Hector Permafrost

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Abstract

Text of abstract

Introduction

Climate change is a problem (CITE: IPCC, NCA, etc.). Important to reduce carbon emissions to meet temperature targets. The extent of anthropogenic emissions reduction depends on what how much help (or push-back) we get from the physical and biological Earth systems.

Permafrost is an important C reservoir. Total northern soil C pool is estimated at 1672 PgC, of which approximately 1466 Pg (88%) is in permafrost (Tarnocai et al., 2009). This frozen C can be released into the atmosphere by several processes related to warming, including aerobic respiration in thawed soil (REF) and anaeribic respiration in thermokarst lakes and wetlands (Turetsky et al., 2002; Wickland et al., 2006). But emissions from wet soils may be offset by high organic matter accumulation rates (Camill et al., 2001). Permafrost thaw in boreal peatlands in north-central Saskatchewan increased CO2 and CH4 fluxes from soil to atmosphere by 1.6 and 30 times, respectively (Turetsky et al., 2002). These impacts are exacerbated by the fact that the Arctic is warming roughly 2.5 (TODO ???) times faster than the global average (TODO REF). Projections of permafrost C emissions vary. (Schuur et al., 2009) estimate 0.8 - 1.1 Pg C yr-1. Back-of-the-envelope estimates from (Zimov, 2006): 10-40 g C m-3 day-1 off the bat, slowing down to equilibrium (?) rate of 0.5-5 g C m-3 day-1 for several years.

On the other hand, warming and CO2 fertilization may increase vegetation productivity, which could increase soil C storage through enhanced litterfall; the balance of these two processes is uncertain (Jones et al., 2005). Several modeling studies generally predict increases in soil C in high latitudes (Burke et al., 2017; Ito et al., 2016; Qian et al., 2010). However, this increase is dampened by including permafrost C (Burke et al., 2017).

(Previous work on modeling permafrost) (Burke et al., 2017) – JULES and ORCHIDEE, with new permafrost scheme, combined with intermediate complexity climate-ocean model (IMOGEN), to look at climate sensitivity to permafrost C emissions. Models are highly sensitive to representation of soil processes, which can be more important than differences in scenario and/or climate drivers (Burke et al., 2017).

(Paragraph on simple climate models.) Hector (Hartin et al., 2015). However, Hector does not have an explicit representation of permafrost C emissions. In this study, we investigate whether the additional complexity and parametric and structural uncertainty of an explicit representation of permafrost may be warranted in Hector. To do this, we evaluate the sensitivity of climate variables (as predicted by Hector) to several different exogenous scenarios of permafrost C emissions. (TODO Modify this to be about economic impact)

Some more relevant references: - (Zimov, 2006) - (Treat and Frolking, 2013) - (Burke et al., 2017; Drake et al., 2015; Hope and Schaefer, 2015; Kessler, 2017; Kuhry et al., 2010; Lee et al., 2011; Schaefer et al., 2014, 2011; Schuur and Abbott, 2011; Schuur et al., 2015)

Methods

Model description: Hector

Hector (Hartin et al., 2015, p.@hartin_2016_ocean). Simple climate model.

(TODO: More details on terrestrial C cycle in Hector). The default heterotrophic respiration (R) scheme for a pool p (detritus or soil) in Hector:

$$R_p = C_p \times f_p \times Q_{10}^{\frac{T}{10}}$$

Model configurations

We evaluate the sensitivity and parametric uncertainty of three different versions of Hector.

The simplest is the "global" version, which corresponds to the standard version of Hector described in (Hartin et al., 2015). The global land carbon sink is modeled as a single entity, with parameterizations corresponding to global averages (originally tuned to match global outputs from CMIP5; TODO REF?). In this configuration, we vary the following parameters: CO_2 fertilization effect (β); temperature sensitivity of heterotrophic respiration, (Q_{RH}^{10}); fraction of net primary production C that goes to vegetation (`f_nppv`), detritus (`f_nppd`), and soil (`1 - f_nppv - f_nppd`); and fraction of vegetation litter C that goes to detritus (`f_litterd`).

The second is the "biome" version, which is the same as the "global" version except that the land carbon sink is divided into two "biomes": "non-permafrost" and "permafrost". Each of these biomes has its own C pools, fluxes, and parameters. For this configuration, we varied all of the "global" parameters (previous paragraph) for *both* biomes ($\beta_{permafrost}$, $\beta_{non-permafrost}$, $Q^10_{RH,permafrost}$, $Q^10_{RH,non-permafrost}$, etc.), as well as the distribution of global pools (vegetation, detritus, soil) and initial primary productivity (`npp_flux0`) across these two biomes and the relative warming factor (compared to the global average) of the permafrost biome.

The third is the "biome + methane" version. This version is the same as the "biome" version, but with an additional process that partitions total heterotrophic respiration ($R_{p,tot}$) into a CO_2 flux (R_{p,CO_2}) and a CH_4 flux (R_p, CH_4) as follows:

$$R_{p,tot} = C_p \times f_p \times Q_{10}^{\frac{T}{10}}$$

$$R_{p,CH_4} = \alpha R_{p,tot}$$

$$R_{p,CO_2} = (1 - \alpha)^{\phi} R_{p,tot}$$

This process is controlled by two new biome-specific parameters: α can be interpreted as the fraction of heterotrophic respiration C that is given off as CH_4 assuming a perfect trade-off between CO_2 and CH_4 emissions. ϕ defines the plasticity of this relationship; at $\phi = 1$, plasticity is perfect, such that $R_{p,tot}$ is evenly split between CO_2 and CH_4; at $\phi = 0$, CO_2 emissions are entirely independent of CH_4 emissions, such that total C emissions increase linearly with α; at $\phi > 1$, CO_2 emissions decline faster than CH_4 emissions increase. As such, the total C emissions attributable to heterotrophic respiration are expected to decrease as ϕ increases. In this version of Hector, we varied all of the parameters in the "biome" verson, as well as α and ϕ for each biome.

Parameter distributions

We drew parameters from loosely informative distributions that span the range of physical plausibility. The distributions are shown in the following table (unless otherwise specified, we used the same parameter distributions for global and biome cases):

Parameter	Distribution	Hector default value
β	Uniform(0, 1)	0.36
$Q^{10}{}_{RH}$	Uniform(0, 10)	2.0
Litter-detritus fraction	Beta(3.92, 0.08)	0.98
NPP vegetation fraction	Dirichlet(**0.35**, 0.60, 0.05)	0.35
NPP detritus fraction	Dirichlet(0.35, **0.60**, 0.05)	0.60
——————————-	—————————	——————-
Permafrost vegetation C fraction	Beta(1, 2)	–
Permafrost soil C fraction	Beta(1.1, 1.1)	–
Permafrost detritus C fraction	Beta(1.1, 1.1)	–
Permafrost warming factor	1 + 3 * Beta(5, 5)	–
——————————-	—————————	——————-
Non-permafrost α	TODO	–
Non-permafrost ϕ	TODO	
Permafrost α	TODO	
Permafrost ϕ	TODO	

We used 5000 Hector simulations for the global case and 10,000 times for the biome case (biome + methane case is TODO).

Analysis of results

We looked at four output variables: Atmospheric CO_2 concentration (`Ca`), total radiative forcing (`Ftot`), radiative forcing from CO_2 alone (`FCO2`), and global mean atmospheric temperature (`Tgav`).

First, as a metric of overall parametric uncertainty for each case, we calculated the mean, standard deviation, and 90% and 95% quantiles of the time series for each variable for each simulation. Second, we evaluated the impact of parameters by plotting the values of each variable at 2100 as a function of input parameter value.

Third, we performed a more rigorous sensitivity and uncertainty analysis based on LeBauer et al. (2013). As a metric of parameter uncertainty, we calculated the coefficient of variation (`cv`) for each input parameter as the ratio of its variance to its mean. We evaluated sensitivity as follows: First, we fit a multivariate Generalized Additive Model (GAM; `mgcv::gam` function in R) for each variable as a function of all the input parameters. Then, we calculate the sensitivity (s) to each parameter (x_i) as the slope (partial derivative) of the resulting GAM at that parameter's median ($\hat{x}$; discretized at +/- 1% of the median), holding all other parameters ($x_{i+1}..x_n$) constant:

$$s = \frac{d(GAM(x_i|x_{i+1}..x_n))}{d(x_i)} = \frac{GAM(1.01x_i|...) - GAM(0.99x_i|...)}{1.01x_i - 0.99x_i}$$

We then define the "elasticity" (ϵ) (or normalized sensitivity) of the model to that parameter as:

$$\epsilon = s \div \frac{\hat{y}}{\hat{x}}$$

Finally, we calculate the "partial variance" of each parameter (the fractional contribution of each parameter's uncertainty to overall model predictive uncertainty) by passing the distribution of each parameter through

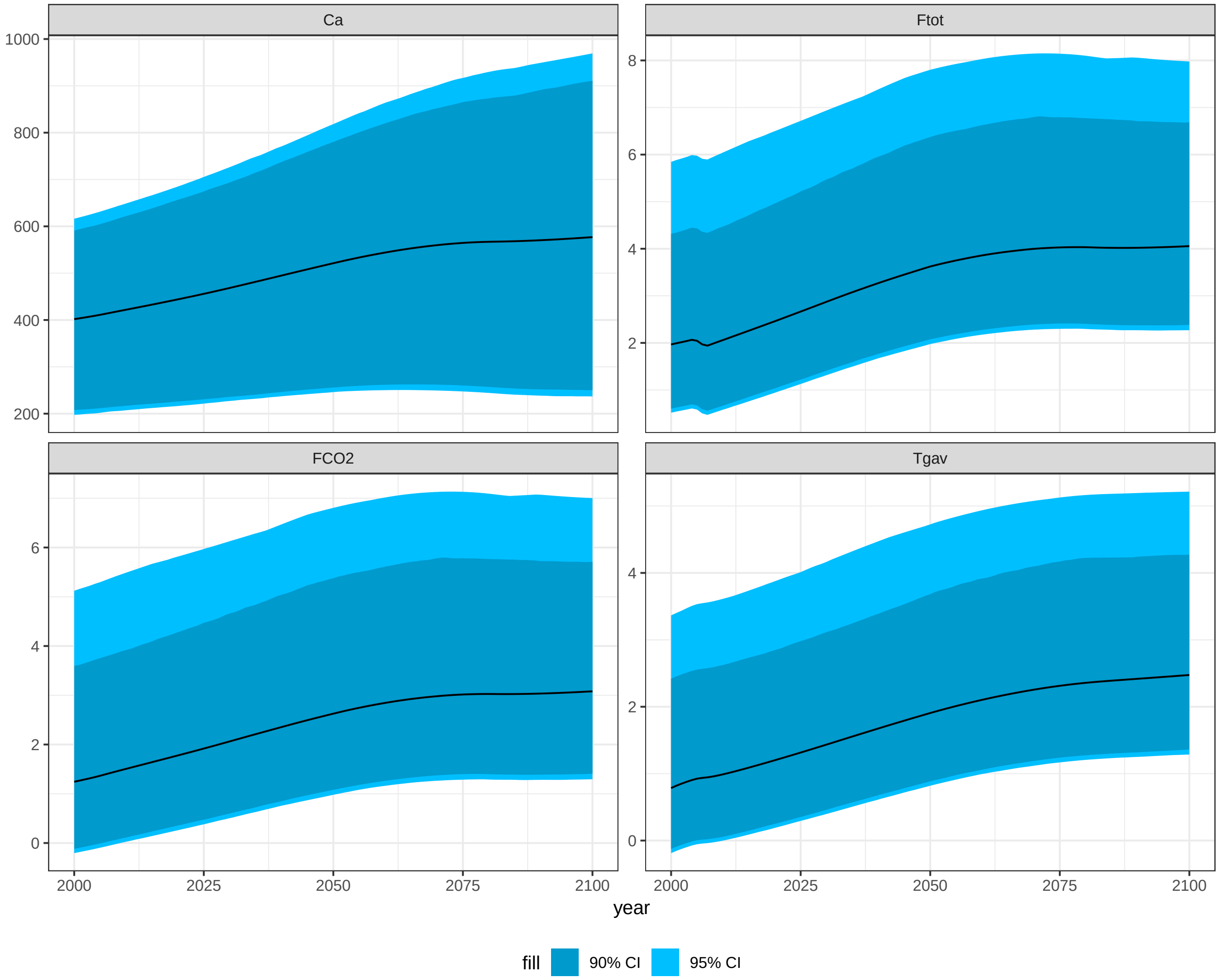

Figure 1: Time series of Hector outputs for different parameter combinations.

the GAM while holding all other parameters constant, calculating the resulting predictive variance for each parameter, and then normalizing these values relative to the sum of all the variances:

$$Var(x_i) \approx Var[GAM(x_i | x_{i+1}..x_n)]$$

$$pvar(x_i) = \frac{Var(x_i)}{\sum_i^n Var(x_i)}$$

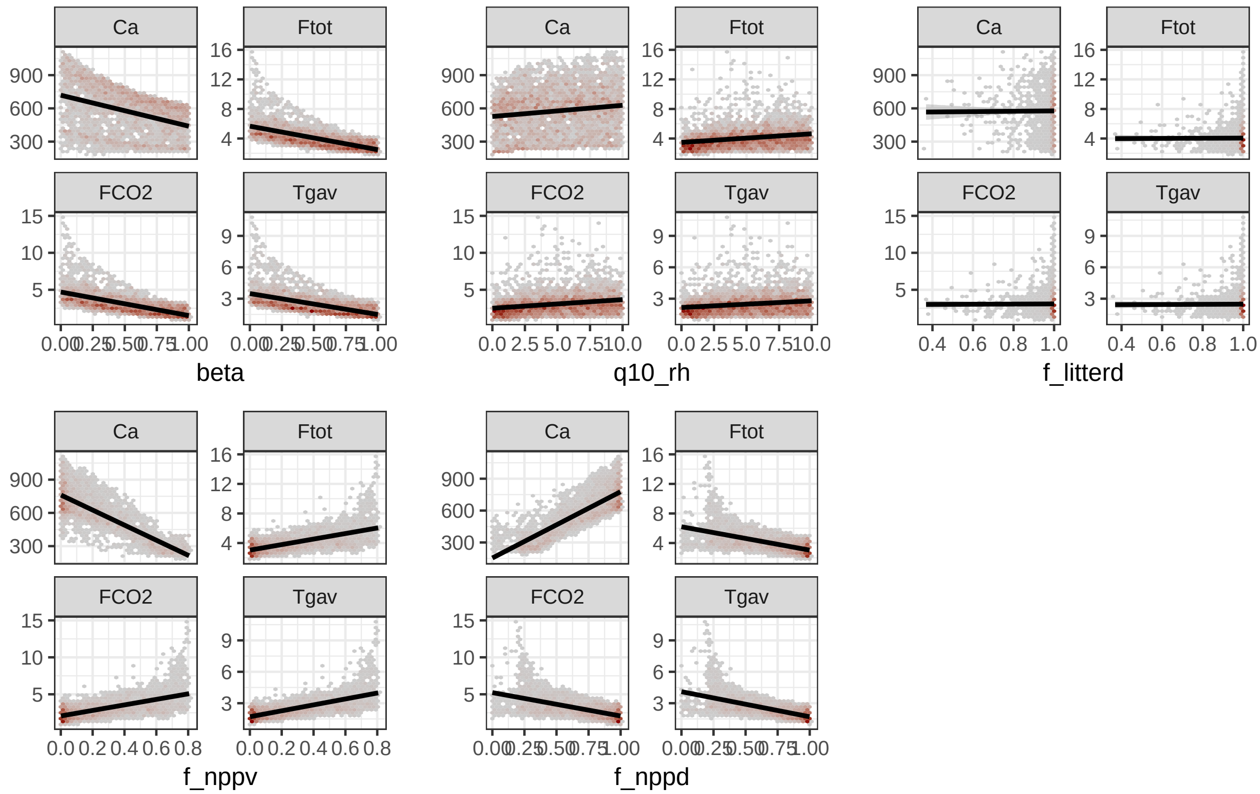

Figure 2: Hector outputs at 2100 as a function of input parameter values.

Results

Global case

Biome case

Permafrost methane emissions

Figure: Hector projections of parameter sensitivity (CI ribbon, or light/transparent lines), colored (faceted?) by case.

Figure: PEcAn-like variance decomposition of parameters (for each parameter: sensitivity, uncertainty, and partial variance)

Discussion

Rate of permafrost C release also depends on soil moisture conditions – drier soils release C much faster ("carbon bomb") than wetter soils ("carbon fizz") (Elberling et al., 2013). Moisture will also affect the balance of aerobic (CO2 release) vs. anaerobic (CH4) C release (Turetsky et al., 2002), to the extent that unclear if anaerobic (wet) areas are C sources or sinks (Wickland et al., 2006). Effects of permafrost thaw on soil moisture are a complex hydrological problem – drainage very sensitive to local (micro-)topography (Wickland et al., 2006). So will vegetation cover (Wickland et al., 2006).

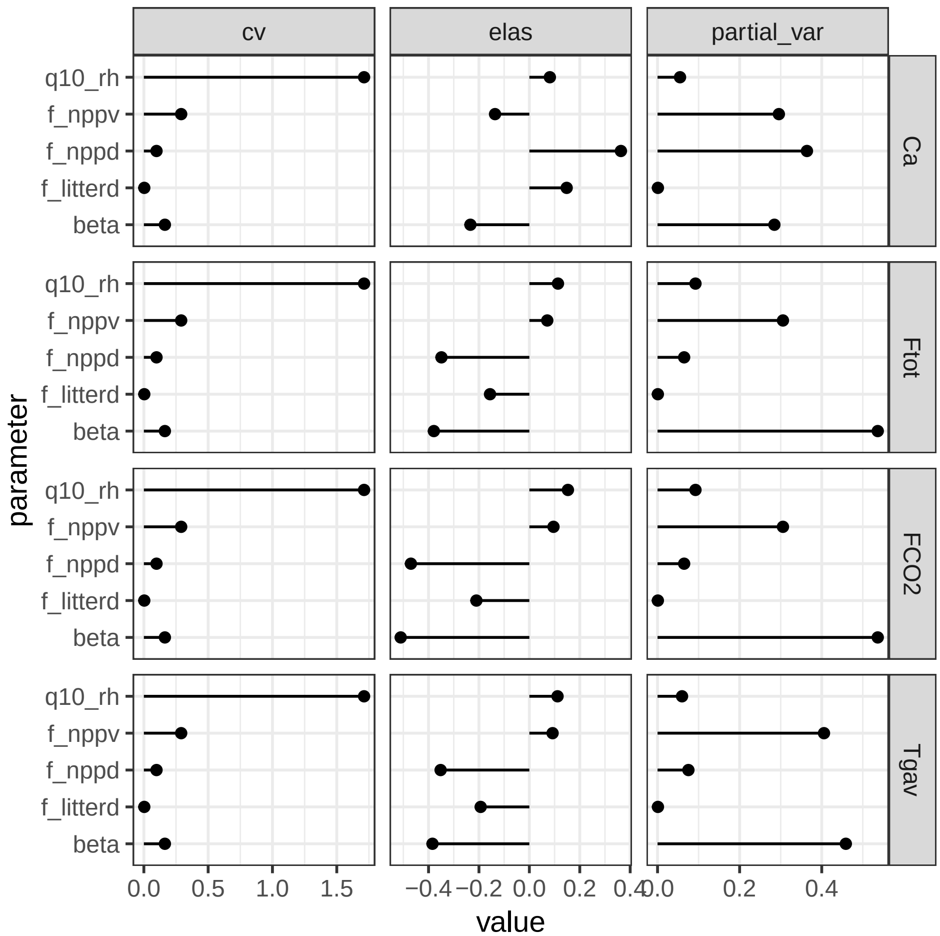

Figure 3: Sensitivity and variance decomposition analysis for global Hector.

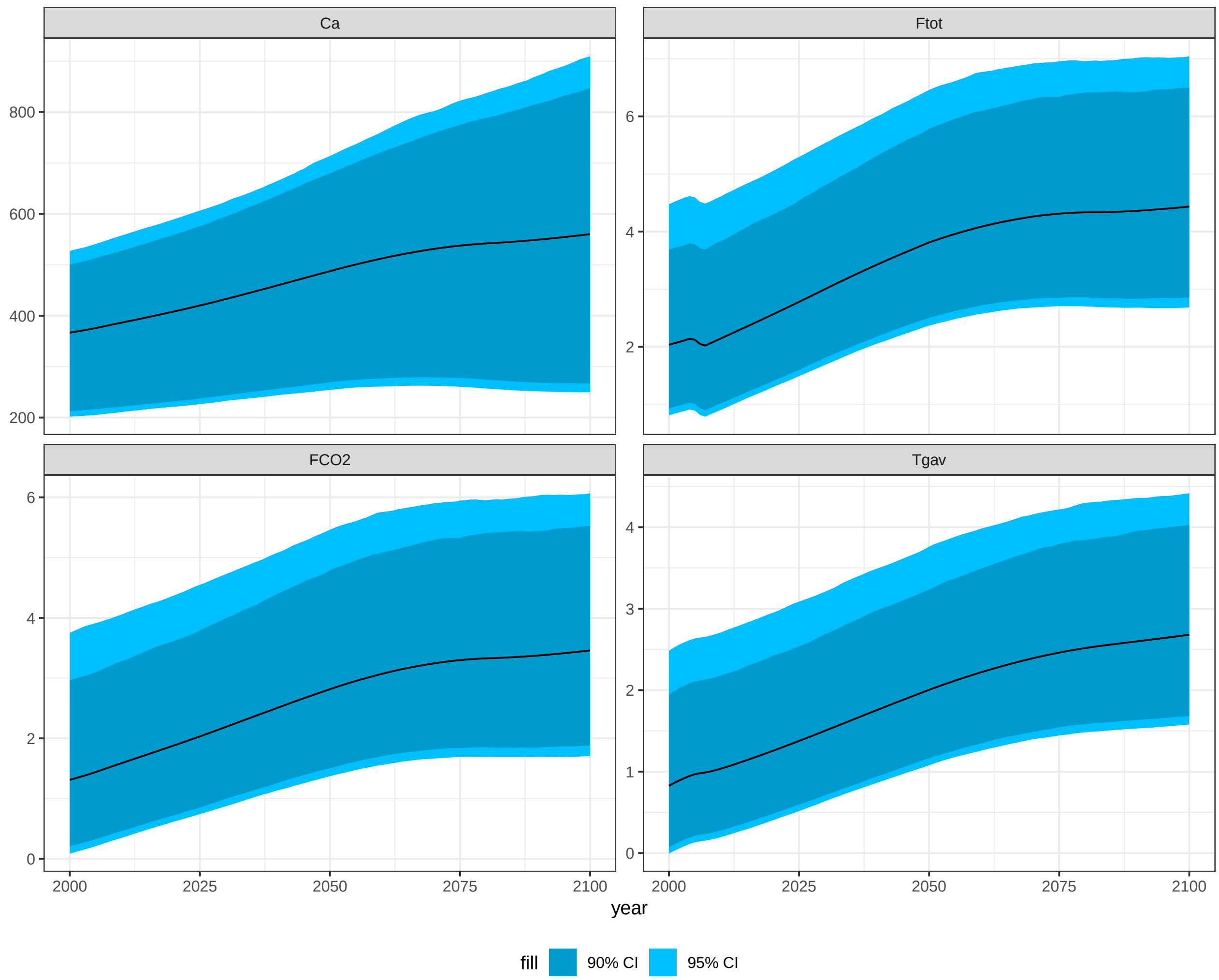

Figure 4: Overall parameter uncertainty of Hector simulations with permafrost biome.

Temperature amplification of permafrost carbon feedback (by 2100) 0.02 to 0.36 °C (Burke et al., 2013; Schneider von Deimling et al., 2015, 2012), or 0.1 to 0.8 °C in (MacDougall et al., 2012, 2013), or 10-40% of peak temperature change (Crichton et al., 2016), or 0.2 to 12% (Burke et al., 2017).

Permafrost carbon has greater impact at lower emissions scenarios (Burke et al., 2017; MacDougall et al., 2012, 2013) .

Conclusion

Acknowledgments

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Miscellaneous notes

Permafrost emissions scenarios

Digitized scenarios from (Schaefer et al., 2011). SiBCASA model predictions of CO2 emissions (permafrost respiration; R_{pc}; note – no methane!) through 2300. These results were digitized using WebPlotDigitizer (https://apps.automeris.io/wpd/), and interpolated to annual resolution (using R `stats::spline` function).

Digitized scenarios from (Hope and Schaefer, 2015). CO2 and CH4 emissions from SiBCASA model.

(Schuur et al., 2009) – Estimate 0.8 - 1.1 Pg C yr-1.

Back-of-the-envelope estimates from (Zimov, 2006): - 500 Gt C in loess that could be completely emitted by 2100 (plus other C sources). - 10-40 g C m-3 day-1 off the bat, slowing down to equilibrium (?) rate of 0.5-5 g C m-3 day-1 for several years. Combine with data on permafrost spatial extent, density, etc. to generate estimates (but can back-calculate from 500 Gt C above?)

Parameter calibration

We used the `BayesianTools` R package (Hartig et al., 2019) for all parameter calibration. The outputs of these calibrations are joint posterior distributions of parameters and their covariances, from which we sample for the sensitivity analysis.

For global parameters, we used the following likelihood:

$$\log(L) = \sum_s Normal(Hector(\beta, Q_{10}, s)|CMIP5(s), \sigma)$$

where s is one of the four representative carbon pathways (RCPs), $CMIP5(s)$ are the CMIP5 global mean outputs for the corresponding variables, and σ is the model error (estimated during the fit). We also used the resulting distributions for β and Q_{10} for the non-permafrost biome in cases 2 and 3. We feel this is appropriate because the CMIP5 models against which these parameters are calibrated do not include permafrost C feedbacks.

For case 2, we calibrated the permafrost-specific β and Q_{10} against various literature sources, including:

- Land surface model simulations (Burke et al., 2017; Hope and Schaefer, 2015; Schaefer et al., 2011).
    - Try to calibrate against NPP and soil respiration if possible

- Literature surveys (Schaefer et al., 2014)
- Warming experiments (Wickland et al., 2006)
- TODO: Others?

Some of these are time series, while others are individual estimates at particular points in time. To give them equal weight in the likelihood, we down-weight the time series likelihoods by the number of time steps.

We derived a distribution for the Arctic warming factor from TODO.

TODO: Table and multi-panel figure of input datasets.

For the α and ϕ parameters in case 3, we looked at the literature on permafrost methane emissions (e.g., Wickland et al., 2006).

Other notes

Frozen carbon residence time (FCRt) from (Burke et al., 2017):

$$FCRt = FCRt0 * exp(-\Delta T/\Gamma)(for \Delta T > 0.2 \check{r} C)$$

- $FCRt_0$ (years) reflects the stability of permafrost C (length of time that permafrost C is stable when $\Delta T = 0$)
- Γ – decay term (°C); temperature change at which "the number of years taken for all of the old permafrost C to be emitted reduces to 1/e of its initial value"

Other Hector parameters to consider.

Variable	INI name	Description	Value
f_{nv}	`f_nppv`	Fraction of NPP C transferred to vegetation	0.35
f_{nd}	`f_nppd`	Fraction of NPP C transferred to detritus	0.60
f_{nd}		Fraction of NPP C transferred to soil	0.05
f_{lv}	`f_lucv`	Fraction of LUC change flux from vegetation	0.10
f_{ld}	`f_lucd`	Fraction of LUC change flux from detritus	0.01
f_{ls}		Fraction of LUC change flux from soil	0.89
f_{ds}		Fraction of detritus C that goes to soil	0.60
f_{rd}		Fraction of respiration C to detritus	0.25
f_{rs}		Fraction of respriation C to soil	0.02

According to (Hartin et al., 2015), these were selected to be "generally consistent with previous simple earth system models (e.g., Meinshausen et al., 2011)".

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References

Burke, E. J., Jones, C. D. and Koven, C. D.: Estimating the permafrost-carbon climate response in the CMIP5 climate models using a simplified approach, Journal of Climate, 26(14), 4897–4909, doi:10.1175/jcli-d-12-00550.1, 2013.

Burke, E. J., Ekici, A., Huang, Y., Chadburn, S. E., Huntingford, C., Ciais, P., Friedlingstein, P., Peng, S. and Krinner, G.: Quantifying uncertainties of permafrost carbon-climate feedbacks, Biogeosciences Discussions, 1–42, doi:10.5194/bg-2016-544, 2017.

Camill, P., Lynch, J. A., Clark, J. S., Adams, J. B. and Jordan, B.: Changes in biomass, aboveground net primary production, and peat accumulation following permafrost thaw in the boreal peatlands of Manitoba, Canada, Ecosystems, 4(5), 461–478, doi:10.1007/s10021-001-0022-3, 2001.

Crichton, K. A., Bouttes, N., Roche, D. M., Chappellaz, J. and Krinner, G.: Permafrost carbon as a missing link to explain CO2 changes during the last deglaciation, Nature Geoscience, 9(9), 683–686, doi:10.1038/ngeo2793, 2016.

Drake, T. W., Wickland, K. P., Spencer, R. G. M., McKnight, D. M. and Striegl, R. G.: Ancient low-molecular-weight organic acids in permafrost fuel rapid carbon dioxide production upon thaw, Proceedings of the National Academy of Sciences, 112(45), 13946–13951, doi:10.1073/pnas.1511705112, 2015.

Elberling, B., Michelsen, A., Schädel, C., Schuur, E. A. G., Christiansen, H. H., Berg, L., Tamstorf, M. P. and Sigsgaard, C.: Long-term CO2 production following permafrost thaw, Nature Climate Change, 3(10), 890–894, doi:10.1038/nclimate1955, 2013.

Hartig, F., Minunno, F. and Paul, S.: BayesianTools: General-purpose mcmc and smc samplers and tools for bayesian statistics. [online] Available from: https://CRAN.R-project.org/package=BayesianTools, 2019.

Hartin, C. A., Patel, P., Schwarber, A., Link, R. P. and Bond-Lamberty, B. P.: A simple object-oriented and open-source model for scientific and policy analyses of the global climate system - Hector v1.0, Geoscientific Model Development, 8(4), 939–955, doi:10.5194/gmd-8-939-2015, 2015.

Hartin, C. A., Bond-Lamberty, B., Patel, P. and Mundra, A.: Ocean acidification over the next three centuries using a simple global climate carbon-cycle model: Projections and sensitivities, Biogeosciences, 13(15), 4329–4342, doi:10.5194/bg-13-4329-2016, 2016.

Hope, C. and Schaefer, K.: Economic impacts of carbon dioxide and methane released from thawing permafrost, Nature Climate Change, 6(1), 56–59, doi:10.1038/nclimate2807, 2015.

Ito, A., Nishina, K. and Noda, H. M.: Impacts of future climate change on the carbon budget of northern high-latitude terrestrial ecosystems: An analysis using ISI-MIP data, Polar Science, 10(3), 346–355, doi:10.1016/j.polar.2015.11.002, 2016.

Jones, C., McConnell, C., Coleman, K., Cox, P., Falloon, P., Jenkinson, D. and Powlson, D.: Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil, Global Change Biology, 11(1), 154–166, doi:10.1111/j.1365-2486.2004.00885.x, 2005.

Kessler, L.: Estimating the economic impact of the permafrost carbon feedback, Climate Change Economics, 08(02), 1750008, doi:10.1142/s2010007817500087, 2017.

Kuhry, P., Dorrepaal, E., Hugelius, G., Schuur, E. A. G. and Tarnocai, C.: Potential remobilization of belowground permafrost carbon under future global warming, Permafrost and Periglacial Processes, 21(2), 208–214, doi:10.1002/ppp.684, 2010.

LeBauer, D. S., Wang, D., Richter, K. T., Davidson, C. C. and Dietze, M. C.: Facilitating feedbacks between field measurements and ecosystem models, Ecological Monographs, 83(2), 133–154, doi:10.1890/12-0137.1, 2013.

Lee, H., Schuur, E. A. G., Inglett, K. S., Lavoie, M. and Chanton, J. P.: The rate of permafrost carbon release under aerobic and anaerobic conditions and its potential effects on climate, Global Change Biology, 18(2), 515–527, doi:10.1111/j.1365-2486.2011.02519.x, 2011.

MacDougall, A. H., Avis, C. A. and Weaver, A. J.: Significant contribution to climate warming from the permafrost carbon feedback, Nature Geoscience, 5(10), 719–721, doi:10.1038/ngeo1573, 2012.

MacDougall, A. H., Eby, M. and Weaver, A. J.: If anthropogenic CO2 emissions cease, will atmospheric CO2 concentration continue to increase?, Journal of Climate, 26(23), 9563–9576, doi:10.1175/jcli-d-12-00751.1, 2013.

Meinshausen, M., Raper, S. C. B. and Wigley, T. M. L.: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, magicc6 - part 1: Model description and calibration, Atmospheric

Chemistry and Physics, 11(4), 1417–1456, doi:10.5194/acp-11-1417-2011, 2011.

Qian, H., Joseph, R. and Zeng, N.: Enhanced terrestrial carbon uptake in the Northern High Latitudes in the 21st century from the Coupled Carbon Cycle Climate Model Intercomparison Project model projections, Global Change Biology, 16(2), 641–656, doi:10.1111/j.1365-2486.2009.01989.x, 2010.

Schaefer, K., Zhang, T., Bruhwiler, L. and Barrett, A. P.: Amount and timing of permafrost carbon release in response to climate warming, Tellus B, 63(2), 165–180, doi:10.1111/j.1600-0889.2011.00527.x, 2011.

Schaefer, K., Lantuit, H., Romanovsky, V. E., Schuur, E. A. G. and Witt, R.: The impact of the permafrost carbon feedback on global climate, Environmental Research Letters, 9(8), 085003, doi:10.1088/1748-9326/9/8/085003, 2014.

Schneider von Deimling, T., Meinshausen, M., Levermann, A., Huber, V., Frieler, K., Lawrence, D. M. and Brovkin, V.: Estimating the near-surface permafrost-carbon feedback on global warming, Biogeosciences, 9(2), 649–665, doi:10.5194/bg-9-649-2012, 2012.

Schneider von Deimling, T., Grosse, G., Strauss, J., Schirrmeister, L., Morgenstern, A., Schaphoff, S., Meinshausen, M. and Boike, J.: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity, Biogeosciences, 12(11), 3469–3488, doi:10.5194/bg-12-3469-2015, 2015.

Schuur, E. A. G. and Abbott, B.: Climate change: High risk of permafrost thaw, Nature, 480(7375), 32–33, doi:10.1038/480032a, 2011.

Schuur, E. A. G., Vogel, J. G., Crummer, K. G., Lee, H., Sickman, J. O. and Osterkamp, T. E.: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, Nature, 459(7246), 556–559, doi:10.1038/nature08031, 2009.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M. and et al.: Climate change and the permafrost carbon feedback, Nature, 520(7546), 171–179, doi:10.1038/nature14338, 2015.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G. and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochemical Cycles, 23(2), n/a–n/a, doi:10.1029/2008gb003327, 2009.

Treat, C. C. and Frolking, S.: A permafrost carbon bomb?, Nature Climate Change, 3(10), 865–867, doi:10.1038/nclimate2010, 2013.

Turetsky, M. R., Wieder, R. and Vitt, D. H.: Boreal peatland C fluxes under varying permafrost regimes, Soil Biology and Biochemistry, 34(7), 907–912, doi:10.1016/s0038-0717(02)00022-6, 2002.

Wickland, K. P., Striegl, R. G., Neff, J. C. and Sachs, T.: Effects of permafrost melting on CO2 and CH4 exchange of a poorly drained black spruce lowland, Journal of Geophysical Research: Biogeosciences, 111(G2), n/a–n/a, doi:10.1029/2005jg000099, 2006.

Zimov, S. A.: Climate change: Permafrost and the global carbon budget, Science, 312(5780), 1612–1613, doi:10.1126/science.1128908, 2006.

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Colophon

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#>    ggplot2                * 3.1.1      2019-04-07 [1] CRAN (R 3.6.0)
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#>    glue                     1.3.1      2019-03-12 [1] CRAN (R 3.6.0)
#>    gtable                   0.3.0      2019-03-25 [1] CRAN (R 3.6.0)
#>    hector                   2.3.0      2019-06-04 [1] local
#>  P hector.permafrost.emit * 0.0.0.9000 2019-05-30 [?] local
#>    hectortools              0.0.0.9000 2019-01-25 [1] local
#>    here                   * 0.1        2017-05-28 [1] CRAN (R 3.6.0)
#>    highr                    0.8        2019-03-20 [1] CRAN (R 3.6.0)
#>    hms                      0.4.2      2018-03-10 [1] CRAN (R 3.6.0)
#>    htmltools                0.3.6      2017-04-28 [1] CRAN (R 3.6.0)
#>    igraph                   1.2.4.1    2019-04-22 [1] CRAN (R 3.6.0)
#>    knitr                    1.23       2019-05-18 [1] CRAN (R 3.6.0)
#>    labeling                 0.3        2014-08-23 [1] CRAN (R 3.6.0)
#>    lattice                  0.20-38    2018-11-04 [3] CRAN (R 3.6.0)
#>    lazyeval                 0.2.2      2019-03-15 [1] CRAN (R 3.6.0)
#>    listenv                  0.7.0      2018-01-21 [1] CRAN (R 3.6.0)
#>    magrittr                 1.5        2014-11-22 [1] CRAN (R 3.6.0)
#>    Matrix                   1.2-17     2019-03-22 [3] CRAN (R 3.6.0)
#>    memoise                  1.1.0      2017-04-21 [1] CRAN (R 3.6.0)
#>    mgcv                     1.8-28     2019-03-21 [3] CRAN (R 3.6.0)
#>    munsell                  0.5.0      2018-06-12 [1] CRAN (R 3.6.0)
```

```
#>    nlme                   3.1-140    2019-05-12 [3] CRAN (R 3.6.0)
#>    pillar                 1.4.1      2019-05-28 [1] CRAN (R 3.6.0)
#>    pkgbuild               1.0.3      2019-03-20 [1] CRAN (R 3.6.0)
#>    pkgconfig              2.0.2      2018-08-16 [1] CRAN (R 3.6.0)
#>    pkgload                1.0.2      2018-10-29 [1] CRAN (R 3.6.0)
#>    plyr                   1.8.4      2016-06-08 [1] CRAN (R 3.6.0)
#>    prettyunits            1.0.2      2015-07-13 [1] CRAN (R 3.6.0)
#>    processx               3.3.1      2019-05-08 [1] CRAN (R 3.6.0)
#>    ps                     1.3.0      2018-12-21 [1] CRAN (R 3.6.0)
#>    purrr                  0.3.2      2019-03-15 [1] CRAN (R 3.6.0)
#>    R6                     2.4.0      2019-02-14 [1] CRAN (R 3.6.0)
#>    RColorBrewer           1.1-2      2014-12-07 [1] CRAN (R 3.6.0)
#>    Rcpp                   1.0.1      2019-03-17 [1] CRAN (R 3.6.0)
#>    readr                * 1.3.1      2018-12-21 [1] CRAN (R 3.6.0)
#>    remotes                2.0.4      2019-04-10 [1] CRAN (R 3.6.0)
#>    reshape                0.8.8      2018-10-23 [1] CRAN (R 3.6.0)
#>    reshape2               1.4.3      2017-12-11 [1] CRAN (R 3.6.0)
#>    rlang                  0.3.4      2019-04-07 [1] CRAN (R 3.6.0)
#>    rmarkdown              1.13       2019-05-22 [1] CRAN (R 3.6.0)
#>    rprojroot              1.3-2      2018-01-03 [1] CRAN (R 3.6.0)
#>    scales                 1.0.0      2018-08-09 [1] CRAN (R 3.6.0)
#>    sessioninfo            1.1.1      2018-11-05 [1] CRAN (R 3.6.0)
#>    storr                  1.2.1      2018-10-18 [1] CRAN (R 3.6.0)
#>    stringi                1.4.3      2019-03-12 [1] CRAN (R 3.6.0)
#>    stringr                1.4.0      2019-02-10 [1] CRAN (R 3.6.0)
#>    testthat               2.1.1      2019-04-23 [1] CRAN (R 3.6.0)
#>    tibble                 2.1.1      2019-03-16 [1] CRAN (R 3.6.0)
#>    tidyr                * 0.8.3      2019-03-01 [1] CRAN (R 3.6.0)
#>    tidyselect             0.2.5      2018-10-11 [1] CRAN (R 3.6.0)
#>    usethis                1.5.0      2019-04-07 [1] CRAN (R 3.6.0)
#>    withr                  2.1.2      2018-03-15 [1] CRAN (R 3.6.0)
#>    xfun                   0.7        2019-05-14 [1] CRAN (R 3.6.0)
#>    yaml                   2.2.0      2018-07-25 [1] CRAN (R 3.6.0)
#>
#> [1] /Users/shik544/R
#> [2] /usr/local/lib/R/3.6/site-library
#> [3] /usr/local/Cellar/r/3.6.0_2/lib/R/library
#>
#>  P -- Loaded and on-disk path mismatch.
```

The current Git commit details are:

```
#> Local:    master /Users/shik544/Box Sync/Projects/hector_project/permafrost_emit
#> Head:     [3fdfce0] 2019-06-04: Add more methods information
```