**Organized SPRUCE Team Response to Advisory Panel Feedback**
**From the 11-13 May 2021 All-Hands Meeting**

**1 September 2021**

Panel comments are presented in standard text and SPRUCE group responses are italicized in blue text.

**General comments**:

We were overall very impressed with the level of scholarship within the group, as both quantity and quality of papers is very high. Several new manuscripts have been published in high impact-factor journals, and this speaks to the overall impact of this experiment on multiple fields of inquiry.

There are several truly cutting-edge scientific advancements coming out of the SPRUCE community, which are cross-cutting multiple fields and labs. A few highlights:

- L. Gu's new photosynthesis model.
- D. Weston et al., work with sphagnum microbiome & moss physiology.
- T. Song et al., extracting microbial community DNA and RNA from porewater.

Data archiving and publication efforts are excellent, and more developed from even last year. This is a valuable resource for everyone involved, including SPRUCE members, outside collaborators, and funding agencies.

*Response: We thank the panel for their positive reactions and kind comments.*

The group has presented their progress on several aspects of understanding how Northern peatlands will respond to warming and to the elevated effects of $CO_2$. The different research groups that presented in the SPRUCE all-hands meeting is highly multi-disciplinary, covering the study of different processes that would affect the biogeochemical cycles in the peatland. I think this a great strength of the progress of the SPRUCE group. I saw great progress in the microbiological studies, particularly on the characterization of methanogens and methanotrophs at the site, which is crucial to understand methane dynamics. I also saw great progress in the study of nutrient cycling, for example it was great to see that warming is enhancing the acquisition capacity of the roots. It is also interesting to see the results on the potential increase of Ca with warming, and the higher TOC with warming. After many years of data collections by different groups, it is evident that great progress has been made and that good scientific papers are on the way.

*Response: Thank you for acknowledging our hard work.*

The meeting was run very smoothly, given the limitations of a virtual space. We appreciated the extra time to meet each day as the Advisory Board.

We were very pleased to see so much involvement of folks from multiple career stages and were especially impressed with all the presentations given by graduate students and post docs.

SPRUCE All-hands 2021 was an intensive 3-day marathon that left me feeling both invigorated and head-spinning as an outside reviewer trying to capture the range and depth of ongoing studies. I appreciated the additional time allotted this year to break-out discussions for the advisory panel, which gave us the opportunity to better synthesize our collective impressions and recommendations.

*Response: We are glad that the meeting organization and spirit of inclusion of all participants was appreciated.*

This was my first year on the advisory panel, and I very much appreciated the opportunity to learn more about SPRUCE and to hear about all the impressive work being done at the site. As someone who currently maintains several long-term global change experiments, I am envious of your ability to impose whole ecosystem warming. I also very much like the regression/response surface approach, although I realize it has its own set of limitations. There is clearly a large, vibrant SPRUCE research community, evidenced by the large turnout for and high level of engagement during the symposium. The collective team is demonstrating a high level of scholarship and productivity. I was also impressed with the number of publicly available data products. Project management is top notch, and we didn't hear many concerns raised about system performance. The main issue, understandably, has been sampling limitations over the past year due to COVID constraints.

*Response: Thank you for your supporting comments. We have strived to continue SPRUCE operations and measurement activities under COVID site access constraints and have mostly succeeded. Examples where that is not the case and where it has impacted our ability to provide expected outputs will be described further below.*

This is an exceptionally well-run project with an impressive amount of top-level science output. It is early in the project, especially when one considers the residence time of the ecosystem studied. The papers I have read from the project have been some of the best I have read over the last four to five years. It is also impressive the training component of the project. There were a lot of graduate students and young scientists presenting results. This is fantastic. As someone who benefited greatly from some giants in peatland science.

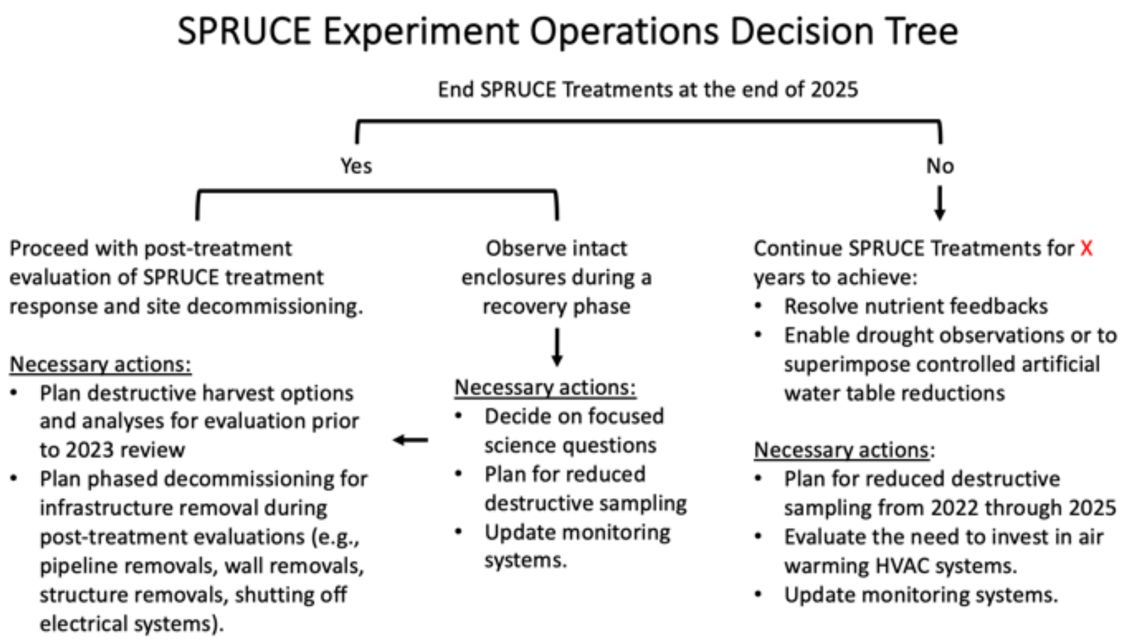
*Response: The SPRUCE group appreciates the positive feedback on our science and the organization of the annual All-Hands meeting. We will strive to continue to provide good value for DOE's investment in our group and hope to organize a vibrant and stimulating meeting in-person in May of 2022. We will continue to engage with university collaborators and their graduate students and partner with interested persons who bring new ideas and disciplinary expertise to the project.*

**Specific comments and recommendations from the May 2021 Virtual All-Hands Meeting**

Duration of the SPRUCE Study

- A key issue raised is whether 10 years is sufficient for this experiment or whether a request should be made to extend the project duration. It seems critical to start this discussion now, to make a decision soon (within the next year?), and to plan accordingly. In particular, decisions need to be made now about how to scale back on destructive sampling to save prime real estate for future sampling post the 10-year mark. Other multi-decadal global change experiments have demonstrated that surprises and trend reversals often take 10-20 years to manifest, providing a strong scientific rationale to continue. However, there may be system constraints (e.g., size of vegetation) that preclude extending much past a decade. It would be useful to see the pros/cons clearly articulated, along with a set of plans for either how sampling protocols will be modified to accommodate a longer experiment or what exactly will happen if the decision is made to terminate the experiment as currently scheduled (e.g., What will the end-of-experiment sampling entail? Will the site be monitored for recovery?

*Response: We appreciate the Panel's input on this topic and following the meeting the SPRUCE group had discussions on this topic that led us to the following decision tree for planning purposes. The path to be followed along this tree is still being considered and awaits further input while SPRUCE response data from the 2020 and 2021 seasons are analyzed. Primary constraints on the longevity of the SPRUCE infrastructure that need to be considered are (1) tree growth leading to treetops "escaping" the warm air space of the enclosures, (2) over sampling of the available plot footprints, and (3) sustaining the function of the air handling and air heating components of the aboveground warming systems for reasonable cost and effort.*



*Additional group reactions to panel member comments regarding sustained operation of SPRUCE beyond the initial decade of operation are noted below.*

- What are the effects of removing multiple cores per year in each enclosure? What is the area affected by core extraction relative to the enclosure area?

*Response: Peat coring was done in all treatment enclosures in 2012 and annually starting in 2014 as outlined in the following table:*

| ***Year*** | ***Cores per Enclosure*** | ***Shallow peat layer area sampled ($m^2$)*** | ***Deep peat layer area sampled (m2)*** |
|---|---|---|---|
| *2012* | *2* | *0.0162* | *0.004* |
| *2014* | *2* | *0.0162* | *0.004* |
| *2015* | *2* | *0.0162* | *0.004* |
| *2016* | *2* | *0.0162* | *0.004* |
| *2017* | *2* | *0.0162* | *0.004* |
| *2018* | *3 shallow, 2 deep* | *0.0243* | *0.004* |
| *2019* | *2* | *0.0162* | *0.004* |
| *2020* | *1 shallow, 2 deep* | *0.04* | *0.004* |
| *2020 suppl.* | *1 shallow* | *0.04* | *0* |
| *2021 planned* | *2* | *0.0162* | *0.004* |
| ***Cumulative Area*** | ***---*** | ***0.218 $m^2$*** | ***0.036 $m^2$*** |
| ***% Plot Area of 66.4 $m^2$*** | ***---*** | ***0.33 %*** | ***0.05 %*** |

*The internal reference area for this amount if sampling is 66.4 $m^2$ within the bounds of the internal octagonal boardwalk. Through planned sampling in 2021 we have sampled less than 0.5 % of the total available studied enclosure area. Planned future sampling will also not exceed 1 percent. However, annual sampling is typically done from a "hollow" reference area and through time those areas have become more difficult to identify from stable boardwalk locations that enable the coring activity. Operation of the SPRUCE project beyond its target decade of operation would likely necessitate skipping some peat sampling years.*

- On the question of how long to keep SPRUCE going, we do advocate for an extension of the experiment for a variety of reasons, and we have several recommendations:
  - A rationale must be outlined for the extension of the experiment beyond 10 years. Some ideas include: to capture pulse disturbance, to capture changes in slow processes like fungal and bacterial community composition (e.g., Harvard Forest), to determine if/when ecosystem equilibrates
  - Need larger range of hydrological conditions; may want to extend if next 5 years continue to be wet.

*Response: Key questions that we are interested in that may require a longer period of operation include the ability to capture key interactions with nutrient cycle feedbacks and hydrologic feedbacks, and hydraulic acclimation of spruce and larch trees. It is interesting to note that the dry 2021 season that we are currently experiencing is finally giving some of the drought and low water table insights that we have been hoping would happen over 10 years of operation.*

- We recommend an assessment of the growth rate of the trees to project if/when they will outgrow the enclosures, and how this may affect the overall lifespan of the project.

*Response: This is already an issue for some enclosures along Transect 3. Plot 19 has trees that have grown above the warm air treatment envelope this year, and some in Plot 20 are not far behind. We are evaluating a few other large trees in other plots as well. An ongoing discussion provides a range of options for continued operation under such conditions.*

1. *Let the trees grow and proceed with data analysis assuming little impact on growth or treatment response. Not an acceptable path forward.*
2. *Clip the trees and keep the study running while assuming minimal impacts on C supply with concerns about nutrients. All clipped material would be weighed and assessed for nutrients for inclusion in plot analyses for whole-study productivity.*
3. *Leave trees unclipped but exclude those tree growth and physiology measurements for future evaluations of warming/e$CO_2$ responses. They would need to be left in place so that tree to tree shading wouldn't impact another tree growth unnecessarily. This approach makes future NEE by plot enclosure assessments difficult as was done in the Hanson (2020) AGU Advances paper.*

*Given current knowledge that C sources are often present in great abundance within a growing tree (Korner 2003) we are not concerned that small C sources reductions would dramatically impact tree responses and are therefore leaning towards option 2. We do, however, want to understand and quantify impacts on internal nutrient allocations in this nutrient-deficient system. Cone seed production measurements by Jalene LaMontagne also need to be considered.*

- We recommend a bird's-eye view of destructive sampling activities to assess which of these need to be ceased or decreased in frequency to extend the life of the plots and decrease the rate of degradation. *A* priority *should be* placed on non-destructive measurements, e.g., pore water, gas fluxes.

*Response: We agree, and this is being done.*

- Based on the above assessment, the SPRUCE team should project how long the plots will be able to produce quality data and make an "end game" plan. There are several possibilities for what to do at the end of the experiment (e.g., study recovery, impose other treatments, add tracers, intensive harvesting).
- If the decision is made not to continue experimental treatment beyond 10 years, then consider looking at ecosystem recovery/resilience.
- A "recovery phase" study would be a potentially important extension of SPRUCE
  - Examine reversibility, explore response to transient stress and recovery hysteresis

- *Such an approach*, should anticipate complex response and focus on a small set of key variables and processes, *and* would likely require multiple years to draw firm conclusion

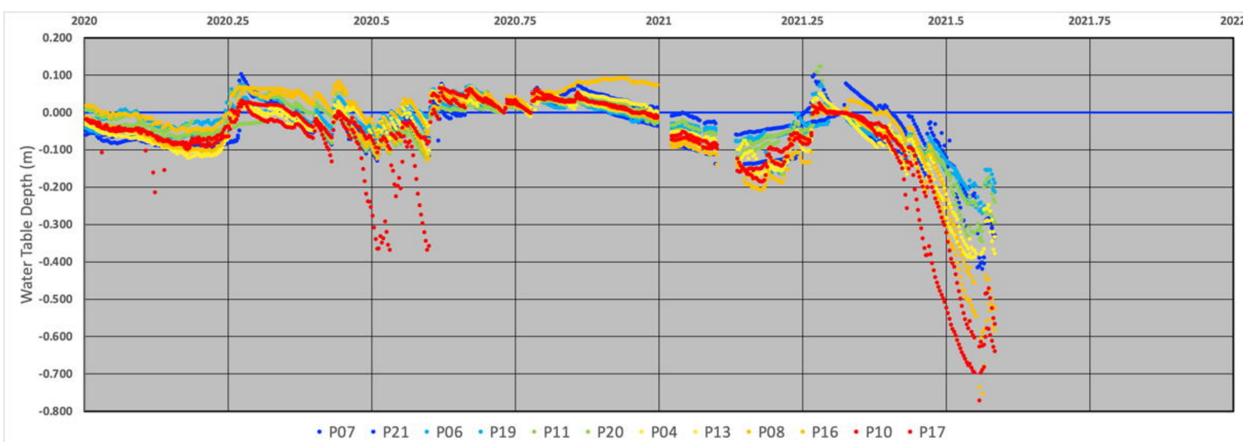
*Response: Such discussions are underway. The only path discussed at the All-Hands meeting that is no longer supported is an investment in observations of simple recovery or relaxation from the imposed treatments. While such an approach might inform baseline mechanisms for environmental response it does not represent a real world trend for future climate conditions around which compelling questions and hypotheses can be developed.*

*Ideas for sustaining the SPRUCE treatments that have group support include sustained water table reductions and the active planting of seedlings within the existing enclosure to test for establishment potential. Some testing of our ability to use sump pumps within the existing subsurface corrals to sustain reduced water table levels under ambient rainfall conditions will need to be tested before plans for such an approach can be made. We look forward to additional thoughts from the Panel.*

Drought interactions

- Drought (or the lack thereof) came up frequently during the meeting, and another rationale for extending the study duration is to increase the likelihood of a natural drought occurring. Alternatively, is there some way to impose drought conditions as an additional experimental manipulation either during or at the end of the experiment? Again, these are conversations that should start happening in earnest now, with a report back at next year's annual meeting at the latest.

*Response: We are very interested in this issue. It represents one of the key reasons operations of the SPRUCE treatments beyond 2025 is on the table. Interestingly, the 2021 growing season does seem to finally be giving us some insight into warming by drought responses sufficient to change water table heights. The following figure show how the deficit of precipitation as indeed led to reduced water table heights proportionate to the warming treatments. Treatment points in the graph are as follows: +0 °C (light blue), +2.25 °C (green), +4.5 °C (yellow), +6.75 °C (orange) and +9 °C (red).*



*These conditions are leading to altered $CO_2$ and $CH_4$ temperature response functions. That is, with dramatic drying and water table reductions the production of both greenhouse gases is reduced as hypothesized.*

<u>Measurement areas that would benefit from more focused efforts</u>

- <u>Peat Surface, Elevation Change, Water Table Elevation</u>
  - There is a clear need to disentangle the surface elevation question—is the observed drop in elevation due to faster decomposition and/or compression/shrinkage of peat due to drying with warming?

*Response: Until 2021 a role for shrinkage from water deficits was simply not apparent. New conditions in 2021 are extending the observed range of water table depths, giving us an opportunity to reevaluate the contributions in subsequent analyses.*

  - Water Table
    - Critical control of C fluxes and other processes
    - How to decouple from temp change? drought/dry year(s) needed
    - Consider outside-plot mesocosm experiments with lowered/raised WT
    - Loss of microtopographic differentiation; what are the cause(s) and consequences?
    - Could loss of sphagnum or shrub expansion be playing a role here?
    - Climate limit to long-term C accumulation; would appear that ambient conditions in S1 are finely balanced with close to net-zero C flux (as compared to other regions/studies)

*Response: We agree and the land surface models for the SPRUCE site also suggest that hypothesized responses should be apparent. The dry 2021 annual cycle should provide a nice opportunity to evaluate hydrologic change impacts on several key response variables. We are also considering options for artificial manipulation of the water table within plots via a collection of internal sumps. Such an approach could give us a new technique to apply to extended operations of SPRUCE beyond 2025.*

  - There seems to be little attention to surface elevation (peat height) - plant production – decomposition - water storage associations. These associations are key to how the feedback works between ecosystem function and the hydrology. It is this feedback that has maintained an average growth of peatlands despite considerable climate variability over millennia. In the SPRUCE experiment, you are introducing transient conditions, and you are seeing transient responses. Still, to determine if the reactions are significant at the systems level, you need to know if they exceed the ecosystem's ability to adjust in the long run. It appears you are observing a loss in surface elevation, and it seems there has been some loss of water storage, though this was not clear to me. But what is important is the change in peat surface relative to the change in water storage and where the water is stored. Has the system moved outside the range of control of the negative feedback loop? Have you pushed the system beyond the tipping points? Maybe all the dramatic changes are the system adjusting. Peatlands, especially ombrotrophic bogs, are complex adaptive systems.

*Response: Prior to the drying that we are seeing in 2021 noted above, we had simply not often seen clear evidence of a correlation between water table height and associated drying with various measured responses. This was true for gaseous efflux data for $CO_2$ and $CH_4$ and for vegetation response (apart from Sphagnum). The 2021 experience with dramatic and sustained drying and water table drops is providing such information and we are excited about the opportunity these new conditions provide. We should have new and unique analyses of temperature by water deficit interactions to present and discuss in the future.*

- Whole-Ecosystem C Exchange
    - The apparent lack of data on whole ecosystem C exchange or even just semi-continuous soil $CO_2$ and methane fluxes seems like a real limitation/gap and something that should be addressed.
    - Continuous measurements of CO2 and methane flux (e.g., hourly) from soil and/or sphagnum – these data are critical for model constraints and verification. Currently missing diurnal, seasonal, hot moments.
    - My recommendation for the group is not to lose focus on the two most important questions for the SPRUCE project: 1) How much carbon from these peatlands will be released as a result of warming and 2) Will this carbon be released in the form of $CH_4$ or $CO_2$, or in what proportion of the two? To answer these two questions there are two main approaches, the first one is to use observations of the $CO_2$ and $CH_4$ fluxes in the enclosures and analyze the differences. This could be operationally difficult but two main approaches exist: the use of soil chambers, or the analysis of gas exchange at the enclosure level, which would be discussed later.
    - Semi-continuous chamber measurements are available from Hanson et al (2016) for the growing seasons from 2011-2014 (before warming) using the large collar method. After warming (from 2014-2015), chamber measurements are provided based on the GCB paper of Gill et al (2017). Then there are fluxes estimated from 2015-2018 from large-collar chambers as described in Hopple et al (2020) but these are only taken 6-8 times per year. I would expect to find high interannual variability as the plots acclimate to long-term warming. Have the most recent years been measured? Are there plans to do auto-chambers again?
    - I am afraid that the potential acclimation of $CO_2$ and $CH_4$ to warming may not be a bit overlooked. Seeing Fig 3 in Hopple et al (2020) a question comes to mind. Are there different temperature response curves to temperature at each of the 5 temperature groups? Could we expect that the respiration at 20 C in the +9C treatment is lower than the respiration at 20C at the control treatment due to acclimation at the warmer temperature? Could this also be the case for methane emissions? I think these are essential questions for the SPRUCE project.

*Response: We did not focus on, nor report out on the $CO_2$ and $CH_4$ flux and C budget analyses during the 2021 meeting because it had been a major focus during the 2020 virtual meeting that had been followed by the Hanson et al. (2020) summary published in AGU Advances that covered such budgets through the 2018 season (i.e., the first 3 years of SPRUCE operation). I encourage the panel to look at that paper and summary graphics from last year's All-Hands meeting if they have not seen them to see how we have been handling the overall C budget comparison across treatments. In addition, because of the pandemic, we were unable to sustain the large collar $CO_2$ and $CH_4$ flux observations during 2020 and therefore did not have new estimates of NEE to share.*

*Significant comments of the panel regarding the desirability to have high temporal resolution continuous observations of both $CO_2$ and $CH_4$ flux throughout the experiment have been noted. A similar wish-list item had previously been noted by the group in early 2020 at a workshop on $CH_4$ cycling. I am very pleased to report that the US DOE has provided the necessary and significant funding needed to allow us to acquire the automatic chambers and analyzers to allow such observations beginning in 2022.*

*We plan to deploy two 50 cm diameter autochambers (Eosense) in each SPRUCE treatment enclosure for continuous (half-hour or better) assessments of $CO_2$ and $CH_4$ efflux (LGR - Ultraportable Greenhouse Gas Analyzer [$CH_4$, $CO_2$, $H_2O$]) from the surface of the Sphagnum-peat column complex. The installed chambers will be placed to account primarily for hollow locations since the shrub-dominated hummocks cannot be included. Fluxes spanning hummock-hollow microtopography and incorporating shrubs will continue to be collected through sustained large-collar monthly observations.*

  - The second one is to create a model that can take into account all of the different processes being affected by the warming and elevated $CO_2$ concentrations, which is currently being done by the ELM-SPRUCE model. It seems to me that the team has been a great effort on producing modeling results, but I think it is important that the observations establish and quantify clear differences first. <u>This would require in my opinion, continuous observations of $CH_4$ flux particularly after several years of warming, where some level of long-term warming acclimation may have been achieved.</u> These continuous measurements would take into account day and night differences that can incorporate the occurrence of hot moments of $CH_4$ and $CO_2$ flux. Continuous measurements of $CO_2$ and $CH_4$ flux are also a great way to integrate all the processes leading to $CO_2$ and $CH_4$ flux and thus can help to understand why the models fail. Knowing when the models fail can lead to the discovery of unexpected responses of the ecosystem to warming or to $CO_2$.

*Response: We appreciated the suggestion and the acknowledgment of our effort with the ELM-SPRUCE model. We admit the observational data are critical and the observed differences should come first before modeling studies. That is exactly what we did in the past few years. Based on the observational data, we constructed the ELM-SPRUCE model to simulate substrate and microbial activities for $CO_2$ and $CH_4$ cycling in the soil profiles. We first validate the ELM-SPRUCE model by comparing the modeled output with observational data for dissolved organic* *carbon, acetate, $CO_2$, and $CH_4$ concentrations along with soil profile, and the surface $CH_4$ flux (Ricciuto et al., 2021; Yuan et al., 2021).*

*For the acclimation effect pointed out by the advisory member, it might be occurring. Evaluation of acclimation processes are part of future planned analyses based on existing observational data, new high temporal resolution flux observations from all enclosures and integrated modeling studies. Thanks for emphasizing this mechanism.*

*The ELM-SPRUCE model has been applied to investigate the warming and elevated $CO_2$ impacts on $CH_4$ cycling. We concluded that although both warming and elevated $CO_2$ stimulated $CH_4$ emission, they occurred via different mechanisms (Yuan et al., 2021). Further analysis on hydrological feedbacks on $CH_4$ flux is under review in the Journal of Hydrology (Yuan et al., 2021, under review). We do admit that knowing when the model fails is more important, and we are working on the follow-up modeling analysis to identify the source of $CH_4$ production, which may explain the discrepancy between modeled and observed $CH_4$ fluxes.*

*For the previous comment on $CH_4$ flux at hourly, daily, and seasonal scales with field observation, the model simulations have some results for the "hot moment" effects. The ELM-SPRUCE did produce a very high variation in $CH_4$ flux, in particular, the "hot moment" in later spring (April and May). The high $CH_4$ emission is observed in our modeled output (see Ricciuto et al., 2021), though a mechanistic analysis has not yet been carried out. Based on our preliminary analysis, the "hot moment" in late spring was likely caused by the trapping mechanism that highlights the frozen surface kept the $CH_4$ produced; those $CH_4$ is released in next spring when the frozen soil is thawed. We plan to carry out a thorough analysis on this topic and organize it into a manuscript.*

- It would be great if the group could explore alternatives from a micrometeorological perspective to achieve continuous measurements of $CO_2$, and $CH_4$ flux and provide a brief discussion of why some of these may or may not work:
    - Putting a lid to the enclosures and create a "very-large chamber" to create a close system.
    - Measurements of concentration of $CO_2$ and $CH_4$ at two heights within the enclosure and based on a flux gradient approach (using a calibrated diffusivity coefficient) calculate the respective flux.
    - I think that a mass balance approach using scalar concentrations inside and outside the enclosures along with the characterization of the entrainment fluxes at the top of the enclosure may lead to the calculation of a flux. To what extent has something like this been considered in the past?
- Are there still plans to set up an eddy covariance system outside of the enclosures?

*Response: We have considered these issues since the beginning of the SPRUCE project, which led to the development of new eddy covariance theory and methods (Gu, 2013; Gu et al., 2012). Whether the large chamber method, the concentration vertical gradient method, and the inside-*

*outside concentration difference method can be applied depend on a consideration of the following factors:*

A. *There is a massive vertical mass flow inside the enclosure caused by the blowers.*
B. *There are constant pressure perturbations inside the enclosure and pressure differentials between inside and outside the enclosure.*
C. *The wall of the enclosure cannot be sealed tightly enough at the peat layer and doors to make the mass flow across the wall much smaller than the natural ecosystem flux.*
D. *The injection rate of $CO_2$ cannot be determined with a sufficient accuracy.*

*After considering these factors, we concluded that the oxidative ratio-based new eddy covariance method (Gu 2013) is probably the most promising one, but this new method will require the development of a fast response $O_2$ analyzer that is accurate to the ppm level, which is not currently available.*

*Currently there is a shrub-level eddy covariance – SIF system in operation outside the enclosures. A canopy-level eddy covariance – SIF system was planned for Transect 4 to better enable scaling to other Picea bogs systems but the funding to install and maintain it has not become available.*

- <u>LAI of trees and shrubs – data critical for model scaling</u>

*Response: Data for tree and shrub LAI is available it was simply not highlighted during the 2021 meeting. Shrub foliar mass data are directly sampled and quantified from the annual 0.5 $m^2$ of random clipped plots in each enclosure when these data are combined with leaf mass per unit area data for each species we derive LAI for woody shrubs, forbs and graminoids. Across all years combined shrub LAI was 1.4 $m^2$ $m^{-2}$. Sphagnum LAI is estimated between 1 and 1.3 $m^2$ $m^{-2}$ within models. Tree LAI estimates are the least constrained by annual measurement data and must be derived from allometric relationships developed on pre-treatment harvested Picea (1.0 $m^2$ $m^{-2}$) and Larix (0.3 $m^2$ $m^{-2}$) trees. We will add an analysis of LAI by treatments for consideration in next year's meeting.*

*We have collected additional allometry and leaf area data from individual trees outside the plots (four trees of increasing size from each species), paired with detailed terrestrial laser scanning (TLS) of those trees, including foliated and de-foliated branches. We plan to leverage these data to derive estimates of leaf area of trees within plots over time by application to TLS derived canopy voxels collected from within each plot.*

- <u>Physiology campaigns</u>
  - Tree and shrub respiration of leaves, wood, roots.
  - For the next large plant physiological measurement effort, is advised that there be a focus on fewer campaigns but more measurements per campaign (e.g., only peak season, which may differ depending on temperature treatment). Also, with the Li-6800, temperature curves of both photosynthesis and respiration are easier and more efficient to perform *in situ*. I don't know if SPRUCE has access to this instrument, but it would be worth considering an investment. The Li-6400s will

be obsolete within a few years. Foliar respiration is ideally measured at night on attached foliage.

*Response: Thank you for these suggestions. Respiration measurements of roots and woody tree and shrub tissue continues to be of interest and will be a focus in 2022. We are planning fewer campaigns with more replicates to assess the high variability in plant response to plot conditions, particularly in the warmest plots. Gas exchange was measured in trees in 2019 and repeated in August 2021 on five trees per species per plot using ~10 cm long samples. We have been slowly shifting to use of LI6800's, as well as leveraging machines from other groups, such that our current campaign used 7 units. Ideally, we would measure gas exchange in situ, but reaching the branches is difficult or not possible in many plots, even with our ladder systems. Thus, for safety and efficiency we continue to measure on cut branches during daytime hours. For future campaigns, we will revisit the idea of in situ measurements from a limited number of plots where this is possible. We are increasing our dark acclimation time to help offset the measurements of respiration during the day.*

- <u>Soil water storage, specific yield</u>

  More emphasis on soil moisture storage above the water table. Linking these measurements to the peat elevation issue.

*Response: We agree that this is a key area of interest and continue to measure soil water content within the plots at two depths and three spatial locations. Due to the variable peat density, we have sensors installed in bulk peat packed columns to provide a uniform, albeit relative, measure of soil water content across the plots. It may be worth collecting a limited number of small destructive peat samples adjacent to our sensors to further improve quantification of actual water content, to correlate to water table depth (capillary rise height) and measurements of surface elevation. Some loss of peat within the packed columns, and some sensor failures have led to the decision to repack new columns and replace all sensors in the coming year.*

- <u>Water balance</u>
  - Needed to sort out relative role of carbon vs. water loss in peat surface decline in warm enclosures
  - Recent isotope tracer-work by Jon Stelling is excellent start
  - Need to better quantify evaporative loss, possibly via continuous concentration measurement or auto-chambers

*Response: We agree, and this topic has been forefront in our minds, not only recently in the context of the Hanson et al. (2020) paper but since the inception of the study. We have long considered a need to address such vital questions about fundamental factors that affect surface elevation responses of peatlands to drivers of interannual and environmental change.*

*In terms of water budgets, the responses of water tables and outflow have been confounded by leakage of subsurface corrals – a problem that was long in being identified and which required considerable effort to address. The exhaustive efforts to rectify leakage were initiated in autumn of 2020 after months of deliberation. The primary challenges facing this effort included the intricate nature SPRUCE belowground infrastructure, high water tables, wide ranging* *temperatures. More than 240 person hours were required during 2019-2020 to diagnose, consider options, and implement the fixes. With an attempt at sealing the subsurface corral having been completed (summer-autumn 2020), now, a period of monitoring is needed to determine whether those efforts were partially or wholly effective. Interestingly, that effort has been complicated by an extremely dry 2021 season. Consequently, data needed for an assessment are currently incomplete. Nonetheless, results are trending towards expected ecosystem responses of the enclosed spaces to elevated temperature (overall drying, with water table and outflow responses that are more consistent with expectations of drying with higher levels of warming, extended durations of low flow during dry periods and correspondence to warming levels, and no occurrences of exceptionally- and unrealistically-high outflow during the brief period of elevated water tables following the highest external water tables during spring).*

*With rewetting of the peat profile in the winter of 2021-2022 following the truly severe drought of 2021 we will be able to assess the impact of water loss on peat elevations. Elevation measurements collected in August 2021 maximum drought and peat profile dryness will be contrasted to fully wetted profiles following snow and ice departures from the peatland (approximately June 2022). Contrasting elevations will reveal the extent of the impact of water on the volume and thus elevation of peat. Throughout the first 5 years of SPRUCE, we have never seen consistent profile drying as observed in 2021 and we will take advantage of this opportunity.*

*Clearly, great progress has been made in identifying long and short-term controls on C losses (gaseous, dissolved, or solid phase) via Hanson et al. (2020) and recently drafted/accepted/published manuscripts (Wilson et al, 2021; Shelley et al, 2021; Wilson et al., in review [carbon loss assessed with radiocarbon techniques]), which disentangle C-cycling processes in terms of elevation loss, decomposition, and C-release mechanisms. An additional prolonged period that includes multiple rainfall or snowmelt runoff events interspersed with a period or periods of low-flow conditions that have not occurred during an unusually dry year of 2021 will enable full evaluation of the water cycle.*

*We greatly appreciate the recognition of our efforts to quantify water-balance components as constrained using water isotope measurements. This work, however, despite identifying some heretofore little-recognized bog-specific ecosystem effects on δD values and previously unrecognized insight on bog hydrology, does not appear to offer the panacea that we (and many others would have) expected with respect to disentangling evaporation in peatlands. This work is ongoing, and a manuscript is being drafted. We hope to report more in coming months and by the next All-Hands-Meeting.*

*In terms of high-frequency measurement of evaporation, we agree that those data would be optimal and complimentary to many ongoing or proposed SPRUCE efforts. Unfortunately, the aforementioned complications (financial and logistical) to the implementation of eddy covariance measurement systems hinder our options. We continue to evaluate this (and other) options.*

- Root traits

  Perhaps something to do with Root respiration?

*Response: We have been discussing potential root respiration measurements with the physiology team and have made tentative plans to collaborate on some of these measurements during the 2022 field season. We are thinking one option may be to sacrifice one of the two paired ingrowth core locations per plot for an instantaneous removal and quantification of roots that we know have been newly grown in the past year. This means less opportunity for quantification of treatment effects on root biomass and chemistry, so we have also reached out to collaborators who previously had a belowground footprint in the enclosures to see if they'd be willing to share their belowground real-estate for this important (but destructive) measurement.*

Integration

- There is a great deal of interesting data on the sphagnum microbiome, root/mycorrhizal fungi, soil organic matter chemistry, and decomposition (i.e., peat, wood cookies, fungal necromass, cotton strips). However, it is unclear to what extent project personnel are working to integrate these datasets to understand drivers of organic matter formation/destabilization across the SPRUCE treatments. Is there any work and/or data on microbial contributions to soil organic matter pools? Are there data on fungal biomass in the plots and the relative contribution of mycorrhizal versus non-mycorrhizal fungi to total biomass? What about total microbial biomass with depth and over time? This seems like a good time to really take stock of all the data available to (1) conduct a thorough synthesis and (2) determine what critical data are missing and need to be collected over the next few years.

*Response: Regarding the decomposition studies, there are several different but complimentary studies that are ongoing and that are evaluating the responses of organic matter decomposition to warming and e$CO_2$. These include decomposition measurements of senesced leaves, roots, Sphagnum, peat, wood branches and bole wood, necromass, and standardized substrates (cotton strips). Further, while we have not yet examined microbial community structure on decomposing litter, we are initiating these measurements on the leaf/root/Sphagnum litter in collaboration with Chris Schadt in 2021 (year 6 litterbag retrieval). We note that most of these decomposition studies are ongoing, and many have a planned duration of 10 years. Therefore, as we are in the middle of our assessment of decomposition dynamics, we have not yet conducted an integrative analysis across these multiple studies. We have, however, begun some initial assessments of the early decomposition data, and are finding that these multiple decomposition studies are strengthening our understanding of organic matter decomposition responses to warming. Specifically, we have found limited warming effects on decomposition of litter (leaves, roots, Sphagnum), but found that labile C (in the form of cotton strips) strongly responds to warming. Together, these two studies suggest that intrinsic chemical characteristics of litter may be a stronger regulator on decomposition dynamics (more so than external drivers such as temperature), at least in the early phases of decomposition (first 2 years of the experiment). This finding of stronger intrinsic vs extrinsic control on decomposition is also supported by a recently published paper by our group (Shelley et al. 2021) that examined intrinsic vs extrinsic controls on moss decomposition at the S1 bog and Bog Lake Fen. In summary, while we are beginning to* *integrate our findings from the multiple decomposition studies, we plan to conduct a more comprehensive assessment towards the end of the SPRUCE project.*

*Collection of microbial biomass data has admittedly been spotty. In 2016, Joel Kostka (Georgia Tech) and Chris Schadt (ORNL) conducted high spatial resolution (11 depths) microbial sequencing from the yearly group sampling activity. Jessica Gutknecht (Univ. Minnesota) has collected PLFA (phospholipid fatty acid) data from the yearly coring events from 5 composited depths approximately 5 times since 2015. In 2018, microbial biomass carbon data was collected in the surface layers (0-20 cm depth) in August and July. The lack of consistent microbial sampling was also discussed at the 2019 All Hands meeting, with particular focus on model needs. Simple chloroform fumigation for total microbial biomass is a minimal level of information about total microbial biomass, but it is also what is used in many models. QPCR (and PLFA) can separate fungi, archaea, and bacteria. 16S and metagenomic sequencing can provide information on taxonomy and gene function, respectively. Collection of microbial data was planned for 2020 but was postponed due to Covid-19. In 2021, we initiated these activities, with a core sampling in June and August (with group sampling activity), and an additional event is planned for October. One core each was collected under the interior boardwalk of plots 4, 6, 7, 8, 10, 11, 13, 16, 17, 19, 20, and 21, split into 11 different depths. Samples were shipped on blue ice to perform chloroform fumigation for microbial biomass at ORNL; and shipped on dry ice to perform QPCR at ORNL and perhaps also 16S and/or metagenomics at Georgia Tech. We hope to continue a more regular microbial sampling in the future, although sampling is subject to limitations of core material discussed elsewhere in this response.*

- What are, and how is the project measuring the system level outputs? There is a tremendous amount of process work but is there any way of backchecking that if it all fits? Do you measure NEE, CH4, water (vapour and runoff), and chemical balances (N, P, DOC, DIC, Hg, etc.)? These should allow a back check on the rates being observed in the process studies. Does it all hang together?

*Response: SPRUCE is measuring system-level inputs and outputs for C, nutrients (N, P), and water. Inputs and outputs of other solutes (anions, cations) are also measured – i.e., in precipitation (input) and lateral outflow (output) – but characterization of these cycles by the entire SPRUCE group is less intensive compared to C, N, P, and water. C, N, and P budgets have been published (pre-treatment C budget in Griffiths et al. (2017), treatment responses of C cycling in Hanson et al. (2020), pre-treatment N and P budgets in Salmon et al. (2021)). We will continue to synthesize the responses of these ecosystem cycles to the SPRUCE treatments; however, as pointed out elsewhere in this document, there are challenges in fully capturing all components of these elemental and water cycles (e.g., difficulties in measuring evaporation [described above], challenges with estimating N and P deposition [described below]). Our continued efforts to synthesize the elemental and water cycle responses to warming and e*$CO_2$ *will include an integration of the process-level work (where appropriate) to better capture the full system dynamics and to bound the flux estimates (and vice versa).*

Nutrient cycles

- What is the role of P? Or N and P co-limitation? There appears to be little information on this, but maybe I missed it, or it simply wasn't highlighted this year.
- Improved measurement of dry/dust deposition, especially for P (as noted last year) would be helpful
- Passive dust-fall collectors deployed by my research group showed P flux ~10x previous estimates of wet-only deposition in northern MN
- Thru-fall and litterfall measurements would help capture P dry-deposition and recycling by vegetation (trees, shrubs)

*Response:*
*As an ombrotrophic bog, the S1 Bog ecosystem is inherently nutrient-limited (Bridgham et al. 1998). Our analysis of vegetation N to P ratios for the site prior to implementation of SPRUCE manipulative treatments was highlighted in a talk. Our results indicate that plants at SPRUCE are generally co-limited by both N and P, with trees falling further towards the N-limited end of the spectrum (Salmon et al. 2021; Figure X). The ratio of N:P can be considered a broad indicator of N and P limitation and, for wetland plants, values over 16 are considered P-limited while values under 14 are generally considered N-limited (Koerselman and Meuleman 1996; Güsewell and Koerselman 2002).*

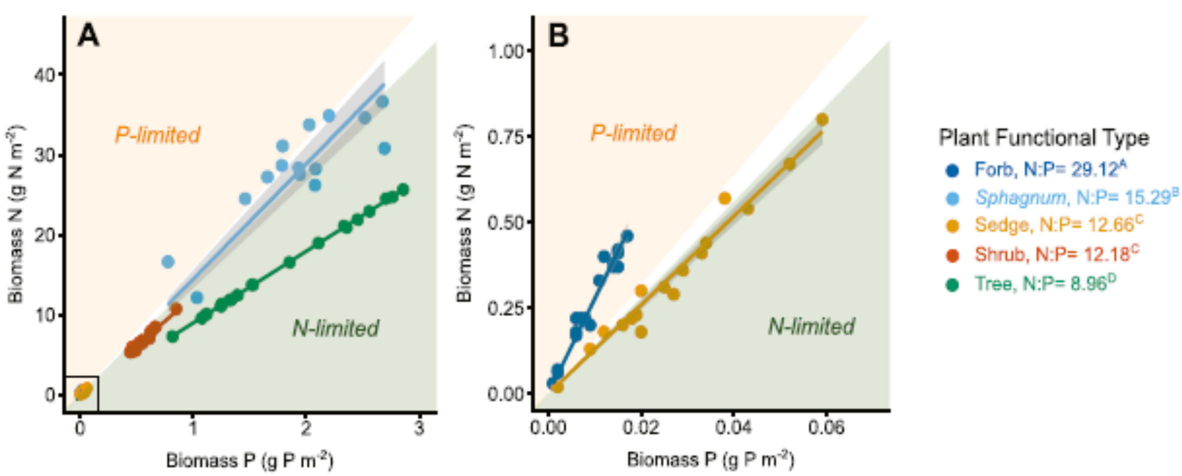



Figure X. Whole-plant biomass N versus P by plant functional type at the S1 Bog. Panel B is a re-scaled view of the area within the black box outlined in panel A. Superscript letters in the legend denote significant differences between plant functional type N:P ratios based on estimated marginal means ($\alpha < 0.05$). Figure from Salmon *et al.* (2021).

*Our pre-treatment analysis also showed that N is accumulating in the ecosystem at 0.2 gN $m^{-2}$ $y^{1}$ while P losses matched balanced by P inputs and a greater proportion of ecosystem P was stored in shallow soils and vegetation compared to ecosystem N (Salmon et al. 2021). Together, these findings suggest P cycling in this ecosystem is generally more constrained than N cycling.*

*Several ongoing observational datasets at SPRUCE are geared towards understanding the impact of temperature and $eCO_2$ treatments on nutrient availability. Due to the long-term nature of the SPRUCE experiment, these datasets are based on non-destructive methods. Resins* *deployed monthly in the soil surface capture mineral forms of N and P in a way that mimics plant roots, while porewater and lateral outflow collections monitor inorganic and organic pools and fluxes of these nutrients. These datasets were highlighted in talks by Colleen Iversen and Natalie Griffiths. We are actively planning a nutrient synthesis to assess the impact of SPRUCE treatments on N and P cycling. This work will be buoyed by recent improvements to the underground corral system (See Water Balance response above) and as well as ongoing measurements of tree and shrub biomass, growth, and chemistry. In 2021, surface soils from SPRUCE were also collected for a lab-based incubation study that will look at the temperature response of N and P mineralization in rhizosphere soils.*

*We agree that dry deposition could contribute an important nutrient flux in this ecosystem and regret that the panel feels we have not addressed their comment from last year. Following the 2020 All Hands meeting, we had a long discussion about whether collectors at Marcell Experimental Forest are capturing wet or dry deposition. Samples are not filtered and therefore we believed that both wet and dry samples are collected (though not separated). To assess whether these collectors are indeed representing bulk deposition, we compared N deposition at our site to EPA Castnet sites in the region that separate fluxes of dry versus wet deposition (https://www.epa.gov/castnet). Unfortunately, P data was not available. CASTNET data from these sites from 2000-2010 show annual bulk deposition rates that are like the annual deposition measured at S1 (2010-2016; 5.28 kg N ha$^{-1}$ y$^{-1}$). We believe that this bolsters our assumption that our collectors are capturing both wet and dry N deposition.*

| | | Wet Deposition (kg N/ ha/ yr) | | | Dry Deposition (kg N/ ha/ yr) | | | Total Deposition (kg N/ ha/ yr) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **N=** | **Mean** | **stdev** | **SE** | **Mean** | **stdev** | **SE** | **Mean** | **stdev** | **SE** |
| Red Lake Nation, MN | 19 | 3.19 | 0.57 | 0.13 | 2.24 | 0.43 | 0.10 | 5.42 | 0.71 | 0.16 |
| Voyagers NP, MN | 19 | 3.30 | 0.59 | 0.14 | 2.24 | 0.31 | 0.07 | 5.54 | 0.78 | 0.18 |

*For P deposition, teasing apart the role of dry versus wet deposition is more complicated. In the pre-treatment budgets presented at the meeting, the deposition flux was derived from historic observations of total phosphorus (TP) concentrations in the region (Table X below). This was due to exceptionally low concentrations of TP at the S1 Bog site that often fell beneath the detection limit of our analytical equipment. We are investigating higher sensitivity methods for analyzing samples. In the meantime, these regional estimates for TP concentration times deposition at the S1 bog represent our most informed estimated of P deposition.*

**Table X. Regional observations of total phosphorus (TP) deposition from existing literature.**

| Reference | Site | Years | Rainfall ($mm\ y^{-1}$) | TP deposition ($g\ P\ m^{-2}\ y^{-1}$) | TP concentration ($mg\ P\ L^{-1}$) |
|---|---|---|---|---|---|
| Wright et al (1976) | Dogfish watershed, MN USA | 1972 | 705 | 0.014 | 0.020 |
| Wright et al (1976) | Meander Watershed, MN USA | 1972 | 695 | 0.014 | 0.020 |
| Wright et al (1976) | Lamb Watershed, MN, USA | 1972 | 714 | 0.014 | 0.020 |
| Schindler et al (1976) | Rawson Lake, Ontario, Canada | 1970-1973 | 790 | 0.033 | 0.042 |
| Verry & Timmons (1977) | Marcell Experimental Forest, MN, USA | 1971-1973 | 775 | 0.048 | 0.062 |
| Eisenreich et al (1977) | Northen Basin, Lake Michigan, USA | 1975-1976 | 442 | 0.022 | 0.050 |
| Eisenreich et al (1977) | Southern Basin, Lake Michigan, USA | 1975-1976 | 568 | 0.036 | 0.063 |
| Rose (1993) | Balsam Lake, WI, USA | 1987-1989 | 699 | 0.005 | 0.007 |
| Miller et al (2000) | Lake Michigan watershed, USA | 1994-1995 | 1130 | 0.005 | 0.004 |
| Twaroski et al (2007) | Cedar River watershed, MN, USA | 1996-2003 | 822 | 0.0469 | 0.057 |
| Twaroski et al (2007) | Des Moines River watershed, MN, USA | 1996-2003 | 707 | 0.0448 | 0.063 |
| Twaroski et al (2007) | Lake Superior watershed, MN, USA | 1996-2003 | 758 | 0.02 | 0.026 |
| Twaroski et al (2007) | Lower Mississippi watershed, MN, USA | 1996-2003 | 831 | 0.0432 | 0.052 |
| Twaroski et al (2007) | Minnesota River watershed, MN, USA | 1996-2003 | 702 | 0.0417 | 0.059 |
| Twaroski et al (2007) | Missouri watershed, MN, USA | 1996-2003 | 679 | 0.0397 | 0.058 |
| Twaroski et al (2007) | Rainy River watershed, MN, USA | 1996-2003 | 695 | 0.0193 | 0.028 |
| Twaroski et al (2007) | Red River watershed, MN, USA | 1996-2003 | 592 | 0.0261 | 0.044 |
| Twaroski et al (2007) | St. Croix River watershed, MN, USA | 1996-2003 | 767 | 0.027 | 0.035 |
| Twaroski et al (2007) | Upper Mississippi watershed, MN, USA | 1996-2003 | 708 | 0.0268 | 0.038 |
| | | *Average* | *724* | *0.028* | *0.039* |
| | | *n=* | *20* | *19* | *19* |
| | | *Standard deviation* | *130* | *0.014* | *0.019* |
| | | *Standard error* | *29* | *0.003* | *0.004* |

*The panel's comment regarding throughfall and litterfall is a pertinent observation. In the fall of 2019, our team deployed several prototype litter collectors outside the SPRUCE plots to see if a non-destructive method for collecting litter in this heterogenous, open canopy ecosystem could be devised. Due to travel restrictions during 2020, these prototypes were left out longer than planned but we plant to revisit litterfall measurements in late 2021. Estimates of throughfall at the SPRUCE site have been made by Kolka et al. (unpublished) and are estimated to be around 0.44 g N $m^{-2}$ $y^{-1}$ and 0.024 gP $m^{-2}$ $y^{-1}$. These are close in magnitude to the estimated bulk deposition fluxes at the S1 Bog (0.50 g N $m^{-2}$ $y^{-1}$ and 0.034 gP $m^{-2}$ $y^{-1}$). Directly observing the impact of the manipulative treatments on throughfall would be difficult due to the aboveground enclosures at the site.*

## Mercury Cycle

- Work on sulfur cycling and Hg methylation picks up on prior work at Marcell (good), but could benefit from genomic assessment of microbial community composition/dynamics
- Increased Hg evasion is a critical question for global Hg cycle, as peatlands represent large and potentially labile pool of terrestrial Hg
- GEM (gaseous elemental Hg) fluxes measured (2017 Haynes et al) showed high variability; there is need for a follow-up study after 5 years of warming
- Response to last year's comments mentions new student on board in 2020 to focus on gaseous fluxes + passive Hg samplers; what is status?

*Response: We have been working mercury microbial specialists at ORNL to better understand the mercury methylation communities and their responses to the SPRUCE treatments. This will be our second year of measuring gaseous mercury fluxes from the chambers using passive air samplers (PAHs) that have been shown to have good results for relatively low cost. The PAHs are currently being used in a new National Atmospheric Deposition Network so SPRUCE will be out in front of the curve. We anticipate the current University of Minnesota M.S. student to defend next spring/early summer, but we plan to continue the PAHs measurements throughout the duration of SPRUCE.*

Scaling/transferring SPRUCE results to other sites

- How transferrable are SPRUCE results to other sites? How are you thinking about this, along with system-level feedbacks with hydrology, the C cycle etc.?
- The proposal for an international meeting with other peatland groups was raised last year and might well have happened were it not for Covid. This idea was also discussed in at least one of this year's break-out sessions, with the question of whether to focus on climate change (across different ecosystems) or on landscape type (peatlands). Ideally it would include both, but a focus on peatlands would be most useful to upscaling SPRUCE results to boreal mires at large.
- How will SPRUCE be used to tell what to expect with the massive stores of carbon in northern peatlands in climate change and land-use change plus atmospheric deposition?

*Response: We plan to use ELM-SPRUCE as a tool to integrate SPRUCE observations and transfer knowledge gained there to other sites. We are currently working to generalize ELM-SPRUCE so that it may be applied at other sites. A first step is the ELM-SPRUCE sensitivity analyses in recent manuscripts (Shi et al., 2021; Ricciuto et al., 2021), which indicate the key processes that drive variability in carbon fluxes and how spatial variability in model parameters may impact the simulations. A manuscript currently in review is exploring the impact of microtopography parameters (e.g., hummock-hollow height difference), and how measuring these properties are important for simulating carbon fluxes accurately. We are in the process of setting up ELM-SPRUCE at the nearby Bog Lake Fen site and will evaluate it against the multi-year eddy covariance dataset there. ELM-SPRUCE is also being adapted for a tropical peatland site in Peru. Before the next all-hands meeting, we plan to take advantage of additional multi-year records in the AmeriFlux database to perform simulations and validate ELM-SPRUCE against CO2 and CH4 fluxes. We are also in the processes of expanding our current two-column hummock-hollow model, which is designed to simulate ombrotrophic peatlands, to a four-column model that can also represent the surrounding uplands and the groundwater influence present in fen systems. This will allow us to develop a regional wetland modeling capability, with an initial focus on peatlands given the suggestions above. We agree that engaging with other peatland groups would be highly useful to test the new modeling framework when it is ready for testing later this year.*

MODEX

- Is there a systems-level view that is emerging? There seems to be a reliance on the modelling to pull it all together. I would assume the empiricists can develop some system-level storylines on how things are working (or not). Is there an 'Eville Gorham' style storyline emerging. Can you see the peatland for the Sphagnum, black spruce and shrubs?

- It was nice to see modelers and experimentalists discussing data needed to improve models and vice versa during one of the breakouts; however, my sense from the meeting is that integration is happening in pockets of the project but is still not a community-wide effort. As noted above, more integration appears to be needed, particularly among the belowground group. Clearly, there has been some MODEX achievement (e.g., phenology, methane, hydrology), but it seems like more is needed, and you are at a very good stage to lean in to model-data integration activities. There was a call during the symposium for the formation of 3-4 data-model working groups, each with a clearly articulated topic and specific goals. These groups would ideally meet regularly (monthly?) to push MODEX forward. I would like to see this happen over the next year, with a report out from each working group at next year's meeting.
- Several instances during the meeting revealed disconnects between modelers and experimentalists. We feel this indicates that MODEX activities need to be prioritized in the next phase of the overall project. Much wonderful, detailed work is being done by numerous labs, and the time is ripe for synthetic activities, especially modeling.
- We recommend developing several focused MODEX working groups around key elements of the modeling activities (e.g., plant physiology, methane & $CO_2$ fluxes, soil microbes, etc.). These working groups should prioritize synthetic activities and meet regularly to identify leads, modeling activities, data needs, and to make plans to move efforts forward.
- Because temperature is directly affecting other environmental variables (e.g., VPD, soil moisture, nutrient availability, growing season), it is important to start paying attention to and attempting to tease apart these environmental drivers statistically and/or within a modeling framework.
- MODEX activities: I had a stronger sense this year that the empiricists and the modeling communities were more siloed than I previously noted, (our break-out sessions, for example), and that a more structured working-group framework (with regular meetings) is needed to facilitate data/model integration.
- Whole-ecosystem syntheses for carbon, water, and nutrient budgets: These are the three overarching components of the SPRUCE experiment and would benefit from mid-study syntheses to identify gaps and uncertainties while there is still time to address them. Although this has been done for carbon for the first 3 years of warming, the water and nutrient budgets have not been and are ripe/ready for synthesis. A revisiting of the C budget would be timely as well.
- Promote ModEx approach throughout SPRUCE. Not just modellers but get the empiricist talking to each other. The biogeochemistry, microbial ecologists, plant physiologist, and hydrologist/physical scientists need to be more engaged with each other's work.

*Response: We agree that we are at a good stage to ramp up our MODEX activities, and we appreciate the suggestions to establish working groups that can better bring together the modelers and the empiricists to work on specific topics while maintaining the broader goal of producing a peatland model that can eventually be integrated into an Earth System model. To date, we have focused on improving the ELM-SPRUCE model by integrating multiple data* *streams simultaneously. However, this has become increasingly cumbersome given the large number of processes and uncertain parameters present in the model, and that has made it difficult at times for experimentalists to see where exactly they should engage. Therefore, upon further reflection we think a "phased MODEX," using multiple versions of ELM-SPRUCE with different degrees of complexity, may work better in the future. These versions of the model also fit naturally with topics that can form the bases for three working groups: 1) hydrology and plant physiology; 2) Vegetation growth and nutrient cycling, and 3) Microbial dynamics and $CH_4$ cycling. Modeling and empiricist co-leads will be identified for each working group, will meet regularly, and will work to prioritize topics for model development, model-data integration, and identifying possible data gaps that could be addressed with future observations.*

*We also continue to explore MODEX activities related to plant and tree physiology. Our current efforts are examining measured temperature response curves of respiration and linkages to a variety of models. Analysis of the extreme 2017 physiology campaign data are almost complete, and data on thermal optimum of respiration, photosynthesis, Vcmax and Jmax will be applied to ELM. Sapflux data are also going to be scaled to plot-level tree transpiration, which will be used to improve models of NEE and parameterization in ELM.*

<u>Vegetation Change</u>

- There is an increase in the abundance of *Vaccinium* in the warming plots. Could this be a consequence of changes in pH? Has this been tested?

*Response: We have not yet determined the cause for the developing dominance of Vaccinium in the shrub layer of the warmer chambers but will be looking at nutrient and peat chemistry as a possible explanation.*

<u>Potential collaborations</u>

- Coordination of UAV multispectral data products and physiology work (Krassovski & Warren).

*Response: This year we have initiated paired physiology and multispectral work using a drone and cameras attached to long poles. We are most interested in linking thermal images and multispectral wavelengths related to the water content (water band index) with direct leaf temperature measurements, plant water potentials and LMA, and linking RGB and multispectral images to N content, chlorophyll/carotenoid content and %N in rubisco. We are also using handheld multispectral cameras to collect data on gas exchange samples. Results from preliminary work this year will be used to further develop campaigns for 2022.*

- Coordination between direct and indirect measurements of LAI (Glenn & Warren).

*Response: This effort is ongoing (see response about LAI above).*

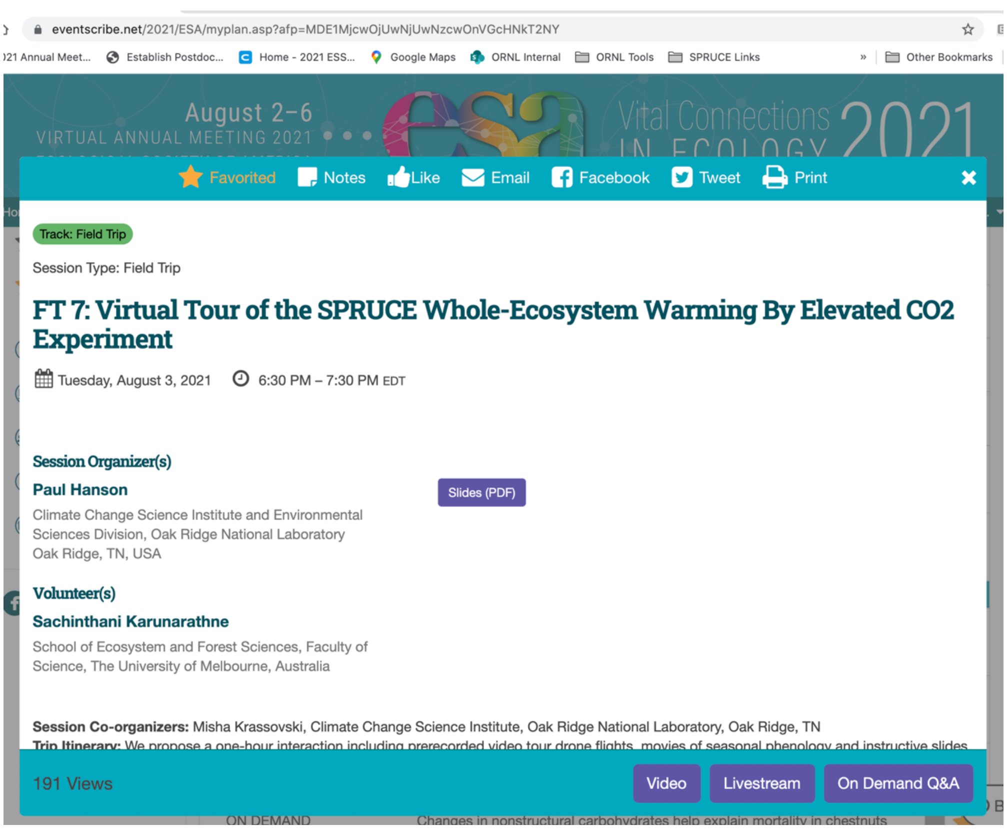
- Coordination between sphagnum shading experiment and soil microbial work (Norby & Kostka).

*Response: The project will ensure that results from the shading experiment are shared across collaborating groups.*

<u>Public Engagement</u>

Consider producing a short SPRUCE video for an educated/lay audience. I viewed and enjoyed the recent SPRUCE virtual tour (YouTube) and, as an experiment, showed the first 3-min intro to a group of dinner guests (close friends with strong environmental leanings) the evening before the All-hands meeting. My audience included, among others, a physician, an architect, an attorney, and a corporate CEO (all retired), but only one other scientist (my spouse). They were all intrigued and impressed, though it was a bit "sciencey" and required additional narration and follow-up Q/A for them to fully appreciate what was going on.

*Response: We have considered producing a shorter and more approachable "Executive Summary" version of the SPRUCE YouTube video. We will work on that as time allows. For the 2021 Ecological Society Annual meeting Paul Hanson did host a virtual tour of the SPRUCE site using portions of the YouTube video and other materials. It is available for post-meeting viewing.*



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