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).

Several studies have attempted to evaluate the potential economic impacts of current and future permafrost C emissions. Lawrence et al. (2012) project declines in near-surface permafrost by 33% and 72% in RCP 2.6 and 8.5, respectively, and permafrost C feedback will stabilize at 2100 in RCP 2.6. More recently, Hope and Schaefer (2015) projected permafrost C emissions using the SiBCASA (TODO: write in full) land surface model and used these projections as inputs to the PAGE09 integrated assessment model (IAM). They found that XXX. Chen et al. (2019) also used PAGE09. Similarly, González-Eguino and Neumann (2016) used the DICE (TODO: write in full) model to XXX. Kessler (2017) also used DICE.

Hope and Schaefer (2015) (and others?) rely on climate damage functions of the general form $\delta GDP = f(\delta T)$. Such functions are, at best, highly uncertain (TODO REF), and possibly conceptually flawed (TODO REF). (TODO More on this). GCAM (TODO full name) is an alternative (TODO REF). (TODO More on GCAM).

(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.

Permafrost emissions scenarios

For all scenarios, we added the emission as a combination of fossil fuel CO2 emissions (`ffi_emissions` column in Hector) and methane emissions (`CH4_emissions` column in Hector). Where these were explicitly separated, we added them accordingly. Where they were presented only in terms of C, we did ???

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?)

Modeling permafrost emissions

Default heterotrophic respiration (R) scheme for a pool p (detritus or soil) in Hector:

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

This is case 1.

Case 2 uses the same formulation, but splits permafrost C into its own "biome", with its own photosynthesis (β) and respiration (Q_{10}) parameters.

Case 3 extends Case 2 by calculating CO_2 and CH_4 emissions as a fraction of the total respiration, controlled by two new parameters α and ϕ:

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

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

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

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).

Initial conditions

For case 1, we use the Hector defaults (Hartin et al., 2015).

For cases 2 and 3, we assumed the same total pool sizes as case 1, but divided them into the permafrost and non-permafrost biomes according to TODO.

Other notes

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

$$FCRt = FCRt0 * exp(-\Delta T/\Gamma)(for \Delta T > 0.2řC)$$

- $FCRt_0$ (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"

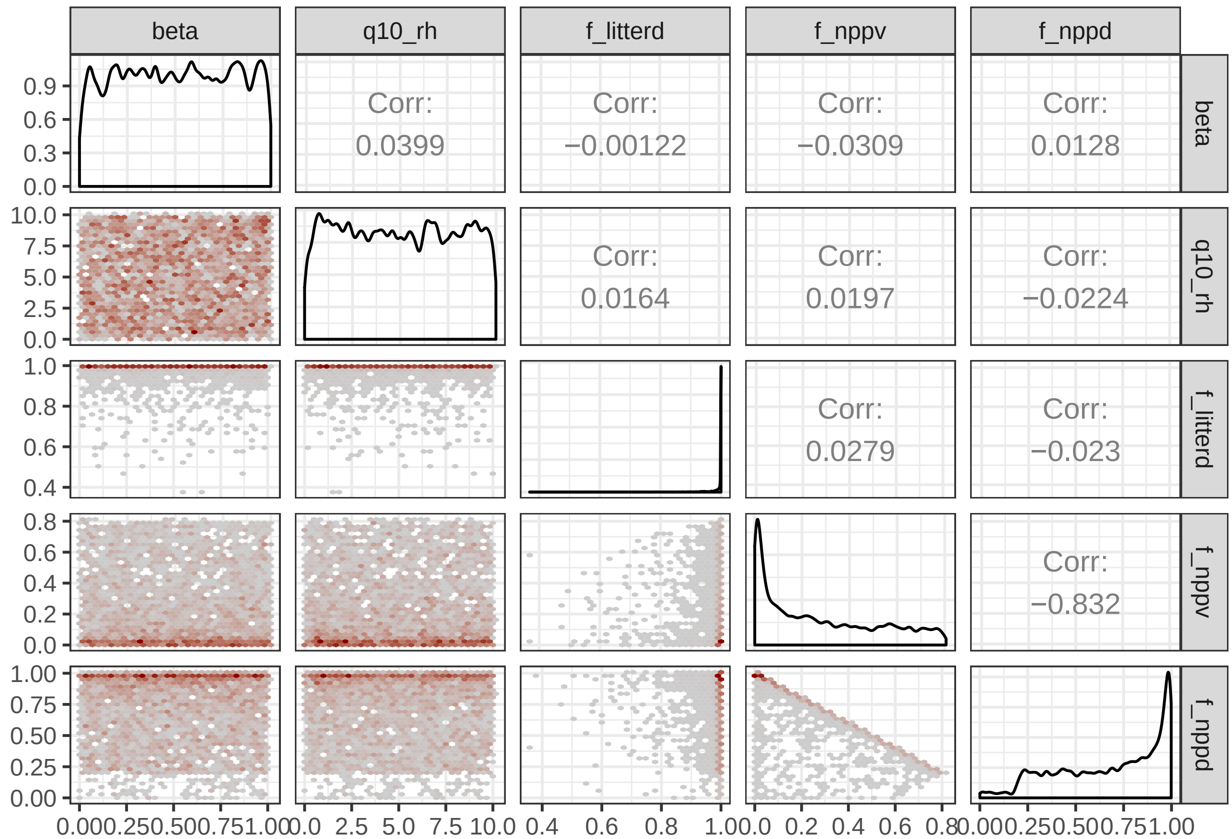

Figure 1: Input parameter distributions for global Hector.

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)".

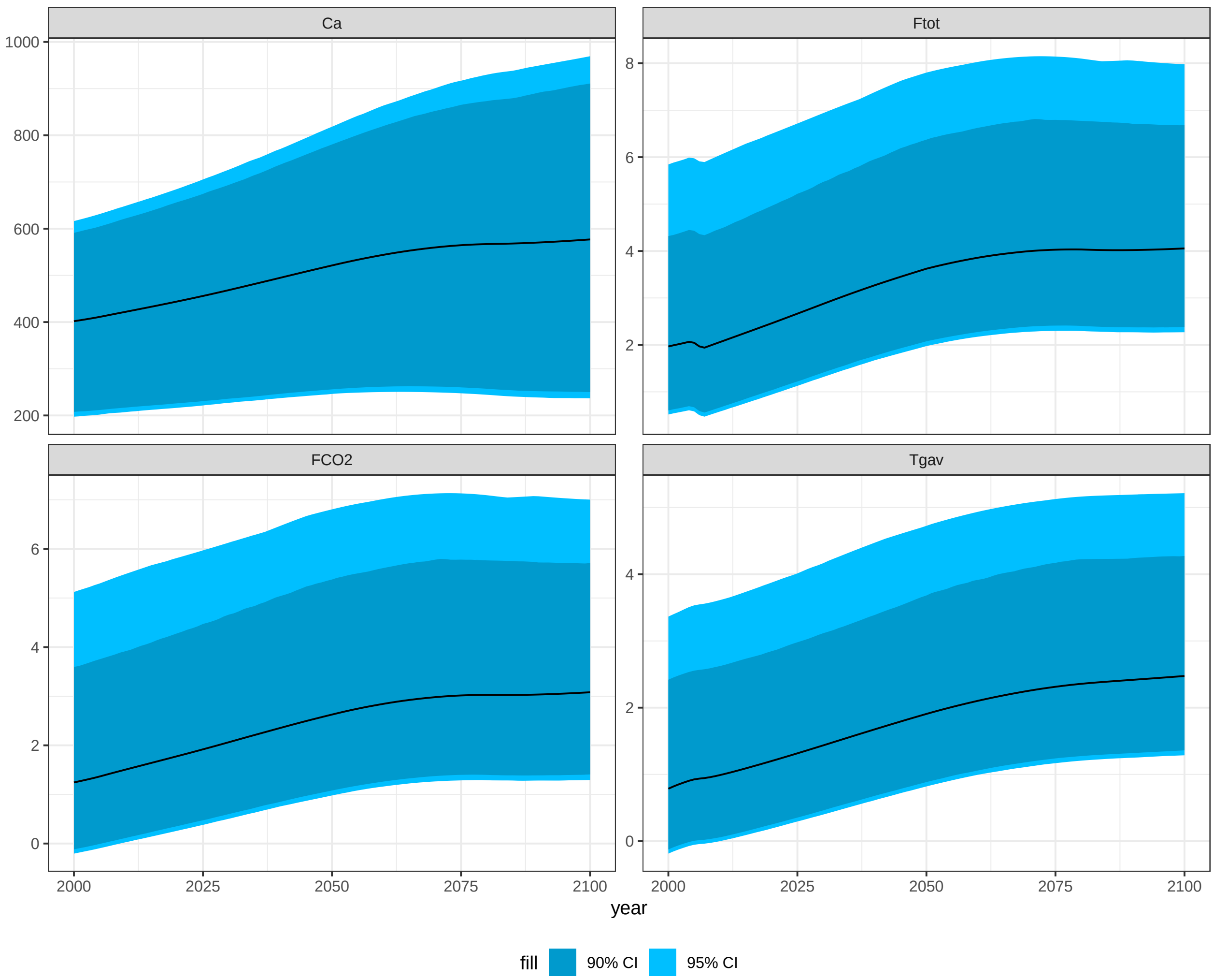

Figure 2: Time series of Hector outputs for different parameter combinations.

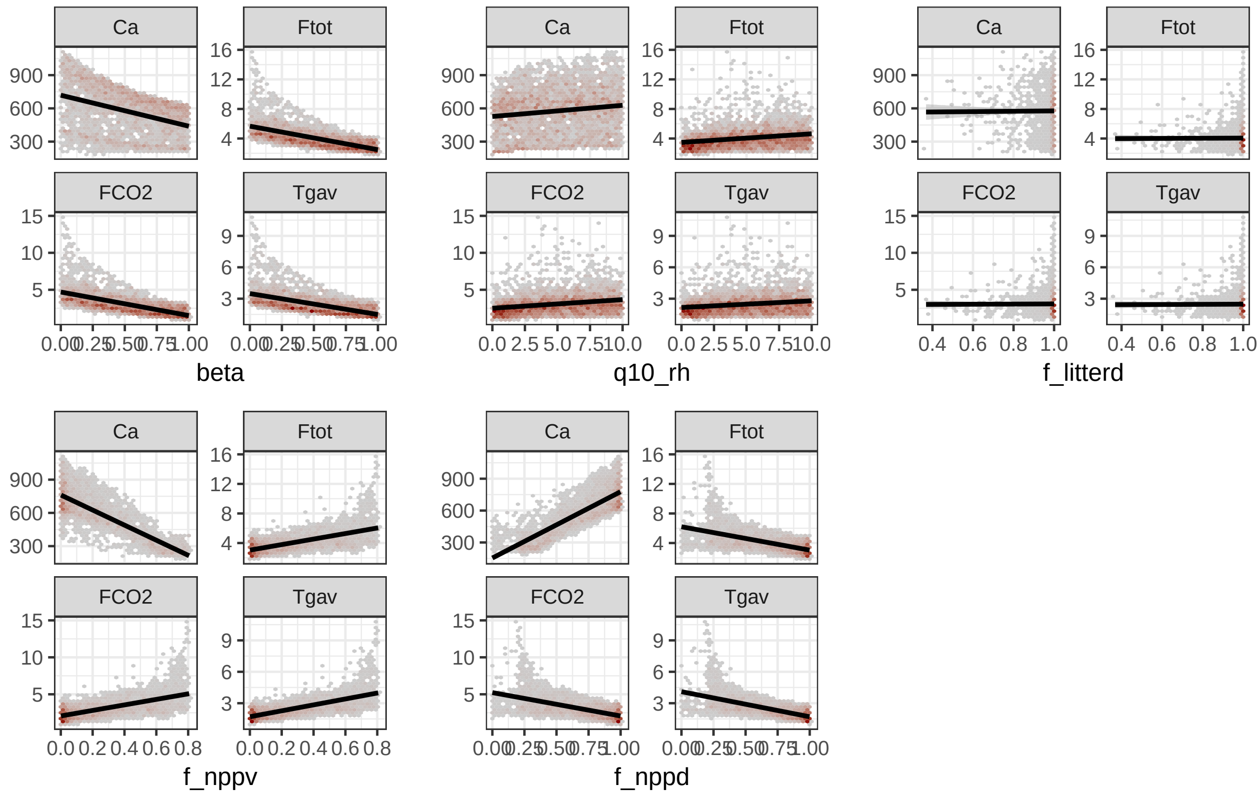

Figure 3: Hector outputs at 2100 as a function of input parameter values.

Results

Global Hector

Permafrost as a biome

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).

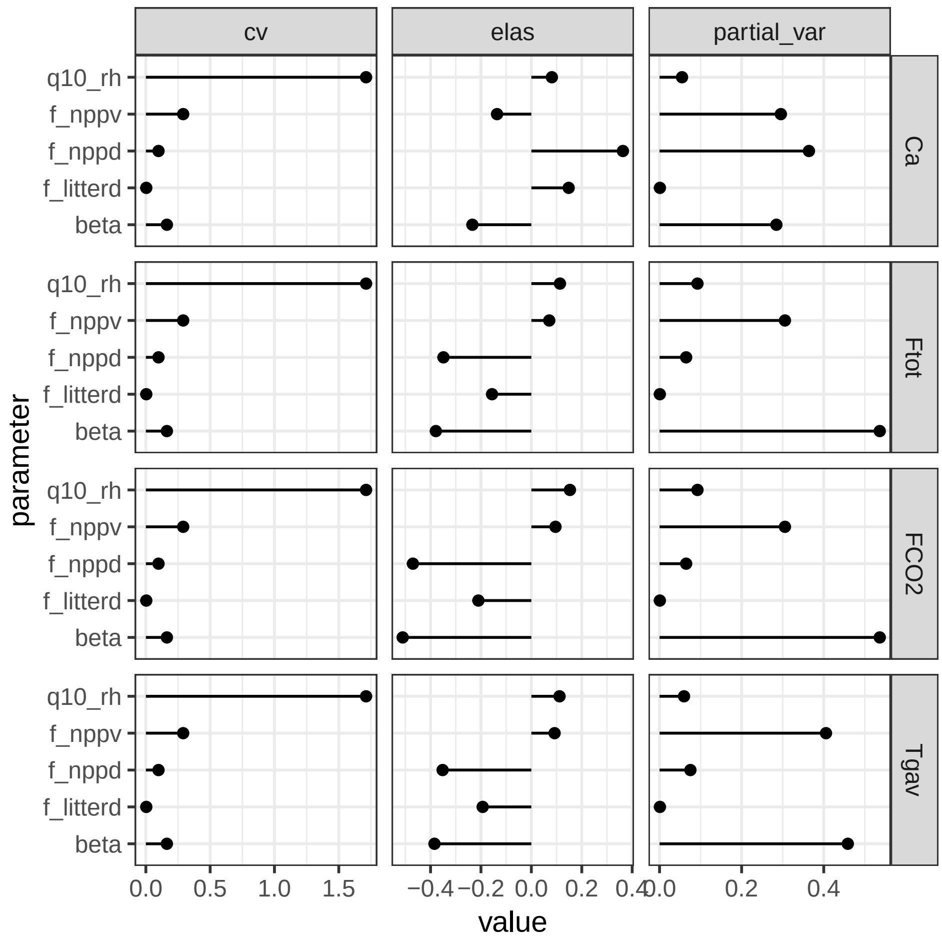

Figure 4: Sensitivity and variance decomposition analysis for global Hector.

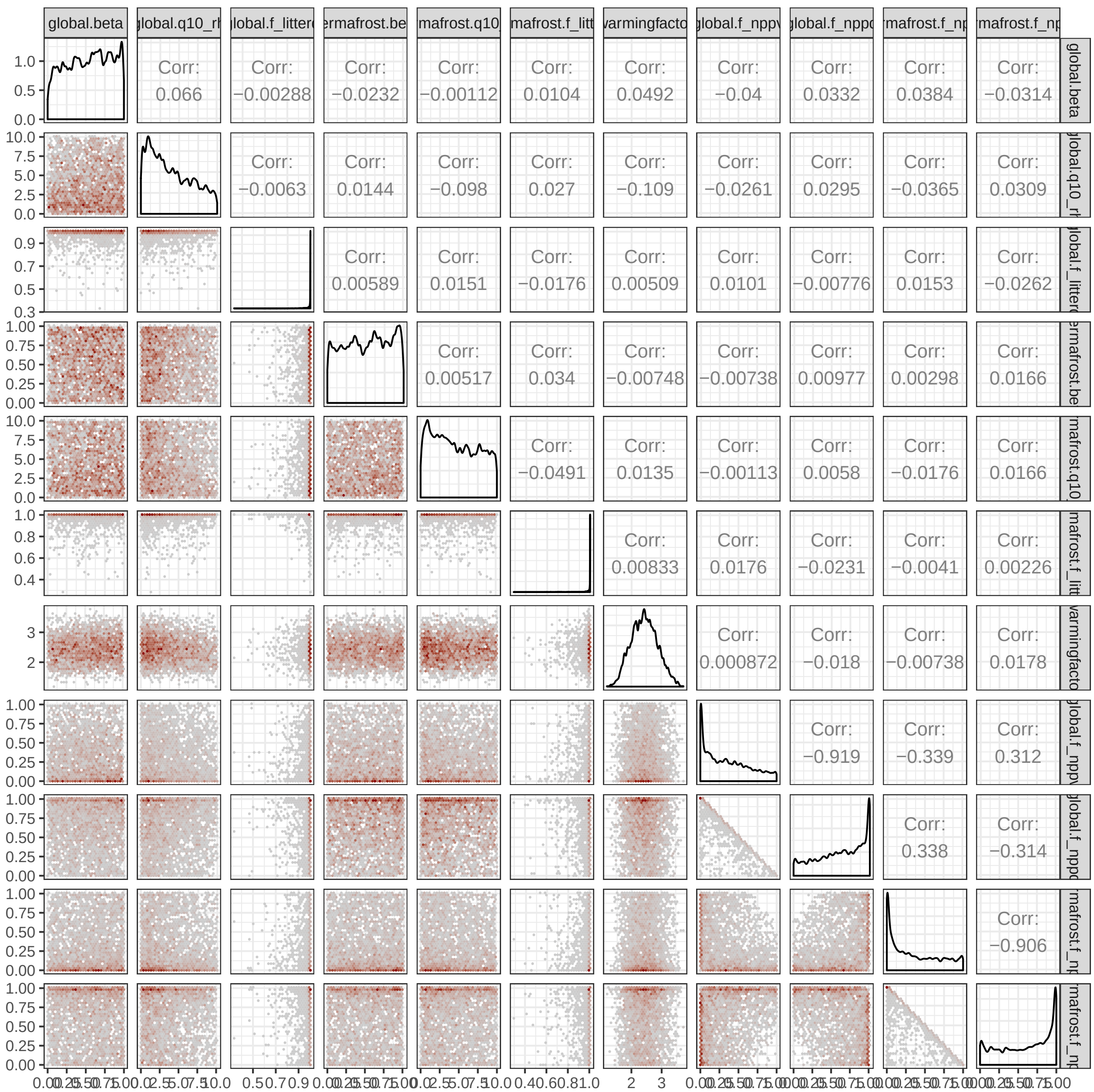

Figure 5: Input parameter distributions for global Hector.

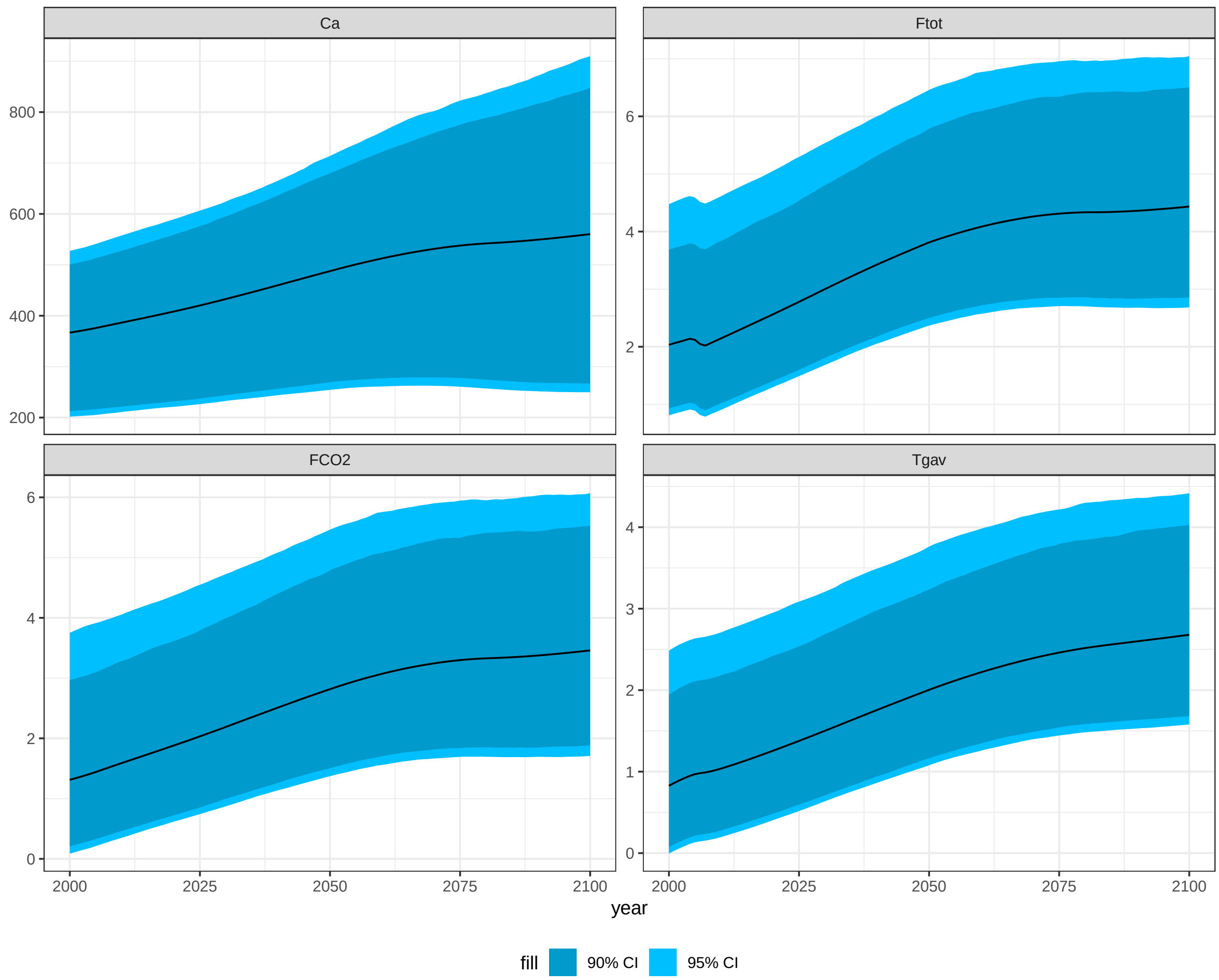

Figure 6: Overall parameter uncertainty of Hector simulations with permafrost biome.

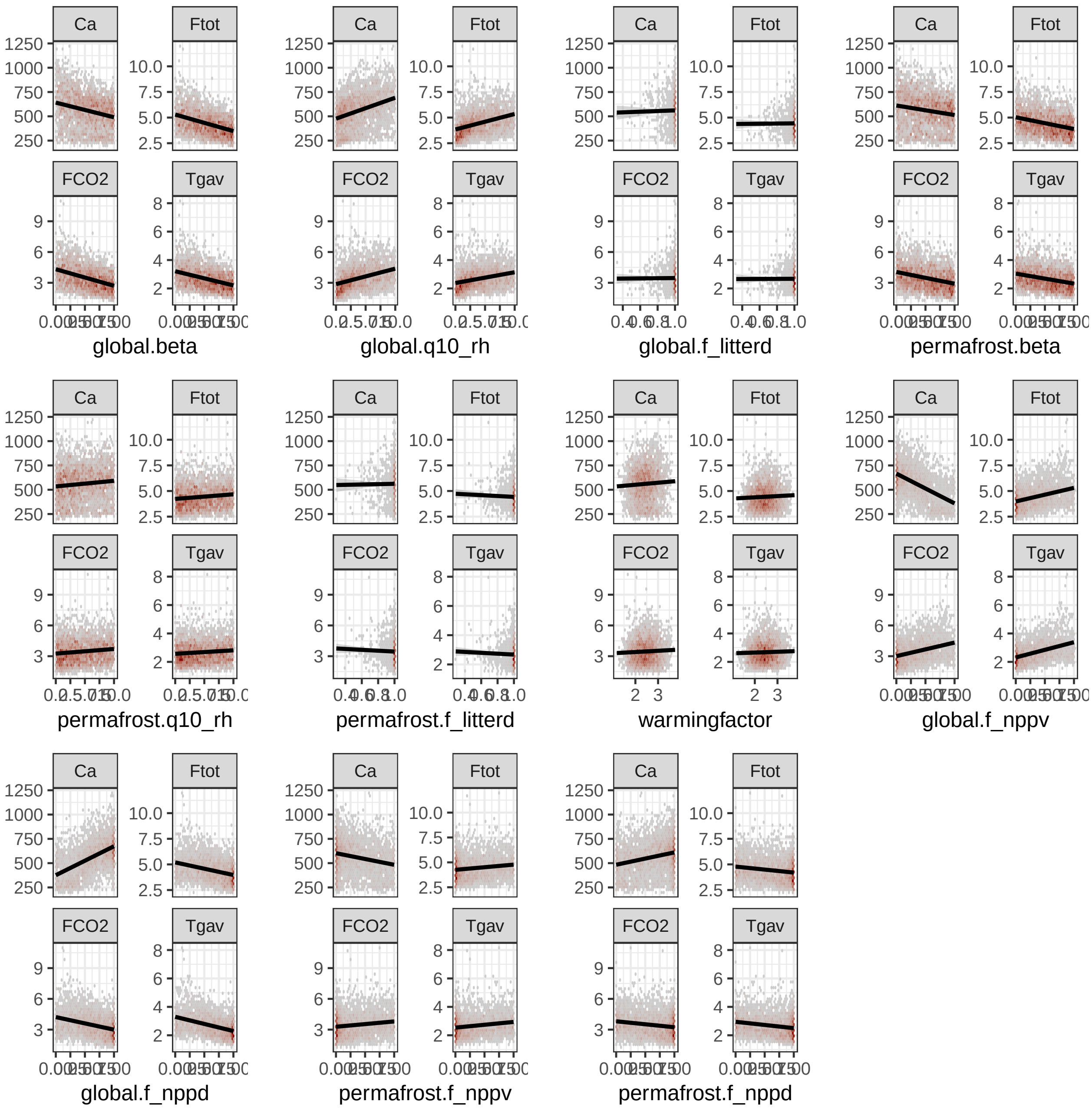

Figure 7: Hector outputs (with permafrost biome) at 2100 as a function of input parameter values.

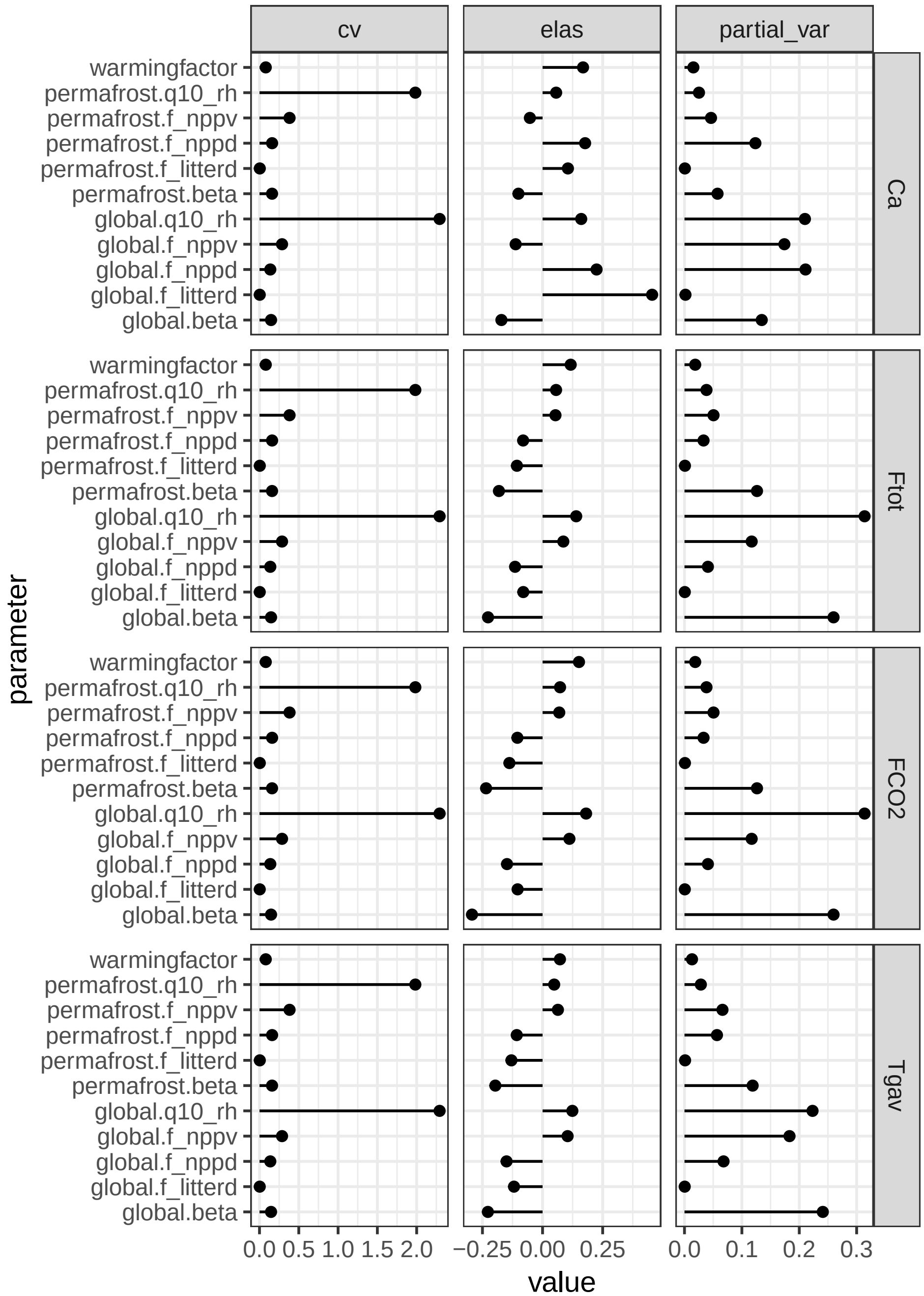

Figure 8: Sensitivity and variance decomposition analysis for Hector with permafrost biome.

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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Colophon

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#>    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:     [da8d741] 2019-06-03: Add biome simulation figures
```