## ENVIRONMENTAL RESEARCH LETTERS

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# Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment

To cite this article: Benjamin W Abbott et al 2016 Environ. Res. Lett. 11 034014

#### Manuscript version: Accepted Manuscript

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1	Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire:
2	an expert assessment.
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#### 92 Abstract

As the permafrost region warms, its large organic carbon pool will be increasingly vulnerable to decomposition, combustion, and hydrologic export. Models predict that some portion of this release will be offset by increased production of Arctic and boreal biomass; however, the lack of robust estimates of net carbon balance increases the risk of further overshooting international emissions targets. Precise empirical or model-based assessments of the critical factors driving carbon balance are unlikely in the near future, so to address this gap, we present estimates from 98 permafrost-region experts of the response of biomass, wildfire, and hydrologic carbon flux to climate change. Results suggest that contrary to model projections, total permafrost-region biomass could decrease due to water stress and disturbance, factors that are not adequately incorporated in current models. Assessments indicate that end-of-the-century organic carbon release from Arctic rivers and collapsing coastlines could increase by 75% while carbon loss via burning could increase four-fold. Experts identified water balance, shifts in vegetation community, and permafrost degradation as the key sources of uncertainty in predicting future system response. In combination with previous findings, results suggest the permafrost region will become a carbon source to the atmosphere by 2100 regardless of warming scenario but that 65 to 85% of permafrost carbon release can still be avoided if human emissions are actively reduced.

a target of limiting warming to 2°C above pre-industrial

111	Introduction
112	Permafrost zone carbon balance
113	The United Nations has set

temperatures to mitigate risk of the most damaging consequences of climate change (UNEP, 2013). Maintaining global climate within this target depends on understanding ecosystem feedbacks to climate change so that adequate limits on human emissions can be set. As high latitudes warm, more of the large permafrost carbon pool will be exposed to decomposition, combustion, and hydrologic export (Harden et al., 2012; Schuur et al., 2015). Up to 220 Petagrams (Pg) carbon could be released from permafrost-region soil by 2100, and 500 Pg by 2300 (Schuur et al., 2013; MacDougall et al., 2012), representing 10 to 30% of greenhouse gas emissions required to push the global climate system beyond the 2°C target (Schaefer et al., 2014). Models project that some permafrost carbon release will be offset by increases in Arctic and boreal primary productivity due to extended growing season, CO<sub>2</sub> fertilization, and nutrient release from decomposing soil organic matter. However, many processes and dynamics known to influence biomass accumulation, such as ecosystem disturbance and nutrient limitation, are incompletely represented or absent in current models (Qian et al., 2010; Koven et al., 2011; Schaefer et al., 2011; Koven et al., 2015b). Likewise, only a few models projecting future permafrost carbon release consider wildfire emissions, and none include hydrologic carbon flux (MacDougall et al., 2012; Koven et al., 2011; Qian et al., 2010; Schaefer et al., 2014; Schaefer et al., 2011), though past hydrologic flux has been simulated (McGuire et al., 2010; Kicklighter et al., 2013; Laudon et al., 2012). Despite clear policy implications of this climate feedback, considerable uncertainty of both carbon inputs and outputs limits our ability to model carbon balance of the permafrost region. To bring to bear the best available quantitative and qualitative scientific information (Joly et al., 2010) on this climate feedback, we present results from expert assessment surveys indicating that there

is little consensus on the magnitude and even sign of change in high-latitude biomass, whereas most researchers expect fire emissions and hydrologic organic carbon flux to substantially increase by the end of the century.

**Expert** assessment

When data are sparse but management decisions are pressing, expert judgements have long been used to constrain possible system response and risk of dangerous or undesired outcomes (Zickfeld et al., 2010; Morgan, 2014). There are multiple methods for collecting and combining expert opinion including formal expert elicitation interviews, interactive software, and surveys (Aspinall, 2010; Morgan, 2014; Javeline et al., 2013). While expert assessment cannot definitively answer questions of future system response, it complements modeling and empirical approaches by allowing the synthesis of formal and informal system information and by identifying research priorities (Fig. 1; Morgan, 2014; Sutherland et al., 2013). The approach is similar to the concept of ensemble models where multiple estimates built on different assumptions and data provide a more robust estimate and measure of variance. Because the experimental unit is an individual researcher, each data point represents an integration of quantitative knowledge from modeling, field, and laboratory studies as well as qualitative information based on professional opinion and personal experience with the system. Expert assessment has been used in risk assessment and forecasting of natural disasters, human impacts on ecosystems, and tipping points in the climate system (Aspinall, 2010; Halpern et al., 2008; Lenton et al., 2008). In a data-limited environment such as the permafrost region, expert assessment allows formal consideration of a range of factors known to affect carbon balance but insufficiently quantified for inclusion in models. For permafrost carbon balance, these factors include nutrient dynamics, non-linear shifts in vegetation community, human disturbance, land-water interactions, and the relationship of permafrost degradation with water balance.

Because precise empirical or model-based assessments of the critical factors driving permafrost-region carbon balance are unlikely in the near future (Harden *et al.*, 2012), we collected estimates of the components of net ecosystem carbon balance from 98 permafrostregion experts (Table 1). We had two major goals: 1. Assess current understanding of the timing and magnitude of non-soil biomass accumulation, hydrologic organic carbon flux, and wildfire carbon emissions, and 2. Identify major sources of uncertainty in high-latitude carbon balance to inform future research.

168 Methods

#### 169 Survey development and design

In the fall of 2013 we administered three expert assessments to address knowledge gaps concerning the response of permafrost-region biomass, wildfire, and hydrologic carbon flux to climate change. Development of assessment methodology began in early 2009 as a part of the Dangerous Climate Change Assessment Project administered by the University of Oxford. We iteratively revised questions, response format, and background information based on four rounds of input from participants, including at the Vulnerability of Permafrost Carbon Research Coordination Network meeting in Seattle 2011 (Schuur et al., 2013). To help survey participants consider all of the evidence available from field and modeling studies, we distributed a system summary document for each questionnaire including regional and pan-Arctic estimates of current carbon pools and fluxes, a brief treatment of historical trends, and a summary of model projections where available (Table 2; Supplementary information Questionnaires and System summaries).

Final Participants were selected based on contribution to peer-reviewed literature or
Participants were selected based on contribution to peer-reviewed literature or
referrals from other experts and had experience in all major boreal and Arctic regions (Table
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1). We identified potential participants by querying Thomas Reuters Web of Science
(webofknowledge.com) with applicable search terms (e.g. Arctic, boreal, biomass, dissolved

organic carbon, fire, permafrost). To reach researchers with applicable expertise who were underrepresented in the literature, we supplemented the list with personal referrals from lead experts and all participants. In total 256 experts were invited to participate. We distributed the surveys and system summaries via email with a two-week deadline. After sending out three reminders and accepting responses for three months after initial invitation, we received 115 responses from 98 experts (38% response rate), with 15 experts participating in more than one survey (Supplementary information List of experts). Experts who provided estimates and input to this paper are coauthors.

Experts provided quantitative estimates of change in biomass, hydrologic flux, or wildfire for three time points (2040, 2100, and 2300), and four regional warming scenarios based on representative concentration pathway (RCP) scenarios from the IPCC Fifth Assessment Report (Moss et al., 2010). Warming scenarios ranged from cessation of human emissions before 2100 (RCP2.6) to sustained human emissions (RCP8.5) and corresponded to permafrost-region mean annual warming of 2 to 7.5°C by 2100. All surveys were driven by the same scenarios of high-latitude warming generated from RCP2.6, 4.5, 6.0, and 8.5 with the National Center for Atmospheric Research's Community Climate System Model 4 (Lawrence et al., 2012). For the purposes of this survey, warming was assumed to stabilize at 2100 levels for all scenarios so that estimates for the 2300 time point would account for lags in ecosystem responses to climate drivers. While climate scenarios were defined by temperature, we asked experts to consider all accompanying direct climate effects (e.g. temperature, precipitation, and atmospheric CO<sub>2</sub>) and indirect effects (e.g. vegetation shifts, permafrost degradation, invasive species, and disturbance). Experts were encouraged to consider all available formal and informal information when generating their estimates including published and unpublished modeled and empirical data as well as professional judgment. Participants listed the major sources of uncertainty in their estimates, self-rated

their confidence and expertise for each question, described rationale for their estimates, andprovided background information (Tables 1 and S1).

The biomass survey consisted of a single question asking for cumulative change in tundra and boreal non-soil biomass including above and belowground living biomass, standing deadwood, and litter. The wildfire survey asked for estimates of change in wildfire extent and CO<sub>2</sub> emissions for the boreal and tundra regions to assess changes in both fire extent and severity. The hydrologic flux survey asked for estimates of dissolved and particulate organic carbon (DOC and POC, respectively) delivery to freshwater ecosystems in the pan-Arctic watershed and delivery to the Arctic Ocean and surrounding seas via riverine flux and coastal erosion, allowing the calculation of losses during transport due to burial or mineralization. Dissolved inorganic carbon fluxes were not included in this survey.

The original questionnaires in 2009 asked for participants to estimate subjective 95% confidence intervals of the whole system response (e.g. total change in high-latitude biomass). Based on expert input during subsequent testing we disaggregated the system into different components to encourage detailed consideration of possibly competing dynamics (e.g. asking for separate estimates of boreal forest and Arctic tundra response; Morgan, 2014). This resulted in a large response table for each question (72-102 quantitative estimates), which we found caused respondent fatigue and decreased the number of experts willing to participate. As a compromise, we asked respondents to provide a single best estimate and indicate confidence with a five-point scale (Table S1). While analysis of best estimates can return narrower uncertainty ranges than subjective probability distributions (Morgan, 2014), we believe this tradeoff resulted in broader expert participation, better representing diversity of opinion across disciplines and compensating for possible underestimation of variability and uncertainty.

<sup>60</sup> 235 Analysis and calculations

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We calculated basic summary statistics, using median values to estimate center and interguartile ranges (IOR) to estimate spread. To calculate the portion of permafrost carbon release offset by biomass accumulation, we combined estimates from this study with reanalyzed data from Schuur et al. (2013). The low IQR for carbon release offset by biomass growth was calculated by dividing the low IQR of uptake by the upper IQR of carbon release and conversely for the high IQR (Fig. 3). All analyses were performed in R 3.0.2. The complete dataset of quantitative estimates and comments from survey participants stripped of personal identifiers is available at www.aoncadis.org/dataset/Permafrost\_carbon\_balance\_survey.html. **Results Carbon pools and fluxes** Expert estimates revealed diverging views on the response of boreal biomass to warming, with over a third of estimates predicting a decrease or no change in boreal biomass across scenarios and time periods (Fig. 2). While median change in boreal biomass was similar across warming scenarios for each time step (3, 9, and 11% increases by 2040, 2100, and 2300, respectively; Figs. 2 and S1), variability was much higher for warmer scenarios. Consequently, all of the interquartile ranges of change in boreal biomass for RCP6.0 and RCP8.5 included zero. Experts projecting a decrease in boreal biomass attributed their estimates primarily to water-stress and disturbance such as fire and permafrost degradation. In contrast, there was general agreement that tundra biomass would respond positively to warming, with end-of-century increases of 6 to 30% projected for RCP2.6 and 10 to 90% for RCP8.5. Because of these contrasting responses to increased warming, tundra accounted for 40% of total biomass gain by 2300 for RCP8.5, though it currently constitutes less than 10% of total permafrost region biomass (based on median values in Fig. 2; Fig. 3a; Table 2). Estimates of boreal biomass were generally symmetrically distributed while tundra biomass 

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#### CONFIDENTIAL - AUTHOR SUBMITTED MANUSCRIPT ERL-102110.R1

estimates were right-skewed, and most datasets had 1 to 4 estimates beyond 1.5 times the interguartile range (Fig. S2). Self-rated confidence was higher for tundra than for boreal forest, but was below 3 (moderately confident) in both cases (Table S1), highlighting considerable uncertainty of individual estimates in addition to variability among respondents. Experts projected major shifts in both fire and hydrologic carbon regimes, with up to a 75% increase of riverine organic carbon flux to the ocean and a four-fold increase in fire emissions by 2100 for RCP8.5 based on interquartile ranges (Fig. 2 and S1). Fire and hydrologic carbon release estimates peaked at 2100, followed by a 10 to 40% decrease by 2300. In contrast to biomass, the response of both fire-driven and hydrologic carbon flux varied strongly by warming scenario, with RCP8.5 resulting in 2 to 6 times more carbon release than RCP2.6. While the boreal forest dominated total wildfire emissions, the relative change in tundra fire emissions was 1.5 and 2-fold greater than the relative boreal response for 2100 and 2300, respectively (Fig. S1). Increases in fire emissions were attributed to changes in fire extent rather than severity, which varied less than 5% among scenarios and time periods. Though dissolved organic carbon (DOC) represented the majority of total hydrologic organic carbon release, experts projected higher relative increases for coastal particulate organic carbon (POC), with end-of-the-century increases of 6 to 50% for RCP2.6 and 13 to 190% for RCP8.5. There was a lack of consensus on the response of DOC delivery to the ocean, with 21% of estimates predicting a decrease or no change. Experts predicting a decrease attributed their estimates to increased mineralization, changes in hydrologic flowpath, and changes in DOC photo- and bio-lability (Corv et al., 2014; Abbott et al., 2014). Responses indicated no change in the proportion of organic carbon mineralized or trapped in sediment before reaching the ocean, with 63-69% of DOC and 68-74% of POC lost in transport. Fire and hydrologic carbon flux estimates were strongly right-skewed with a few experts projecting extreme change well beyond 1.5 times the interquartile range for each 

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timestep and warming scenario combination (Figs. S3 and S4). Average self-rated confidence
was between 2 and 3 for all questions except tundra fire emissions which had average
confidence of 2.0 and 1.7 (Table S1).

289 Sources of uncertainty

Along with quantitative estimates of carbon balance, experts identified sources of uncertainty currently limiting the prediction of system response to climate change (Table 3). Water balance, including precipitation, soil moisture, runoff, infiltration, and discharge, was the most frequently mentioned source of uncertainty for both biomass and hydrologic organic carbon flux, and the second most mentioned for wildfire. Many experts noted that water balance is as or more important than temperature in controlling future carbon balance, yet projections of water balance are less well constrained (Zhang et al., 2013; Bintanja and Selten, 2014). Almost three-quarters of wildfire experts identified the future distribution of vegetation as the primary source of uncertainty in projecting wildfire, noting strong differences in flammability between different boreal and tundra species. Permafrost degradation was identified as an important source of uncertainty for biomass, hydrologic flux, and wildfire, due to both disturbance from ground collapse (thermokarst) and interactions with water-table dynamics and surface soil moisture as deeper thaw affects soil drainage. Discussion

**Carbon balance** 

Arctic tundra and boreal forest have accumulated a vast pool of organic carbon, twice as large as the atmospheric carbon pool and three times as large as the carbon contained by all living things (Hugelius et al., 2014; Schuur et al., 2015). Over the past several decades, the permafrost region has removed an average of 500 Tg carbon yr<sup>-1</sup> from the atmosphere (McGuire et al., 2009; Pan et al., 2011; Hayes et al., 2011). Combining our estimates of biomass uptake with a recent projection of permafrost soil carbon release (Schuur et al.,

2013) suggests that the permafrost region will become a carbon source to the atmosphere by 2100 for all warming scenarios (Fig. 3b). Experts predicted that boreal and Arctic biomass could respond more quickly to warming than soil carbon release, offsetting -33 to 200% of mid-century emissions from permafrost-region soil (Fig. 3b). However, because estimates of change in biomass are similar across warming scenarios but permafrost carbon release is strongly temperature-sensitive, the emissions gap widens for warmer scenarios, resulting in 5-times more net carbon release under RCP8.5 than RCP2.6. This suggests that 65 to 85% of permafrost carbon release could be avoided if human emissions are actively reduced—*i.e.* if emissions follow RCP2.6 instead of RCP8.5 (Fig. 4).

#### **Comparison with quantitative models**

Model projections of future boreal and Arctic biomass agree in sign but vary widely in magnitude, with increases of 9 to 61 Pg carbon projected by 2100 (Qian et al., 2010; Koven et al., 2011; Schaefer et al., 2011; Falloon et al., 2012). While some of these models fall within the range estimated here of -20 to 28 Pg carbon by 2100, none include zero or negative change in biomass as predicted by over a third of participants in our expert assessment. Two potential reasons for this disagreement are an overestimation of the effect of CO<sub>2</sub> fertilization or an underestimation of the role of disturbance in some models. Firstly, CO<sub>2</sub> fertilization exerts a larger effect on carbon balance than all other climate effects in many models (Balshi et al., 2009), with up to 88 Pg carbon difference between model runs with and without CO<sub>2</sub> fertilization effects for some models (Koven *et al.*, 2011). However, there is little field evidence that CO<sub>2</sub> fertilization results in long-term biomass accumulation in tundra and boreal ecosystems (Hickler et al., 2008; Peñuelas et al., 2011; Gedalof and Berg, 2010). Additionally, many models with large CO<sub>2</sub> effects do not include other limiting factors, such as nutrients and water, known to interact with CO<sub>2</sub> fertilization (Hyvonen et al., 2007; Yarie and Van Cleve, 2010; Thornton et al., 2007; Koven et al., 2015a; Maaroufi et al., 

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2015). Secondly, models that do not account for disturbance such as wildfire, permafrost
collapse, insect damage, and human resource extraction likely overestimate the positive
response of biomass to climate change (Kurz *et al.*, 2008; Abbott and Jones, 2015; Hewitt *et al.*, 2015).

Considering the scenario of a complete biome shift is useful in evaluating both model projections of change and estimates from our expert assessment. If all boreal forest became temperate forest, living biomass would increase by 27%, resulting in the uptake of 16 Pg carbon based on average carbon densities from both ecosystems (Pan et al., 2011). However, 22 Pg carbon would be lost due to decreases in dead wood and litter, resulting in a net circumboreal loss of 6 Pg carbon. If all tundra became boreal forest, non-soil biomass would increase by 205% (Epstein et al., 2012; Raynolds et al., 2012; Saugier et al., 2001), taking up 17 Pg carbon. This scenario may not represent the upper limit of possible carbon uptake if other unforeseen shifts in C allocation take place; however, it highlights the relatively modest carbon gains probable on century timescales.

While regional projections from models of boreal wildfire vary in sign and magnitude (Supplementary information System summaries), most models agree that at the circumboreal scale, fire emissions will increase several-fold, with increases of 200 to 560% projected by the end of the century (Kloster et al., 2012; Flannigan et al., 2009). Interquartile ranges from our study are somewhat lower (40 to 300%, median 170%), but participant confidence in these estimates was low, suggesting considerable uncertainty in the future response of boreal fire. The 60 to 480% increase in tundra fire projected by our study would represent an even larger ecological shift than experienced by the boreal forest, with implications for regional biomass, habitat, and carbon balance, though there are few models that project changes in tundra fire (Rupp et al., 2000) and none at a circumarctic scale (Mack et al., 2011).

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The production of Arctic DOC and POC depends on abundance of carbon sources in terrestrial ecosystems (influenced by biomass, wildfire, temperature, and permafrost degradation) and the ability of hydrologic flow to transport that carbon (determined by factors such as precipitation, runoff, depth of flow through soil, and coastal erosion; Guo et al., 2007; Kicklighter et al., 2013; Abbott et al., 2015; Larouche et al., 2015). Due to these complexities and others, there are currently no quantitative projections of future DOC and POC flux from the circumarctic. However, estimates from our study suggest a substantial departure from historical rates of change. For RCP8.5, hydrologic organic carbon loading would increase 4-20 times faster in the 21<sup>st</sup> century than it did in the 20<sup>th</sup> (Kicklighter *et al.*, 2013), representing a non-linear response to high-latitude warming. The lack of consensus on the response of DOC, the largest component of hydrologic organic carbon flux, highlights the importance of developing and testing conceptual frameworks to be incorporated into models (Laudon et al., 2012). 

An alternative explanation for differences between expert estimates and modeled projections is the possibility of bias in the group of experts. Participants in our assessment tended to have more field than modeling experience (Table 1) and may have therefore been skeptical of simulated ecosystem responses that have not been observed in the field such as CO<sub>2</sub> fertilization and rapid migration of treeline (McGuire et al., 2009). Because future dynamics cannot always reliably be predicted on the basis of past system behavior, this bias may or may not result in overly conservative estimates. Furthermore, because experts are likely to base projections on the study areas with which they are most familiar, regional differences could be a source of bias. Fundamental differences among regions in the response of DOC flux and fire-regime to warming have been observed (Kicklighter et al., 2013; de Groot et al., 2013; Supplementary information System summaries). Asia, which represents more than half of the total permafrost region, was under-represented in all three surveys,

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particularly wildfire (Table 1). However, the regional bias in this study may not be greater
than that of model projections, which depend on observational and experimental data that are
not evenly distributed throughout the permafrost region.

**388** Reducing uncertainty surrounding the permafrost carbon feedback

Experts identified water balance, vegetation distribution, and permafrost degradation as the most important sources of uncertainty in predicting the timing and magnitude of the permafrost carbon feedback (Table 3). These three processes are closely interconnected by several internal feedbacks (Jorgenson et al., 2013; Shur and Jorgenson, 2007; Anisimov and Reneva, 2006; Girardin et al., 2016). For example, wildfire or drought can trigger a transition from coniferous to deciduous dominance, warming permafrost by up to 7°C due to loss of insulating moss and associated changes (Shur and Jorgenson, 2007; Sturm et al., 2001; Yarie and Van Cleve, 2010). The subsequent recovery trajectories of vegetation and permafrost, as well as the proportion of thawed carbon released CO<sub>2</sub> or CH<sub>4</sub>, then depend largely on near-surface hydrologic conditions (Myers-Smith et al., 2008; O'Donnell et al., 2011; Jorgenson et al., 2010; Chapin et al., 2010; Lawrence et al., 2015; Payette et al., 2004). These interdepencies mean that improving projections of the permafrost carbon feedback will require conceptualizing these parameters together. The question of water balance is additionally important in Arctic and boreal ecosystems where hydrologic carbon flux can be the determining factor causing net carbon uptake or release (Kling *et al.*, 1991; Raymond *et* al., 2013; Aufdenkampe et al., 2011). The lack of model projections of hydrologic carbon fluxes is a major gap in our ability to estimate the permafrost carbon feedback.

406 The permafrost region has responded differently to various climatic perturbations in
407 the past, representing another tool to constrain possible future response (Zachos *et al.*, 2008).
408 During the Paleocene-Eocene Thermal Maximum, high-latitude temperature warmed more
409 than 10°C, causing almost complete loss of permafrost and the mineralization of most

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permafrost soil organic matter (DeConto et al., 2012; Bowen and Zachos, 2010). More recently, the 2-4°C warming at high-latitudes during the early Holocene caused active-layer deepening throughout the permafrost region but did not trigger complete permafrost loss or widespread carbon release (French, 1999; Schirrmeister et al., 2002; Jorgenson et al., 2013). While there are many differences between the Paleozoic and Holocene warming events, one clear distinction is the degree of warming. There may have been a threshold between 4 and 10°C high-latitude warming due to positive feedbacks such as a shift from a coniferous to a deciduous dominated system or an abrupt change in hydrology. If a tipping point does exist between 4 and 10°C high-latitude warming, it would fall between scenarios RCP4.5 and RCP8.5, representing maximum atmospheric CO<sub>2</sub> of 650 and 850 ppm, respectively (Moss et al., 2010; Lawrence et al., 2012). RCP4.5 is still widely accepted as politically and technically attainable, though it assumes global CO<sub>2</sub> emissions peak before 2050 and decrease by half by 2080 (Moss et al., 2010).

423 Conclusions

The permafrost climate feedback has been portrayed in popular media (and to a lesser extent in peer-reviewed literature) as an all-or-nothing scenario. Permafrost greenhouse gas release has been described as a tipping point, a runaway climate feedback, and, most dramatically, a time bomb (Wieczorek et al., 2011; Treat and Frolking, 2013; Whiteman et al., 2013). On the other extreme, some have dismissed the importance of this feedback, asserting that increases in biomass will offset any carbon losses from soil, or that changes will occur too slowly to concern current governments (Idso et al., 2014). Our study highlights that Arctic and boreal biomass should not be counted on to offset permafrost carbon release and suggests that the permafrost region will become a carbon source to the atmosphere by 2100 regardless of warming scenario. Perhaps more importantly, our results indicate a 5-fold difference in emissions between the business as usual scenario (RCP8.5) and active reduction

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human emissions (RCP2.6), suggesting that up to 85% of carbon release from the mafrost region can still be avoided, though the window of opportunity for keeping that bon in the ground is rapidly closing. Models projecting a strong boreal carbon sink and dels that do not consider hydrologic and fire emissions may substantially underestimate carbon release from the permafrost region. If such projections are used as the basis for issions negotiations, climate targets are likely to be overshot.

#### knowledgments

Peter J. Fix provided valuable input on the methods and manuscript. This work was ported by the National Science Foundation ARCSS program and Vulnerability of mafrost Carbon Research Coordination Network (grants OPP-0806465, OPP-0806394, 1955713) with additional funding from SITES (Swedish Science Foundation) and Future rest (Mistra). This work complies with the U.S. HHS Policy for Protection of Human search Subjects. Any use of trade, firm, or product names is for descriptive purposes only does not imply endorsement by the U.S. Government.

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Figure 1. Conceptual model of the role of expert assessment in generating and communicating scientific understanding. Modelling and field research generate quantitative and qualitative understanding of the system (in this case the permafrost zone). Expert assessment synthesizes current understanding including qualitative information not yet included in numerical models or field studies. These syntheses provide perspective to the scientific community and wholistic summaries of the state of the knowledge to the nonscientific community with the goal of improving management of the system. 

Figure 2. Estimates of change in non-soil biomass, wildfire emissions, and hydrologic carbon flux from the permafrost region for four warming scenarios at three time points. All values represent change from current pools or fluxes reported in Table 2. Biomass includes above and belowground living biomass, standing deadwood, and litter. Dissolved and particulate organic carbon (DOC and POC respectively) fluxes represent transfer of carbon from terrestrial to aquatic ecosystems. "Coast" represents POC released by coastal erosion. Representative concentration pathway (RCP) scenarios range from aggressive emissions reductions (RCP2.6) to sustained human emissions (RCP8.5). Box plots represent median, quartiles, and minimum and maximum within 1.5 times the interquartile range. Relative change (percent change from current state) is presented in Fig. S1 and full distributions are presented in Figs. S2 to S4.

Figure 3. Total change in non-soil biomass (a) and percentage of permafrost region carbon release offset by change in non-soil biomass (b). Estimates of permafrost carbon release used in estimating percentage offset are recalculated from data presented in Schuur et al. (2013). See Fig. 2 for definition of RCP scenarios and symbology. Error bars represent propogated

error between the interquartile ranges of carbon release from permafrost soil and carbonuptake by biomass (see Methods).

Figure 4. A comparison of soil carbon release recalculated from Schuur et al. (2013) and non-soil biomass uptake in the permafrost region from this study for the business as usual scenario (RCP8.5) and the active reduction of human emissions scenario (RCP2.6). Polygons represent median cumulative change and dotted lines represent the interquartile range. Biomass carbon uptake is overlayed on soil carbon release to show the proportion of carbon release potentially offset by biomass. Linear rates of change were assumed between the three

- 758 dates where estimates were provided.

<b>Table 1.</b> Composition and characteristics of participant group						
	Biomass	Wildfire	Hydrologic flux			
Number of respondents	46	34	35			
Average responses per question*	41	28	32			
Primary region of study						
Asia	10	3	8			
Europe	12	5	9			
North America	27	27	18			
Circumpolar	12	6	9			
Primary biome of study						
Arctic	31	13	27			
Boreal	27	29	18			
Both	14	9	12			
Average modeling/field self rating**	3.6	3.7	4.1			
Combined years of experience	762	533	521			
Ratio male:female	2.6	2.8	4.9			

**T** 1 1 C • . • ما ما م atomistics of participant

Background information on survey participants. Experts could indicate multiple regions and 

biomes of study. \*Not all experts provided estimates for all questions. \*\*Experts rated 

themselves on a 1-5 scale where 1=exclusive modeler and 5=exclusive field researcher. 

Biomass					
A	Aboveground biomass	Belowground	biomass <sup>a</sup> Dead woo	d <sup>b</sup> Litter	Total non-soil biomass
Boreal forest (Pg C)	43.6 <sup>c</sup>	16.1	16	27 <sup>b</sup>	102.7
Arctic Tundra (Pg C)	2.4 <sup>d</sup>	4.0		2 <sup>e</sup>	8.4
Wildfire					
	Boreal forest (Eura	isia) Boreal	orest (N. America)	Total Boreal fore	st <sup>f</sup> Total Tundr
Area burned (km <sup>2</sup> yr <sup>-1</sup> )	62,100		22,500	84,600	4,200 <sup>g</sup>
CO <sub>2</sub> emissions from fire (Tg C yr	<sup>1</sup> ) 194		56		8 <sup>h</sup>
Hydrologic organic carbon flux					
· · · · ·		DOC	POC (Riverine)	POC (coasta	al) Total OC
Delivery to freshwater ecosystems (Tg yr <sup>-1</sup> )		100 <sup>c</sup>	$20^{i}$	na	120
Delivery to Arctic Ocean and surrounding seas (Tg yr <sup>-1</sup> )		36 <sup>j</sup>	6 <sup>c</sup>	18 <sup>ck</sup>	60

<sup>764</sup> "Saugier *et al.*, 2001, "Pan *et al.*, 2011, "McGuire *et al.*, 2009, "Epstein *et al.*, 2012, "Potter and Klooster, 1997, "Baisn *et al.*, 2007, Giglio *et al.*, 2010;
 <sup>765</sup> Hayes *et al.*, 2011; van der Werf *et al.*, 2010, "Rocha *et al.*, 2012, "Mack *et al.*, 2011, "Aufdenkampe *et al.*, 2011; Battin *et al.*, 2009, "Holmes *et al.*, 2012, "Konk *et al.*, 2012. Literature-based estimates of belowground biomass were calculated from aboveground or total biomass with ratios from
 <sup>766</sup> Saugier *et al.*, (2001). POC delivery to freshwater ecosystems was calculated from ocean POC delivery with downscaled global ratio of 0.75
 <sup>768</sup> for sedimentation. POC from coastal erosion is the sum of Vonk *et al.*, (2012) and McGuire *et al.*, (2009). Considerable uncertainty remains
 <sup>769</sup> around many of these estimates.

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3	770								
4 5		Table 3. Sources of unce	3. Sources of uncertainty in system response to climate change						
6	Biomass			Wildfire	Hydrologic OC flux				
7		Source of uncertainty	%	Source of uncertainty	%	Source of uncertainty	%		
8		Water balance	56	Vegetation shift	73	Water balance	41		
9		Wildfire	47	Water balance	58	Hydrologic flowpath	39		
10		Permafrost degradation	40	Human disturbance	27	Permafrost degradation	24		
12		Human disturbance	29	Permatrost degradation	18	Photo and bio-lability	24		
13		Insect damage	27	Seasonality	15	Vegetation shift	20		
14		Vegetation shift	24	Regional differences	12	Fluvial erosion	11		
15		Nutriont availability	10						
16		Non-insect herbivores	11						
17	771	Major factors contributin	<u>σ 110</u>	ertainty to projections of fu	iture	system response based on	exnert		
19	772	comments Rank is based	g une l on n	ercent of experts who liste	d eacl	h factor in their responses	Δ11		
20	773	sources listed by 10% or	more	of each group are included	l caci l here	Water balance includes	ЛП		
21	777	comments mentioning pr	ecinit	ation soil moisture runoff	i nere i infil	tration or discharge Perm	afrost		
22	775	degradation includes com	ment	s referring to permafrost of	olland	(thermokarst) and active	laver		
23	776	deepening	mem	is referring to permanost e	onapa	se (mermokarst) and active	ayer		
24 25	770	deepening.							
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