APPENDIX 1:

SUPPLEMENTARY METHODS AND SURVEY FORM

Supplementary methods:

Survey design

The survey used to collect expert assessment of the vulnerability of permafrost C was divided into three questions. Experts were asked to provide quantitative estimates of surface permafrost degradation (Q1), permafrost C release (Q2), and CH_4 emissions (Q3). Because permafrost temperature and extent vary within regions of the northern circumpolar permafrost zone, numerical estimates were reported separately for the continuous zone, discontinuous zone, and the sporadic/isolated zone (Brown et al. 1998). The assessment of permafrost change by zone was made for each of four warming scenarios over three time frames. Time frames were chosen to represent short-term change (cumulative change between present (~2010) and the year 2040), medium-term change (cumulative until 2100), and long-term change (cumulative to 2300). The short- and medium-term time frames are more directly policy-relevant, whereas the long-term time frame provides perspective on important Earth system changes.

The warming scenarios were based on four representative concentration pathways (RCP 2.6, 4.5, 6.0, 8.5) specified as part of the new Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) development process (Moss et al. 2010). These scenarios span possible atmospheric trajectories including one scenario of steadily increasing greenhouse gases (RCP 8.5, >1370 ppm CO_2 equivalent in 2100), two scenarios of atmospheric stabilization after 2100 (RCP 4.5, RCP 6.0, 650 ppm and 850 ppm CO_2 equivalent), and one scenario of atmospheric stabilization then decline before 2100 (RCP 2.6, 490 ppm CO_2 equivalent at peak). These RCPs were used to generate four scenarios of Arctic warming using the Community Climate System Model 4 (Gent et al. 2011). Future temperatures (Table 1,

Figure 1 in **Appendix 1**) were plotted as a 7-yr running average anomaly from the 1985-2004 average baseline temperature for the terrestrial Arctic region (Greenland excluded). Modeled Arctic temperature increases over land are roughly 2.5 times that of the global average, thus the strongest warming scenario that predicted 7.5°C higher temperature by 2100 corresponds to ~3°C higher global mean temperature. By the year 2040, the modeled arctic surface air temperature increases ranged from 1.5-2.5°C higher than a 1985-2004 average baseline, and from 2.0-7.5°C higher by the year 2100. While modeled temperature under some RCPs continue to change beyond 2100, the scenarios presented in the survey assumed that the temperature increase reached by 2100 stabilized at that level and remained there through 2300. This evaluated the time lag in the response of permafrost C to climate change over longer time scales, rather than the influence of additional climate change that itself becomes less certain farther out in time. For every question, each expert provided 36 numerical responses that covered all warming scenario, time frame, and permafrost zone combinations.

For Q1, experts estimated change in surface permafrost extent reported in percent loss from the current extent of ~$14.6x10^6$ km^2 (Zhang et al. 1999). Surface permafrost was defined as permafrost occurring within the top 3 meters of the ground. For Q2, experts assessed the net change in soil C stocks in the permafrost region, reported in cumulative Pg ($1x10^{15}$g) C emitted to the atmosphere as CO_2 and CH_4. Current estimates of the permafrost region C pool size partitioned by zone and depth were provided as background. This question included the entire soil C stock in the northern circumpolar permafrost zone. It was noted that while the discontinuous and sporadic/isolated zones are only partially underlain by permafrost, there still may be changes in non-permafrost soils in a future warmer world. Experts were asked not to include changes in vegetation C stocks in their estimate, but to include losses and gains of C that may occur in the surface soil (*active layer*) that becomes unfrozen seasonally in permafrost soils. Question 3 asked for an assessment of the amount of C from Q2 that would be emitted as CH_4, reported in Tg ($1x10^{12}$g) C. For all three questions it is important to note that, while future climate scenarios were defined solely by temperature increase, experts were asked to include both direct and indirect changes in climate likely to be associated with each warming scenario. These changes included but were not limited to: climatic variables such as precipitation, seasonality, etc, and landscape changes such as fire regime, surface and subsurface hydrology, wetting/drying, etc.

For each of the three survey questions, respondents were asked to provide an overall score of their *expertise* in that particular area from 1 (low) to 4 (high) based on criteria outlined in the survey form. And finally, the respondents were asked to provide an overall *confidence* score for each different warming scenario within each question from 1 (low) to 4 (high) based on criteria outlined in the survey form. Thus, each question answered by an expert had 1 expertise rating and 4 confidence ratings corresponding to the 4 warming scenarios evaluated for each question.

Survey Development and Implementation

Survey results were obtained from a group of experts that attended a three-day workshop in June 2011 in Seattle, WA, USA, as part of the Vulnerability of Permafrost Carbon Research Coordination Network (RCN) (www.biology.ufl.edu/permafrostcarbon) (**Appendix 2**). Forty international participants attended the workshop, having been selected from the larger scientific community by the RCN steering committee (Schuur, McGuire, Canadell, Harden, Kuhry, Romanovsky, Turetsky) for their particular expertise and previous work on this topic. Thirty-eight of these participants returned completed survey forms, though some questions were intentionally left blank. In addition, three other experts (Chapin, Ciais, Zimov) who were unable to attend the workshop but were previously involved in the survey and/or workshop development process, returned surveys. In total, there were 38 responses for Question 1, 38 responses for Question 2, and 35 responses for Question 3.

The survey was revised on two occasions before final survey data were collected. The first iteration occurred in 2009 as part of larger assessment of Earth system change. This larger assessment was called the Dangerous Climate Change Assessment Project (DanCCAP), led by Oxford University and the

Tyndall Centre for Climate Change Research (Sky et al. 2010). This project provided an outline for the survey methods used, and helped in the original development of the system definition and the format of the questions. The permafrost questions used in this study were a subset of a larger set of Arctic survey questions used for DanCCAP. Responses from a few individuals to the permafrost questions in that phase led to revisions in the questionnaire.

A near-final version of the survey was distributed to the RCN workshop participants with the format discussed by the group at the workshop. The survey was emailed a month prior to the meeting and the participants independently filled out the survey with the option of referring to relevant literature and data. These results were submitted before the start of the meeting. During the workshop, the participants were shown anonymous mean and median results of the compiled surveys. In the discussion that followed, it became clear that not all participants had considered the questions in the same way. Specific clarifications were identified over the course of the workshop and added to the survey instructions. Also as a result of that discussion, warming scenarios for the final survey were updated to correspond to the newly available IPCC representative concentration pathways. For the dataset reported here, experts completed final surveys at their home institution during a period 2-4 weeks after the Seattle workshop.

Analyses

For each response we also calculated C emissions in CO_2 equivalent (units of Pg C) by subtracting CH_4 emission (Q3) from total C emission (Q2), multiplying CH_4 by its 100-year or 20-year global warming potential (GWP) of 33 and 105 respectively while also accounting for the weight difference between CO_2 and CH_4 gas, and adding that value back to total C emission (Shindell et al. 2009). While the use of a fixed GWP doesn't account for many important complexities in the climate system (Shine et al. 2005, Forster et al. 2007, Manning and Reisinger 2011), it still provides a quantitative method for the rough comparison of the impact of permafrost CH_4 and CO_2 emissions on climate. It is important to note that GWP for CH_4 increases when considering shorter time scales. Most values use the 100-year GWP for consistency with other literature, but the 20-year GWP is shown for comparison in some cases. The 100-year GWP CO_2-equivalent is viewed as the century-scale impact of C releases emitted within a particular time interval, but warming by 2100 is actually influenced by both a shorter (20-year) and longer (100-year) GWP since emissions are likely occurring throughout the period from 2010 until 2100. We also calculated percentage CH_4 of the total C emission by dividing CH_4 emission (Q3) by the total C emission (Q2). Carbon emissions in CO_2 equivalent and percent CH_4 were calculated for each permafrost zone, time frame, and warming scenario individually.

For the numbers reported in the text, responses with a self-rated expertise of 1 (little or no expertise) were excluded. This removed individual answers provided by experts that judged themselves to be at the lowest end of the expertise scale for any particular question. For CO_2 equivalent and percent CH_4 (which are derived from Questions 2 and 3), any responses with an expertise of 1 for either Q2 or Q3 were excluded. While this screening process did not end up having an overall directional effect on the mean or median response of the group for any particular question, it addressed imperfections in the expert selection process and considered the comfort level of individual experts in providing such an assessment. The screened dataset had 33 responses for Q1, 34 for Q2, and 27 for Q3, and thus also 27 responses for CO_2 equivalent and percent methane. We analyzed the effect of this data screening by comparing the statistical distribution of responses of the final dataset to unscreened data (all respondents), as well as to a dataset that used only answers from the upper half of the expertise scale (expertise ≥ 3 included). Results of screening are presented only for total C, but are representative of results from all questions.

Across much the final dataset, the distribution of values fit a lognormal distribution with a skew towards higher values such that mean responses across the dataset are larger in all cases than median values. To describe the distribution of the data most succinctly, we present untransformed values of the mean and standard error of the mean derived from a natural log transformation of the raw data. All natural log distributions were significant at $p<0.05$ unless otherwise noted. In four cases (of 36), the data were normally distributed and no transformation was necessary. Ranges reported in the text represent the 95% confidence interval.

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Survey form:

Vulnerability of Permafrost Carbon: Survey Questions

Introduction

The goal of this survey is to determine the magnitude of permafrost degradation and subsequent carbon release in response to arctic and boreal warming scenarios. Possible thresholds and tipping points in the relationship between temperature increase and permafrost loss and carbon release are of particular interest, since such non-linearity is difficult to predict on the basis of models.

You will be asked to provide estimates of permafrost loss and carbon release for the three major permafrost zones (continuous, discontinuous, and sporadic/isolated) over short-term (2010-2040), medium-term (2010-2100), and long-term (2010-2300) time scales

We recognize that climate-change-driven feedbacks in complex Earth systems are not, and cannot be, precisely and definitively modeled. As such, we are only asking for your informed opinion, realizing that some of the included parameters may not be well understood. By administering this survey to scientists with the most applicable expertise, we want to identify and evaluate the possible and probable magnitude of permafrost response in the arctic and subarctic.

Instructions

In addition to answering each question, you will have a chance to indicate your level of confidence and expertise concerning your answer; and provide additional comments on how you selected your estimated magnitudes of climate/carbon feedback response. These follow-up questions allow us to compare responses from multiple experts. If the answer to a particular question is currently unknown, but there is a particular piece of research that you think could resolve some of that uncertainty, please indicate what that would be in the “comments” space provided, or at the end of the survey. If you have little or no expertise concerning a particular question, please skip it.

The four-point “**Confidence level**” scale is defined as follows:

- **1=** My answer is my best guess but I am not confident in it; it could easily be far off the mark. Scientific uncertainty on this issue is very large.
- **2=** I am moderately confident that my answer is as good as anyone can offer at this time but there is large scientific uncertainty on this issue and the true value may be quite different.
- **3=** I am very confident that my answer is the best anyone can offer at this time; there is moderate scientific uncertainty, so the true value is likely to be somewhat different from my answer, but it is unlikely to be dramatically different.
- **4=** I would be very surprised if my answer were far off from the true value.

The four-point “**Expertise level**” scale is defined as follows:

- **1=** I have little familiarity with the literature and I do not actively work on these particular questions.
- **2=** I have some familiarity with the literature and I’ve worked on related questions but haven't contributed to the literature on this issue; it is not an area of central expertise for me.
- **3=** I have worked on related issues and have contributed to the relevant literature but do not consider myself one of the foremost experts on this particular issue.
- **4=** I contribute actively to the literature directly concerned with this issue, and I consider myself one of the foremost experts on it.

We also ask that you provide key literature references in support of your view; however, in many cases there may be no clarity in the literature on the issue at hand. Nevertheless, if you have a view concerning the magnitude of the feedback, please provide it. If there is not yet clear supporting evidence in the literature, but you have some basis for an estimate based on expert professional judgment, please make a note of that.

Warming Scenarios

You will be asked to estimate the Arctic system response to four warming scenarios. These scenarios of regional Arctic warming were generated with NCAR's Community Climate System Model (CCSM4) with inputs from the most recent IPCC radiative forcing scenarios (**Figure 1**).

To minimize the possibility of misinterpretation, we have also provided a table showing the amount of warming predicted in Figure 1 by the end of each of the three time scales (**Table 1**).

	Warming at 2040 (°C)	**Warming at 2100 (°C)**	**Warming at 2300 (°C)**
WS 1	1.5	2.0	2.0
WS 2	2.0	3.0	3.0
WS 3	2.0	4.5	4.5
WS 4	2.5	7.5	7.5

Table 1. Temperature increases for the four warming scenarios (designated here as WS1-4). Values given represent the regional Arctic temperature increase achieved by the year indicated. Values for WS1-4 correspond to the IPCC representative concentration pathways (RCP): 2.6, 4.5, 6.0, and 8.5 respectively.

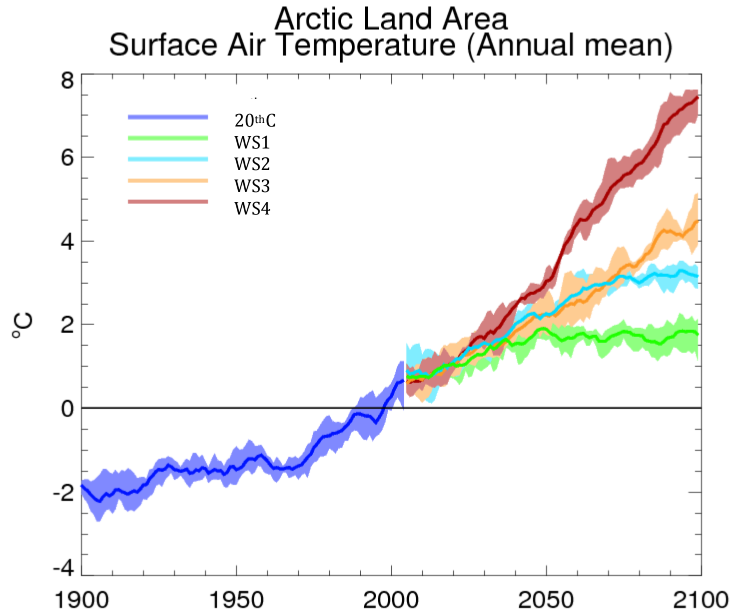

Figure 1. CCSM4: Anomaly from 1985-2004 (7-yr running average; Greenland excluded). Though not shown in this figure, temperature increase is assumed to stabilize and level off after 2100 for the purposes of this survey.

Updates from Workshop

The following decisions were discussed specifically at the workshop and are listed here for clarity:

1) Repeat survey as final statement of this group

2) Use actual IPCC Arctic warming scenarios (shown above)

3) Response should be **net change in the soil/permafrost C stock**, reported as cumulative Pg C, noting that it is also useful to check per year emission. Do not include changes in vegetation C, but do consider losses and gains of C that may occur in the surface soil as part of your response.

4) Remember to consider change in entire soil C stock in permafrost zone, noting that only some fraction is underlain by permafrost but there still may be changes in non-permafrost soils in a future warmer world.

5) Continuous, discontinuous, and sporadic+isolated permafrost zones should be considered in terms of their current geographic areas throughout all time horizons.

6) The warming scenarios are expressed as temperature increase, but your answer could reasonably include both direct and indirect changes in climate (i.e. precipitation, etc) and landscape changes (i.e. fire regime, etc) that are likely to be associated with warming at that magnitude.

7) Please revisit your expertise level (see page 1) based on the range of expertise found within our group

Questions

1. How much change in the extent of near-surface permafrost (loss of permafrost in at least the top three meters of soil from the current permafrost extent of ~14.6×10^6 km^2 [Zhang et al. 2000]) would result from the following pan-arctic warming scenarios? Note that a possible range of 0-100% should be used for each zone.

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **permafrost extent response** (% decrease)			**Medium-term** (2010-2100) **permafrost extent response** (% decrease)			**Long-term** (2010-2300) **permafrost extent response** (% decrease)			**Confidence level (1-4)**
	Continuous	**Discontinuous**	**Sporadic and Isolated**	**Continuous**	**Discontinuous**	**Sporadic and Isolated**	**Continuous**	**Discontinuous**	**Sporadic and Isolated**	
WS1										
WS2										
WS3										
WS4										
Comments:									**Expertise level (1-4)**	
Additional key literature that you relied on, not yet cited in other materials with this survey:										

2. How much cumulative carbon release to the atmosphere (Pg carbon emitted as either CO_2 or CH_4 from soils in the circumpolar north permafrost region) would occur due to the following pan-arctic warming scenarios? **Note:** Your estimate of release should be a change current stock of **soil/permafrost carbon** in the entire permafrost zone. The table below provides estimates of the shallow and deep carbon pool sizes for the three permafrost zones, including carbon stored in both permafrost and non-permafrost soils. For a more detailed breakdown refer to the system definition text.

	% of total permafrost area*	**Shallow (0-3m) C Pg****	**Deep (>3 m) C Pg*****	**Total Pg C**
Continuous	60	614	570	1185
Discontinuous	13	133	130	263
Sporadic/Isolated	26	266		266

*Zhang et al. 1999, **Tarnocai et al. 2009, ***Tarnocai et al. 2009 but estimated by zone here

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **C release** (cumulative Pg C)			**Medium-term** (2010-2100) **C release** (cumulative Pg C)			**Long-term** (2010-2300) **C release** (cumulative Pg C)			**Confidence level (1-4)**
	Continuous	**Discontinuous**	**Sporadic and Isolated**	**Continuous**	**Discontinuous**	**Sporadic and Isolated**	**Continuous**	**Discontinuous**	**Sporadic and Isolated**	
WS1										
WS2										
WS3										
WS4										
Comments:										**Expertise level (1-4)**
Additional key literature that you relied on, not yet cited in other materials with this survey:										

3. How much of the C release calculated for Question 2 will be emitted as methane (reported as **cumulative Tg** CH_4–C) from soils in the circumpolar north permafrost zone due to the following pan-arctic warming scenarios?

Warming Scenario (use Table 1 for temperature increase)	**Short-term** (2010-2040) **CH_4 release** (cumulative Tg as CH_4)			**Medium-term** (2010-2100) **CH_4 release** (cumulative Tg as CH_4)			**Long-term** (2010-2300) **CH_4 release** (cumulative Tg as CH_4)			**Confidence level (1-4)**
	Continuous	**Discontinuous**	**Sporadic and Isolated**	**Continuous**	**Discontinuous**	**Sporadic and Isolated**	**Continuous**	**Discontinuous**	**Sporadic and Isolated**	
WS1										
WS2										
WS3										
WS4										
Comments:									**Expertise level (1-4)**	
Additional key literature that you relied on, not yet cited in other materials with this survey:										

4. What additional comments or insights do you have concerning the content, format and implementation of this survey?