Response to Anonymous Referee #2 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 #2:

The manuscript by Fu et al., entitled "Spatiotemporal changes in the boreal forest in Siberia over the period 1985–2015 against the background of climate change" presents a change analysis in forest cover over a broad area in Central Siberia. The changes in forest are then examined in the context of climate change. The analysis is based on time series of Landsat TM images that are validated with high resolution images from a satellite instrument named Gaofen-2. The specific research questions ask 1) what the extent of change in forest cover and proportions of tree species are, 2) at what latitude forest cover and tree species are most sensitive to climate change, and 3) which climate change factor is the main driver influencing the observed changes. The main findings state that the total forest cover increased over the study period, with coniferous and broadleaved forests showing different patterns of change at different latitudes. The authors identified the forest changes are driven mostly by temperature instead of precipitation.

As the authors state, global change is especially affecting and driving changes in the high latitude boreal forests. These changes are less often studied in boreal forests of northern Eurasia compared to, e.g., North America. Hence, the premise of the study is interesting and the topic merits examination. The study covers a broad area, and the quality of the technical work is very high. However, I do not think that all the conclusions of the study are credible. This concern is especially related to research question three that examines the connection between the climatic variables and forest changes. In my opinion, the changes observed in forest cover and the proportion of deciduous and coniferous forest are too easily attributed to climate change. Furthermore, the role of natural forest dynamics and disturbances is completely disregarded in the manuscript although they could have a strong explanatory power on the observed changes. I think the results need to be interpreted also in this context! I also think that the quality of the study could be increased with a more thorough examination of the used remote sensing data. For example, what is the proportion of non-forest land turning into forest dominated by broadleaved forest during the study period, what influence do major disturbances such as fire have on the results? I think the material used in this study (i.e., Landsat images) would also enable considering the role of forest disturbances. As a second major concern, I think that the text needs a thorough revision to enhance its readability. These and my other concerns are described in more detail below.

Major comments:

1. I am not convinced that the observed increase in the proportion of broadleaved forest is solely driven by changes in temperature – correlation does not necessarily mean causation. The natural

succession of Siberian boreal forests typically follows a pathway where broadleaved trees or *Larix spp.* dominate the early successional stage. In later successional stages the broadleaved trees with short longevity are often replaced by conifers such as *Pinus spp.* and *Picea spp.* if stand-replacing disturbances remain absent. The disturbance regime of the area examined in this study includes both ground and crown fires, the latter occurring especially in young coniferous forests that also have woody debris that acts as a fuel load. According to Kharuk et al. 2021 (https://doi.org/10.1007/s13280-020-01490-x) and fire maps complied by Global Forest Watch, large fires have occurred in the studied area, even during the study period. I would be interested to know what is the role of these disturbances and forest dynamics in, e.g., explaining the observed increases in the proportion of broadleaved trees? Similarly, cessation of anthropogenic land use, such as abandonment of agricultural land and clearcutting without reforesting may start a natural succession and increase the proportion of broadleaved trees (as hinted by the authors at L. 325). I think the role of these processes should be examined prior stating that the observed changes are driven by climate change. Maybe you could use the Landsat images to quantify the rate at which non-forest land converted to broadleaved or conifer forest during the study period, and check whether disturbances could explain some of this conversion (see https://doi.org/10.1016/j.rse.2019.111403)? Forest fire and climate are also interlinked as rising temperatures and potentially declining precipitation may increase the fire prevalence in Siberia. This could also be considered in the paper.

Reply: Thank you for your constructive suggestions. We agree with you that wildfire or natural succession could have an impact on changes in forest cover and forest types. This paper mainly considers the role of human factors and natural factors in the temporal and spatial changes of forests, and we consciously chose regions with less human activities, especially in high latitudes. Forest fire is indeed an important influencing factor of forest change, and we treat it as a natural factor in the research area with less human activities. In a large time space range, forest fire is also closely related to climate change, just as the referee mentioned, so the unsteady impact due to forest fire over a long period of time is also considered as part of the background of climate change in this paper.

We have added a discussion of the effects of wildfire and natural succession on changes in forest cover and forest types. Moreover, the influence of climatic variables on forest fires was also considered.

Line 268-281

There are a variety of evidence points to complex connections (and changes) in the relationship between disturbance regimes and climate change in boreal forest (Kasischke and Turetsky 2006; Balshi et al., 2009; de Groot et al., 2013). In particular, studies have found that warming and drying trends in Canada's boreal regions favor higher frequency of both fire and insect disturbance (Sulla-Menashe, et al., 2018). While in Siberia, Warming has led to an increase in the frequency and area of wildfires that have reached the Arctic Ocean shore, which is the most important factor in taiga dynamics; furthermore, larch and Scots pine have evolved under conditions of periodic forest fires, thereby gaining a competitive advantage over non-fire adapted species (Kharuk et al., 2021), which may affect forest cover and forest type change in the region. It can be seen from Figure 9(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. In general, species will be more resilient at the centers of their present-day distributions, while changes in succession and species composition will be most rapid at the boundaries. Based on current knowledge, the boreal climate zones are expected to shift 5–10 times faster than the speed of natural range expansion achievable by most tree species (McLachlan et al., 2005; McKenney et al., 2007; Aitken et al., 2008; Loarie et al., 2009).

Line 286-293

Previous studies have shown that early northward colonization of tundra ecozones may be dominated by black and white spruces, which are often already established at the treeline. Where soil conditions permit (or where they are improving as a result of warming and drying), air-borne seeds from birch and aspen are likely to arrive and germinate success fully, leading gradually to a forest with significantly greater deciduous content (Price et al., 2013). 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 type did not change much over the period studied. Therefore, the key to the validity of the response of boreal forests to climate change is to determine whether climate warming is driving significant expansion beyond the present-day forest extent, or faster stand growth and replacement (Zhu et al., 2013).

Line 384-389

Additionally, forest fires and climate are interrelated, and increasing temperatures and potential decreases in precipitation possibly increase the frequency of wildfires in Siberia, which will inevitably result in changes in forest cover and forest type dynamics (kuaruk et al., 2021). Most importantly, given the projected rate of climate change in the Siberian boreal forest, continued research is necessary to more fully understand how future changes in temperature and precipitation regimes in the boreal region will affect coupled patterns of forest cover and forest type change in this vulnerable, geographically extensive biome.

2. How were coniferous and broadleaved trees separated in the study? According to the paragraph title this should be explained in the paragraph starting at L. 110, but I do not find the information from therein. According to Hovi et al. 2017 (https://doi.org/10.14214/sf.7753), *Larix spp.* and certain deciduous trees have similar spectral characteristics. Is it possible that certain *Larix spp.* stands were falsely classified as broadleaved trees, influencing the obtained results?

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 coniferous and broadleaved forests. 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., *Larix spp.* and certain deciduous trees have similar spectral characteristics (Hovi et al., 2017)).

Line 158-162

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.

3. I would be interested to know if the observed changes in forest cover are due to forests with open canopy structure becoming denser or conversion of previously non-forested land into forests? These two processes have very different significance for forest dynamics. Including results of this examination in the study would increase its information content and general interest.

Reply: Thanks for your suggestion. The change in forest cover over the study time period was due to the conversion of previously non-forested land to forested land. We carefully checked the classification results for forested and non-forested lands to ensure the reliability of the results (overall accuracy of 90.37%).

Minor comments:

L. 1 (title): In the manuscript text the authors state that the study area ranges from temperate to boreal forests. If that is the case, I suggest rephrasing the title of the study.

Reply: Thanks. According to Brandt (2009), the boreal zone was defined as the broad, circumpolar vegetation zone of high northern latitudes covered principally with forests and other wooded land, includes the temperate zone. Therefore, we contained the temperate zone in the boreal forest in this paper.

L. 10: At a faster rate compared to where?

Reply: Thanks. Climate change has been proven to be an indisputable fact and to be occurring at a faster rate (compared to the other regions of the world) in boreal forest areas. We have revised the relevant expressions. (Line 10-11)

L. 11 – 12: I would argue that there is quite a lot of evidence on how the climate change is changing boreal forests. This view is shared by the authors as the introduction at L. 45 states that "There has been much research on the effect of climate change on boreal forest". I think that in this context there has been limited focus on Central Russian boreal forests. Please rephrase the introduction.

Reply: Thanks for your valuable suggestion. According to your suggestion, we have added research on how the climate change is changing the boreal forests in central Russia.

Line 52-66

Over the past 30 years, spring and autumn temperatures over northern latitudes have increased by about 1.1 ℃ and 0.8 ℃, 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 ℃ 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).

L. 15: At first, I did not know what was meant by the term "forest species", but after reading on I understood that they refer to broadleaved and coniferous forests. I would not call these "forest species" but forest types. I would change "forest species" to "forest type" and explicitly say that by forest type you mean coniferous and broadleaved forests.
Reply: Based on your suggestion, we have revised the term "forest species" to "forest type".

L. 31 – 32: What is "geographical footprint"? Largest area?
Reply: Thanks. The sentence means that the boreal forest biome has one of the largest geographic footprints of any terrestrial biome on the planet (Olson et al. 2001). (Line 31-32)

L. 32: Remove "and encircles the globe at northern latitudes" as circumpolar distribution is already mentioned at L. 30.
Reply: Thanks. We have deleted the sentence.

L. 32 – 35: I find the ending of this sentence paradoxical. It reads that research of range shifts in boreal forests has focused on species-specific responses on temperate tree species (i.e., different biome). Please rephrase what is meant by this.
Reply: Thanks. We have rewritten the sentence that "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 (Zhu et al. 2012)". (Line 32-34)

L. 40 – 41: Could you be a bit more specific – what kind of changes in biodiversity are expected due to climate change?
Reply: Thanks. We have added the corresponding expression.
Changes to biodiversity are one of the expected responses to climate change, for example, some of the most important conifer species in British Columbia are expected to lose a large portion of their suitable habitat (Hamann and Wang, 2006). (Line 39-41)

L. 42 – 44: The message of this sentence is very difficult to understand. Please clarify the point that the sentence tries to make.

Reply: Thanks. We have rewritten the sentence based on your suggestion.
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 shown to be an indirect indicator of biodiversity, correlated with geographic variation in species richness (Coops et al., 2008; Nelson et al., 2014). (Line 42-45)

L. 46 – 47: Could you give an example of the spatiotemporal differences in tree growth in the boreal biome that are caused by climate change?
Reply: Thanks. We have added the corresponding expression.
However, there are clear spatiotemporal differences in these effects (Alibakhshi et al., 2020). For example, Hou et al. (2020) found that vegetation phenology indicators in Finland's boreal forests showed spatiotemporal differences in response to climate variables in different months, i.e., vegetation in different regions showed different patterns of response to climate variables. (Line 48-50)

L. 49: White spruce (Picea glauca) is a species that is native to boreal North America. Changes in growth of white spruce are then hardly relevant in the context of Eurasian boreal forest, right? Could this be replaced with an example from the same study region?
Reply: Thanks for your careful suggestion. This paragraph is to support the statement that "It has been observed that the growth of boreal forest has been influenced by global warming in the past decade or more". Based on your suggestion, we have added the example of larch (*Larix spp.*) in Siberia.
Line 57-59
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.

L. 59 – 61: This statement is not true. See, e.g., https://doi.org/10.1007/s10980-020-00979-w on the use of multispectral aerial photographs for this purpose.
Reply: Thanks for your careful suggestion. We have revised the statement that the Landsat series data are the most widely used multispectral dataset 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). (Line 73-76)

L. 70 – 71: What is meant by "from the temperature to the frigid zones"?
Reply: Thanks. This word "temperature" is a misnomer, we revised "temperature" to "temperate". In addition, Brandt (2009) defined the boreal zone as the broad, circumpolar vegetation zone of high northern latitudes covered principally with forests and other wooded land, includes the temperate zone. The study area of this work, Krasnoyarskiy Kray, encompasses the temperate to frigid zones.

L. 83 (Fig. 1): An inset map would be helpful in locating the study region.
Reply: According to your suggestion, we revised Figure 1 to locate the study area.

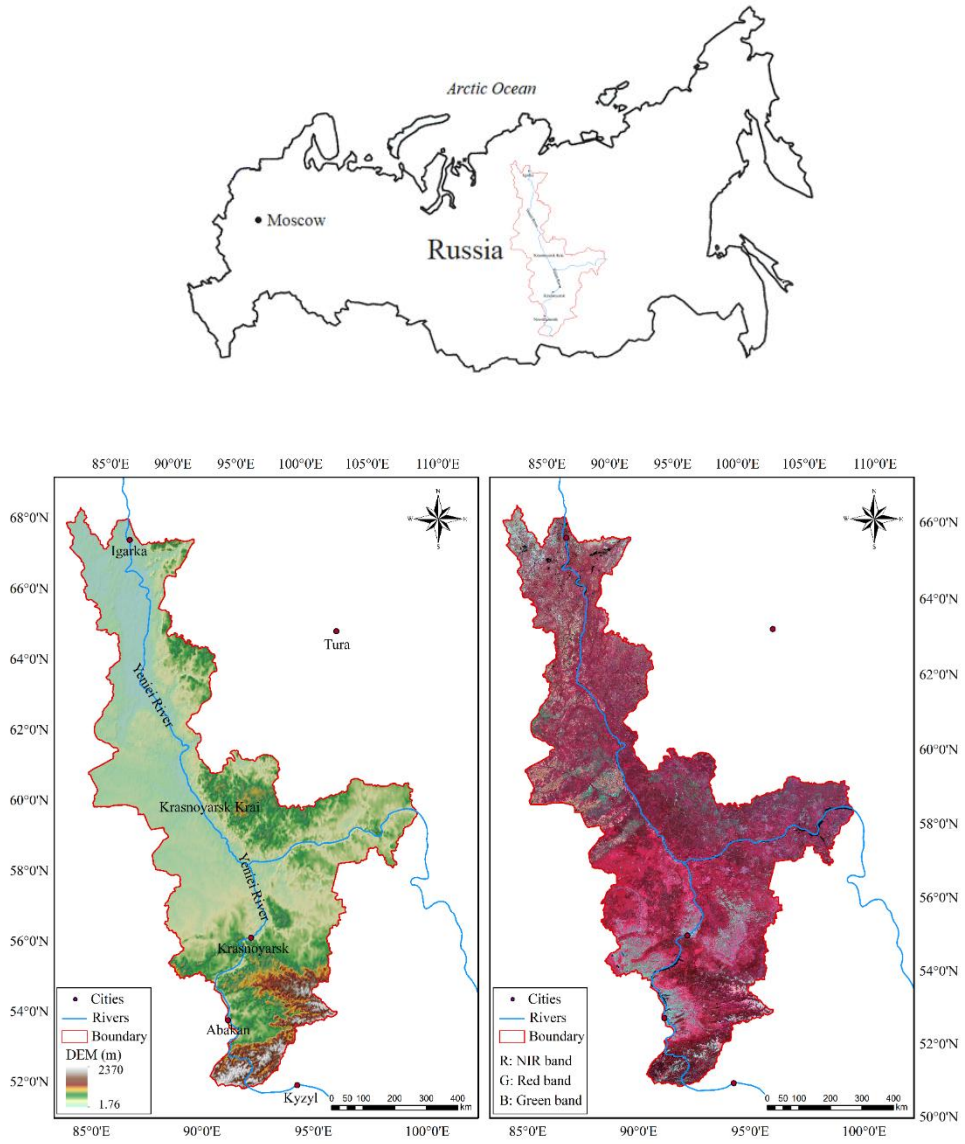

Figure 1. Location of the study area together with the DEM and false-color composite of Landsat 8 images.

L. 111 – 118: Why is discriminating forested/vegetated areas from non-vegetated areas presented twice in these paragraphs?

Reply: Thanks for your careful suggestion. We have revised the paragraph to correctly express that "Finally, a random forest (RF) algorithm was used to discriminate coniferous and broadleaved forests 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)". (Line 150-152)

L. 126: Did you visually classify the sampling points based on GF-2 images?

Reply: Yes. 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).

L. 153 – 154: That the forest cover has not changed much over the study period does not mean that the forests are not significantly affected by climate change but that the influence does not

manifest as changes in forest cover. Please rephrase.

Reply: Thanks. We have rewritten the sentence that "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 cover of boreal forest in this zone has not been significantly affected by climate change".

L. 157 – 158: Similar to the previous comment, from the fact that the strongest change in forest cover was observed in the northernmost zone it does not follow that the forests in these areas were mostly affected by climate change (see also my comment on forest dynamics). Rephrase "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" for example to "The fastest change was observed in the northernmost zone (63 °N–69 °N) that is also the zone where the climate warming is also projected to be the highest".

Reply: Thanks. According to your suggestion, we have rewritten the sentence that "The fastest change was observed in the northernmost zone (63 °N–69 °N) that is also the zone where the climate warming is also projected to be the highest".

L. 187: Change to "not found north of the latitude 67°N in the studied region.

Reply: Thanks. we have rewritten the sentence that "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 in the studied region".

L. 202: Change "increase" to "change" as the forest cover may also decrease, right?

Reply: Yes. Based on your suggestion, we have revised the word "increase" to "change".

L. 217 – 219: As I have stated in my previous comments, the fact that the coverage of broadleaved forests has increased in the study region is not necessarily only due to climate change. Please revise.

Reply: Thanks. We have rewritten the sentence that "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 may have promoted the growth of broad-leaved species across the study area during the three decades of the study".

L. 228 – 229: Also, other drivers than climate change may explain the decrease in the cover of coniferous forest. Please revise.

Reply: Thanks. We have rewritten the sentence that "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 may have had a negative impact on coniferous forest growth in this zone".

L. 254 – 255: See the previous two comments.

Reply: Thanks. We have rewritten the sentence that "Given that the amount of human activity in the study area is limited, it is reasonable to assume that the changes in the forest may be driven

mainly by climate variables".

L. 318 – 320: For me it is uncertain if the author suggest that the results indicate a northwards shift in the range of temperate biome. Such range shifts occur during longer time scales than those considered in this study. Please clarify what is meant by this sentence.
Reply: Thanks. This sentence is to support the statement that "In addition, it can be seen from Figure 12(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", not to suggest that "the northwards shift in the range of temperate biome".

L. 319: Replace "temperature" with "temperate".
Reply: Based on your suggestion, we have revised the word "temperature" to "temperate".

L. 320: Are you suggesting that the southernmost forests of the study region are transforming into subtropical or tropical forests? Please rephrase.
Reply: Thanks. We have rewritten the sentence that "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 temperate forests will 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, 2003)".

L. 324: Also other drivers than climate change may explain the identified patterns.
Reply: Thanks. We have rewritten the sentence that "Furthermore, warming has a positive effect on ΔR_{bl}, meaning that the observed increase in ΔR_{bl} was may be caused by a rise in temperatures".

L. 333 – 334: The term "significant difference" refers to differences that are statistically significant. However, the significance of the changes in forest cover was not statistically tested in the study. Please rephrase.
Reply: Thanks for your careful suggestion. we have rewritten the sentence that "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 differences in the changes that were observed across the study area".

L. 335 – 336: That the forest cover changed increased the most in the northernmost latitudes does not automatically mean that this region is the most sensitive to climate change. Instead, these forest might be – for example – recovering from a major disturbance. Please revise.
Reply: We have rewritten the sentence that "Overall, the total forest area increased continuously over the three decades of the study, particularly in the high-latitude part of the study area, which may indicate that the boreal forest in this region is the most sensitive to climate change".

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

References

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.

Alibakhshi, S., Naimi, B., Hovi, A., Crowther, T.W., and Rautiainen, M.: Quantitative analysis of the links between forest structure and land surface albedo on a global scale. Remote Sens. Environ., 246, 1–12, https://doi.org/10.1016/j.rse.2020.111854, 2020.

Assiri, A.: Anomaly classification using genetic algorithm-based random forest model for network attack detection. Comput. Mater. Contin., 66, 769–778, https://doi.org/10.32604/cmc.2020.013813, 2021.

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.

Brandt J.P.: The extent of the North American boreal zone. Environ. Rev., 17, 101–161, https://doi.org/10.1139/A09-004, 2009.

Breiman, L.: Random forests. Mach. Learn., 45, 5–32, https://doi.org/10.1016/j.rse.2020.11185410.1023/A:1010933404324, 2001.

Climent, F., Momparler, A., and Carmona, P.: Anticipating bank distress in the Eurozone: An Extreme Gradient Boosting approach. J. Bus. Res., 101, 885–896, https://doi.org/10.1016/j.jbusres.2018.11.015, 2019.

Cutler, D.R., Edwards, J.T.C., Beard, K.H., Cutler, A., Hess, K.T., Gibson, J., and Lawler, J.J.: Random forest for classification in ecology. Ecology, 88, 2783–2792, https://doi.org/10.1890/07–0539.1, 2008.

Coops, N.C., Wulder, M.A., Duro, D., Han, T., and Berry, S.: The development of a Canadian dynamic habitat index using multi-temporal satellite estimates of canopy light absorbance. Ecol. Indic., 8, 754–766, https://doi.org/10.1016/j.ecolind.2008.01.007, 2008.

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.

Gong, P., Wang, J., Yu, L., Zhao, Y.C., Zhao, Y.Y., Liang, L., Niu, Z.G., Huang, X.M., Fu, H.H., and Liu, S.: Fine resolution observation and monitoring of global land cover: First mapping results with Landsat TM and ETM+ data. Int. J. Remote Sens., 34, 2607–2654, https://doi.org/10.1080/01431161.2012.748992, 2013.

Hadi, Korhonen, L., Hovi, A., Rönnholm, P., and Rautiainen,M.: The accuracy of large-area forest canopy cover estimation using Landsat in boreal region. Int. J. Appl. Earth Obs., 53, 118–127, https://doi.org/10.1016/j.jag.2016.08.009, 2016.

Hamann, A., and Wang, T.: Potential effects of climate change on ecosystem and tree species distribution in British Columbia. Ecology, 87, 2773–2786, https://doi.org/10.1890/0012-9658(2006)87[2773:PEOCCO]2.0.CO;2, 2006.

Harsch, M.A., Hulme, P.E., McGlone, M.S., and Duncan, R.P.: Are treelines advancing? A global meta-analysis of treeline response to climate warming. Ecol. Lett., 12, 1040–1049, https://doi.org/10.1111/j.1461-0248.2009.01355.x, 2009.

Hermosilla, T., Wulder, M.A., White, J.C., and Coops, N.C.: Prevalence of multiple forest disturbances and impact on vegetation regrowth from interannual Landsat time series (1985–2015). Remote Sens. Environ., 223, 111403, https://doi.org/10.1016/j.rse.2019.111403, 2019.

Hermosilla, T., Wulder, M.A., White, J.C., Coops, N.C.: Prevalence of multiple forest disturbances and impact on vegetation regrowth from interannual Landsat time series (1985–2015). Remote Sens. Environ., 233, 111403, https://doi.org/10.1016/j.rse.2019.111403, 2019.

Hirota, M., Nobre, C., Oyama, M.D., and Bustamante, M.M.: The climatic sensitivity of the forest, savanna and forest-savanna transition in tropical south america. New Phytologist, 187, 707–719, https://doi.org/10.2307/40792416, 2010.

Hou, M., Venäläinen, A.K., Wang, L., Pirinen I P., Gao, Y., Jin, S., Zhu, Y., Qin, F., and Hu, Y.: Spatio-temporal divergence in the responses of Finland's boreal forests to climate variables. Int. J. Appl. Earth Obs. Geoinformation, 92, 102186, https://doi.org/10.1016/j.jag.2020.102186, 2020.

Hovi A., Raitio P., Rautiainen M.: A spectral analysis of 25 boreal tree species. Silva Fenn., 51, 7753, https://doi.org/10.14214/sf.7753, 2017.

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.

Kharuk, V.I., Ponomarev E.I., Ivanova, G.A., Dvinskaya, M.L., Coogan, S.C.P., Flannigan, M.D.: Wildfires in the Siberian taiga. Ambio, 50, 1953–1974, https://doi.org/10.1007/s13280-020-01490-x, 2021.

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.

Matasci, G., Hermosill, T., Wulder, M.A., White, J.C., Coops, N.C., Hobart, G.W., and Zald, H.S.J.: Large-area mapping of Canadian boreal forest cover, height, biomass and other structural attributes using Landsat composites and lidar plots. Remote Sens. Environ., 209, 90–106, https://doi.org/10.1016/j.rse.2017.12.020, 2018.

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.

Nelson, T.A., Coops, N.C., Wulder, M.A., Perez, L., Fitterer, J., Powers, R., and Fontana, F.: Predicting climate change impacts to the Canadian boreal forest. Diversity, 6, 133–157, https://doi.org/10.3390/d6010133, 2014.

Olson D.M., Dinerstein E., Wikramanayake E.D., Burgess N.D., Powell G.V.N., and Underwood E.C.: Terrestrial ecoregions of the world: a new map of life on Earth. BioScience, 51, 933–

938, https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2, 2001.

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., Fleming, R.A., Hogg, E.H., Girardin, M.P., Lakusta, T., Johnston, M., McKenney, D., Pedlar, J.H., Stratton, T., Sturrock, R.N., Thompson, I.D., Trofymow, J.A., and Venier, L.: Anticipating the consequences of climate change for Cananda's boreal forest ecosystems. Environ. Rev., 21, 322–365, https://doi.org/10.1139/er-2013-0042, 2013.

Price, D.T., Alfaro, R.I., Brown, K.J., Flannigan, M., Fleming, R.A., Hogg, E.H., Girardin, M.P., Lakusta, T., Johnston, M., McKenney, D., Pedlar, J.H., Stratton, T., Sturrock, R.N., Thompson, I.D., Trofymow, J.A., and Venier, L.: Anticipating the consequences of climate change for Cananda'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.

Rodriguez-Galiano, V.F., Ghimire, B., Rogan, J., Chica-Olmo, M., and Rigol-Sanchez, J.P.: An assessment of the effectiveness of a random forest classifier for land-cover classification. ISPRS J. Photogramm. Remote Sens., 67, 93–104, https://doi.org/10.1016/j.isprsjprs.2011.11.002, 2012.

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.

Strobl, C., Boulesteix, AL., Zeileis, A., and Hothorn, T.: Bias in random forest variable importance measures: Illustrations, sources and a solution. BMC Bioinform., 8, 25, https://doi.org/10.1186/1471-2105-8-25, 2007.

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.

Svetnik, V., Liaw, A., Tong, C., Culberson, J.C., Sheridan, R.P., and Feuston, B.P.: Random forest: A classification and regression tool for compound classification and QSAR modeling. J. Chem. Inf. Comput. Sci., 43, 1974–1958, https://doi.org/10.1021/ci034160g, 2003.

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.

Zhu, K., Woodall, C.W., and Clark, J.S., 2012: Failure to migrate: lack of tree range expansion in response to climate change. Glob. Change Biol., 18, 1042–1052, https://doi.org/10.1111/j.1365-2486.2011.02571.x, 2012.

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 Biol., 20(1), 251–264,

https://doi.org/10.1111/gcb.12382, 2013.