Response to Anonymous Referee #1 Comments

Dear Editors and Referee:

Thanks for your kind comments concerning our manuscript entitled "Spatiotemporal changes in the boreal forest in Siberia over the period 1985–2015 against the background of climate change". Those comments are all valuable and very helpful for improving our paper, and we have made correction which we hope meet with approval. Revised portion are marked in the manuscript. The main corrections in the paper and the responds to the reviewer's comments are as flowing:

Anonymous Referee #1:

The study is comprehensive with relevant details regarding research focus, methods, results, and concluding remarks presented. However, the background of the research focus could be improved to highlight the novelty of the present study. Some parts of the manuscript need improvements.

Introduction

Line 50: "Therefore, the extent of the boreal forest response to climate change is still not fully understood". The author should point out why? What current research has been done, what are the important methods, and what main conclusions are related to this aspect?

Reply: Thanks for your suggestion. Based on your suggestion, we now added the current status of research on the response of boreal forests to climate change and also pointed out the existing challenges and main conclusions. (Line 52-67)

Over the past 30 years, spring and autumn temperatures over northern latitudes have increased by about 1.1 °C and 0.8 °C, respectively (Mitchell and Jones 2005), and the thermal potential growing season has lengthened by about 10.5 days (Barichivich et al., 2013). Several studies indicate that increasing warming may result in accelerating the northward expansion of boreal forests (Veraverbeke et al., 2017), as well as the observation of a greening trend characterized by a longer growing season and greater photosynthetic activity (Piao et al., 2008). Shuman et al. (2011) showed that climate warming may convert Siberia's deciduous larch (*Larix spp.*) to evergreen conifer forests, and thus decrease regional surface albedo; At the continental scale, when temperature is increased, larch-dominated sites become vulnerable to early replacement by evergreen conifers. Ratcliffe et al. (2017) investigated a forested peatland in western Siberia and showed that climate change has caused the expansion of forested peatlands and increased tree cover. In addition, it is highly probable that the annual mean temperature in Canada's boreal forest region will increase by at least 2°C by 2050 in this century, which may lead to effects on the ecological functioning of the region's boreal forests, such as triggering a process of forest decline and re-establishment lasting several decades, while also releasing significant quantities of greenhouse gases that will amplify the future global warming trend (Price, et al., 2013). In practice, it is a challenge to quantify the 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.

Line 60: I guess there are studies that have used Landsat to quantify the spatiotemporal changes

occurring in the boreal forests in Siberia or other places. It would be nice to see more backgrounds related to this here.
In general, the introduction needs to be improved and the contextual description is weak.
Reply: We have added background to the introduction on the use of Landsat data to quantify spatial and temporal variability in boreal forests and made it more readable. (Line 78-83)

For example, White, et al. (2017) used the extensive Landsat archive to produce annual, gap-free surface reflectance composites for exploring forest disturbance and recovery characteristics in Canadian boreal forests. Sulla-Menashe, et al. (2018) used normalized difference vegetation index (NDVI) time series from Landsat to explore geographic patterns of greening and browning in Canadian boreal forests, and revealed that continued long-term climate change has the potential to significantly alter the character and function of Canadian boreal forests, with greening observed to be most prevalent in eastern Canada and browning to occur primarily in western Canada.

Study area
Adding a layer of DEM and Landsat RGB images for the study area is necessary.
Reply: Thanks. According to your suggestion, we have added DEM and Landsat RGB images layers for the study area, and also added location information for the study area. (Line 104-105)

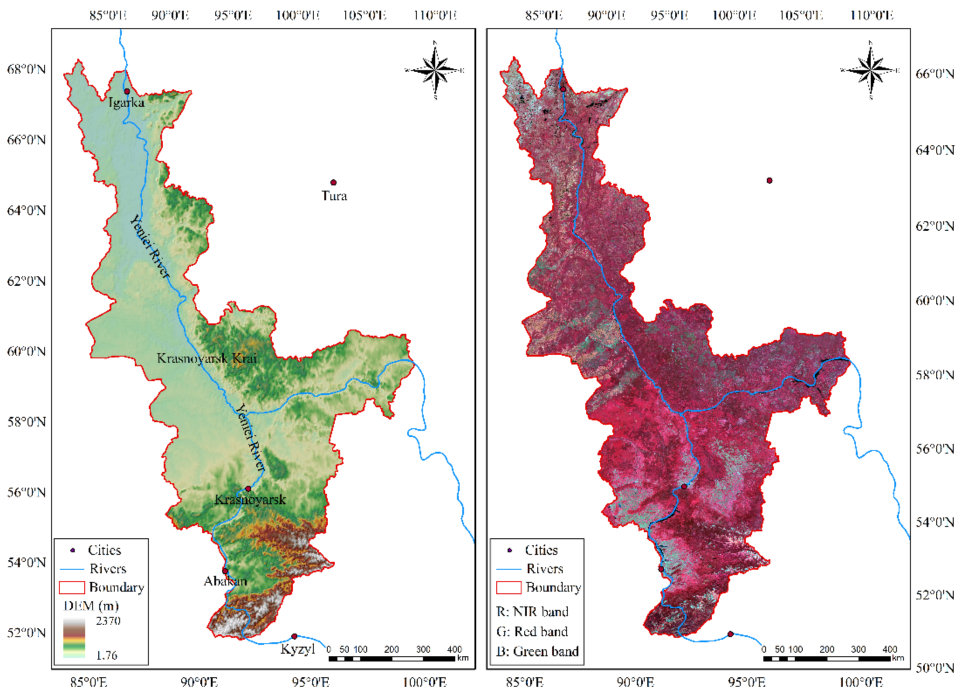

Figure 1. Location of the study area together with the DEM and false-color composite of Landsat 8 images.

Input data

How many tiles of Landsat images could cover the study area?

Reply: About 40 Landsat images are required to cover the study area.

“Mainly in the years 1985, 1995, 2005, and 2015”, Why did you use this ten years interval? Why did you choose level1 data? USGS also provides level-2 datasets that have been atmosphere corrected, which could significantly reduce the workload in data processing. Why are most of the images acquired from June to September, and what about the others? Please specify them!!

Reply: Thanks for this comment. On the one hand, changes in forests, especially in forest types, may require 10 years or even decades to be observed, and on the other hand, limited by Landsat data availability, thus we chose ten years interval data for this study.

Level 1 Tier 1 data with a spatial resolution of 30 m were used in this work. Landsat scenes with the highest available data quality are placed into Tier 1 and are considered suitable for time-series analysis. Tier 1 includes Level-1 Precision and Terrain (L1TP) corrected data that have well-characterized radiometry and are inter-calibrated across the different Landsat instruments. On this basis, we performed a series of pre-processing of the Level 1 Tier 1 data, including radiation correction, atmospheric correction and HOT algorithm to remove cloud noise (Figure 2), to ensure that the processed data could well support the subsequent forest cover and species classification. Therefore, this dataset could well support the monitoring of dynamic changes of boreal forest cover and species in this study. Certainly, we support your point of view that the atmosphere corrected level 2 dataset can significantly reduce the workload in data processing. We would consider using this dataset for the future research.

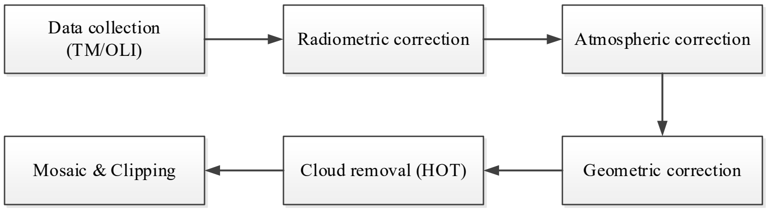

Figure 2. Preprocessing of Landsat Thematic Mapper (TM)/Operational Land Imager (OLI) scenes.

In this work, most of the images were acquired in summer seasons, mainly between June and September. Due to cooler temperatures in the other months of the study area, there may be snowfall or yellowing and shedding of broadleaf forest leaves, etc., which may lead to accuracy of forest cover and species classification. Therefore, the image time was chosen in summer. Several data acquired in October are used to make up the images due to data deficiency in the current years. In fact, there were only 3 scenes in October, and over relatively warm areas. We also checked these images with no snow. The information has been added in this manuscript. (Line 118-120)

Line 102 What is the spatial resolution of ERA5-land?
Reply: The ERA5-land data with a resolution of 0.1° × 0.1°, i.e., native resolution is 9 km.

Data processing
The description of the data processing is very shallow. Given that spatial and temporal change is the key part of this paper, how to proceed with cloud, anomalies, and alignment correction of images is very critical.
Reply: According to your suggestion, we have added a detailed introduction to the pre-processing of Landsat data, including radiometric correction, atmospheric correction, image cloud removal, etc. The information has been added in this manuscript. (Line 129-141)

Forest cover and species classification
Why not use random forest classification directly, but use rule-based classification first, and then random forest? I am very skeptical about the final classification result. Due to the large latitudinal differences in the study area, using NDVI threshold classification may result in some forests being removed incorrectly. In addition, there will be subtle differences in NDVI values over the years. Anyway, the threshold classification method should be used with caution in applying large spatial scales and change detection. How many training samples were used for the classifications? Did you use the same training samples for different years?
Reply: Thanks for your careful suggestion. We used a hierarchical classification method for forest cover and forest species, i.e., we first used decision trees to distinguish between forested and non-forested land, and then used a random forest approach to classify forest species. This can effectively avoid the influence on the final classification results due to same object with different spectrums and same spectrum of different objects (e.g., grassland and cultivated land with very similar spectral profiles to forest).
We agree with you that the NDVI values have subtly varied over the years. We have checked the effect of NDVI thresholds on the classification of forest land and non-forest land, and the results show that the classification of forest land and non-forest land for different years using an NDVI value of 0.62 was satisfactory. Moreover, a total of 2352 training samples were used for model

training in this study. Different years used the training samples of the corresponding (different) years.

Accuracy validation

What about the accuracy for other yearsï¼ Yes, I agree that the collection of validation samples is difficult in earlier years? But you only classify forest and non-forest, the collection of samples directly from Landsat images is also possible in the early years.

Reply: 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. 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.

It is an interesting attempt to collect samples directly from early Landsat images for accuracy validation. We collected 584 sample points from 1985 Landsat images for accuracy validation, and the overall accuracy in 1985 was 89.04%, with F1 scores of 0.87, 0.89 and 0.91 for broadleaf, coniferous and non-forested forests, respectively. Considering the potential uncertainty of the sample collection process, the classification accuracy in 1985 is acceptable.

Results and discussion

Overall, the results and discussion are overloaded with descriptions of the methods and results, but lack analysis of the results. It is not recommended to put the results and discussion together. The discussion needs to be improved. The results need to be better integrated with the context of the study. E.g., what is the significance of your results? Rather than simply describing the results.

Reply: Thanks. According to your suggestions, we have improved the discussion to better integrate it with the context of the study and to highlight the research significance of this work. The information has been added in this manuscript.

All above revisions are highlighted in the manuscript information. We hope you will be satisfied with our changes. Thanks again for your good suggestions.

Specifically,

1. Where can I find the classification accuracy?

Reply: 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. (Line 158-160)

2. Did the authors ever consider the collinearity between climate variables? From Fig 10, the curve of TEM_Growmax is very similar to the curve of TEM_Grow.

Reply: Thanks for your careful suggestion. As you mentioned, the climate variables selected in this study are to some extent interrelated, which may lead to over-fitting of the regression model. Therefore, we chose a partial least squares regression model for assessing the response of forest change to climate variables. The PLS regression method is a robust multivariate technique that combines features of principal component analysis and multiple regression (Abdi, 2010) and is more parsimonious and statistically robust than principal components regression (Smoliak et al., 2015). Moreover, PLS regression can effectively deal with the problem of multicollinearity (Hou et al., 2020). So, PLS regression is particularly suitable for our case. The information has been added in this manuscript. (Line 318-324)

3. From Fig 11, it seems like the relationship between the forest cover and species changes and climate variables was conducted at a regional scale, not a pixel scale. Why?
Reply: The objectives of this work were to quantify the spatiotemporal changes occurring in the boreal forests in Siberia and then to find which climate factor was the main driver of these changes. At the regional scale, the partial least squares regression models successfully presented the response of boreal forest cover and species change to climate variables, and confirm that temperature is the main climatic factor driving the change. The holistic response of boreal forests to climate variables at the regional scale will enable a macroscopic understanding of trends in boreal forests under the context of climate change. Smaller scales, e.g., a pixel scale, the response of boreal forests to climate change needs more of our efforts to be studied.

4. Why did not contain coniferous forests in Fig 11?
Reply: Thanks. We have also conducted relevant studies on coniferous forests. However, the results show that coniferous forests are less sensitive and regular in response to climate change compared with broad-leaved forests. And the purpose of this study is mainly to focus on the changes of broad-leaved forests in Siberia. Therefore, coniferous forests are not included in Figure 11.

5. Where is the Q^2 value for each PLS regression model?
Reply: 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. (Line 342-343)

6. The correlation coefficients in Table 5 are too low to account for the impact of climate on forest cover changes. In the text Line, 289 is correlation coefficients, and the title of Table 5 is standardized regression coefficients, please check regression coefficients and correlation coefficients are not the same thing and should not be used in confusion, this puzzled me.
Reply: We have revised the “regression coefficients” to “standardized regression coefficients” in the paper. (Line 341)

7. It is possible to compare whether the local temperature exceeds the vegetation's optimum growth temperature.
Reply: Thanks for your valuable suggestion. Exploring the dynamics of optimal growth temperature of vegetation under climate change is one of our current ongoing works.
Thanks again for your constructive comments.

Reference

Abdi, H.: Partial least squares regression and projection on latent structure regression (PLS Regression). Wiley Interdiscip. Rev. Comput. Stat., 2(1), 97–106, https://doi.org/10.1002/wics.51, 2010.

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., and Curtis‐McLane, S.: Adaptation, migration or extirpation: climate change outcomes for tree populations. Evol. Appl., 1(1), 95–111, https://doi.org/10.1111/j.1752-4571.2007.00013.x, 2008.

Balshi, M.S., Mcguire, A.D., Duffy, P., Flannigan, M., Kicklighter, D.W., and Melillo, J.: Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. Glob. Change Biol., 15, 1491–510, https://doi.org/10.1111/j.1365-2486.2009.01877.x, 2009.

Barichivich, J., Briffa, K.R., Myneni, R.B., Osborn, T.J., Melvin, T.M., Ciais, P., Piao, S. and Tucker, C.: Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO2 at high northern latitudes from 1950 to 2011. Glob Change Biol., 19, 3167–3183, https://doi.org/10.1111/gcb.12283, 2013.

de Groot, W.J., Flannigan, M.D., and Cantin, A.S.: Climate change impacts on future boreal fire regimes. Forest Ecol. Manage., 294, 35–44, https://doi.org/10.1016/j.foreco.2012.09.027, 2013.

Kasischke, E.S., and Turetsky, M.R.: Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska. Geophys. Res. Lett., 33, L09703, https://doi.org/10.1029/2006GL025677, 2006.

Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., and Ackerly, D.D.: The velocity of climate change. Nature, 462(7276), 1052–1055, https://doi.org/10.1038/nature08649, 2009.

McKenney, D.W., Pedlar, J.H., Lawrence, K., Campbell, K., and Hutchinson, M.F.: Potential impacts of climate change on the distribution of North American trees. BioScience, 57(11), 939–948, https://doi.org/10.1641/B571106, 2007.

McLachlan, J.S., Clark, J.S., and Manos, P.S.: Molecular indicators of tree migration capacity under rapid climate change. Ecology, 86, 2088–2098, https://doi.org/10.1890/04-1036, 2005.

Mitchell, T. D. & Jones, P. D. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol., 25, 693–712, https://doi.org/10.1002/joc.1181, 2005.

Piao, S., Ciais, P., Friedlingstein, P., Peylin P., Reichstein, M., Luyssaert, S., Margolis, H., Fang, J., Barr, A., Chen, A., Grelle, A., Hollinger, D., Laurila, T., Lindroth, A., Richardson, A., and Vesala, T.: Net carbon dioxide losses of northern ecosystems in response to autumn warming. Nature, 451, 49–52, https://doi.org/10.1038/nature06444, 2008.

Price, D.T., Alfaro R.I., Brown, K.J., Flannigan, M.D., Fleming, R.A., Hogg, E.H., Girardin, M.P., LakustaT., JohnstonM., McKenneyD.W., PedlarJ.H., StrattonT., SturrockR.N., ThompsonI.D., Trofymow, J.A., and Venier, L.A.: Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environ. Rev., 21, 322–365, https://doi.org/10.1139/er-2013-0042, 2013.

Ratcliffe, J.L., Creevy, A., Andersen, R., Zarov, E., Gaffney, P.P.J., Taggart, M.A., Mazei, Y., Tsyganov, A.N., Rowson, J.G., Lapshina, E.D., Payne, R.J.: Ecological and environmental transition across the forested-to-open bog ecotone in a west Siberian peatland. Sci. Total Environ., 607, 816–828, https://doi.org/10.1016/j.scitotenv.2017.06.276, 2017.

Shuman, J.K., Shugart, H.H., O'Halloran, T.L.: Sensitivity of Siberian larch forests to climate change. Global Change Biol., 17(7), 2370–2384, https://doi.org/10.1111/j.1365-2486.2011.02417.x, 2011.

Smoliak, B.V., Wallace, J.M., Lin, P., and Fu, Q.: Dynamical adjustment of the northern hemisphere surface air temperature Field: methodology and application to observations. J. Climate, 28, 1613–1629, https://doi.org/10.1175/JCLI-D-14-00111.1, 2015.

Sulla-Menashe, D., Woodcock, C., Friedl, M.: Canadian boreal forest greening and browning trends: an analysis of biogeographic patterns and the relative roles of disturbance versus climate drivers. Environ. Res. Lett, 13, 014007, https://doi.org/10.1088/1748-9326/aa9b8, 2018.

Tian, L. Fu, W.: Bi-Temporal Analysis of Spatial Changes of Boreal Forest Cover and Species in Siberia for the Years 1985 and 2015. Remote Sens., 12, 4116, https://doi.org/10.3390/rs12244116, 2020.

Veraverbeke, S., Rogers, B., Goulden, M., Jandt, R., Miller, C., Wiggins, E., and Randerson, J.: Lightning as a major driver of recent large fire years in North American boreal forests. Nature Clim. Change, 7, 529–534, https://doi.org/10.1038/nclimate3329, 2017.

White, J., Wulder, M., Hermosilla, T., Coops, N., Hobart, G.: A nationwide annual characterization of 25years of forest disturbance and recovery for Canada using Landsat time series, Remote Sens. Environ., 194, 303–321, https://doi.org/10.1016/j.rse.2017.03.035, 2017.

Zhu, K., Woodall, C.W., Ghosh, S., Gelfand, A.E., and Clark, J.S.: Dual impacts of climate change: forest migration and turnover through life history. Global change biolo., 20(1), 251–264, https://doi.org/10.1111/gcb.12382, 2013.