Referee's comments in black
Authors' responses in blue

Responses to Michael Klinge (Referee 2)

General comments

In this work the authors present their results of bio-ecological investigation on tundra shrubs. They used an experimental setup for examining the change of physiological plant conditions induced by actual climate change. The basic assumption was that climate warming leads to enhanced permafrost thaw, which simultaneously will add nutrients to the system. Leaf and stem traits of four different shrubs species were statistically analysed. The manuscript is generally well structured, clearly written and substantially justified by literature. The results about the potential adjustments of plant growing strategies contribute new insights for future environmental development in the subarctic region.

We thank Michael Klinge for his time to review our manuscript and for providing constructive and relevant comments, which will improve our manuscript.

Specific comments

There are two general obstacles in the experiment setup, which I propose to consider more for discussion and conclusion: A main result of the experiment was that no significant response of plant traits was found due to permafrost thaw, whereas significant plant-trait response to fertilization was proofed. The general assumption was that the nutrient supply will increase caused by enhanced mineralization and thawed soil due to climate warming. This means that solely the soil heating would already lead to an increase of nutrient supply during the experiment. I am wondering, why an effect of increased nutrient supply is not observed in the data for the solely heating part of the experiment. Parallel soil analyses would have underlined the presumed causal chains.

We agree on the expected increase of nutrient supply in heating plots through two potential mechanisms, namely enhanced mineralization (if soil temperature increases) and thawed soil material containing nutrients. Parallel soil analyses have been performed and are reported in Wang *et al.*, 2017 (supplementary material). These analyses based on buried resin bags showed no increase of exchangeable nutrients in the non-fertilized unheated and heated plots for nitrogen and phosphorus. In the fertilized plots an increase in the top soil (5cm) was found for nitrogen (4x) and phosphorus (5x), and only slightly (but significantly) increased at a depth of 25 cm for nitrogen, but not for phosphorus. Increasing the energy input into the soil might result in a very low increase of temperature under humid conditions (i.e. high soil thermal conductivity) close to the permafrost table, where the cables were buried, as the energy might be partitioned towards the thawing process, and not towards heating the soil. Hence, the increase in mineralization rate might be rather limited in the plots with heated cables due to limited increase in temperature.

We will add a corresponding short section to the discussion, as suggested by the reviewer.

Wang, P., Limpens, J., Mommer, l., van Ruijven, J., Nauta, A.L., Berendse, F., Schaepman-Strub, G., Blok, D., Maximov, T.C., Heijmans, M.M.P.D. (2017). Above and belowground responses of four tundra plant functional types to deep soil heating and surface soil fertilization. *Journal of Ecology*, 105, 164−175.

The fertilization part of the experiment represents an extraordinary nutrient input into the system, which are marginal under natural conditions, when a slight input of nitrified dust from anthropogenic sources, desiccated lakes and desertificated landscapes is taken into account. The heating cables are buried in a depth of 15 cm. This brings along a systematic problem for the study design when compared to expected environmental changes under natural conditions. Climate warming controls soil temperatures along air temperatures. Thus, soil heating begins at the top surface and temperature changes move downward with decreasing amplitude. The high content of organic material in subarctic topsoil has a specific influence on the thermal conductivity into the subsoil. During summer, it may have an isolating effect, when it becomes dried-up; during winter, the thermal conductivity increases caused by soil moisture content.

The fertilization indeed represents a large nutrient input into the ecosystem, much larger than the atmospheric nutrient input. The goal of adding fertilizer was to mimic future increased nutrient availability in the soil resulting from increased mineralization of nutrients in the soil organic layer in future warmer soils. The nutrient input is perhaps extraordinary compared to the atmospheric input, which is extremely low in the Arctic, but less so compared to soil nutrient availability and other fertilization experiments in Arctic tundra.

The fertilizer was added in the form of slow-release tablets. As the release rate depends on soil temperature, which is low at our study site, we applied a rather high dose. This dose should be seen as the maximum, probably not all of the nutrients have been released. When we performed measurements in the plots two years after application, we found some intact tablets in dry moss, indicating not all of the nutrients added had become available.

As stated by the reviewer, soil moisture conditions along the vertical profile will impact the energy partitioning within the soil towards heating and permafrost thawing. As mentioned above, the aim of this experiment was to simulate permafrost thaw and not soil warming. As stated in Wang *et al.,* 2017, 'The deep soil heating treatment increased June–July thawing depth without increasing soil temperatures in the upper organic soil layer, for the first time enabling us to separate the effects of increased thawing depth from the effects of surface soil environmental changes in the tundra.'

We will add a section in the introduction to make this more explicit.

Wang, P., Limpens, J., Mommer, I., van Ruijven, J., Nauta, A.L., Berendse, F., Schaepman-Strub, G., Blok, D., Maximov, T.C., Heijmans, M.M.P.D. (2017). Above and belowground responses of four tundra plant functional types to deep soil heating and surface soil fertilization. *Journal of Ecology*, 105, 164−175.

Technical corrections

L25: Here you are talking of "all four species" but until now you didn't introduce them in the abstract.

We will add this information to L21: "…in four shrub species (*Betula nana, Salix pulchra, Ledum palustre, Vaccinium vitis-idaea)*, which were sampled in the experimental plots".

L59: Please give detailed information about the distinct methods used in "several experiments and satellite imagery"

We will add more information about the distinct methods used in "several experiments and satellite imagery".

"Several warming experiments (Elmendorf *et al.*, 2012), satellite imagery − i.e. AVHRR, MODIS and Landsat multi-decadal records of the normalized difference vegetation index (NDVI) (Myers-Smith et al., 2011) − and repeat multi-decadal aerial photography (Tape *et al.*, 2012) have shown effects of recent climate warming on tundra vegetation growth, productivity and distribution, especially on shrubs (Myers-Smith *et al.,* 2015; Myers-Smith & Hik, 2018)".

Elmendorf, S.C., Henry, G.H.R., Hollister, R.D., Björk, R.G., Bjorkman, A.D., Callaghan, T.V., …, Wookey, P.A. (2012). Global assessment of experimental climate warming on tundra vegetation: heterogeneity over space and time. *Ecology Letters*, 15, 164−175.

Myers-Smith, I.H., Elmendorf, S.C., Beck, P.S.A., Wilmking, M., Hallinger, M., Blok, D., …, Vellend, M. (2015). Climate sensitivity of shrub growth across the tundra biome. *Nature Climate Change*, 5, 887−891.

Myers-Smith, I.H., Forbes, B.C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., …, Hik, D.S. (2011). Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental Research Letters*, 6, 045509 (15 pp).

Myers-Smith, I.H. and Hik, D.S. (2018). Climate warming as a driver of tundra shrubline advance. *Journal of Ecology*, 106, 887−891.

Tape, K.D., Hallinger, M., Welker, J.M., Ruess, R.W. (2012). Landscape heterogeneity of shrub expansion in Arctic Alaska, *Ecosystems,* 15, 711−724.

L120: When did you select and cut the individuals? I think after 4 years at the end of the experiment. This should be mentioned here. In addition: Why not selecting the individuals already in the beginning of the experiment; to measure some initial parameters such as plant height and LA? Then you would be able to document relative changes for individuals over the period?

Yes, the individuals were selected and sampled at the end of the experiment (year 4 of the experiment (2014)). We will add a sentence with this information to subsection “2.4 Study species and sampling”.

The aim of this study was to test treatment effects on plant traits by comparing treatment plots with control plots after 4 years of experiment and not to document relative changes for individuals over the experimental period. Because of this reason, we did not select individuals nor measured individual traits, such as height and LA, at the beginning of the experiment. Furthermore, we focused on assessing treatment effects on groups of traits, instead of on individual traits, to identify changes in shrub strategies. Changes on the selected strategies might provide insight on shrub community shifts in Arctic tundra under future climatic conditions expected for the Arctic, such as rising temperature and increasing permafrost thaw (IPCC 2013, Turetsky *et al.* 2020, Voigt *et al., 2017*).

IPCC: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex, and PM Midgley), Cambridge, United Kingdom and New York, NY, USA.

Turetsky, M.R., Abbot, B.W., Jones, M.C., Anthony, K.W., Olefeldt, D., Schuur, E.A.G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D.M., Gibson, C., Sannel, A.B.K., McGuire, A.D. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*, 13, 138 −143.

Voigt, C., Marushchak, M.E., Lamprecht, R.E., Jackowicz-Korczyński, Lingren, A., Mastepanov, M., Granlund, L., Cristensen, T.R., Tahvanainen, T., Martikainen, P.J., Biasi, C. (2017). Increased nitrous oxide from Arctic peatlands after permafrost thaw. *PNAS*, 114 (24), 6238−6243.

L135: Space between 1 and cm2

OK.