Authors response to reviewer comments
Title: Arctic aquatic graminoid tundra responses to nutrient availability
Author(s): Christian G. Andresen and Vanessa L. Lougheed
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Dear Reviewer,
First and foremost, the authors will like to thank you for taking the time to review in detail the manuscript and provide thoughtful and in-depth comments that made the manuscript stronger. Below, we addressed every point with a comment and the corresponding change to the manuscript text.

General Comments from Reviewer:
Andresen and Lougheed present a well-written, interesting study on the natural responses of an aquatic plant nutrients along environmental nutrient gradient, as determined through biogeochemical methods and remote sensing-derived productivities proxies. A main strong point of this study is that it investigates the nutrient status along a terrestrial-aquatic interface, which is understudied. The main comments I have are around clarification around methodological reasoning as well as the framing of the discussion. Overall, I think this paper would be of interest to the Biogeosciences audience and adds some understanding to the role of nutrient availability in tundra plants and how these can be assessed using remote sensing (spectral signatures).

Specific Comments from Reviewer- (Author's answers in Blue)

Abstract
Line 21-22: Add the r^2 value to indicate strength of relationship
We added the R^2 values to the abstract:
"..we identified soil phosphorus as the main limiting nutrient factor given that it was the principal driver of biomass (R^2=0.34, p=0.002) and Normalize Difference Vegetation Index (NDVI) (R^2=0.47, p=0.002) in both species."
Line 25: I would suggest taking out energy balance, as that goes beyond the scope of this paper
We deleted "energy" from sentence to read: "…mobilization between terrestrial-aquatic systems and their potential influence on productivity and land-atmosphere carbon balance."

Introduction
Line 37: Also López-Blanco et al. (2020), Multi-year data-model evaluation reveals the importance of nutrient availability over climate in arctic ecosystem C dynamics, ERL 15:094007.
Added suggested citation
Line 37-39: The first half of this sentence makes the previous sentence a bit redundant; I would add something about nutrient availability being the main driver of increased tundra productivity in this sentence and remove the previous one.
Modified the sentence to read: "Increased tundra productivity has generally been explained by ~~warming-mediated processes including~~ increases in nutrient availability through soil warming, heterotrophic decomposition, and nutrient release from mineralization of organic matter and permafrost thaw."
Line 43: I would suggest removing the reference to energy budgets and Swann et al. (2010), as that reference is largely referring to Arctic boreal shifts to deciduous cover. Here we are dealing with bare (tundra) surfaces.
Text changed as suggested
Line 49-50: The latter half of this sentence (specifically "plant accumulated nutrients") is unclear.
Modified text to "aboveground plant nutrients"

Line 57-68: This paragraph belongs later in the introduction and could be shortened and incorporated into the concluding paragraph of the introduction.
The authors moved this paragraph to later in the intro as suggested, after remote sensing paragraph and before the concluding paragraph in the intro.

Methods
Line 118-119: The authors describe four categories of sites, however Figure 1 is labelled as though there are 5 categories of sites. Consider relabelling the detailed maps using letters rather than numbers.
Changed to letters as suggested.
Line 155: I would specific that this is Total nitrogen, as opposed to just nitrate from the soil samples.
Added "Total" to sentence for clarity.

Line 164-165: Consider including the analysis method used for macronutrients. Also, what is the reasoning for selecting nitrate specifically rather also investigating total N, ammonium, and/or the organic pool? And the rationale for selecting total P rather than phosphate (as you selected the anionic form of N)?
Soil analyses only included nitrate and not TN or ammonium due to lab logistical reasons.
We clarify this in the text by adding: "(For logistical reasons, only P, K, and Nitrate were analyze)"
Line 169: Is the aboveground plant biomass harvested here separate from the 10-15 plants collected for nutrient analysis?
Yes, plants for nutrient analysis were collected outside the biomass plots. No concerns emerged given that plants and densities were similar within each site.

Line 170: Include a description of the sky/solar conditions and time of day around the time of measurements
We added the following sentence to clarify sampling: "reflectance measurements were collected during clear sky conditions between 12 and 4 pm for maximum solar zenith angle in early August"

Line 170-171: What were water table conditions like at locations of reflectance measurements? How were measurements taken to ensure that they were representative of the aquatic emergent tundra without inference of water reflectance?
That's a good point that needs clarification in the methods. We clarified this by adding:
"*Following Andresen et al (2018), reflectance measurements were collected during sunny conditions between 12 and 4 pm for maximum solar elevation angles (29^0-33^0, ~2pm is highest https://www.esrl.noaa.gov/) and to best match satellite observations. The person doing the collection was standing in the opposite direction of the solar azimuth angle to avoid any effects of shading by the instrument or person. All plots for both aquatic species were inundated at time of sampling (including soil, plant and spectral samples) with a water depth (±SD) of 25.2 ± 4.6 for A. fulva and 10.3 ± 3.22 cm for C. aquatilis. Solar specular reflection of water on aquatic emergent plant spectral measurements was insignificant given that solar elevation angles are relatively low in the Arctic (~33^0, peak season) and solar specular reflection was outside of the ~1 m spectral footprint of the measured plot.*"

Line 175-183: This section is almost identical to text of another manuscript published by the authors in Andresen et al. (2018) and needs to be rewrite
We modified the text to now read:
"The reflectance ratio was estimated between plot radiance at nadir and the calibration standard radiance. White calibration standard (38 mm wide) was positioned 30 mm at nadir below the field

spectrometer optic fiber (field of view of 25°) at each calibration, then capped closed to minimize degradation. NDVI measurements from 5 scans were averaged in each plot, and 4–6 plots per pond for comparison with leaf nutrients. Normalized Difference Vegetation Index (NDVI) was estimated from reflectance ratio values using the formula: NDVI = (800 nm− 680 nm) / (800 nm+ 680 nm). NDVI is a standard proxy of plant productivity and biomass in the Arctic and has been used to track plot (Andresen et al., 2018; Gamon et al., 2013; Soudani et al., 2012) to regional and global seasonal and decade time-scale productivity trends (Bhatt et al., 2010; Walker et al., 2012b; Zeng and Jia, 2013)."

Original text:
"Target radiance was cross-calibrated at every pond site using a certified 99% reflective white spectralon calibration standard (WS-1, Labsphere), which allowed for the estimation of the reflectance ratio between plot radiance and the calibration standard radiance. Reflectance ratio measurements were acquired with a circular footprint of ~1 m diameter at a nadir angle from terrain. We averaged NDVI measurements from 5 scans in each plot, and 4–6 plots per pond for comparison with leaf nutrients. Normalized Difference Vegetation Index (NDVI) was estimated from reflectance ratio values in the red and infrared wavelengths using the formula: NDVI = (800 nm− 680 nm) / (800 nm+ 680 nm). NDVI has become a standard proxy of plant productivity and biomass in the Arctic and has been used to track plot (Andresen et al., 2018; Gamon et al., 2013; Soudani et al., 2012) to regional and global seasonal and decade time-scale greening trends (Bhatt et al., 2010; Walker et al., 2012b; Zeng and Jia, 2013)."

Line 176-179: What is the nature of the reflectance outputs from the spectrometer employed? Did you consider averaging reflectance values from the NIR and red ranges (i.e. 62-750 nm for red) rather than using a single wavelength value?
This is a good point that also needs clarification. Reflectance outputs are pretty fair for the spectrometer. Nonetheless, we applied a moving average of 3 channels. We clarify this detail in the manuscript by adding: "We ran a moving average of 6nm (3 spectral channels) to smooth each spectral measurements and minimize noise".

Results

Line 202-204: Figure 3 does not directly back up this statement. I would move the sentence above the lack of significant relationships between plant leaf N and biomass to back this up.
We clarify the statement and added statistical values; text now reads:
Examining the relationships between plant biomass and macronutrient (N, P) content of the plant leaves and soil revealed that plant leaf phosphorus content was a primary determinant of aquatic plant biomass, significantly explaining 40% of the variation in biomass of *C. aquatilis* (p=0.01) and 32% of the biomass variation of *A. fulva* (marginally significant at p=0.6). Combining both aquatic species, leaf P significantly explains 34% of aboveground biomass variability with p=0.002 (Figure 3).

Original text: Examining the relationships between plant biomass and macronutrient (N, P) content of the plant leaves and soil revealed that plant leaf phosphorus content was a primary determinant of plant biomass, significantly explaining one-third of the variation in biomass for both species (Figure 3).

Line 207: This is the first instance of root nutrient content being brought up in this paper, although it was not directly analyzed for (only collected and separate from plant leaves, according to the methods). Considering removing.

We removed "..nor between root nutrient content and soil nutrients"

Line 240: I would put section 3.2 ahead of section 3.1, as all your figures and tables describe *C. aquatilis*
before *A. fulva* (when reading left to right).
Thank you for the observation. We kept the sections as is (alphabetical order) and modified the figures and tables to read in alphabetical order left to right for consistency (A fulva on left side and C aquatilis on right side).

Figure 3: To help make the caption less cluttered to read, consider adding the relationships for both species with biomass and NDVI (and their respective r^2) to the plots, as well as adding r2 values for the species relationships to the plots.
Changed Figure 3 as suggested.

Figure 5: It would be helpful for readers for ease of comparison to be consistent with symbols used for site categories. Include percent of explained variability in brackets on axes titles.
Changed Figure 5 as suggested.

Discussion

There is a lot of focus on leaf nutrient status, but it would be good to see some discussion around the role of the soil nutrients and framed as a bottom-up approach (i.e. discussion of soil nutrients, the role that plays in leaf nutrient and biomass, and how that is manifested in NDVI and GEI). The latter half of this study could also benefit from discussion of study limitations, like how point-in-time measurements at peak season would differ greatly from a time-series seasonal snapshot.

Seasonal variability is an interesting point that should be further investigated. Because we compared sites along a nutrient gradient during peak growing season (peak biomass and greeness), no major concerns arise about our snapshot sampling. However, we felt that it was important to note why we performed the study during peak season and acknowledge seasonal dynamics to provide a better picture to the reader. We strengthen section 4.1 and 4.2 by adding the following sentences:

a) Regarding limitations such as how point-in-time measurements at peak season would differ greatly from a time-series seasonal snapshot, we added to the discussion (**Section 4.1**):

"This study focused on peak season to reflect peak biomass (Andresen et al., 2017) and greenness (Andresen et al., 2018) of aquatic graminoid tundra with different environmental nutrient status. In addition, peak season is the preferred timing for assessing long-term Arctic greenness trends from satellite platforms (Bhatt et al., 2010; Walker et al., 2012a). Nutrients are known to affect seasonal phenology of aquatic graminoids by promoting earlier green-up date as well as higher season greenness (Andresen et al., 2018). However, the relationship between environmental nutrient status and seasonal plant nutrient dynamics is unclear in tundra graminoids and should be further investigated.
There are other important seasonal considerations that are worth noting. Concentrations of leaf nutrients have been shown to vary through the growing season in tundra vegetation communities. In graminoids, N and P peak within 10 days of snowmelt and gradually decrease to half of their concentration over the course of the growing season Chapin 75. On the other hand, water and soil nutrients may increase over the season in ponds as active layer thaws and soil biogeochemical processes activate (e.g. N mineralization) resulting in increased nutrient leaching from terrestrial to

aquatic systems. Evaporation and evapotranspiration likely help increase nutrient concentrations in small ponds. As climate change continues to stretch the growing season, we need to further understand seasonal dynamics of plant nutrients and its implications on productivity and land-atmosphere carbon exchange."

b) Role of nutrients on greening (**Section 4.2**):

"Aquatic tundra graminoids studied here showed higher biomass in nutrient rich sites which translated to higher plot-level greenness (e.g. NDVI, GEI). We suspect that the combination of nutrient-induced factors such as (i) increased plant density thorough increased foliage and leaf area as well as (ii) plant vitality from chlorophyll production and other pigments enhanced NDVI and GEI spectral signatures. "

Line 296-314: Much of this first paragraph talks about existing research; I would suggest the authors try to tie in more of the work from this study into this discussion. Additionally, the comparisons on nutrient limitation made here are largely to moist and wet tundra systems, however those systems can vary substantially from tundra pond environments that were studied in this manuscript. Some more justification for this is needed.

We are aware that the comparisons are to moist/wet graminoid tundra given that (to our best knowledge) there is no study on aquatic graminoid to compare to. We shorten the paragraph and added clarity to the statements.

Paragraph now reads:
Similar to aquatic growth forms, moist and wet tundra *C. aquatilis* and *A. fulva* appear to be P limited (Beermann et al., 2015; Boelman et al., 2003; Chapin et al., 1995; Mack et al., 2004) attributed to highly organic soil which enhances recycling of N by mineralization of soil organic matter (Beermann et al., 2015; Chapin et al., 1975). On the aquatic side, primary productivity of phytoplankton and periphyton in tundra ponds in the Utqiagvik area (including some of our sites) have been shown to be largely NP co-limited (Lougheed et al., 2015).

Original text:
Arctic wet sedge in particular, has been noted to be P limited given the highly organic soil which enhances recycling of N by mineralization of soil organic matter (Beermann et al., 2015; Chapin et al., 1975). Primary productivity of phytoplankton and periphyton in tundra ponds in the Utqiagvik area (including some of our study sites) have been shown to be largely NP co-limited (Lougheed et al., 2015). In line with other studies in moist and wet tundra, aquatic *C. aquatilis* and *A. fulva* appear to be P limited (Beermann et al., 2015; Boelman et al., 2003; Chapin et al., 1995; Mack et al., 2004) as observed by the significant relationship between biomass and P leaf content (Figure 1).

Line 315-319: It would be useful for readers to see some of this data displayed as a figure (i.e. bar graph) to visualize the changes.
We decided to keep it as text intead of a figure given that is not part of the main objective of the paper and it was ancillary information worth noting in the discussion. Otherwise, it will have to be in the results section and it will likely detract from the main take-aways of the manuscript.

Line 339-341: References for this statement? Also the statement is very generalized, as other elements not studied here have been shown to be contributing factors (i.e. growing season length, water availability, etc).
We added the appropriate references to the statement in lines 339-341:
Our study supports previous studies on the importance of spectral measurements to be a function

of environmental nutrient availability through the enhancement of tundra biomass and leaf greenness at the plot level (Andresen et al., 2018; Boelman et al., 2005).

Conclusion

Line 377: A few sentences summarizing main findings and addressing the original research questions posed in the Introduction (line 97-99) would be helpful to tie things back together.
We improved the conclusion as suggested and tied back our research questions by adding the following sentence in the conclusion:
"In particular, we addressed that (i) aquatic graminoids were responding to higher soil and water nutrient availability through increased biomass and greenness, (ii) phosphorus was the principal limiting nutrient driving aquatic graminoid plant biomass as well as (iii) positively enhancing plot-level NDVI spectral signatures."

Technical Corrections

Line 33: "nutrient availability" instead of "nutrients" Line 112: should be "on" vs "in" the edge Line 151: "randomly" would be more appropriate than "haphazardly" Line 290: should be "non-experimental"
We made the indicated corrections as suggested

Thank you,
C.A. & V.L.