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LETTER

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

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Supplementary material for this article is available online

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%–85% of permafrost carbon release can still be avoided if human emissions are actively reduced.

Introduction

Permafrost zone carbon balance

The United Nations has set a target of limiting warming to 2 °C above pre-industrial 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 (MacDougall *et al* 2012, Schuur *et al* 2013), representing 10%–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_2 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 (Qian *et al* 2010, Koven *et al* 2011, Schaefer *et al* 2011, MacDougall *et al* 2012, Schaefer *et al* 2014), though past hydrologic flux has been simulated (McGuire *et al* 2010, Laudon *et al* 2012, Kicklighter *et al* 2013). 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, Javeline *et al* 2013, Morgan 2014). 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 (figure 1; Sutherland *et al* 2013, Morgan 2014). 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

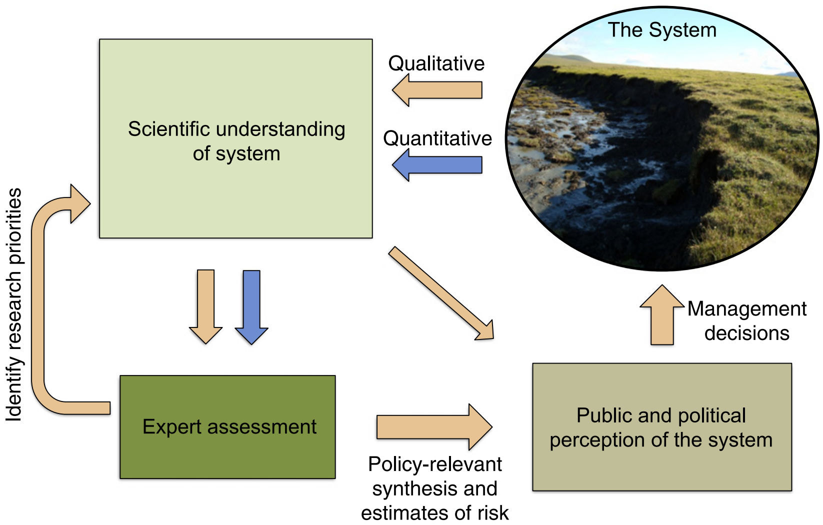

Figure 1. Conceptual model of the role of expert assessment in generating and communicating scientific understanding. Modeling and field research generate quantitative and qualitative understanding of the system (in this case the permafrost zone). Expert assessment synthesizes current understanding including 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 non-scientific community with the goal of improving management of the system.

(Halpern *et al* 2008, Lenton *et al* 2008, Aspinall 2010). 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, nonlinear 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 permafrost-region 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.

Table 1. Composition and characteristics of participant group.

	Biomass	Wildfire	Hydrologic flux
Number of respondents	46	34	35
Average responses per question[a]	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[b]	3.6	3.7	4.1
Combined years of experience	762	533	521
Ratio male:female	2.6	2.8	4.9

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

[a] Not all experts provided estimates for all questions.

[b] Experts rated themselves on a 1–5 scale where 1 = exclusive modeler and 5 = exclusive field researcher.

Methods

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

Table 2. Estimates of current permafrost region organic carbon pools and fluxes. Literature-based estimates of belowground biomass were calculated from aboveground or total biomass with ratios from Saugier *et al* (2001). POC delivery to freshwater ecosystems was calculated from ocean POC delivery with downscaled global ratio of 0.75 for sedimentation. POC from coastal erosion is the sum of Vonk *et al* (2012) and McGuire *et al* (2009). Considerable uncertainty remains around many of these estimates.

Biomass

	Aboveground biomass	Belowground biomass[a]	Dead wood[b]	Litter	Total non-soil biomass
Boreal forest (Pg C)	43.6[c]	16.1	16	27[b]	102.7
Arctic Tundra (Pg C)	2.4[d]	4.0		2[e]	8.4

Wildfire

	Boreal forest (Eurasia)	Boreal forest (N. America)	Total Boreal forest[f]	Total Tundra
Area burned (km^2 yr^{-1})	62 100	22 500	84 600	4200[g]
CO_2 emissions from fire (Tg C yr^{-1})	194	56	250	8[h]

Hydrologic organic carbon flux

	DOC	POC (Riverine)	POC (coastal)	Total OC
Delivery to freshwater ecosystems (Tg yr^{-1})	100[c]	20[i]	na	120
Delivery to Arctic Ocean and surrounding seas (Tg yr^{-1})	36[j]	6[c]	18[ck]	60

[a] Saugier *et al* (2001).
[b] Pan *et al* (2011).
[c] McGuire *et al* (2009).
[d] Epstein *et al* (2012).
[e] Potter and Klooster (1997).
[f] Balshi *et al* (2007), Giglio *et al* (2010), Hayes *et al* (2011), van der Werf *et al* (2010).
[g] Rocha *et al* (2012).
[h] Mack *et al* (2011).
[i] Aufdenkampe *et al* (2011), Battin *et al* (2009).
[j] Holmes *et al* (2012).
[k] Vonk *et al* (2012).

where available (table 2; supplementary information questionnaires and system summaries).

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 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 °C–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_2) 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, and provided background information (table 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_2 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.

Analysis and calculations

We calculated basic summary statistics, using median values to estimate center and interquartile ranges (IQR) 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 (figure 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 (figure 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; figure 2 and S1), variability was much higher for warmer scenarios. Consequently, all of the IQR 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%–30% projected for RCP2.6 and 10%–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 figures 2, 3(a) and table 2). Estimates of boreal biomass were generally symmetrically distributed while tundra biomass estimates were right-skewed, and most datasets had 1–4 estimates beyond 1.5 times the interquartile range (figure 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 fourfold increase in fire emissions by 2100 for RCP8.5 based on IQR (figure 2 and S1). Fire and hydrologic carbon release estimates peaked at 2100, followed by a 10%–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 2–6 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 (figure

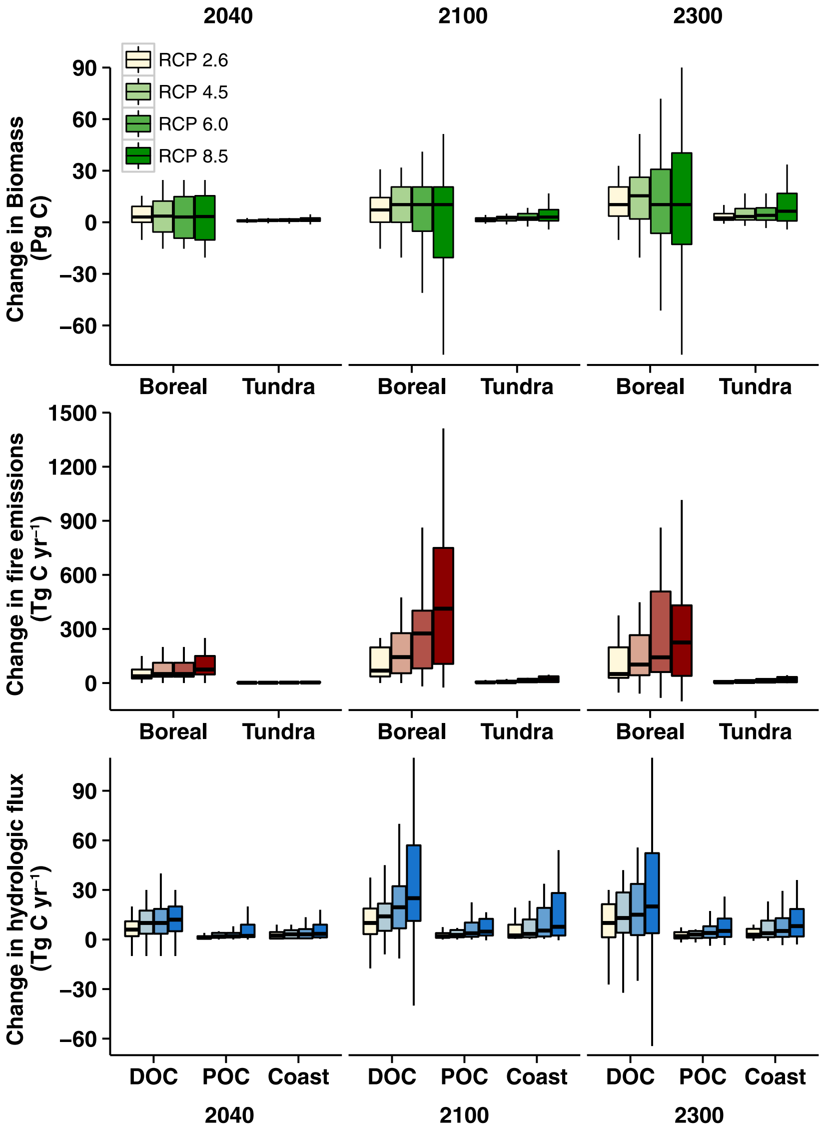

Figure 2. Estimates of change in non-soil biomass, wildfire emissions, and hydrologic carbon flux from the permafrost region for four warming scenarios at three time points. All values represent change from current pools or fluxes reported in table 2. Biomass includes above and belowground living biomass, 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 figure S1 and full distributions are presented in figures S2–S4.

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 POC, with end-of-the-century increases of 6%–50% for RCP2.6 and 13%–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 (Cory *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 timestep and warming scenario combination (figures 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).

Sources of uncertainty

Along with quantitative estimates of carbon balance, experts identified sources of uncertainty currently

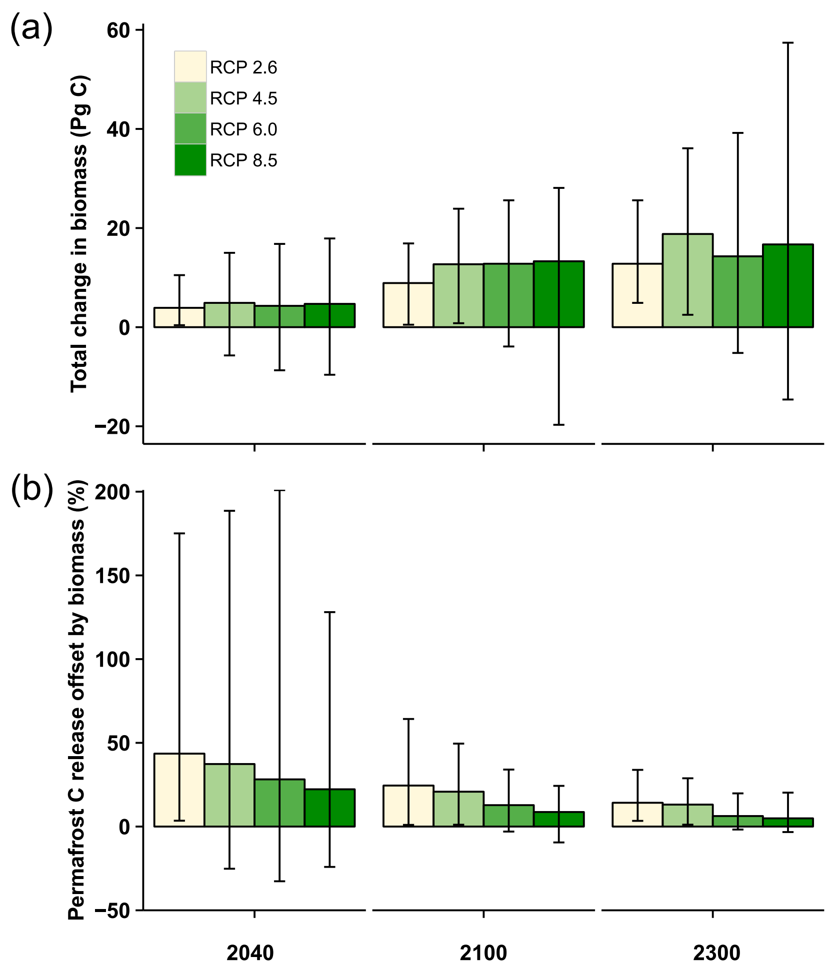

Figure 3. Total change in non-soil biomass (a) and percentage of permafrost region carbon release offset by change in non-soil biomass (b). Estimates of permafrost carbon release used in estimating percentage offset are recalculated from data presented in Schuur *et al* (2013). See figure 2 for definition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

Table 3. Sources of uncertainty in system response to climate change.

Biomass		Wildfire		Hydrologic OC flux	
Source of uncertainty	%	Source of uncertainty	%	Source of uncertainty	%
Water balance	56	Vegetation shift	73	Water balance	41
Wildfire	47	Water balance	58	Hydrologic flowpath	39
Permafrost degradation	40	Human disturbance	27	Permafrost degradation	24
Human disturbance	29	Permafrost degradation	18	Photo and bio-lability	24
Insect damage	27	Seasonality	15	Vegetation shift	20
Vegetation shift	24	Regional differences	12	Fluvial erosion	11
Treeline dynamics	16				
Nutrient availability	13				
Non-insect herbivores	11				

Major factors contributing uncertainty to projections of future system response based on expert comments. Rank is based on percent of experts who listed each factor in their responses. All sources listed by 10% or more of each group are included here. Water balance includes comments mentioning precipitation, soil moisture, runoff, infiltration, or discharge. Permafrost degradation includes comments referring to permafrost collapse (thermokarst) and active layer deepening.

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

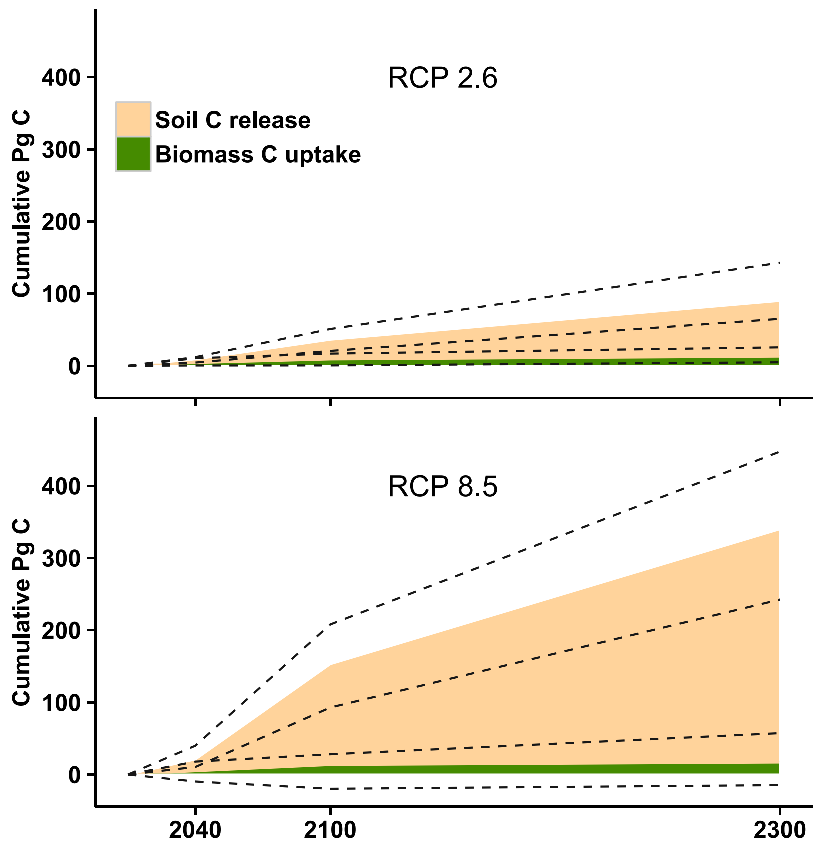

Figure 4. A comparison of soil carbon release recalculated from Schuur *et al* (2013) and non-soil biomass uptake in the permafrost region from this study for the business as usual scenario (RCP8.5) and the active reduction of human emissions scenario (RCP2.6). Polygons represent median cumulative change 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 dates where estimates were provided.

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^{-1} 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 (figure 3(b)). 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 (figure 3(b)). 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 five-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 (figure 4).

Comparison with quantitative models

Model projections of future boreal and Arctic biomass agree in sign but vary widely in magnitude, with increases of 9–61 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_2 fertilization or an underestimation of the role of disturbance in some models. Firstly, CO_2 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_2 fertilization effects for some models (Koven *et al* 2011). However, there is little field evidence that CO_2 fertilization results in long-term biomass accumulation in tundra and boreal ecosystems (Hickler *et al* 2008, Gedalof and Berg 2010, Peñuelas *et al* 2011). Additionally, many models with large CO_2 effects do not include other limiting factors, such as nutrients and water, known to interact with CO_2 fertilization (Hyvonen *et al* 2007, Thornton *et al* 2007, Yarie and Van Cleve 2010, Maaroufi *et al* 2015, Koven *et al* 2015a). 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% (Saugier *et al* 2001, Epstein *et al* 2012, Raynolds *et al* 2012), 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%–560% projected by the end of the century (Flannigan *et al* 2009, Kloster *et al* 2012). IQR 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%–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).

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 21st century than it did in the 20th (Kicklighter *et al* 2013), representing a nonlinear 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_2 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, 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.

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 (Anisimov and Reneva 2006, Shur and Jorgenson 2007, Jorgenson *et al* 2013, 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 (Sturm *et al* 2001, Shur and Jorgenson 2007, Yarie and Van Cleve 2010). The subsequent recovery trajectories of vegetation and permafrost, as well as the proportion of thawed carbon released CO_2 or CH_4, then depend largely on near-surface hydrologic conditions (Payette *et al* 2004, Myers-Smith *et al* 2008, Jorgenson *et al* 2010, Chapin *et al* 2010, O'Donnell *et al* 2011, Lawrence *et al* 2015). 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, Aufdenkampe *et al* 2011, Raymond *et al* 2013). The lack of model projections of hydrologic carbon fluxes is a major gap in our ability to estimate the permafrost carbon feedback.

The permafrost region has responded differently to various climatic perturbations in the past, representing another tool to constrain possible future response (Zachos *et al* 2008). During the Paleocene–Eocene thermal maximum, high-latitude temperature warmed more than 10 °C, causing almost complete loss of permafrost and the mineralization of most permafrost soil organic matter (Bowen and Zachos 2010, DeConto *et al* 2012). More recently, the 2 °C–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 °C 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_2 of 650 ppm 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_2 emissions peak before 2050 and decrease by half by 2080 (Moss *et al* 2010).

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

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