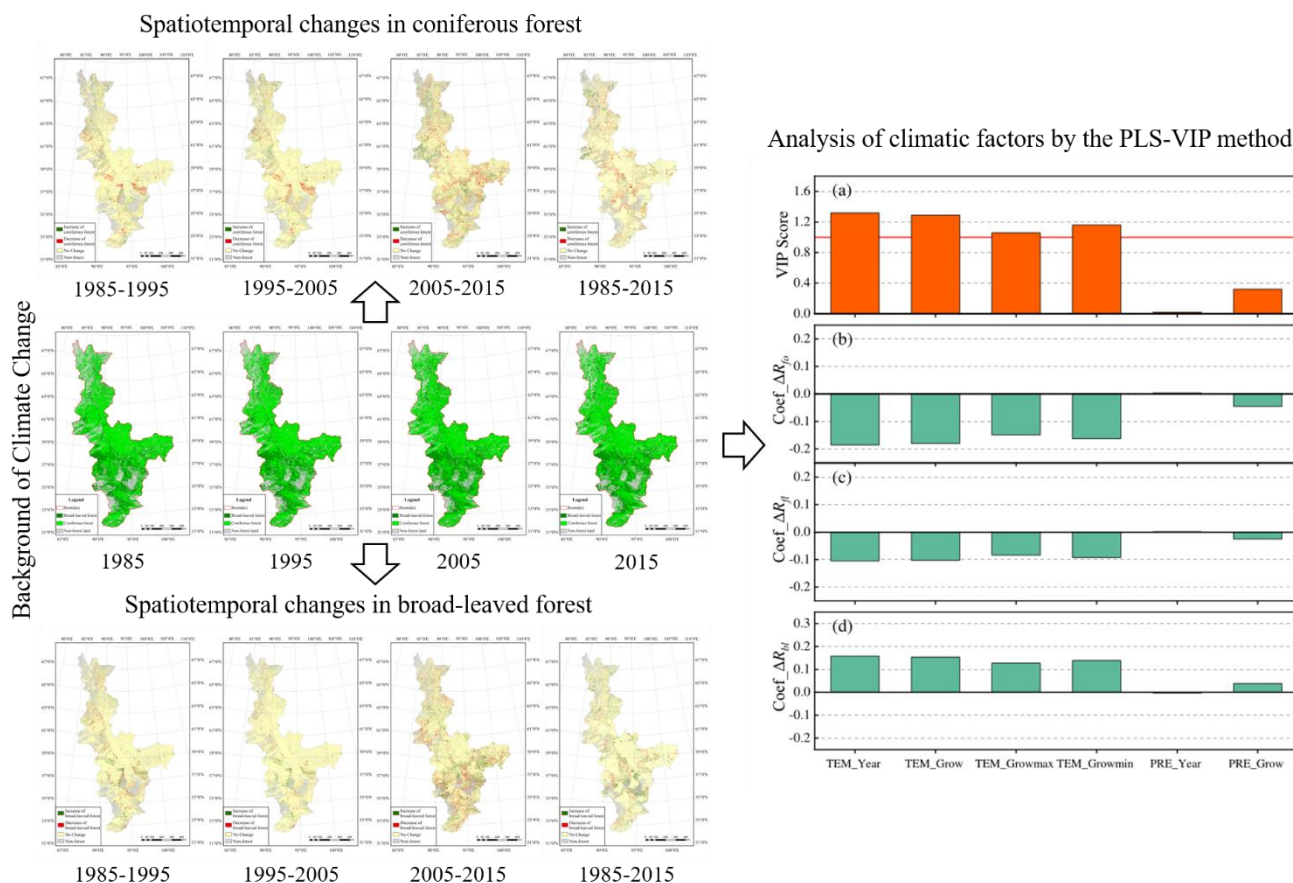
10 **Abstract.** Climate change has been proven to be an indisputable fact and to be occurring at a faster rate in boreal forest areas. Climate change has been observed to have a strong influence on forests; however, until now, the amount of quantitative information on the climate drivers that are producing changes in boreal forest is limited. The objectives of this work were to quantify the spatiotemporal characteristics of boreal forest and forest species and to find the significant climate drivers that are producing changes in boreal forest. The boreal forest in Krasnoyarskiy Kray, Siberia, Russia, which lies within the latitude 15 range 51°N–69°N, was selected as the study area. The distribution of the boreal forest and forest species in the years 1985, 1995, 2005 and 2015 were derived from a series of Landsat data. The spatiotemporal changes in the boreal forest and species that occurred over each ten-year period within each 2° latitudinal zone between 51°N and 69°N from 1985 to 2015 were then comprehensively analyzed. The results show that the total area of forest increased over the study period and that the increase was fastest in the high-latitude zone between 63°N and 69°N. The increases in the areas of broad-leaved and coniferous forests 20 were found to have different characteristics. In the medium-latitude zone between 57°N and 63°N in particular, the area of broad-leaved forest grew faster than that of the coniferous forest. Finally, the influence of the climate factors of temperature and precipitation on changes in the forests was analyzed. The results indicate that temperature rather than precipitation is the main climate factor that is driving change.

25 **Graphical Abstract**

1 Introduction

Boreal forests occupy between 8% and 11% of the Earth's land surface and store a large fraction of global terrestrial carbon. These forests are found throughout the polar regions of the northern hemisphere (at latitudes of 45°N–70°N) and cover 33%

30 of the total circumpolar region, mainly in the Nordic countries (Finland, Sweden, Norway and Iceland), Russia and North America (Canada and Alaska) (Allison and Treseder, 2011). The boreal forest biome has one of the largest geographic footprints of any terrestrial biome on the planet and encircles the globe at northern latitudes (Olson et al. 2001). To date, research into shifts in the range of this biome has predominately focused on the advance of boreal tree species into tundra or alpine habitats (i.e., treeline advance; see Harsch et al. 2009), or on the species-specific responses of temperate tree species

35 (Zhu et al. 2012).

Climate change is expected to lead to changes in temperature and precipitation – factors which strongly influence boreal forests. In addition, the dynamics of the boreal forest will have a significant impact on global climate–biosphere feedback. Research has indicated that latitudes north of 40° are expected to experience the greatest temperature increases due to climate change

(Serreze et al., 2000; Michael et al., 2021). In northern regions, the impacts of climate change are expected to be acute and the
40   ecological response to climate change will vary spatially (Walther et al., 2002). Changes to biodiversity are one of the expected
responses to climate change (Hamann and Wang, 2006). These changes will lead to significant spatiotemporal changes in
boreal forest. Most importantly, climate change is expected to reduce climatic constraints on plant growth (Nemani et al.,
2003): warmer, wetter conditions will result in increased vegetation productivity, which has been demonstrated to be an indirect
indicator of biodiversity that is correlated with geographic variation in species richness (Coops et al., 2008; Nelson et al., 2014).
45   There has been much research on the effect of climate change on boreal forest. It has been observed that the growth of boreal
forest has been influenced by global warming in the past decade or more. However, there are clear spatiotemporal differences
in these effects (Hou et al., 2020; Alibakhshi et al., 2020). Models and investigations have suggested that warming will induce
northern migration of the treeline and an alteration in the mosaic structure of boreal forests; it has also been shown that, as
temperatures increase, white spruce tree growth is declining (Soja et al., 2007). In practice, it is a challenge to quantify the
50   effects of climate change on boreal forest because there are great uncertainties attached to possible interactions among them,
as well as with other land-use pressures (Price et al., 2013). Therefore, the extent of the boreal forest response to climate change
is still not fully understood.

A practical method of examining trends in forest cover at large scales is to employ remotely sensed data. Satellite-based
monitoring can be implemented consistently across large regions at annual or inter-annual intervals. Time-series of MODIS
55   (Moderate-resolution Imaging Spectroradiometer) satellite data have been commonly used as a data source in many forest
studies. However, the relatively coarse spatial resolution of these data is not sufficient to detect forest-cover changes accurately
as it has been shown that a substantial proportion of land-cover changes occur at scales below 250 m (Jia et al., 2014; Heiskanen
et al., 2012). Medium-resolution data, such as that acquired by the Landsat series of sensors including the Thematic Mapper
(TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI), represent the only multispectral datasets
60   that can be used for monitoring natural and human-induced landscape changes at the scale of tens of meters over periods of
years or decades (Matasci et al., 2018; Hadi et al., 2016; Hermosilla et al., 2019). These data have been widely used for forest-
cover mapping and change detection because changes in forest cover due to anthropogenic factors usually happen at small
scales (Townshend et al., 2012).

The objectives of this work were to quantify the spatiotemporal changes occurring in the boreal forests in Siberia and then to
65   find which climate factor was the main driver of these changes. To do this, we tried to answer the following questions. (i)
What is the extent of the changes in boreal forest cover and species that are occurring? (ii) In which latitude zones are the
forest cover and species most sensitive to climate change? (iii) Which climate change factor is the main driver influencing
change in the boreal forest in Siberia?

In order to answer the questions and meet our objectives, the following work was undertaken.

70   (1) A typical area of Siberian boreal forest in Krasnoyarskiy Kray, Russia, which extended from the temperature to the frigid
zones, was selected as a research area. Forest cover and species data for the years 1985, 1995, 2005 and 2015 were retrieved
from the Landsat series of imagery.

(2) The characteristics of the spatiotemporal changes in the boreal forest cover and species within different latitude zones over the period 1985–2015 were quantified. The results were validated using 987 points sampled from high-resolution Gaofeng-2
75 satellite images (spatial resolution: 0.81 m) and were found to have an overall accuracy of about 90.37%.

(3) The influences of two climate factors – temperature and precipitation – on changes in boreal forest were analyzed so that the main climate factor driving these changes could be identified.

2 Study area

The boreal forest in Krasnoyarskiy Kray in central Russia, which is also located in the middle of Siberia (Figure 1), was
80 selected as the study area. This area extends from approximately 51°N to 69°N and from 84°E to 110°E. The climatic zones found in this area range from temperate in the south to frigid in the north, which means that the latitude range was considered sufficiently large for an analysis of the sensitivity of the forest to climate change to be carried out.

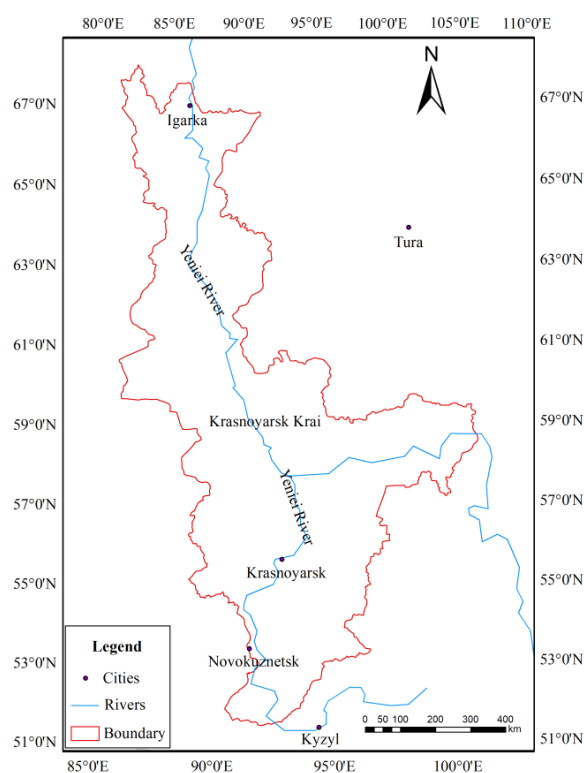



Figure 1. Location of the study area.

85 The climate in the study area is strongly continental with a large temperature gradient from south to north. In the north there are fewer than 40 days each year with temperatures above 10 °C, whereas in the south there are about 110–120 such days. The

average temperature in January is −36 °C in the north and −18 °C in the south, and in July 10 °C in the north and 20 °C in the south. The annual precipitation in the north of the area is 200–300 mm; in the south it is about 1000 mm. The area is sparsely populated; a small number of towns and villages are scattered across the south, surrounded by areas of farmland. We divided the study area into nine latitude zones, each with a width of 2°, from south to north. The area of each of these zones is shown in Table 1.

Table 1. List of the latitude zones and their areas.

Latitude zones (°N)	Area (km^2)
67−69	19596.45
65−67	58813.18
63−65	58364.09
61−63	66364.15
59−61	130507.24
57−59	155232.73
55−57	114456.67
53−55	77579.58
51−53	33564.27
Total	714478.36

3 Materials and Methods

3.1 Data

More than 300 Landsat Thematic Mapper (TM) and Operational Land Imager (OLI) scenes of the study area containing little to no cloud cover were obtained from the United States Geological Survey (USGS) (http://glovis.usgs.gov/). These images were acquired mainly in the years 1985, 1995, 2005 and 2015. Most of the images were acquired during summer (June to September), and some data from adjacent years were used to make up for the lack of data in the target years. Level L1T data with a spatial resolution of 30 m were used. In addition, four Gaofen-2 (GF-2) satellite panchromatic images acquired in 2015 that had a spatial resolution of 0.81 m were acquired for validation purposes.

The climate datasets ERA5-Land (Hersbach et al., 2020) and ERA-20CM (Hersbach et al, 2015), obtained from the European Centre for Medium Range Weather Forecasts (ECMWF), were used as the source of temperature and precipitation data. The SRTM (Shuttle Radar Topography Mission) digital elevation model (DEM), which has a spatial resolution of, 30 m, was also used in this study so that the influence of the elevation could be analyzed.

3.2 Methods

3.2.1 Landsat data preprocessing

Image preprocessing, including radiometric and atmospheric correction to eliminate radiometric and geometric distortion, was carried out. Following this, a haze optimized transformation (HOT) algorithm was used to identify and remove noise due to thin clouds (Zhang et al., 2002; Li et al., 2019; Liu et al., 2017).

3.2.2 Forest cover and species classification

First, a simple decision tree algorithm was used to distinguish vegetation from non-vegetation. The decision tree classification rules were determined based on sample training: pixels with a normalized differential vegetation index (NDVI) value greater than 0.62 and ratio vegetation index (RVI) value greater than 6.0 were classified as vegetation (Qin et al., 2015). Next, the areas of vegetation were further classified as being forest or 'other' vegetation. In this work, it was found that different plants have different spectral reflectance peaks in the near-infrared band; this band is highly sensitive to the differences in reflectance that results from different types of leaves having different internal structures. Vegetation objects with reflectance values of less than 0.38 in the near-infrared were determined as being forest land.

Finally, a random forest (RF) algorithm was used to discriminate forest and non-forest lands from areas of vegetation (Breiman 2001; Strobl et al., 2007; Cutler et al., 2008; Svetnik et al., 2003; Rodriguez-Galiano et al., 2013; Assiri 2021; Climent et al., 2019). Representative training samples are one of the most critical components of the RF algorithm. In this study, we selected the sample points used for the classification based on Landsat images refer to GF-2 images and Google Earth images (Gong et al., 2013). Six bands, Landsat TM bands 1–5 and 7, and Landsat OLI bands 2–7, were selected as characteristic spectral variables, and meanwhile NDVI, the normalized difference index (NDI) (Rodríguez-Moreno and Bullock, 2014) and the RVI were also selected as index characteristic variables for classification in RF.

3.3 Accuracy validation

We selected 987 randomly distributed sampling points from the GF-2 images acquired in 2015 for the accuracy validation. The overall accuracy was found to be 90.37%, and the F1-scores for the broad-leaved, coniferous forest and non-forest land were 0.85, 0.93 and 0.91, respectively (Pontius and Millones, 2011). Considering the consistency of the Landsat series of images, the above validation was still considered to be valid for the earlier years because it is difficult to obtain the measured data or the high-resolution satellite images of the study area for these times.

4. Results and discussion

4.1 Spatiotemporal changes in forest characteristics within the different latitude zones

First of all, as shown in Figure 2, we analyzed the spatial distribution of the boreal forest within the different latitude zones in 1985, 1995, 2005 and 2015. The overall forest coverage in the study area was high – up to 80.5% – but with significant spatial variations. As the amount of human activity in the study area is limited, these differences can be considered to be caused mainly by natural factors. It was found that the forest coverage within the zones with latitudes in the range 51°N–67°N was above 60% but that this declined sharply to about 34.4% at 67°N–69°N. The highest rate of forest coverage – about 90% – occurred in the 57°N–59°N zone. In the lower latitude zones in the range 53°N–57°N, the forest coverage was slightly lower as a result of a certain amount of human activity.

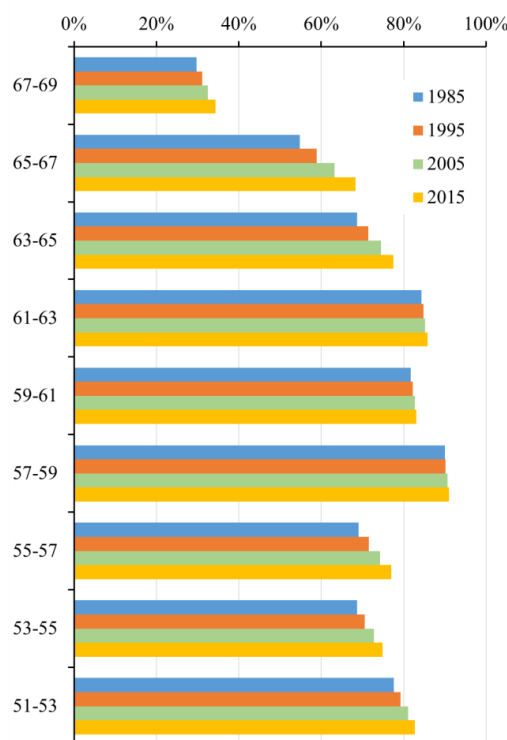



Figure 2. Boreal forest land cover within different latitude zones in four times.

An important problem that we focused on was the significant spatiotemporal change in the boreal forest coverage that occurred over the three decades of the study period. We retrieved the changes for the four times intervals of 1985–1995, 1995–2005, 2005–2015 and 1985–2015 – the results are shown in Figure 3. The first three images reflect the changes that occurred over each 10−year interval; the final image shows the overall change over the three decades. Quantitative information about the changes that occurred over the four different time intervals is given in Table 2, and charts detailing the spatiotemporal changes are shown in Figure 4.

Overall, the forest coverage within all of the latitude zones increased continuously over the three decades of the study. We first analyzed the characteristics of the ratio ΔR_{fo}, which is the ratio of the increase in the area of forest to the original area, as well

150 as of ΔR_{fl}, which is the ratio of the increase in the area of forest to the total land area. First, it can be seen that, in the center of the study area from 57°N–63°N, ΔR_{fo} and ΔR_{fl} were relatively stable and had average values of less than 2% over the period 1985– 2015. Taking into account the accuracy of the forest cover retrieval, it can be considered that the forest coverage in this zone has not changed over the study period, which means that the boreal forest in this zone has not been significantly affected by climate change. The rate of forest coverage in this zone was also highest in the study area – more than 80% in some areas

155 – as has been discussed above.

In the other latitude zones, the values of the ratios ΔR_{fo} and ΔR_{fl} were significantly higher. The fastest change was observed in the northern zone from 63°N–69°N, which means that this is the area where the forest has been most affected by climate change. Over the period 1985–2015, the average value of ΔR_{fo} was about 17%; for ΔR_{fl}, it was about 9%. The highest rates of increase in forest cover occurred in the zone 65°N–67°N, where ΔR_{fo} and ΔR_{fl} were about 24.61% and 13.50%, respectively,

160 which is equivalent to average annual values of about 0.76% and 0.44%. Finally, in the southern zone from 51°N–57°N, the average value of ΔR_{fo} was about 9% and of ΔR_{fl} about 6%.

There were also temporal variations in the changes in forest coverage, especially in the high-latitude zones. For example, between 65°N and 69°N, the amount of forest coverage showed an accelerating trend over the study period, with average values of ΔR_{fo} and ΔR_{fl} of 6.00% and 2.70%, respectively, for the time interval 1985–1995 and 7.00% and 3.50%, respectively,

165 for 2005–2015. However, the rates of increase in forest coverage in the other latitude zones were relatively stable over the study period.

(a) (b) (c) (d)

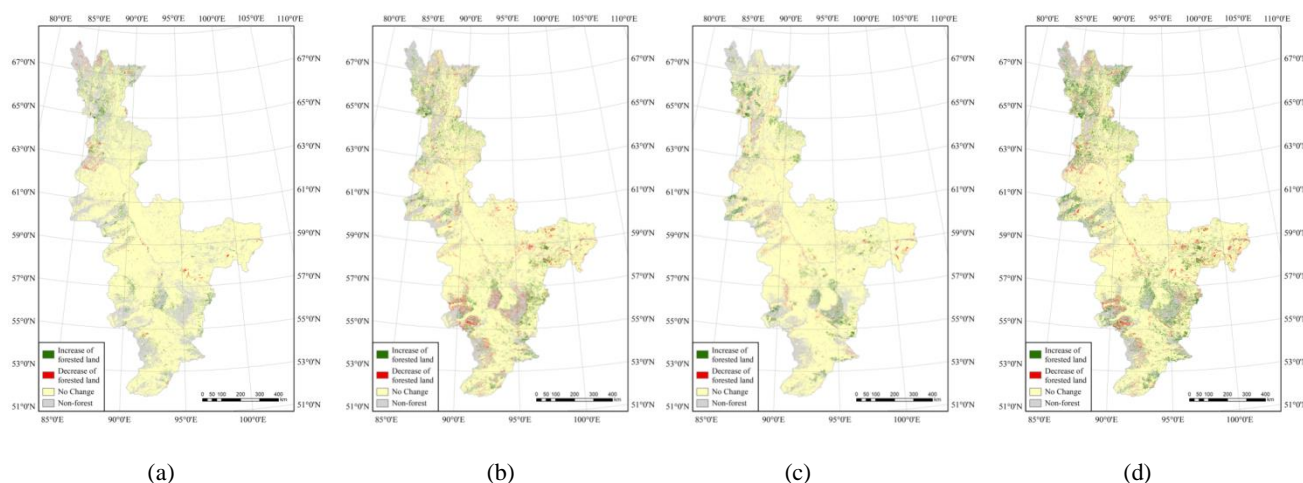



Figure 3. Changes in boreal forest coverage in the time intervals (a) 1985–1995, (b) 1995–2005, (c) 2005–2015 and (d) 1985–2015.

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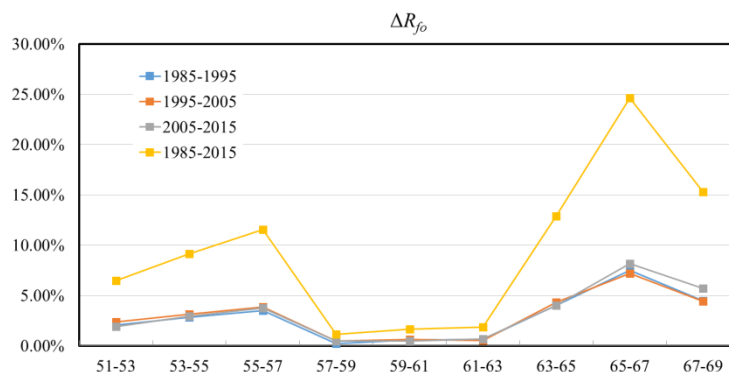
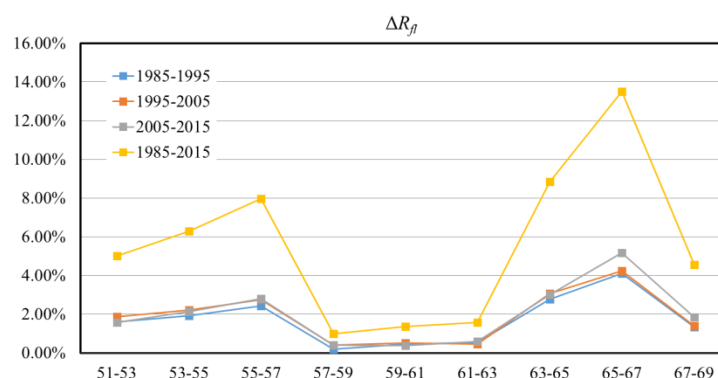
Table 2. Quantitative details of the changes in boreal forest coverage in each latitude zone.

Latitude	1985–1995		1995–2005		2005–2015		1985–2015	
(°N)	ΔR_{fo}	ΔR_{fl}	ΔR_{fo}	ΔR_{fl}	ΔR_{fo}	ΔR_{fl}	ΔR_{fo}	ΔR_{fl}
51–53	2.06%	1.60%	2.35%	1.86%	1.93%	1.56%	6.47%	5.02%
53–55	2.82%	1.93%	3.12%	2.20%	2.94%	2.14%	9.14%	6.28%
55–57	3.50%	2.42%	3.84%	2.75%	3.76%	2.79%	11.52%	7.96%
57–59	0.21%	0.19%	0.45%	0.40%	0.46%	0.41%	1.11%	1.00%
59–61	0.57%	0.47%	0.62%	0.51%	0.47%	0.39%	1.67%	1.37%
61–63	0.63%	0.53%	0.54%	0.46%	0.68%	0.58%	1.86%	1.57%
63–65	4.03%	2.77%	4.30%	3.07%	4.03%	3.00%	12.87%	8.84%
65–67	7.47%	4.10%	7.18%	4.23%	8.17%	5.16%	24.61%	13.50%
67–69	4.45%	1.32%	4.43%	1.38%	5.70%	1.85%	15.28%	4.55%

(a)

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(b)

Figure 4. Forest coverage changes in different latitude zones during different time intervals as measured by (a) ΔR_{fo} and (b) ΔR_{fl}.

4.2. Spatiotemporal characteristics of changes in forest species

4.2.1 Spatiotemporal differences in the ranges of forest species

We also analyzed the spatiotemporal changes in the broad-leaved and coniferous forest coverage. R_{bf} was defined as the ratio

180   of the broad-leaved forest area to the total forest area; the corresponding ratio for coniferous forest, R_{cf}, was then given by $1 - R_{bf}$. Similarly, R_{bl} was used to represent the ratio of the broad-leaved forest area to the total land area; the corresponding measure for coniferous forest was denoted as R_{cl}. Quantitative information about the species coverage can be found in Table 3, and the differences between these ratios are shown in Figure 5.

It can be seen from Figure 5(a) that the region most suited to coniferous forest within the study area is the medium latitude

185   zone 57°N–63°N, which has a value of R_{cl} of about 70%. In the northernmost zone (67°N–69°N), R_{cl} is still above 25% whereas R_{bl} is only about 5%, which indicates that coniferous forest is more resistant to cold and that broad-leaved forest is essentially not found north of latitude 67°N.

Broad-leaved forest cover is low in the north and high in the south; the highest R_{bl} value – over 40% –occurs in the 53°N–57°N zone; however, this falls sharply to less than 20% at latitudes above 57°N. In the 51°N–57°N zone, there may be some

190   human activity that affects the forest coverage, which leads to the slightly lower values of R_{bl} and R_{cl}.

Broad-leaved forest co-exists with coniferous forest across the whole study area, and the proportions of the two types of forest are similar in the 53°N–57°N zone (Figure 5(c)). However, in the other zones, coniferous forest is the dominant species and R_{cf} is above 70%.
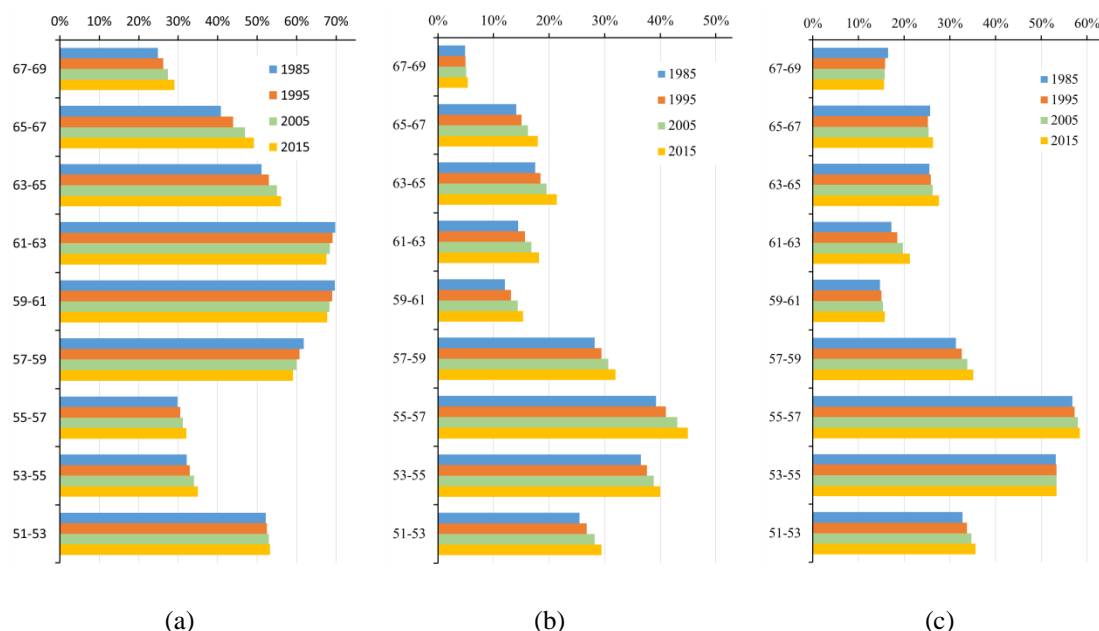
Figure 5. Differences between the rates of broad-leaved and coniferous forest coverage as measured by (a) R_{cl}, (b) R_{bl} and (c) R_{bf}.

Table 3. Quantitative details of the coverage of different forest species.

Latitude (°N)	1985			1995			2005			2015		
	R_{bf}	R_{bl}	R_{cl}	R_{bf}	R_{bl}	R_{cl}	R_{bf}	R_{bl}	R_{cl}	R_{bf}	R_{bl}	R_{cl}
51–53	32.79%	25.46%	52.18%	33.76%	26.75%	52.49%	34.75%	28.18%	52.92%	35.59%	29.42%	53.25%
53–55	53.17%	36.50%	32.15%	53.31%	37.63%	32.96%	53.36%	38.84%	33.95%	53.35%	39.98%	34.96%
55–57	56.78%	39.22%	29.85%	57.32%	40.98%	30.51%	58.02%	43.07%	31.17%	58.41%	44.99%	32.04%
57–59	31.34%	28.20%	61.79%	32.61%	29.41%	60.77%	33.84%	30.65%	59.93%	35.08%	31.92%	59.07%
59–61	14.71%	12.03%	69.71%	16.02%	13.17%	69.03%	17.34%	14.34%	68.37%	18.48%	15.36%	67.74%
61–63	17.18%	14.47%	69.77%	18.47%	15.66%	69.12%	19.74%	16.83%	68.41%	21.23%	18.22%	67.60%
63–65	25.50%	17.51%	51.17%	25.85%	18.47%	52.97%	26.21%	19.53%	54.99%	27.61%	21.41%	56.11%
65–67	25.68%	14.08%	40.76%	25.50%	15.03%	43.91%	25.64%	16.20%	46.98%	26.29%	17.97%	50.37%
67–69	16.47%	4.91%	24.89%	15.87%	4.94%	26.18%	15.72%	5.11%	27.39%	15.59%	5.35%	29.00%

4.2.2 Spatiotemporal characteristics of changes in forest species

200 The characteristics of the changes in forest species were also analyzed. The spatiotemporal characteristics of these changes for the time intervals 1985–1995, 1995–2005, 2005–2015 and 1985–2015 are shown in Figure 6 and Figure 7, and related quantitative information is shown in Table 4. We denoted ΔR_{bl} and ΔR_{cl} as representing the ratios of the increase in broad-leaved and coniferous forest coverage to the total land area, respectively, meaning that these are measures of the absolute increase in these forest types. ΔR_{bf} and ΔR_{cf} denote the increase in the ratio of the area of broad-leaved forest and coniferous

205 forest to the total area of forest, respectively, meaning that these are measures of the relative increase in the area of forest; ΔR_{cf} = −ΔR_{bf}.
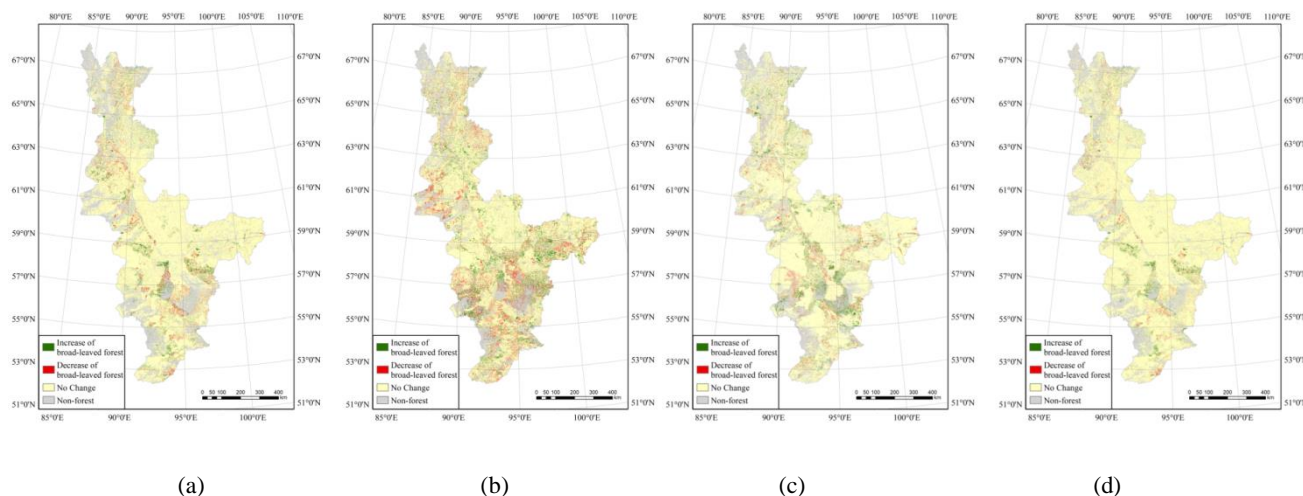
Figure 6. Changes in broad-leaved forest area for (a) 1985–1995, (b) 1995–2005, (c) 2005–2015 and (d) 1985–2015.

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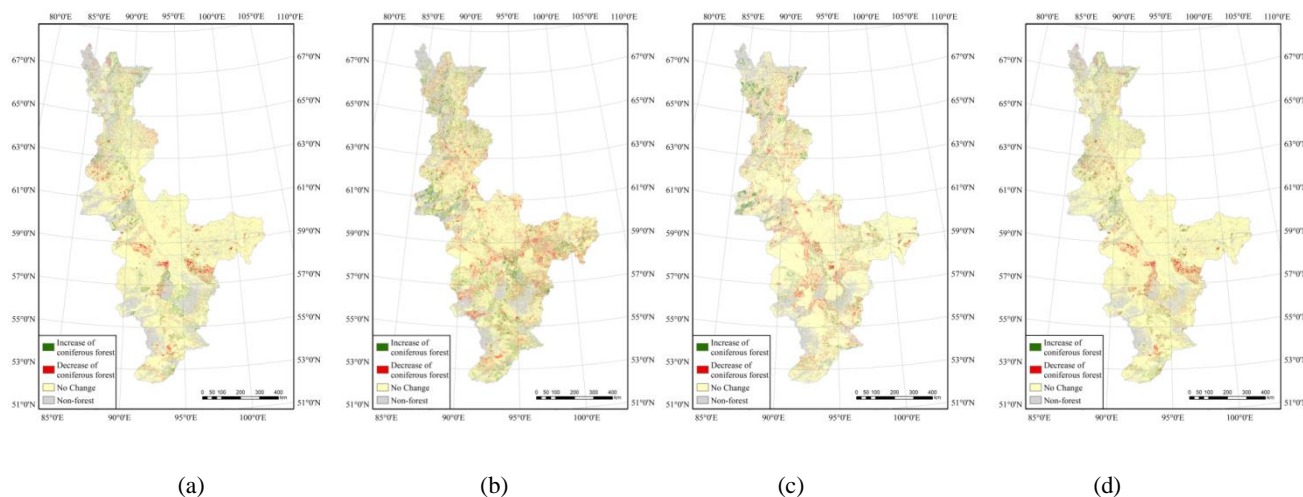
Figure 7. Changes in coniferous forest area for (a) 1985–1995, (b) 1995–2005, (c) 2005–2015 and (d) 1985–2015.

Table 4. Quantitative details of the changes in forest species.

Latitude	1985–1995			1995–2005			2005–2015			1985–2015		
(°N)	ΔR_{bl}	ΔR_{cl}	ΔR_{bf}	ΔR_{bl}	ΔR_{cl}	ΔR_{bf}	ΔR_{bl}	ΔR_{cl}	ΔR_{bf}	ΔR_{bl}	ΔR_{cl}	ΔR_{bf}
51–53	1.29%	0.31%	0.97%	1.43%	0.43%	0.99%	1.24%	0.33%	0.84%	3.96%	1.06%	2.79%
53–55	1.13%	0.81%	0.14%	1.21%	0.99%	0.05%	1.14%	1.00%	-0.01%	3.47%	2.80%	0.18%
55–57	1.76%	0.66%	0.54%	2.09%	0.66%	0.69%	1.92%	0.87%	0.39%	5.77%	2.19%	1.63%
57–59	1.21%	-1.02%	1.28%	1.24%	-0.84%	1.22%	1.27%	-0.86%	1.24%	3.72%	-2.72%	3.74%

59–61	1.14%	-0.68%	1.31%	1.17%	-0.66%	1.32%	1.02%	-0.63%	1.15%	3.33%	-1.97%	3.77%
61–63	1.19%	-0.65%	1.29%	1.17%	-0.71%	1.27%	1.39%	-0.81%	1.48%	3.74%	-2.18%	4.05%
63–65	0.96%	1.81%	0.35%	1.06%	2.01%	0.36%	1.88%	1.13%	1.40%	3.89%	4.95%	2.11%
65–67	0.95%	3.15%	-0.18%	1.17%	3.06%	0.14%	1.77%	3.39%	0.65%	3.89%	9.61%	0.62%
67–69	0.03%	1.29%	-0.60%	0.17%	1.21%	-0.15%	0.24%	1.61%	-0.14%	0.45%	4.11%	-0.89%

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We analyzed the spatial characteristics of the changes in forest species, and details of the spatiotemporal changes in these species are shown in Figure 8. Overall, it can be seen that the broad-leaved forest coverage increased in every latitude zone, which means that the climate change that has been occurring promoted the growth of broad-leaved species across the study area during the three decades of the study. In the 51°N–67°N zone, the overall value of ΔR_{bl} is above 3.3%; however, the value

220 of this measure declines rapidly to about 0.45% north of 67°N, which can be considered as being equivalent to there being no change in R_{bl} in this area. The largest value of ΔR_{bl} over the three decades of the study was 5.77%, which occurred in the latitude zone 55°N–57°N; this is equivalent to an average annual increase of 0.19% and indicates that the broad-leaved forest in this zone was the most sensitive to climate change and its area increased the fastest.

However, coniferous forest showed different change characteristics from those of broad-leaved forest. The latitude zones in

225 the study area can clearly be divided into three parts according to the characteristics of the changes in the coniferous forest area. First, in the zone 51°N–57°N, the average value of ΔR_{cl} is about 2.0%. However, the area of coniferous forest in the medium latitude zone 57°N–63°N has declined slightly over the three decades of the study with a value of ΔR_{cl} of about – 2.3%; in comparison ΔR_{bl} is about 3.9%, which means that climate change has had a negative impact on coniferous forest growth in this zone. The area of coniferous forest increased relatively rapidly in the northern zone between 63°N and 69°N

230 with an average ΔR_{cl} greater than 4.0%. The largest value of ΔR_{cl} – 9.61% – occurs in the latitude zone 65°N–67°N, which is equivalent to an average annual increase of 0.32%; for comparison, this zone has a value of ΔR_{bl} of 3.89%.

It should be noted that ΔR_{bf} is an important parameter for evaluating the relative proportions of the two forest species and can reflect the different characteristics of their responses to climate change. A positive ΔR_{bf} indicates that the proportion of broad-leaved forest relative to the total forest area is increasing faster than that of coniferous forest and that broad-leaved forest is

235 tending to become the dominant tree species. It can be seen from Figure 8(c) that, in the zone 57°N–63°N, ΔR_{bf} is above 3.8%. Meanwhile, as discussed above, the absolute increase given by ΔR_{cl} is negative whereas ΔR_{bl} is positive in this zone. Also, as R_{bf} had a value of 35.08% in 2015 in the zone 57°N–59°N, at the current rate of change, broad-leaved forest will replace coniferous forest as the dominant tree species in this zone in about 120 years.

The changes in the area of broad-leaved forest exhibit considerable variations with time, especially in the zone from 61°N–

240 67°N, where the increase in the area of broad-leaved forest accelerated over the three decades of the study. It can be seen from Figure 8(a) that, in the 65°N–67°N zone, ΔR_{bl} reached 1.93% in the period 2005–2015, whereas it was 1.17% in 1995–2005 and 0.79% in 1985–1995. The results for ΔR_{bf} in this zone show similar trends, indicating that broad-leaved forest is highly sensitive to climate change and that the increase in its area has been accelerating. However, in the 51°N–61°N and 67°N–69°N

zones, the values of ΔR_{bl}, ΔR_{cl} and ΔR_{bf} are relatively stable, which shows that the rate of increase in these forest species did

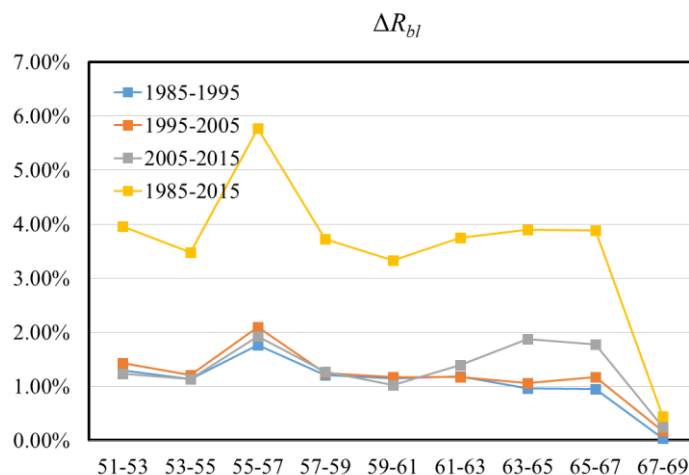
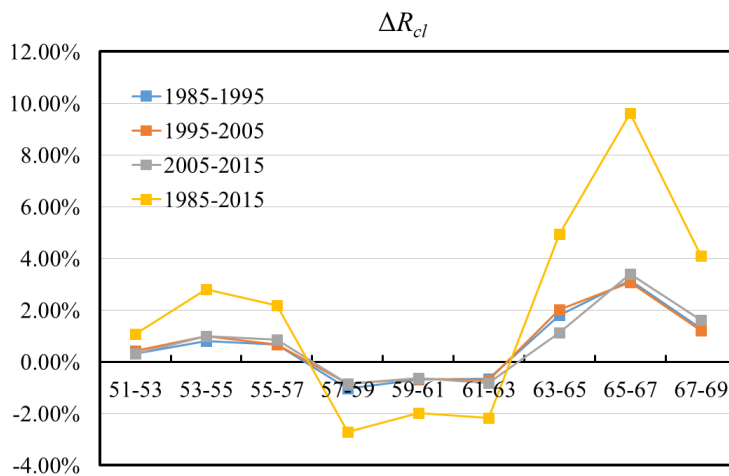
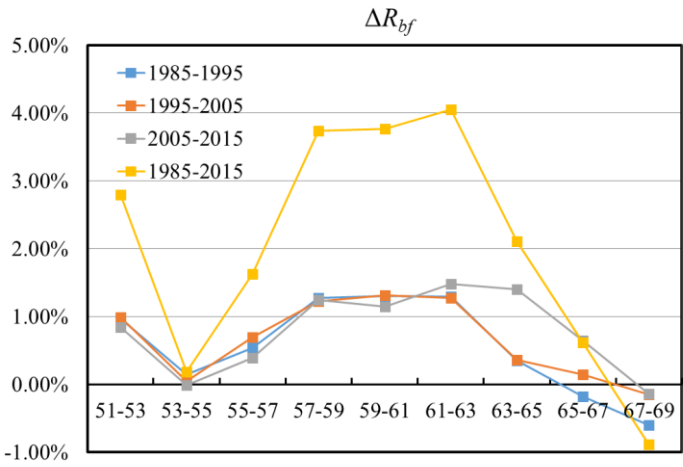
245   not change much over the period studied.

(a)

(b)

(c)

Figure 8. Changes in different forest species in with different latitude zones: (a) ΔR_{bl}, (b) ΔR_{cl} and (c) ΔR_{bf}.

4.3 Analysis of the influences of climate factors on changes in the boreal forest

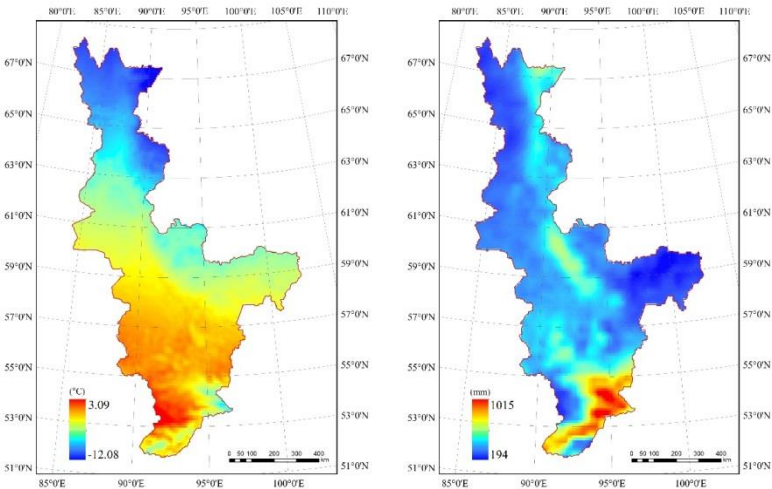
Given that the amount of human activity in the study area is limited, it is reasonable to assume that the changes in the forest are being driven mainly by climate variables. Two climate factors, temperature and precipitation, were analyzed to find which was the main driving factor behind these changes. The raster climate data were clipped and resampled. The average temperature and total precipitation for the year 2000 are shown in Figure 9. It can be seen that, on the whole, both the temperature and precipitation were lower in the high-latitude zone than in the low-latitude zone.

(a)   (b)

Figure 9. (a) Average temperature and (b) total precipitation in the study area for the year 2000.

Considering the delay response of the forest to the climate change, the climate data of the time intervals 5–year, 10–year and 15–year before the forest change were chosen for the influence analysis respectively, to determine which the driving interval was. The climate variables used in this study included the average annual temperature (TEM_Year), the growing season

265   temperature (TEM_Grow: the average temperature during the growing season (June to September)), the average maximum temperature during the growing season (TEM_Growmax), the average minimum temperature during the growing season (TEM_Growmin), the total annual precipitation (PRE_Year) and the total precipitation during the growing season (PRE_Grow), which have also been used in some previous researches (Hou, et al.,2020, He, et al., 2020). The statistics of climate variables in the study area from 1971 to 2015 are shown in Figure 10.

270   The partial least squares (PLS) regression method was adopted for analyzing the effect of the climate factors on forest cover and changes in species. The PLS method is a robust multivariate technique that combines features of principal component analysis and multiple regression (Abdi 2010); this makes it more parsimonious and statistically robust than principal component regression (Smoliak et al., 2015). In addition, the variable importance in projection (VIP) score was used to estimate the importance of each independent variable in the PLS regression – the VIP score represents the statistical contribution of

275   each independent variable to the overall fitted PLS regression model across all latent vectors (Matthes et al., 2015). A higher VIP score for an independent variable indicates that the variable is more important in explaining the volatility of the dependent variable(s), and independent variables with a VIP score greater than 1 are considered significant (Chong et al., 2005). The cross-validated R^2 value, which is the square of the correlation between the actual and predicted values, is often called Q^2 in PLS regression analysis. A PLS component can be kept and is considered statistically significant in the regression model if its

280   Q^2 value is greater than or equal to 0.0975 (Abdi 2010).

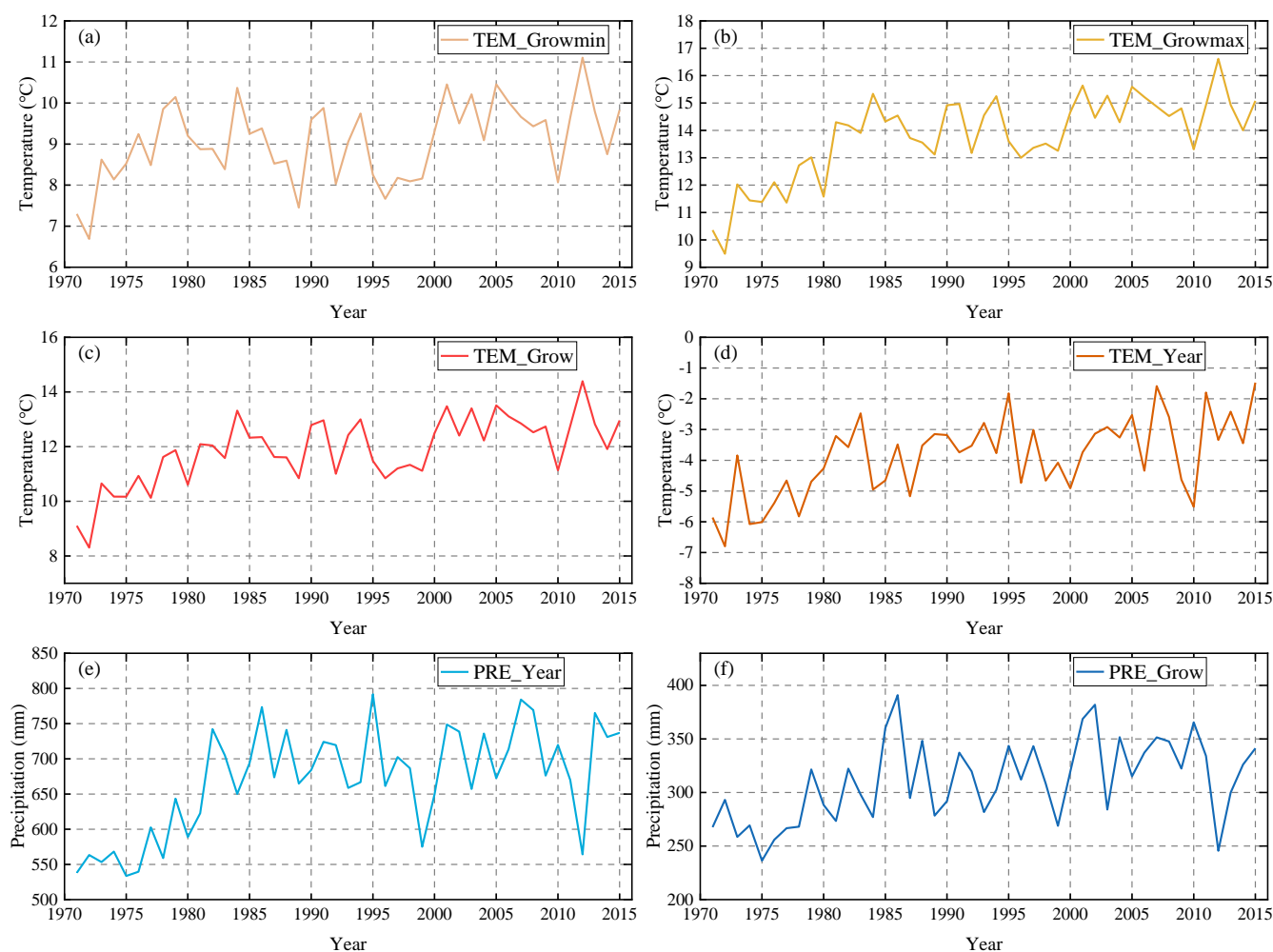



Figure 10. Statistics of temperature and precipitation in study area from 1971 to 2015: (a) average minimum temperature during the growing season, (b) average maximum temperature during the growing season, (c) average temperature during the growing season, (d) average annual temperature, (e) total annual precipitation and (f) total precipitation during the growing season.

285 Using the PLS–VIP method, VIP scores were calculated for use in the interpretation of the contribution of each climate variable to changes in the forest cover and species in the study area. The VIP scores for the six climate variables were ranked in descending order. The independent variable with the highest VIP score was considered to be the most important variable (Hou et al., 2020). To clearly show the effect of each climate variable on the forest cover and species type for each time interval (5 years, 10 years or 15 years), we also calculated the correlation coefficients (Table 5) and Q^2 value for each PLS regression

290 model. The Q^2 values for the effect of the climate variables on the forest cover and species changes in the PLS regression models for the 5–year, 10–year, and 15–year time intervals were 0.22, 0.21, and 0.20, respectively. This indicates that the climate variables for the 5–year intervals were slightly better correlated with the changes in forest cover and species and that

they explain the changes in the boreal forest the best. Therefore, a 5–year time interval was selected for subsequent analysis of the response of the forest to climate change.

295 **Table 5.** The VIP scores of climate variables for different time intervals and their corresponding standardized regression coefficients.

Climate Variables	5–year time interval				10–year time interval				15–year time interval			
	VIP score	Coef_Δ R_{fo}	Coef_Δ R_{fl}	Coef_Δ R_{bl}	VIP score	Coef_Δ R_{fo}	Coef_Δ R_{fl}	Coef_Δ R_{bl}	VIP score	Coef_Δ R_{fo}	Coef_Δ R_{fl}	Coef_Δ R_{bl}
TEM_Year	1.32	-0.19	-0.11	0.16	1.29	-0.19	-0.11	0.15	1.29	-0.17	-0.10	0.15
TEM_Grow	1.29	-0.18	-0.10	0.15	1.29	-0.19	-0.11	0.15	1.25	-0.17	-0.09	0.14
TEM_Growmax	1.06	-0.15	-0.08	0.13	1.12	-0.16	-0.09	0.13	1.20	-0.16	-0.09	0.14
TEM_Growmin	1.16	-0.16	-0.09	0.14	1.14	-0.16	-0.10	0.13	1.08	-0.15	-0.08	0.12
PRE_Year	0.02	0.00	0.00	-0.00	0.03	-0.00	-0.00	0.00	0.05	-0.01	-0.00	0.01
PRE_Grow	0.32	-0.05	-0.03	0.04	0.39	-0.06	-0.03	0.04	0.38	-0.05	-0.03	0.04

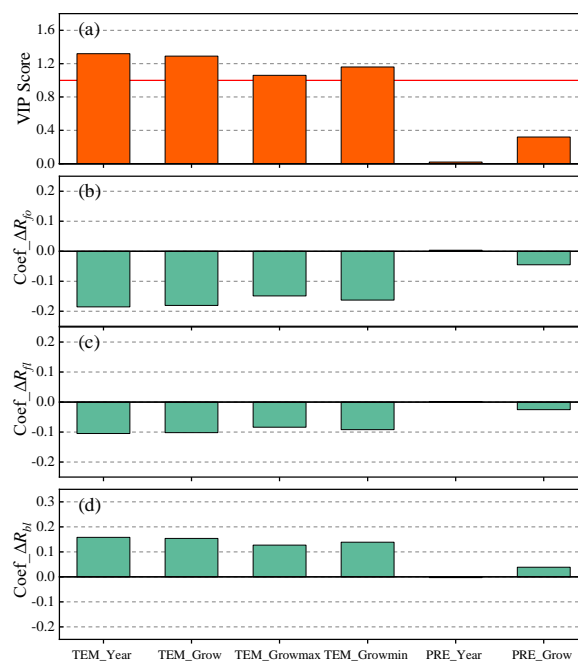



Figure 11. Relationship between the forest cover and species changes and climate variables for 5–year intervals obtained using PLS regression models: (a) VIP scores; (b), (c), (d) show the corresponding standardized regression coefficients.

300 Based on the PLS correlation results, we tried to identify the dominant climate variables causing changes in the boreal forest for 5–year intervals. As illustrated in Figure 11(a), TEM_Year is the most significant variable, followed by TEM_Grow, TEM_Growmax and TEM_Growmin. This indicates that temperature is the main climate factor influencing the boreal forest cover. This result is consistent with previous studies which have demonstrated that temperature is the key factor controlling vegetation growth in most areas of the northern hemisphere (Chen et al.,2018; Menzel et al., 2006; Wang et al., 2011).

305 According to the regression coefficients, ΔR_{fo} and ΔR_{fl} have negative responses to all the temperature variables although the correlation coefficients vary (Figure 11(b) and (c)). In other words, an increase in temperature least to a decrease in the total forest coverage. Unexpectedly, precipitation was not found to be a significant variable in terms of boreal forest change (Figure 11(a)). This may be because increasing temperatures affect the response of vegetation to other climate variables (e.g., precipitation). For example, since the mid-1990s, the absence of summer precipitation associated with rising temperatures has

310 had a negative impact on the greenness of boreal forests in western central Eurasia (Buermann et al., 2014). It may also be the case that forest growth is not affected by the drought stress caused by insufficient precipitation – however, this depends on the ability of the forest to access soil water and local microsite conditions (Nicolai-Shaw et al. 2017).

In addition, it can be seen from Figure 11(d) that ΔR_{bl} responds positively to an increase in temperature, which indicates that broad-leaved forest is sensitive to warming and benefits from higher temperatures. A warming climate provides more favorable

315 conditions for the growth and regeneration of plants that previously experienced harsh conditions, thus allowing broad-leaved forest species to survive in the cold north of the study area where they were previously unable to grow (Hoonyoung Park et al, 2015; Høgda et al., 2013; Salminen and Jalkanen, 2015). This pattern has also been observed in Finland (Kauppi et al., 2014). Moreover, it has been found that the distribution of many forest types is beginning to expand towards the poles, with temperate forests gradually shifting into areas previously covered by boreal forests; the southern parts of these temperature forests will

320 be replaced by subtropical or tropical forests. The northern boundary of temperate forests is also shifting towards the poles (Hirota et al., 2010; Parmesan and Yohe, 2013). Similarly, the effect of precipitation on ΔR_{bl} was found to be insignificant; however, the precipitation variables are not negligible in terms of the response of boreal forests to climate change as this response is a result of the effects of different interrelated climate variables (Hou et al., 2020). Furthermore, warming has a positive effect on ΔR_{bl}, meaning that the observed increase in ΔR_{bl} was caused by a rise in temperatures. The increased area of

325 broad-leaved forest may be due to broad-leaved forest growing in areas that were previously coniferous or not-forest land – further quantitative investigation into the details of these changes is still needed. Finally, it can be seen from Figure 11(c) and (d) that ΔR_{fl} and ΔR_{bl} have opposing responses to the climate factors that were investigated, which means that, where the expansion in the total forest cover is limited, the increase in boreal forest may be mainly due to changes in tree species within the forest (see Figure 6(d) and Figure 7(d)). Several recent studies in Canada have also indicated that the response of forest

330 covers to climate warming varies by tree species (McManus et al., 2012; Weijers et al., 2018).

5. Conclusion

In this study, changes in the area of the Siberian boreal forest and the forest species in Krasnoyarskiy Kray, Russia, were quantified using remote sensing data covering the period 1985 to 2015. The results show that there are significant differences in the changes that were observed across the study area. Overall, the total forest area increased continuously over the three

335 decades of the study, particularly in the high-latitude part of the study area, which indicates that the boreal forest in this region is the most sensitive to climate change. It was also found that the changes in broad-leaved and coniferous forest differ according

to latitude. At the medium-latitude zone between 57°N and 63°N, the rate of increase in the area of broad-leaved forest was faster than that of coniferous forest, which means that there is a trend towards broad-leaved forest replacing coniferous forest as the dominant tree species in the future.

340 Overall, it was found that an increase in temperature tends to inhibit the expansion of the forest; however, an increase can promote the growth of broad-leaved forest. The effect of precipitation on the total forest area and types of forest species present was found to be negligible. In addition, the influence of anthropogenic factors may affect the response of the forest to climate change and, to some degree, reduce the effects of climate change. High spatial resolution data (e.g., WorldView, GF-2 data) have the potential to provide accurate information about vegetation at a fine scale; however, the use of such data may be limited

345 by the low temporal resolution and the extent of cloud cover over Siberia.

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Competing Interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability. All Landsat Thematic Mapper (TM) and Operational Land Imager (OLI) data of the study area openly

355 available from the United States Geological Survey (USGS) (http://glovis.usgs.gov/). The climate datasets ERA5-Land are included in Hersbach et al. (2020), https://doi.org/10.1002/qj.3803. The climate datasets ERA-20CM are included in Hersbach et al. (2015), https://doi.org/10.1002/qj.2528.

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