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Missing pieces to modeling the Arctic-Boreal puzzle

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EDITORIAL • OPEN ACCESS

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Abstract

NASA has launched the decade-long Arctic-Boreal Vulnerability Experiment (ABoVE). While the initial phases focus on field and airborne data collection, early integration with modeling activities is important to benefit future modeling syntheses. We compiled feedback from ecosystem modeling teams on key data needs, which encompass carbon biogeochemistry, vegetation, permafrost, hydrology, and disturbance dynamics. A suite of variables was identified as part of this activity with a critical requirement that they are collected concurrently and representatively over space and time. Individual projects in ABoVE may not capture all these needs, and thus there is both demand and opportunity for the augmentation of field observations, and synthesis of the observations that are collected, to ensure that science questions and integrated modeling activities are successfully implemented.

Climate is changing worldwide, but temperatures are rising disproportionately in the high northern latitudes, i.e. the Arctic-Boreal Region—home to the largest biome in the world (Chapman and Walsh 2007, Hinzman *et al* 2005, IPCC 2007, 2014, McGuire *et al* 2006, Overpeck *et al* 1997, Screen and Simmonds 2010, Serreze and Barry 2011, Winton 2006). Warming temperatures in such cold environments may benefit plants, improve productivity, enable a green-up of new areas, accelerate nutrient cycling, and increase CO₂ uptake from the atmosphere (Euskirchen *et al* 2009, Forkel *et al* 2016, Jia *et al* 2003, Mack *et al* 2004, Myneni *et al* 1997, Natali *et al* 2012, Qian *et al* 2010). However, rising temperatures are also thawing permafrost, altering hydrology and ecology, changing albedo, browning and decreasing productivity in some areas, increasing fire frequency/severity and disease infestations, and exposing enormous amounts of previously preserved soil organic carbon to the atmosphere (Beck and Goetz 2011, Goetz *et al* 2005, Koven *et al* 2011, Lloyd and Bunn 2007, McGuire *et al* 2009, Olefeldt *et al* 2013, Schädel *et al* 2016, Schaefer *et al* 2011, Schuur *et al* 2009, Zimov *et al* 2006). This stored soil carbon has accumulated over millennia, and its exposure and mobilization is tipping the historical carbon sink of the Arctic-Boreal Region into a volatile source of increasing carbon to the atmosphere (Belshe *et al* 2013, Hayes *et al* 2011, Oechel *et al* 1993, Schaefer *et al* 2014, Schuur *et al* 2013, Turetsky *et al* 2011, Zona *et al* 2016).

Our predictive ecosystem modeling capabilities for the region have substantial uncertainties due to the complexity of these interacting ecosystem components, tipping carbon sink/source dynamics, large and remote area, extreme environment, and consequent dearth of measurements. As a result, carbon cycle dynamics in the Arctic-Boreal Region are among the largest sources of identified uncertainties to global climate projections (Chapin *et al* 2000, IPCC 2014, Ito *et al* 2016, Koven *et al* 2011, McGuire *et al* 2006, Parmentier *et al* 2015, Schaefer *et al* 2014, Snyder and Liess 2014, Zhang *et al* 2017). These uncertainties can be conceptually considered as missing pieces to a modeling ‘puzzle’ that can inform ecosystem function and dynamics with changing climate. Models are challenged in how to initialize current conditions and carbon pools, determine the precise sensitivities of soil and vegetation responses to changing temperature and hydrological regimes, and scale highly heterogeneous processes to large grid sizes (Fisher *et al* 2014a, Fisher *et al* 2014b, Hayes *et al* 2014, Lorant *et al* 2014, McGuire *et al* 2012, Melton *et al* 2013, Rogers *et al* 2017, Schuur *et al* 2015, Sitch *et al* 2007). The lack of observational data has limited model improvements, testing, and evaluation for the Arctic-Boreal Region: evidence of this is seen in the fact that models have exhibited nearly every possible combination of carbon sink/source dynamics with orders of magnitude differences in carbon stocks (Fisher *et al* 2014b, McGuire *et al* 2006, McGuire *et al* 2012, Melton *et al* 2013, Schuur *et al* 2015, Sitch *et al* 2007).

In 2015, NASA launched the decade-long Arctic-Boreal Vulnerability Experiment (ABOVE) focused in Alaska and Western Canada to study the ecosystems in response to a changing environment (above.nasa.gov). NASA is able to leverage its remote sensing strengths to combine airborne and satellite observations with *in situ* measurements to capture ecosystem dynamics across large scales (Goetz *et al* 2011, Griffith *et al* 2012, Kasischke *et al* 2013). ABOVE is partitioned into three phases, with the first two phases focused predominantly on science-driven intensive data collection from field studies and airborne campaigns; the last phase is focused on analysis and synthesis of these data, including integration with modeling. Although the last phase is reserved for model integration, with foresight NASA included a model–data integration framework in Phase I (Stofferahn *et al* 2016). This framework lays the foundation for the modeling activities, connects modeling efforts to the field activities early on, and aims to ensure that the data collected meet the needs of the modeling community. This is a lesson learned from previous large-scale NASA campaigns. For example, in the Large-Scale Biosphere-Atmosphere Experiment in Amazonia an extensive network of flux towers was installed throughout Amazonia, but did not include sensors for downwelling longwave radiation, a crucial input for modelers (de Gonçalves *et al* 2013). Including the instruments during installation would have been relatively cheap and easy, but doing so after the fact proved very difficult and time-consuming. Although many ABOVE projects are primarily field- and remote sensing-based studies targeting individual science questions with specific data collection requirements, opportunities exist for ABOVE-sponsored projects and/or ABOVE-affiliated projects to include additional data needed by the modeling community. However, the modeling community must define their data requirements now so that NASA and the ABOVE project teams can augment their implementation plans in time to collect the critical observations.

We surveyed 18 modeling teams from around the world on data needs for modeling terrestrial ecosystem dynamics in the Arctic-Boreal Region. Our focus was on global terrestrial biosphere models used within global climate projections, and whose inter-model variabilities define global uncertainties (Friedlingstein *et al* 2006, Friedlingstein *et al* 2014, IPCC 2007, 2014). The 18 models included: CABLE (Wang *et al* 2010), Biome-BGC (Thornton *et al* 2002), CLM (Koven *et al* 2015), CLM4 V IC (Lei *et al* 2014), DLEM (Tian *et al* 2014), ECOSYS (Grant *et al* 2009), ISAM (Jain and Yang 2005), JeDI (Pavlick *et al* 2013), JULES (Clark *et al* 2011), LPJ (Zhang *et al* 2016), MC2 (Bachelet *et al* 2015), Noah-MP (Niu *et al* 2011), ORCHIDEE (Krinner *et al* 2005), SiB4 (Baker *et al* 2008), SSiB (Xue *et al* 1991), TEM (Hayes *et al* 2011), VEGAS (Zeng *et al* 2005), and VISIT (Ito 2010). Some models represent more processes than others with respect

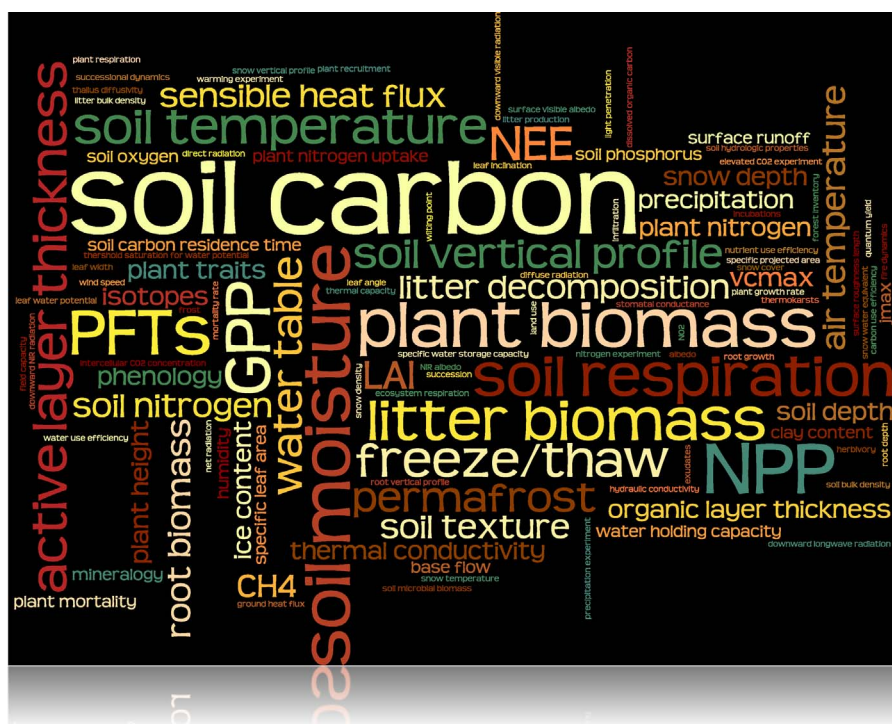


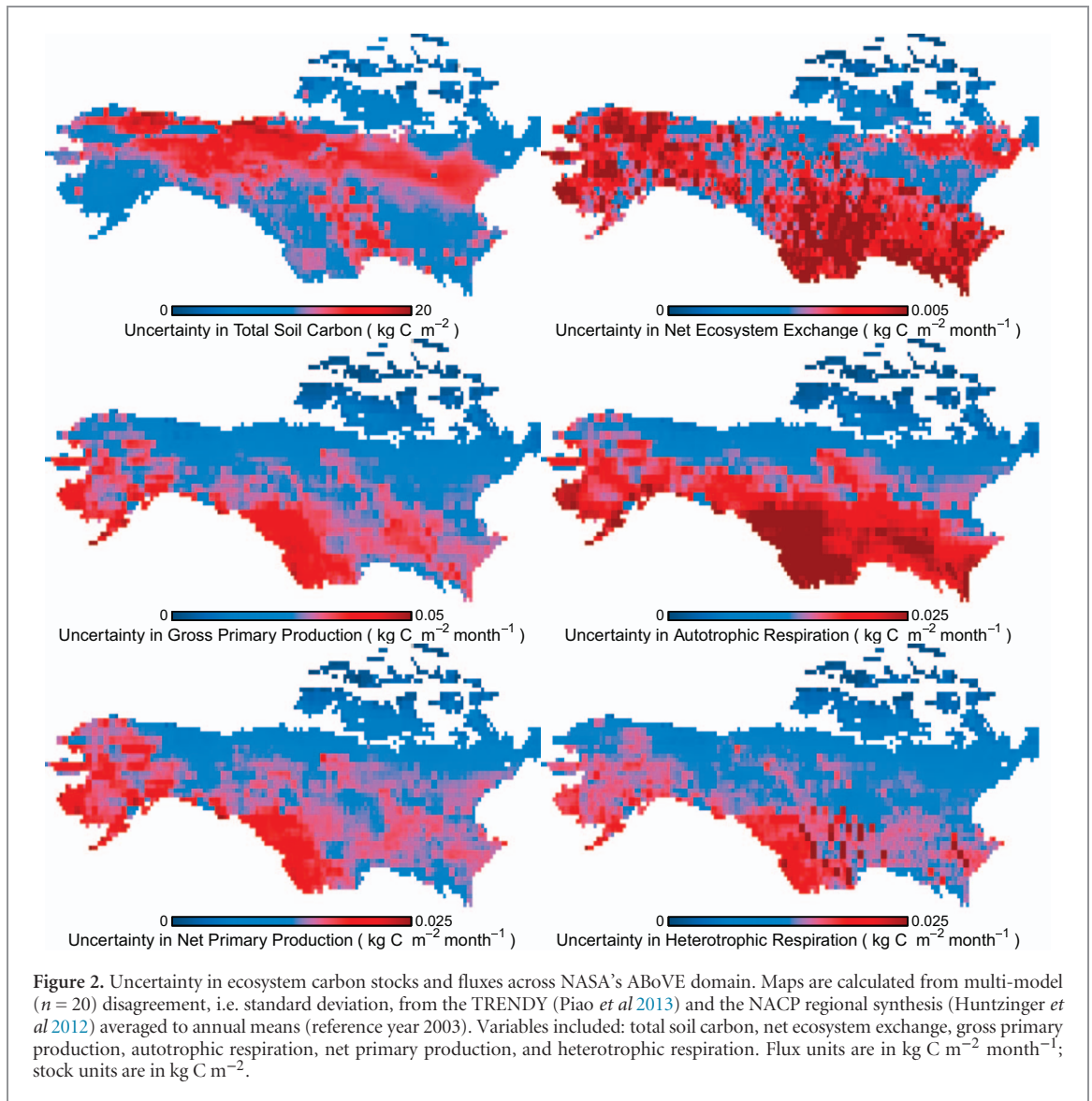
Figure 1. Terrestrial biosphere modeling needs for the Arctic-Boreal Region highlight soil and vegetation dynamics, as illustrated by font size proportional to frequency of response from 18 modeling groups.

to Arctic-Boreal ecosystem dynamics, but all show divergent results in terms of carbon pools and fluxes (Fisher *et al* 2014b). Our survey centered on ecosystem dynamics, building on previous similar inquiries focused specifically on soil carbon dynamics (Luo *et al* 2016, Tian *et al* 2015). Further, we used a set of 20 models featured in a previous analysis of Alaskan carbon dynamics (Fisher *et al* 2014b) to calculate the inter-model variability for the ABoVE domain (western North America) as an indicator of modeling community disagreement, or uncertainty; these models were also included in the TRENDY (Sitch *et al* 2015) and North American Carbon Program (NACP) regional synthesis (Huntzinger *et al* 2012).

The modeling teams provided a wide range of responses, which we grouped into common categorical phrases for analysis. There was a total of 115 unique phrases, which, for illustration we plotted as a ‘Wordle’ (wordle.net), where the font size of the word is proportional to the frequency of the response (figure 1). By far the most common response was soil carbon, followed by net primary productivity (NPP), plant biomass, soil moisture, plant functional types, and gross primary productivity (GPP). The next tier of modeling needs included soil respiration, litter biomass, active layer thickness, freeze/thaw dynamics, net ecosystem exchange (NEE), soil temperature, evapotranspiration, water table, permafrost, soil vertical profile, and leaf area index. We note that other types of data, such as meteorology, are critical model inputs, but are more commonly available so are less in demand. We

also note that some of these variables are somewhat ambiguously defined or not directly aligned with exact measurements. Some key variables to modelers may be overlooked due to inherent biases or lack of knowledge of arctic-boreal processes. Still, the diversity of responses contributed by modelers points to the overall lack of observational data, which must be addressed, but also highlights that the very fundamental processes governing terrestrial carbon cycling are poorly understood and constrained in Arctic-Boreal ecosystems. Indeed, this list would likely mirror modeling needs for most global biomes (Fisher *et al* 2014a)—but, with additional key requirements related to permafrost, active layer thickness, and freeze/thaw dynamics, reinforcing the top priority of understanding the magnitude and fate of soil carbon, particular to northern high latitude terrestrial ecosystems (Koven *et al* 2017).

It is important to emphasize that many of these variables are needed concurrently, and such that they sufficiently represent variability over space and time. Concurrency forms the basis of the response functions that structures models (e.g. temperature versus respiration)—variables collected in isolation may lack the spatiotemporal robustness needed to inform and improve the model as a whole. These concurrency requirements enable modelers to extrapolate spatially beyond existing intensive but sparse study sites, as well as refine sensitivities and tipping points/thresholds temporally. This is particularly acute for residence time and turnover of soil and plant carbon stocks; implicit here is turnover related to disturbance with respect to



accurate quantification of fuels, fates, and frequencies. A particular strength of ABoVE for modeling is that there is a concerted effort to scale up site level data through airborne and satellite observations (see: above.nasa.gov/images/Scaling%20Diagram_169.jpg). This allows an improved direct comparison between the coarse model pixels and the ground data. Spatially, we identify where these variables should be collected based on uncertainty in modeled soil carbon, NEE, NPP, GPP, heterotrophic respiration, and autotrophic respiration (figure 2). We show absolute uncertainty for transparency and direct connection to measurements, though other statistical metrics, such as interannual variability, can readily be derived. Low uncertainty regions may be classed as such due to our uncertainty definition, but models may have converged due to equifinality or other shared assumptions, while uncertainty by other definitions may be large. Much of the carbon flux uncertainty is co-located in the southwest areas of Alaska and the Canadian part of the ABoVE domain (roughly congruent with boreal biome extent), while the soil carbon uncertainty is

located throughout tundra regions of northern Canada and Alaska, and the Yukon area (areas with high soil carbon concentration).

Generally, the survey results align with five of ABoVE's overarching science themes—carbon biogeochemistry, vegetation, permafrost, hydrology, and disturbance. ABoVE's field and airborne campaigns have targeted known geographic areas of interest and uncertainty, though our uncertainty maps in figure 2 provide direct and quantitative guidance to these campaigns specifically where models most need data. For instance, it may be that the feedbacks between ecosystem dynamics and atmospheric conditions unique to particular locations expose particular model sensitivities, thereby causing large divergence; data specifically from these areas may help both to constrain these sensitivities as well as to provide benchmark data to assess the accuracy of models. Multiple field-based projects are funded by or affiliated with ABoVE within each of these categories, so this alignment may bode well for data capture for modeling requirements. A live list of measurements being

collected in ABoVE as of this writing can be found online (above.nasa.gov/cgi-bin/above_meas.pl). Synthesis activities across projects, especially, can help integrate datasets within modeling frameworks. However, many of the variables required by models may be absent, non-concurrent with other variables, or lacking the spatial or temporal resolutions and domains from the field campaigns needed to sufficiently refine model performance. For instance, soil carbon dynamics, such as stocks and change trajectories/sensitivities to various forcing variables, were clearly the highest demand by the modelers. At the time of this writing there were 20 projects listed under the Carbon Dynamics category within ABoVE. Nonetheless, most of these projects were not focused on soil carbon (due in part, for example, to available proposals, solicitation wording, and technical difficulty). Rather, they focus predominantly on carbon fluxes between the land surface and the atmosphere, which while critically important to the modeling community, may overlook some of the key data needs for modelers, presenting a potentially worrisome gap for model–data integration.

There is an enormous wealth of complementary data and information existing or in development by programs outside of ABoVE that are relevant to modelers. These include, for example: DOE's N-GEE Arctic (Wullschlegel *et al* 2011), ESA's GlobPermafrost (Bartsch *et al* 2017), the Permafrost Carbon Network (Schuur and Abbott 2011), the International Soil Carbon Network (Jandl *et al* 2014), the Northern Circumpolar Soil Carbon Database (Hugelius *et al* 2013), the Study of Environmental Arctic Change (Bromwich *et al* 2010), the Arctic System Reanalysis (Bromwich *et al* 2016), the Polar Geospatial Center (Noh and Howat 2015), the National Ecological Observatory Network (Keller *et al* 2008), the Long-Term Ecological Research network (Hobbie *et al* 2003), and individual AmeriFlux/FLUXNET sites (Oechel *et al* 2014). Other agencies such as the Interagency Arctic Research Policy Committee (IARPC) coordinates among some of these networks (Arctic Research and Policy Act 1984); but, a stronger international cooperative effort is still greatly needed, especially in the face of international politics that may present barriers to scientific collaboration. ABoVE has been coordinating with each of these programs and it may be that some potential gaps in ABoVE's data collection will be filled by these other efforts. However, while such datasets will be useful for model initialization, benchmarking, and evaluation, they may not meet the equally critical demand for variables to be collected concurrently, which is essential for advancing model development and performance. Moreover, these data are primarily focused in N. America, whereas there is an even greater data dearth in the larger pan-Arctic and Boreal region across the globe.

The modeling community additionally needs infrastructure to allow repeatable evaluation of model performance compared to benchmark datasets. The benchmark datasets, constructed from a suite of

observations, must thoroughly confront and challenge models against the processes and response functions important to Arctic-Boreal ecosystem dynamics for models to improve. The ABoVE model–data integration framework facilitates the construction, integration, connection, and flow of the valuable data collected by the ABoVE science teams and other data networks to the modeling community (Stofferahn *et al* 2016). Through the ABoVE Science Cloud central data repository (daac.ornl.gov/cgi-bin/dataset_lister.pl?p=34), the framework provides a back-end database link to a front-end web user interface to access the ABoVE data. These data can and should be used by the modeling community to update and refine model parameterization and structural process representation, especially where data highlight key gaps in process representation in models (e.g. Li *et al* 2010). In turn, as model versions advance, the framework can be used as a benchmarking system to test improvement in model performance against key ABoVE indicators and science questions related specifically to important Arctic-Boreal Region ecosystem dynamics. Moreover, the integrated framework readily identifies key missing datasets or uncertainties required to test and advance models across the ABoVE indicators—highly useful for feedback to ground campaigns. The benchmarking system is based on the International Land Model Benchmarking project (Collier *et al* 2016, Hoffman *et al* 2016, Luo *et al* 2012), and affiliated with the Permafrost Benchmarking System (Schaefer *et al* 2016) (i.e. some shared datasets and statistical metrics). Additionally, the model–data integration framework provides relatively high-quality and high-resolution model driver data for regional-scale runs, critical for modeling high latitudes (Guimberteau *et al* 2017). In sum, this framework helps ease the workload of connecting to all of these disparate but related databases for the modeling community.

There is tremendous and well-justified interest, effort, and activity in understanding the Arctic-Boreal Region. Much of the current focus is on identifying what is happening now under a changing climate, but there is particular interest in and concern for what changes may occur in the future. Mathematical and computational models of the terrestrial biosphere are essential for understanding potential future changes, and are ultimately the great integrators of our information now. With large and long-term investments such as NASA's ABoVE currently underway, it is critical that a community-wide modeling framework is incorporated into data collection early so that we can add substantially to the value of assimilating currently available data assets. The challenge is in connecting the wide array of datasets and focused science interests to a cohesive and coherent integrated larger picture. A coordinated and supported effort across these field and modeling components will help complete the missing pieces to modeling the complex dynamics and feedbacks of the Arctic-Boreal puzzle.

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