Environmental Research Letters

OPEN ACCESS

RECEIVED
15 September 2017

ACCEPTED FOR PUBLICATION
28 November 2017

PUBLISHED
13 February 2018



EDITORIAL

# Missing pieces to modeling the Arctic-Boreal puzzle

Joshua B Fisher[1,24], Daniel J Hayes[2], Christopher R Schwalm[3], Deborah N Huntzinger[4], Eric Stofferahn[1], Kevin Schaefer[5], Yiqi Luo[6], Stan D Wullschleger[7], Scott Goetz[8], Charles E Miller[1], Peter Griffith[9], Sarah Chadburn[10], Abhishek Chatterjee[9,11], Philippe Ciais[12], Thomas A Douglas[13], Hélène Genet[14], Akihiko Ito[15], Christopher S R Neigh[9], Benjamin Poulter[9], Brendan M Rogers[3], Oliver Sonnentag[16], Hanqin Tian[17], Weile Wang[18,19], Yongkang Xue[20], Zong-Liang Yang[21], Ning Zeng[22] and Zhen Zhang[23]

1 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109, United States of America
2 School of Forest Resources, University of Maine, 233 Nutting Hall, Orono, ME, 4469–5755, United States of America
3 Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA, 02540-1644, United States of America
4 School of Earth Sciences and Environmental Sustainability, Northern Arizona University, PO Box 5694, Flagstaff, AZ, 86011-5697, United States of America
5 National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, 1540 30th Street #376, Boulder, CO, 80303, United States of America
6 Department of Microbiology and Plant Biology, University of Oklahoma, Norman, OK, 73019, United States of America
7 Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, 37831-6301, United States of America
8 School of Informatics, Computing and Cyber Systems, Northern Arizona University, PO Box 5693, Flagstaff, AZ, 86011-5693, United States of America
9 NASA Goddard Space Flight Center, Greenbelt, MD, 20771, United States of America
10 University of Leeds, School of Earth and Environment, Leeds, LS2 9JT, United Kingdom
11 Universities Space Research Association, 7178 Columbia Gateway Drive, Columbia, MD, 21046, United States of America
12 Laboratoire des Sciences du Climat et l'Environnement, Orme des Merisiers, bat. 701—Point courier 129, 91191 Gif Sur Yvette, France
13 US Army Cold Regions Research and Engineering Laboratory, Fort Wainwright, AK, 99703, United States of America
14 Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK, 99775, United States of America
15 National Institute for Environmental Studies, Tsukuba, 3058506, Japan
16 Université de Montréal, Département de géographie and Centre d'études nordiques, 520 Chemin de la Côte Sainte-Catherine, Montréal, QC, H2V 2B8, Canada
17 International Center for Climate and Global Change Research, School of Forestry and Wildlife Sciences, Auburn University, 602 Duncan Drive, Auburn, AL, 36849, United States of America
18 NASA Ames Research Center, Moffett Field, CA, 94035, United States of America
19 California State University Monterey Bay, Seaside, CA, 93955, United States of America
20 Department of Geography, University of California, Los Angeles, CA, 900945, United States of America
21 Department of Geological Sciences, Jackson School of Geosciences, 1 University Station #C1100, University of Texas at Austin, Austin, TX, 78712-0254, United States of America
22 Department of Atmospheric and Oceanic Science, University of Maryland, 2417 Computer and Space Sciences Building, College Park, MD, 20742-2425, United States of America
23 Department of Geographical Sciences, University of Maryland, College Park, MD 20740, United States of America
24 Author to whom any correspondence should be addressed.

E-mail: jbfisher@jpl.nasa.gov

**Keywords:** ABoVE, arctic, arctic boreal vulnerability experiment, boreal, model, requirements, uncertainty

## 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 $CO_2$ 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, Loranty *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

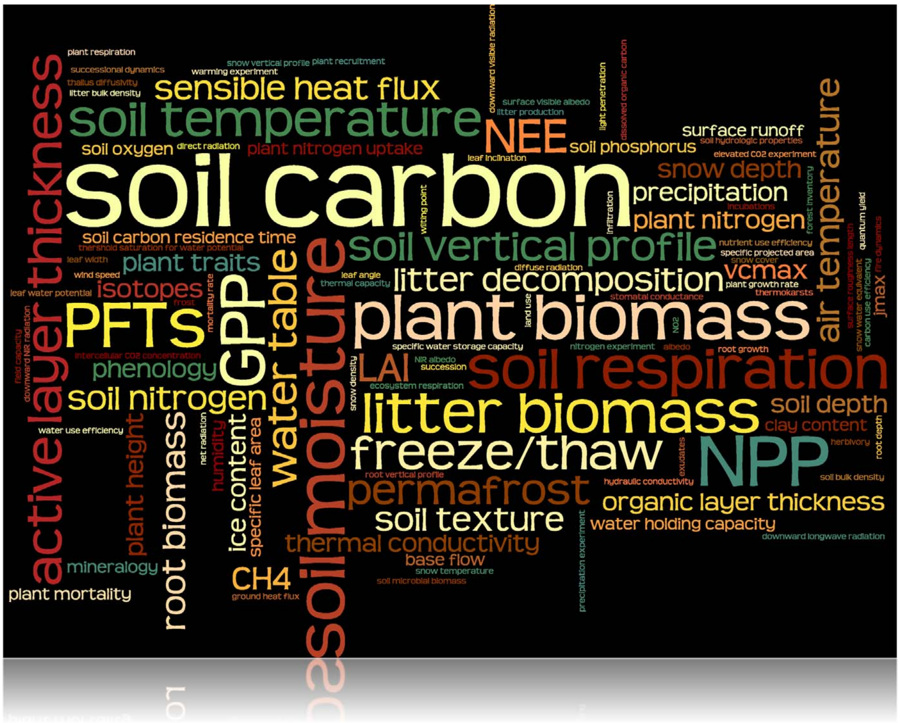


**Figure 1.** Terrestrial biosphere modeling needs for the Arctic-Boreal Region highlight soil and vegetation dynamics, as illustrated by font size proportional to frequency of response from 18 modeling groups.

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

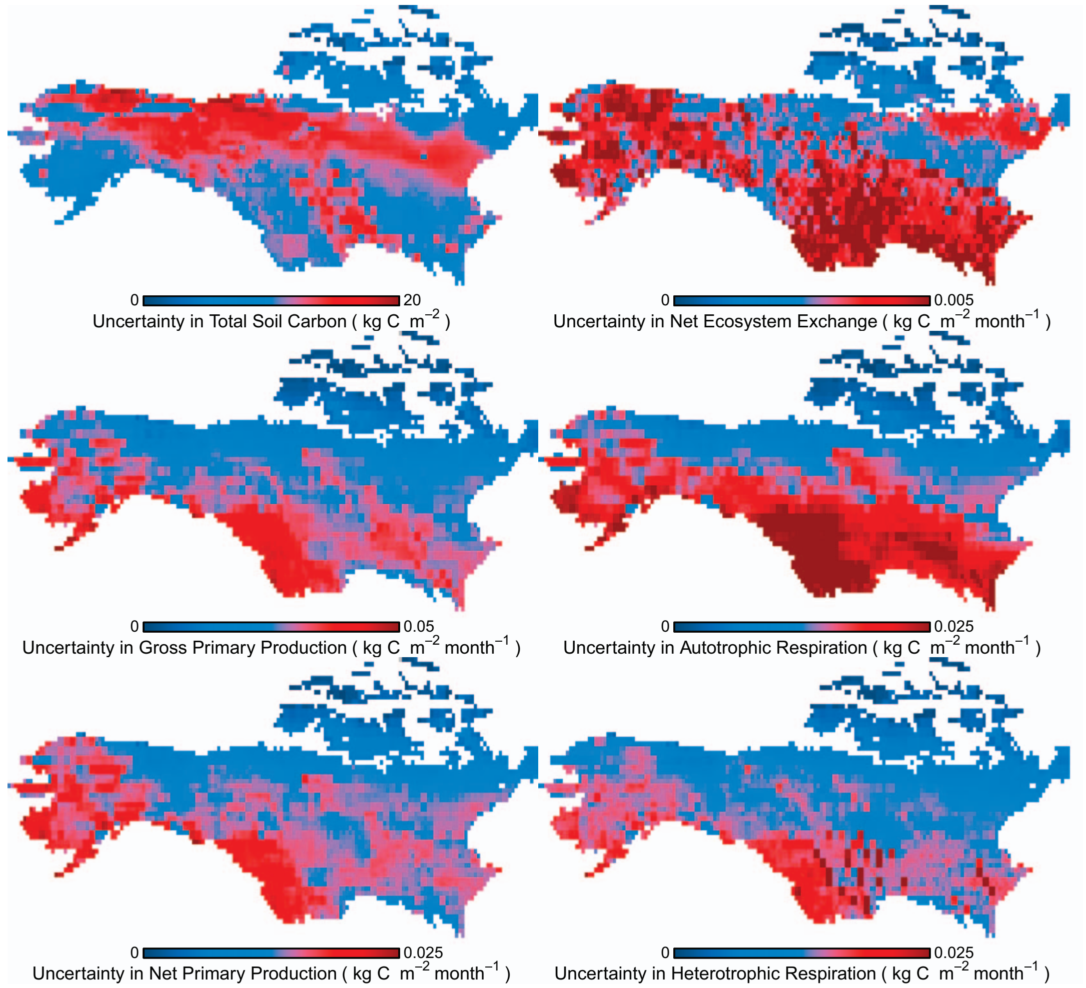


**Figure 2.** Uncertainty in ecosystem carbon stocks and fluxes across NASA's ABoVE domain. Maps are calculated from multi-model ($n = 20$) disagreement, i.e. standard deviation, from the TRENDY (Piao *et al* 2013) and the NACP regional synthesis (Huntzinger *et al* 2012) averaged to annual means (reference year 2003). Variables included: total soil carbon, net ecosystem exchange, gross primary production, autotrophic respiration, net primary production, and heterotrophic respiration. Flux units are in kg C m$^{-2}$ month$^{-1}$; stock units are in kg C m$^{-2}$.

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 NGEE Arctic (Wullschleger *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.

## Acknowledgments

We thank D Bachelet, N French, R Grant, A Harper, K Haynes, M Huang, A Jain, C Koven, J Metsaranta, M Sikka, R Pavlick, and S Veraverbeke for survey inputs and/or paper comments. This work was supported by NASA's Arctic Boreal Vulnerability Experiment (ABoVE); NNN13D504T (JBF), NNX17AE44G (SJG). TAD was supported by the US Army Engineer Research and Development Center Basic Research (6.1) Program. Computing resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Center for Climate Simulation (NCCS) at Goddard Space Flight Center. The paper was led from the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. California Institute of Technology. Government sponsorship acknowledged. 

## ORCID iDs

Joshua B Fisher https://orcid.org/0000-0003-4734-9085
Abhishek Chatterjee https://orcid.org/0000-0002-3680-0160

## References

Arctic Research and Policy Act 1984 Arctic research and policy act of 1984 (amended 1990) *Public Law* **98** 373

Bachelet D, Ferschweiler K, Sheehan T J, Sleeter B M and Zhu Z 2015 Projected carbon stocks in the conterminous USA with land use and variable fire regimes *Glob. Change Biol.* **21** 4548–60

Baker I T, Prihodko L, Denning A S, Goulden M, Miller S and da Rocha H R 2008 Seasonal drought stress in the Amazon: reconciling models and observations *J. Geophys. Res.* **113** G00B01

Bartsch A, Grosse G, Kääb A, Westermann S, Strozzi T, Wiesmann A, Duguay C, Seifert F M, Obu J and Nitze I 2017 Examining environmental gradients with remotely sensed data-the ESA globpermafrost project *Paper presented at EGU General Assembly Conference Abstracts*

Beck P S and Goetz S J 2011 Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences *Environ. Res. Lett.* **6** 045501

Belshe E F, Schuur E A G and Bolker B M 2013 Tundra ecosystems observed to be $CO_2$ sources due to differential amplification of the carbon cycle *Ecol. Lett.* **16** 1307–15

Bromwich D H, Kuo Y H, Serreze M, Walsh J, Bai L S, Barlage M, Hines K and Slater A 2010 Arctic system reanalysis: call for community involvement *Eos, Trans. Am. Geophys. Union* **91** 13–4

Bromwich D H, Wilson A B, Bai L-S, Moore G W and Bauer P 2016 A comparison of the regional arctic system reanalysis and the global ERA-interim reanalysis for the arctic *Q. J. R. Meteorol. Soc.* **142** 644–58

Chapin F, McGuire A, Randerson J, Pielke R, Baldocchi D, Hobbie S, Roulet N, Eugster W, Kasischke E and Rastetter E 2000 Arctic and boreal ecosystems of western north America as components of the climate system *Glob. Change Biol.* **6** 211–23

Chapman W L and Walsh J E 2007 Simulations of Arctic temperature and pressure by global coupled models *J. Clim.* **20** 609–32

Clark D B *et al* 2011 The joint UK land environment simulator (JULES), model description—part 2: carbon fluxes and vegetation dynamics *Geosci. Model. Dev.* **4** 701–22

Collier N, Hoffman F M, Mu M, Randerson J T and Riley W J 2016 International land Model Benchmarking (ILAMB) BGCF-DATA (Biogeochemistry (BGC) Feedbacks)

de Gonçalves L G G *et al* 2013 Overview of the large-scale biosphere–atmosphere experiment in Amazonia data model intercomparison project (LBA-DMIP) *Agric. Forest Meteorol.* **182–183** 111–27

Euskirchen E S, McGuire A D, Chapin F S, Yi S and Thompson C C 2009 Changes in vegetation in northern Alaska under scenarios of climate change, 2003–2100: implications for climate feedbacks *Ecol. Appl.* **19** 1022–43

Fisher J B, Huntzinger D N, Schwalm C R and Sitch S 2014a Modeling the terrestrial biosphere *Annu. Rev. Environ. Resour.* **39** 91–123

Fisher J B *et al* 2014b Carbon cycle uncertainty in the Alaskan Arctic *Biogeosciences* **11** 4271–88

Forkel M, Carvalhais N, Rödenbeck C, Keeling R, Heimann M, Thonicke K, Zaehle S and Reichstein M 2016 Enhanced seasonal $CO_2$ exchange caused by amplified plant productivity in northern ecosystems *Science* **351** 696–9

Friedlingstein P *et al* 2006 Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison *J. Clim.* **19** 3337–53

Friedlingstein P, Meinshausen M, Arora V K, Jones C D, Anav A, Liddicoat S K and Knutti R 2014 Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks *J. Clim.* **27** 511–26

Goetz S J, Bunn A G, Fiske G J and Houghton R 2005 Satellite-observed photosynthetic trends across boreal north America associated with climate and fire disturbance *Proc. Natl Acad. Sci. USA* **102** 13521–5

Goetz S J, Kimball J, Mack M and Kasischke E 2011 Scoping completed for an experiment to assess vulnerability of Arctic and boreal ecosystems *Eos Trans. AGU* **92** 150–1

Grant R F, Barr A G, Black T A, Margolis H A, Dunn A L, Metsaranta J, Wang S, McCaughey J H and Bourque C A 2009 Interannual variation in net ecosystem productivity of Canadian forests as affected by regional weather patterns—a Fluxnet-Canada synthesis *Agric. Forest Meteorol.* **149** 2022–39

Griffith P, Goetz S, Kasischke E, Mack M and Wickland D 2012 The arctic-boreal vulnerability experiment: a NASA terrestrial ecology field Campaign *Paper presented at AGU Fall Meeting Abstracts*

Guimberteau M *et al* 2017 ORCHIDEE-MICT (revision 4126), a land surface model for the high-latitudes: model description and validation *Geosci. Model Dev. Discuss.* **2017** 1–65

Hayes D J, Kicklighter D W, McGuire A D, Chen M, Zhuang Q, Yuan F, Melillo J M and Wullschleger S D 2014 The impacts of recent permafrost thaw on land–atmosphere greenhouse gas exchange *Environ. Res. Lett.* **9** 045005

Hayes D J, McGuire A D, Kicklighter D W, Gurney K R, Burnside T J and Melillo J M 2011 Is the northern high-latitude land-based $CO_2$ sink weakening? *Glob. Biogeochem. Cycles* **25** GB3018

Hinzman L D, Bettez N D, Bolton W R, Chapin F S, Dyurgerov M B, Fastie C L, Griffith B, Hollister R D, Hope A and Huntington H P 2005 Evidence and implications of recent climate change in northern Alaska and other arctic regions *Clim. Change* **72** 251–98

Hobbie J E, Carpenter S R, Grimm N B, Gosz J R and Seastedt T R 2003 The US long term ecological research program *BioScience* **53** 21–32

Hoffman F M, Riley W J, Randerson J T, Keppel-Aleks G, Lawrence D M and Koven C D 2016 *2016 International Land Model Benchmarking (ILAMB) Workshop ReportRep.* (Washington, DC: USDOE Office of Science)

Hugelius G, Tarnocai C, Broll G, Canadell J, Kuhry P and Swanson D 2013 The northern circumpolar soil carbon database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions *Earth Syst.Sci. Data* **5** 3

Huntzinger D N *et al* 2012 North American carbon program (NACP) regional interim synthesis: terrestrial biospheric model intercomparison *Ecol. Model.* **232** 144–57

IPCC 2007 *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Climate Change 2007: The Physical Science Basis* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) p 996

IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A Global Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) p 1132

Ito A 2010 Changing ecophysiological processes and carbon budget in East Asian ecosystems under near-future changes in climate: implications for long-term monitoring from a process-based model *J. Plant Res.* **123** 577–88

Ito A, Nishina K and Noda H M 2016 Impacts of future climate change on the carbon budget of northern high-latitude terrestrial ecosystems: an analysis using ISI-MIP data *Polar Sci.* **10** 346–55

Jain A K and Yang X 2005 Modeling the effects of two different land cover change data sets on the carbon stocks of plants and soils in concert with $CO_2$ and climate change *Glob. Biogeochem. Cycles* **19** GB2015

Jandl R, Rodeghiero M, Martinez C, Cotrufo M F, Bampa F, van Wesemael B, Harrison R B, Guerrini I A, deB Richter D and Rustad L 2014 Current status, uncertainty and future needs in soil organic carbon monitoring *Sci. Total Environ.* **468** 376–83

Jia G J, Epstein H E and Walker D A 2003 Greening of Arctic Alaska, 1981–2001 *Geophys. Res. Lett.* **30** 1–4

Kasischke E, Hayes D, Griffith P, Larson E and Wickland D 2013 NASA's Arctic-Boreal vulnerability experiment: a large-scale study of environmental change in western North America and its implications for ecological systems and society *Paper presented at AGU Fall Meeting Abstracts*

Keller M, Schimel D S, Hargrove W W and Hoffman F M 2008 A continental strategy for the national ecological observatory network *Front. Ecol. Environ.* **6** 282–4

Koven C D, Hugelius G, Lawrence D M and Wieder W R 2017 Higher climatological temperature sensitivity of soil carbon in cold than warm climates *Nat. Clim.* **7** 817

Koven C D, Lawrence D M and Riley W J 2015 Permafrost carbon–climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics *Proc. Natl Acad. Sci.* **112** 3752–57

Koven C D, Ringeval B, Friedlingstein P, Ciais P, Cadule P, Khvorostyanov D, Krinner G and Tarnocai C 2011 Permafrost carbon-climate feedbacks accelerate global warming *Proc. Natl Acad. Sci.* **108** 14769–74

Krinner G, Viovy N, de Noblet-Ducoudré N, Ogée J, Polcher J, Friedlingstein P, Ciais P, Sitch S and Prentice I C 2005 A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system *Glob. Biogeochem. Cycles* **19** GB1015

Lei H, Huang M, Leung L R, Yang D, Shi X, Mao J, Hayes D J, Schwalm C R, Wei Y and Liu S 2014 Sensitivity of global terrestrial gross primary production to hydrologic states simulated by the community land model using two runoff parameterizations *J. Adv. Model. Earth Syst.* **6** 658–79

Li Q, Sun S and Xue Y 2010 Analyses and development of a hierarchy of frozen soil models for cold region study *J. Geophys. Res.: Atmos.* **115** 1–18

Lloyd A H and Bunn A G 2007 Responses of the circumpolar boreal forest to 20th century climate variability *Environ. Res. Lett.* **2** 045013

Loranty M M, Berner L T, Goetz S J, Jin Y and Randerson J T 2014 Vegetation controls on northern high latitude snow-albedo feedback: observations and CMIP5 model simulations *Glob. Change Biol.* **20** 594–606

Luo Y, Ahlström A, Allison S D, Batjes N H, Brovkin V, Carvalhais N, Chappell A, Ciais P, Davidson E A and Finzi A 2016 Toward more realistic projections of soil carbon dynamics by Earth system models *Glob. Biogeochem. Cycles* **30** 40–56

Luo Y *et al* 2012 A framework for benchmarking land models *Biogeosci.* **9** 3857–74

Mack M C, Schuur E A G, Bret-Harte M S, Shaver G R and Chapin F S 2004 Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization *Nature* **431** 440–3

McGuire A, Anderson L G, Christensen T R, Dallimore S, Guo L, Hayes D J, Heimann M, Lorenson T D, Macdonald R W and Roulet N 2009 Sensitivity of the carbon cycle in the Arctic to climate change *Ecol. Monogr.* **79** 523–55

McGuire A, Chapin F S, Walsh J E and Wirth C 2006 Integrated regional changes in Arctic climate feedbacks: implications for the global climate system *Annu. Rev. Environ. Resour.* **31** 61–91

McGuire A *et al* 2012 An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions *Biogeosci.* **9** 3185–204

Melton J R *et al* 2013 Present state of global wetland extent and wetland methane modelling: conclusions from a model inter-comparison project (WETCHIMP) *Biogeosci.* **10** 753–88

Myneni R B, Keeling C D, Tucker C J, Asrar G and Nemani R R 1997 Increased plant growth in the northern high latitudes between 1981–1991 *Nature* **386** 1380–93

Natali S M, Schuur E A G and Rubin R L 2012 Increased plant productivity in Alaskan tundra as a result of experimental warming of soil and permafrost *J. Ecol.* **100** 488–98

Niu G Y, Yang Z L, Mitchell K E, Chen F, Ek M B, Barlage M, Kumar A, Manning K, Niyogi D and Rosero E 2011 The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements *J. Geophys. Res.: Atmos.* **116** 1–19

Noh M-J and Howat I M 2015 Automated stereo-photogrammetric DEM generation at high latitudes: surface Extraction with TIN-based search-space minimization (SETSM) validation and demonstration over glaciated regions *GIScі. Remote Sens.* **52** 198–217

Oechel W C, Hastings S J, Vourlrtis G, Jenkins M, Riechers G and Grulke N 1993 Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source *Nature* **361** 520–3

Oechel W C, Laskowski C A, Burba G, Gioli B and Kalhori A A 2014 Annual patterns and budget of $CO_2$ flux in an Arctic tussock tundra ecosystem *J. Geophys. Res.: Biogeosci.* **119** 323–39

Olefeldt D, Turetsky M R, Crill P M and McGuire A D 2013 Environmental and physical controls on northern terrestrial methane emissions across permafrost zones *Glob. Change Biol.* **19** 589–603

Overpeck J *et al* 1997 Arctic environmental change of the last four centuries *Science* **278** 1251–6

Parmentier F J W, Zhang W, Mi Y, Zhu X, Huissteden J, Hayes D J, Zhuang Q, Christensen T R and McGuire A D 2015 Rising methane emissions from northern wetlands associated with sea ice decline *Geophys. Res. Lett.* **42** 7214–22

Pavlick R, Drewry D T, Bohn K, Reu B and Kleidon A 2013 The Jena diversity-dynamic global vegetation model (JeDi-DGVM): a diverse approach to representing terrestrial biogeography and biogeochemistry based on plant functional trade-offs *Biogeosciences* **10** 4137–77

Piao S *et al* 2013 Evaluation of terrestrial carbon cycle models for their response to climate variability and to $CO_2$ trends *Glob. Change Biol.* **19** 2117–32

Qian H, Joseph R and Zeng N 2010 Enhanced terrestrial carbon uptake in the northern high latitudes in the 21st century from the coupled carbon cycle climate model intercomparison project model projections *Glob. Change Biol.* **16** 641–56

Rogers A, Serbin S P, Ely K S, Sloan V L and Wullschleger S D 2017 Terrestrial biosphere models underestimate photosynthetic capacity and $CO_2$ assimilation in the Arctic *New Phytol.* **216** 1090–1103

Schädel C, Bader M K-F, Schuur E A, Biasi C, Bracho R, Čapek P, De Baets S, Diáková K, Ernakovich J and Estop-Aragones C 2016 Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils *Nat. Clim. Change* **6** 950–3

Schaefer K, Jafarov E, Piper M and Schwalm C 2016 A permafrost benchmark system to evaluate permafrost models *ILaMB* (Washington, DC)

Schaefer K, Lantuit H, Romanovsky V E, Schuur E A and Witt R 2014 The impact of the permafrost carbon feedback on global climate *Environ. Res. Lett.* **9** 085003

Schaefer K, Zhang T, Bruhwiler L and Barrett A P 2011 Amount and timing of permafrost carbon release in response to climate warming *Tellus* B **63** 165–80

Schuur E and Abbott B 2011 Climate change: high risk of permafrost thaw *Nature* **480** 32–3

Schuur E *et al* 2013 Expert assessment of vulnerability of permafrost carbon to climate change *Clim. Change* **119** 359–74

Schuur E, McGuire A, Schädel C, Grosse G, Harden J, Hayes D, Hugelius G, Koven C, Kuhry P and Lawrence D 2015 Climate change and the permafrost carbon feedback *Nature* **520** 171

Schuur E, Vogel J G, Crummer K G, Lee H, Sickman J O and Osterkamp T E 2009 The effect of permafrost thaw on old carbon release and net carbon exchange from tundra *Nature* **459** 556–9

Screen J A and Simmonds I 2010 The central role of diminishing sea ice in recent Arctic temperature amplification *Nature* **464** 1334

Serreze M C and Barry R G 2011 Processes and impacts of Arctic amplification: a research synthesis *Glob. Planet. Change* **77** 85–96

Sitch S, Friedlingstein P, Gruber N, Jones S, Murray-Tortarolo G, Ahlström A, Doney S C, Graven H, Heinze C and Huntingford C 2015 Recent trends and drivers of regional sources and sinks of carbon dioxide *Biogeosciences* **12** 653–79

Sitch S, McGuire A D, Kimball J, Gedney N, Gamon J, Engstrom R, Wolf A, Zhuang Q, Clein J and McDonald K C 2007 Assessing the carbon balance of circumpolar Arctic tundra using remote sensing and process modeling *Ecol. Appl.* **17** 213–34

Snyder P K and Liess S 2014 The simulated atmospheric response to expansion of the Arctic boreal forest biome *Clim. Dyn.* **42** 487–503

Stofferahn E, Fisher J B, Hayes D J, Huntzinger D N and Schwalm C 2016 How well does your model capture the terrestrial ecosystem dynamics of the Arctic-boreal region *American Geophysical Union Fall Meeting* (San Francisco)

Thornton P E *et al* 2002 Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests *Agric. Forest Meteorol.* **113** 185–222

Tian H, Chen G, Lu C, Xu X, Hayes D J, Ren W, Pan S, Huntzinger D N and Wofsy S C 2014 North American terrestrial $CO_2$ uptake largely offset by $CH_4$ and $N_2O$ emissions: toward a full accounting of the greenhouse gas budget *Clim. Change* **129** 413–26

Tian H, Lu C, Yang J, Banger K, Huntzinger D N, Schwalm C R, Michalak A M, Cook R, Ciais P and Hayes D 2015 Global patterns and controls of soil organic carbon dynamics as simulated by multiple terrestrial biosphere models: current status and future directions *Glob. Biogeochem. Cycles* **29** 775–92

Turetsky M R, Kane E S, Harden J W, Ottmar R D, Manies K L, Hoy E and Kasischke E S 2011 Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands *Nat. Geosci.* **4** 27

Wang Y P, Law R M and Pak B 2010 A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere *Biogeosciences* **7** 2261–82

Winton M 2006 Amplified Arctic climate change: what does surface albedo feedback have to do with it? *Geophys. Res. Lett.* **33** 1–4

Wullschleger S D, Hinzman L D and Wilson C J 2011 Planning the next generation of Arctic ecosystem experiments *Eos Trans. AGU* **92** 145

Xue Y, Sellers P J, Kinter J L and Shukla J 1991 A simplified biosphere model for global climate studies *J. Clim.* **4** 345–64

Zeng N, Qian H, Roedenbeck C and Heimann M 2005 Impact of 1998–2002 midlatitude drought and warming on terrestrial ecosystem and the global carbon cycle *Geophys. Res. Lett.* **32** L22709

Zhang Z, Zimmermann N E, Kaplan J O and Poulter B 2016 Modeling spatiotemporal dynamics of global wetlands: comprehensive evaluation of a new sub-grid TOPMODEL parameterization and uncertainties *Biogeosciences* **13** 1387–408

Zhang Z, Zimmermann N E, Stenke A, Li X, Hodson E L, Zhu G, Huang C and Poulter B 2017 Emerging role of wetland methane emissions in driving 21st century climate change *Proc. Natl Acad. Sci.* **114** 9647–52

Zimov S A, Schuur E A G and Chapin F S 2006 Permafrost and the global carbon budget *Science* **312** 1612–3

Zona D, Gioli B, Commane R, Lindaas J, Wofsy S C, Miller C E, Dinardo S J, Dengel S, Sweeney C and Karion A 2016 Cold season emissions dominate the Arctic tundra methane budget *Proc. Natl Acad. Sci.* **113** 40–5