

1 **Meta-analysis of high-latitude nitrogen-addition and warming studies implies**  
2 **ecological mechanisms overlooked by land models**

3  
4 **Nicholas J Bouskill ([njbouskill@lbl.gov](mailto:njbouskill@lbl.gov)), William J Riley ([wjriley@lbl.gov](mailto:wjriley@lbl.gov)),**  
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6  
7 **Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA,**  
8 **94720.**

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10  
11 **Reviewer comments, point by point responses and a marked up version of the**  
12 **manuscript.**

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16  
17 **Comment from Bond-Lamberty**

18  
19 We thank Dr. Bond-Lamberty for this comment and have made the appropriate  
20 change in the title.

21  
22  
23 **Review from Steve Allison**

24  
25 We thank Dr. Allison for his positive and constructive comments. We believe the  
26 manuscript has been significantly improved by his comments on this draft of the  
27 manuscript and a previously submitted draft.

28  
29 **That said, I think there are two key messages from the nitrogen analysis that**  
30 **could be more explicit or delivered more concisely in the paper discussion.**  
31 **One issue is that most addition rates are too high to represent what will**  
32 **happen with global change in northern ecosystems. So we are lacking in**  
33 **relevant data and manipulations. That said, the second message is that the**  
34 **models cannot replicate the (unrealistic) experimental manipulations. A good**  
35 **model should be able to replicate any observations if it has the right**  
36 **underlying mechanisms. The question here is whether we care about the**  
37 **mechanisms underlying microbial response to extremely high N addition in**  
38 **the tundra and boreal. Maybe we don't, but the analysis is still disconcerting**  
39 **because it means the models may fail in lower latitude systems with higher N**  
40 **inputs.**

41  
42 *We believe Dr. Allison is right and in rewriting aspects of the discussion we have*  
43 *included a more explicit statement representing both of these points.*

44  
45  
46 **12383:24- Report the error on the soil moisture change**

47

48 *This has been added to the results section.*

49

50

51 **12383:16- I don't think it's a good idea to abbreviate litter decomposition, or**  
52 **microbial biomass for that matter. The whole manuscript seems to have gone**  
53 **a bit overboard with the acronyms–don't use them unless they are necessary**  
54 **and well-established in the community. Otherwise it makes it hard for readers**  
55 **outside our discipline.**

56

57 *We have revised the manuscript to minimize the use of abbreviations. Only GPP and*  
58 *SOM are left as abbreviated response factors.*

59

60

61 **12384: What was the surface soil moisture response to warming in the**  
62 **models?**

63

64 *Soil moisture increased, but not statistically significantly, in both models (CLM-CN:*  
65 *38% ± 42%; CLM-Century: 7% ± 33%). We have added a statement in the results to*  
66 *reflect this point.*

67

68

69 **12386:21- “of” emergent responses.**

70

71 *We have changed this now.*

72

73

74 **12387:14- “result in”**

75

76 *We have made this correction*

77

78

79 **12387:19-24- the writing on the priming mechanism is somewhat unclear**  
80 **here. There are also too many “howevers”**

81

82 *We have re-written this section to address this comment.*

83

84

85 **12389:9- I suggest avoiding the word “acclimation” or “adaptation” in this**  
86 **context because they have specific meanings that may not be intended here.**  
87 **Karhu et al. in a very recent Nature paper coined the term “community-level**  
88 **response” to describe these processes. I would use that.**

89

90 *We take Dr. Allison's point on the use of different terms and have re-written this*  
91 *section to remove any terms that might be confusing, including instead the term*  
92 *'community-level response'.*

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**12390:10- “published”**

*We have made this correction*

**Comments from Reviewer 2.**

**The main strength of the paper is that it presents both a new meta-analysis of high latitude warming/N additions experiments and a model-data comparison. It uses the results to demonstrate key patterns that fundamentally differ between the models and the field studies. The largest weaknesses of the paper are the long and challenging to follow discussion and the lack of key information for the simulation protocol that could influence the results.**

**The discussion and conclusion section read like the authors are laying every issue with the CLM on the table. The manuscript could greatly benefit from a better-organized discussion that clearly distinguishes the important points from the secondary points. Furthermore, section 4.3 seems to be about issues associated with the model-data comparison, but most of the paragraphs in the section don’t address issues with benchmarking. For example, the paragraph on nitrogen fixation only addresses issues with nitrogen fixation not benchmarking. I recommend focusing this section.**

*We thank the reviewer for their constructive comments on our manuscript, they have been very helpful for re-focusing the manuscript. We agree with the reviewer that the manuscript discussion was too long have revised it in the current draft of the manuscript, reducing the length by 2 pages and introducing more sub-headings to help with flow. Furthermore, we have restructured aspects in accordance with the reviewer’s comments below.*

**Individual scientific/issues**

**Page 12377, Line 14: I would emphasize the role of nutrients in climate-decomposition increased growth rates feedbacks. As it reads, decomposition directly increases growth rather than increases in N mineralization increasing growth.**

*We have re-written this section for clarity.*

**Page 12377, line 26 – Page 12378, line 10: The argument for why a meta-analysis approach is different from the site-level comparison used in Thomas et al. 2013 is not clear. Both approaches use perturbation simulations in ESMs**

139 and extract gridcell level output that correspond to grid-cells with  
140 experiences. Both approaches use short-term perturbations. Both approaches  
141 focus on means across many sites. Is the unique contribution the use of meta-  
142 analysis statistics? It seems that the Thomas et al. study is broadly similar to  
143 this study and the key distinction being drawn here is between model-data  
144 comparisons that use many sites and focus on broad patterns but don't try to  
145 simulate each site perfectly and model-data comparisons that focus on a few  
146 sites but focus on matching the conditions of the study perfectly and examine  
147 detailed dynamics. (e.g., the FACE comparison by Zaehle et al. 2014). Overall, a  
148 better argument for why the meta-analysis approach is unique and  
149 particularly useful is needed.

150

151 *It was not our original intent to directly compare our approach with that laid out in*  
152 *Thomas et al., 2013. However, we realize that it is easy to interpret this paragraph in*  
153 *this way. We believe the approach described by Thomas et al., 2013 and*  
154 *the approach laid out in the current manuscript are largely complementary. The point*  
155 *we were trying to make is that such an approach doesn't capture the spatial*  
156 *heterogeneity of responses the way a data synthesis of studies spanning thousands of*  
157 *kilometers might. We have re-phrased this paragraph to avoid confusion.*

158

159 **Page 12379, Line 7: How was GPP estimated? Was GPP a modeled outcome**  
160 **from the partitioning of NEE into GEP and RE? If so, this should be stated.**

161

162 *This line actually refers to the measured GPP from the field experiments. However, the*  
163 *modeled GPP was simulated directly from CLM as net leaf photosynthesis using the*  
164 *Farquhar model (Farquhar et al. 1980) for C3 plants and the Collatz model (Collatz et*  
165 *al., 1992) for C4 plants.*

166

167 **Page 12379, Line: It might be useful to list the summaries statistics (range and**  
168 **mean) for the warming in the observations. It would help the reader**  
169 **understand why ← 1C warming was targeted in the CLM simulations**

170

171 *This information is given in the results, however, we have added a sentence directing*  
172 *the reader to these data.*

173

174 **Page 12379, Line 20: The focus of the manuscript is on nitrogen-carbon**  
175 **interactions but studies with P and K were used. How many studies were**  
176 **multi-element additions? How would this influence the results?**

177

178 *In the present data set approximately 0 to 40% (depending on the response measured)*  
179 *of the studies used an NPK fertilizer instead of NH<sub>4</sub>NO<sub>3</sub>, and these studies were*  
180 *generally in Europe. Table S1 in the supplemental material breaks the responses down*  
181 *by N-species added and there is an affect on microbial biomass from using*  
182 *NPK compared with NH<sub>4</sub>NO<sub>3</sub>. However, other response ratios (e.g., below*  
183 *ground respiration) came from studies that only used NH<sub>4</sub>NO<sub>3</sub> as the nitrogen source*

184 and in general we included only data using  $\text{NH}_4\text{NO}_3$  fertilization, so we don't believe  
185 the use of NPK has influenced the overall conclusions to a great degree.

186

187 **Page 12382, first paragraph in section 2.3: Model protocol description is**  
188 **severely lacking. For example, what resolution was the model run? What**  
189 **climate forcing was used? Was 1500 years suitable for the carbon stocks to**  
190 **come to equilibrium?**

191

192 *We have included additional information on the model protocol, specifically;*

193

194 *'All simulations were run at a spatial resolution of  $1.9^\circ \times 2.5^\circ$ , using the Qian et al.,*  
195 *{Qian:2006wd} dataset for atmospheric forcing. The models were spun up for 1500*  
196 *years to preindustrial equilibrium following an improved spinup approach (Koven et*  
197 *al., 2013) that allows the models to reach equilibrium after 1000 years. Simulations*  
198 *were then run from 1850 to 1979 under contemporary climate forcing before the onset*  
199 *of perturbation conditions over the following 21 years (from 1980 to 2000). Model*  
200 *vegetation was specified according to the MODIS vegetation continuous fields (Oleson*  
201 *et al., 2013).'*

202

203 **Page 12382, line 7: How does changing the atmospheric forcing violate the**  
204 **energy budget? Can't the temperature in the input file be increased by 1C?**  
205 **Understanding this better may help other models simulate warming**  
206 **experiments.**

207

208 *CLM4.5 calculates the surface energy budget explicitly, such that the soil thermal*  
209 *dynamics are driven by residual energy flux from the net radiation, latent heat flux,*  
210 *and sensible heat flux. We first attempted to increase the input temperature by 1C, but*  
211 *the simulation failed to produce soil warming comparable to the available*  
212 *observations. A second approach we tried was to directly warm the soil by 1 C, but this*  
213 *approach creates unrealistic responses associated with the imposed energy imbalance.*  
214 *We subsequently found modifying aerodynamic resistance produced a more realistic*  
215 *warming compared to other approaches, such as changing wind speed.*

216

217 **Page 12382, Line 13-16: Well done with accounting for the intra-annual**  
218 **experimental treatments.**

219

220 *We thank the reviewer for this comment.*

221

222 **Page 12382, Lines 17-27: More detail about the model simulations is**  
223 **necessary. Did the plant functional type used in the simulation match the plant**  
224 **type in the experiment?**

225

226 *As documented in the technique note for CLM4.5 (Oleson et al., 2013; section 21.3.3),*  
227 *the plant functional types are specified based on MODIS vegetation continuous fields*  
228 *product (Hansen et al., 2003). Therefore, although it is unlikely the model simulation*  
229 *could match the site data perfectly everywhere, the agreement is expected to be*

230 *largely reasonable at the model's spatial resolution.*

231

232 *We have added a sentence to the materials and methods to reflect this.*

233

234 **Did the duration of the simulation match the duration of the experiment? For**  
235 **example, if the N fertilization experiment was only 3 years was only the first 3**  
236 **years of the 21-year N fertilization simulation used? If the entire 21-year**  
237 **simulation was used then that would explain why the N fertilization response**  
238 **in CLM was much higher than the observations.**

239

240 *To account for this problem, we grouped our observationally-inferred effect sizes by*  
241 *experiment duration bins, where it was practical (lines 148 – 149, 156, Figure 3,*  
242 *Figure S1). The majority of the experimental studies were short-term (1 – 7 years long)*  
243 *with fewer longer term (20 year studies), and those studies dominate the effect sizes*  
244 *we report. For that reason, we evaluate our effect sizes with the same temporal*  
245 *window since experiment inception.*

246

247 **Page 1283, Line 25: Why were the models different? Don't they have the same**  
248 **bio-geophysics modules?**

249

250 *The models do have the same bio-geophysical formulations. However, differences*  
251 *result from differences in the belowground carbon and nitrogen representations and*  
252 *the resulting impacts on leaf phenology and gross primary production. In general,*  
253 *CLM-CN and CLM-CENTURY behave quite differently in their soil carbon and nutrient*  
254 *cycles, leading to different nitrogen regulation impacts on plant productivity. The*  
255 *different plant productivity subsequently leads to different leaf phenology and*  
256 *different surface energy budgets.*

257

258 **Page 12384, Line 4-5: The average warming in the ESMs was different from**  
259 **each other and lower than the field studies. Since the models are sensitive to**  
260 **warming, how would the 0.3 C difference between the models influence the**  
261 **results? Similarly, the CLM-CN was 0.5 C lower than the observed change in**  
262 **temperature. This is half of the goal temperature change (1 C). What are the**  
263 **implications of the temperature changes not matching?**

264

265 *The formulations of CLM-CN and CLM-CENTURY are linear functions of the relative*  
266 *soil organic matter pools, and the temperature response functions are monotonic  $Q_{10}$*   
267 *based functions. The modeled magnitude of warming was not significantly different*  
268 *from the observed increased soil temperatures, therefore we do not expect the modeled*  
269 *functional response to change qualitatively (which is the focus in this study). In*  
270 *addition, given the large soil carbon stocks in cold regions and that the model*  
271 *simulated results are opposite to empirical data, additional warming in the model*  
272 *would produce even stronger contrasts between model simulations and the*  
273 *measurements. We have added a sentence to the Discussion section addressing this*  
274 *point.*

275

276 **Page 12386, Line 21: This sentence isn't clear. If we don't benchmark using**  
277 **observations then what do we use?**

278

279 *We wished to emphasize that observations that are emergent and relatively small*  
280 *responses compared to the component processes that affect them, and where those*  
281 *component processes have different environmental, antecedent, or mechanistic*  
282 *controls, are not good tests of model fidelity. We have clarified this point in the revised*  
283 *manuscript.*

284

285 **Page 12386, Line 23: While it is important point that NEE is potentially a small**  
286 **difference of two large fluxes (GPP and RE), it is also important to note that**  
287 **GPP and RE are modeled fluxes based on NEE.**

288

289 *Our original point was not to evaluate the methods used to disaggregate measured*  
290 *NEE into inferred GPP and RH, but rather to indicate that an emergent system*  
291 *response that is relatively small compared to it's component drivers (e.g., NEE) is likely*  
292 *not a good variable to calibrate or test a model.*

293

294 **Discussion in general: I recommend a better presentation of the take-home**  
295 **messages. I also recommend synthesizing what you learned across the N**  
296 **fertilization and warming experiments? Are there common lessons learned in**  
297 **the two experiment types? Are the lessons learned that would not be found by**  
298 **focusing just on N fertilization or warming experiments?**

299

300 **Overall, I am wondering what the priorities are for CLM development**  
301 **based on the results from the study.**

302

303 **Also, the discussion uses the term "benchmarking" but doesn't providing**  
304 **insights into the key metrics from the study that are benchmarks for other**  
305 **models to use.**

306

307 **What metrics do the authors think that ESMs should focus on?**

308

309 *We have added an additional section (section 4.3, lines 697 - 744) prior to the*  
310 *conclusions that identifies several metrics (e.g., nitrogen mineralization, litter*  
311 *decomposition) that we recommend for benchmarking. Furthermore, we have also*  
312 *highlighted conclusions reached from the meta-analysis that could contribute to the*  
313 *development of the CLM-biogeochemistry codes.*

314

315

316 **Section 4.1: It seems that key result from the model-data comparison is the**  
317 **lack of an N mineralization response in the warming studies and large**  
318 **responses in the CLM. Why are the differences so large? What mechanisms**  
319 **need to be included in CLM to capture this? Why to the N mineralization**  
320 **response in the meta-analysis differ from other metaanalysis (Rustad et al**  
321 **2001) and studies (Melillo et al. 2011)?**

322

323 **I would consider leading the discussion with the N mineralization response to**  
324 **warming because it is a core process in the climate-carbon feedback and the**  
325 **most striking difference between the observations and the models.**

326

327 *We agree with the reviewer in this case and have rearranged the discussion section to*  
328 *begin with the focus on nitrogen mineralization. In this new text we have addressed all*  
329 *of the reviewer questions posed here.*

330

331 **Page 12392, line 5: Other studies have found limited nitrate leaching in the**  
332 **CLM-CN (see Thomas et al. 2013).**

333

334 *We have reworded this section to note that nitrate losses are mainly from*  
335 *denitrification.*

336

337 **Section 4.3: This section does not maintain focus on the topic of barriers to**  
338 **experiment based model benchmarking. We know that CLM is lacking**  
339 **processes to perfectly simulate the globe but why is that a barrier to**  
340 **benchmarking. It seems that the processes that are listed should be the focus**  
341 **of model development through benchmarking. Overall, it seems like an odd**  
342 **place to provide model caveats (lack of P cycle, poor representation of N**  
343 **fixation, etc). The section would be more informative for other modeling**  
344 **groups if it explores the positives and negatives of the meta-analysis approach**  
345 **for benchmarking.**

346

347 *We have re-focused this section into four parts that address four concerns for the*  
348 *model versus data comparison. We also added several sentences describing criteria to*  
349 *be used to ensure that the imposed perturbation in the model reasonably represents*  
350 *the perturbation impacts in the field sites.*

351

352 *We have also added a further section that briefly highlights the positives and negatives*  
353 *of this approach.*

354

355 **Figure 2: The current size of the figure and line thickness make the figure**  
356 **difficult to read.**

357

358 *We have improved the spacing within these figures.*

359

360 **Figure 3: Use either GEP or GPP. One is used in the figure and the other in the**  
361 **caption.**

362

363 *We have altered this caption to reflect the use of GPP.*

364

365

366

367

368 | **Meta-analysis of high-latitude nitrogen-addition and warming studies implies,**  
369 **ecological mechanisms overlooked by land models**

370  
371 **Nicholas J Bouskill ([njbouskill@lbl.gov](mailto:njbouskill@lbl.gov)), William J Riley ([wjriley@lbl.gov](mailto:wjriley@lbl.gov)),**  
372 **Jinyun Tang ([jinyuntang@lbl.gov](mailto:jinyuntang@lbl.gov))**

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375 **94720.**

376  
377 **Running title:** Testing model performance via meta-analysis

378  
379 **Keywords:** Carbon cycling, High-latitude soils, climate change, nitrogen cycling,  
380 warming, model benchmarking.

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415 **Abstract**

416

417 Accurate representation of ecosystem processes in land models is crucial for

418 reducing predictive uncertainty in energy and greenhouse gas feedbacks with the

419 climate. Here we describe an observational and modeling meta-analysis approach to

420 benchmark land models, and apply the method to the land model CLM4.5 with two

421 versions of belowground biogeochemistry. We focused our analysis on the above

422 and belowground responses to warming and nitrogen addition in high-latitude

423 ecosystems, and identified absent, or poorly parameterized mechanisms in CLM4.5.

424 While the two model versions predicted similar soil carbon stocks trajectories

425 following both warming and nitrogen addition, other predicted variables (e.g.,

426 belowground respiration) differed from the observations in both magnitude and

427 direction, indicating CLM4.5 has inadequate underlying mechanisms for

428 representing high-latitude ecosystems. On the basis of observational synthesis we

429 attribute these differences to missing representations of microbial dynamics,

430 characterization of above and belowground coupling, and nutrient competition. We

431 use the observational meta-analyses to discuss potential approaches to improving

432 the current models (e.g., the inclusion of dynamic vegetation or different microbial

433 functional guilds). However, we also caution the selection of data sets and

434 experiments for meta-analysis. For example, the concentrations of nitrogen applied

435 in the synthesized field experiments (average = 72 kg ha<sup>-1</sup> yr<sup>-1</sup>) are many times

436 higher than projected soil nitrogen concentrations (from nitrogen deposition and

437 release during mineralization), which precludes a rigorous evaluation of the model

438 responses to likely nitrogen perturbations. Overall, we demonstrate that elucidating

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452 | ecological mechanisms via meta-analysis can identify deficiencies in ecosystem  
453 | models and empirical experiments.

454

## 455 | **1 Introduction**

456

457 | Northern Hemisphere high latitude soils are among the largest global stores  
458 | of soil organic matter (SOM) (Grosse et al., 2011). Recent studies have estimated  
459 | SOM storage within permafrost regions to be ~1700 Pg to 3 m depth (Schuur et al.,  
460 | 2012), representing nearly 50% of global terrestrial organic carbon, or nearly twice  
461 | that currently in the atmosphere (King et al., 2007). Permafrost SOM is stabilized by  
462 | cold temperatures, and is therefore vulnerable to the warming that high-latitude  
463 | regions will experience over the next century (Schuur and Abbott, 2011). However,  
464 | the response of high-latitude ecosystems to global climate change is complex. Under  
465 | warming, the active layers of permafrost soils thicken, and may serve as a reservoir  
466 | of chemically labile organic carbon. Carbon released from these soils (mostly as CO<sub>2</sub>  
467 | or CH<sub>4</sub>) may accelerate the rate of warming and form a positive feedback to climate  
468 | change (Koven et al., 2011). Alternatively, elevated rates of organic matter  
469 | decomposition release limiting nutrients (e.g., nitrogen) that could stimulate plant  
470 | productivity, sequestering CO<sub>2</sub> from the atmosphere, serving as a negative feedback  
471 | on climate change (Shaver et al., 1992).

472 | Predictions of how future climate change will alter high-latitude soil carbon  
473 | are derived mainly from (a) conclusions of in situ field manipulation studies and (b)  
474 | output of land models either coupled or uncoupled with an atmospheric model. The  
475 | coupled Earth System Models (ESMs) couple land and atmospheric processes by

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477 | simulating land biogeochemical and biophysical states and fluxes (including soil  
478 | carbon dynamics and effluxes) and feedbacks to atmospheric carbon concentrations  
479 | across decadal, centennial, and millennial time scales (Kaplan et al., 2002; Koven et  
480 | al., 2011) . Current ESMS have high uncertainty in their predicted magnitude of  
481 | carbon-climate feedbacks (Arora et al., 2013; Friedlingstein et al., 2006) because of  
482 | insufficiencies in model structure and parameterization (Bonan et al., 2011; Jung et  
483 | al., 2007; Zaehle et al., 2005).

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484 | Benchmarking the performance of land models has been challenging (Luo et  
485 | al., 2012) . One approach has been to compare model output against the output of  
486 | distinct manipulation studies (Thomas et al., 2013b) that acutely perturb  
487 | ecosystems on short time scales (months to years). However, the broad spatial  
488 | heterogeneity of high-latitude soils may not be well represented by the  
489 | concentration of high-latitude field studies within a few sites. Herein, we benchmark  
490 | the models by compiling data from a range of studies measuring the same variables  
491 | across spatial gradients. This approach can determine an overall ecosystem  
492 | response to perturbation, eliminating the weight placed on any one study. Data  
493 | compilation can also identify important mechanisms that determine the fate of soil  
494 | carbon but are currently not represented in the land models.

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**Deleted:** field experiments with short experimental timeframes (months to years) and high rates of perturbation may not be representative of the long-term (decadal to centennial), and chronic nature of anthropogenic climate change. Furthermore,

495 | In the present study, we examined the fate of high-latitude soil carbon based  
496 | on conclusions drawn from (1) meta-analyses of high-latitude field studies ( $\geq 60^\circ$  N)  
497 | focusing on ecosystem responses to warming and nitrogen additions and (2) meta-  
498 | analyses of simulations mimicking the experiments using the land component  
499 | (CLM4.5) of the Community Earth System Model (CESM). We address four

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512 questions: (1) Do the models and synthesized data predict a similar response of  
513 carbon and nutrient cycling to ecosystem warming and nitrogen addition? (2) In  
514 what areas do the models and experiments diverge? (3) What are the mechanisms,  
515 including those absent in the models, the field experiments demonstrate to be  
516 important for evaluating the fate of soil C? (4) What types of observationally derived  
517 model benchmarks are appropriate for the various ecosystem processes relevant to  
518 high-latitude soil C dynamics?

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519

## 520 2 Materials and Methods

521

### 522 2.1 Literature search

523 We compiled published observations for replicated field studies from high-  
524 latitude ecosystems ( $\geq 60^\circ$  N) (Fig. 1) examining responses of belowground  
525 biogeochemistry to warming and nitrogen addition. The data were mainly extracted  
526 from published figures or tables, or directly from the authors in cases where  
527 unpublished results were referenced in a published study. Manipulation studies  
528 were located by searching the ISI Web of Knowledge, using the following principal  
529 terms: "Arctic", "Permafrost", "High-latitude", paired with: "Manipulation",  
530 "Nitrogen", "Warming". Where available, we collected data from control and  
531 perturbed soils on microbial (i.e., bacterial + fungal) biomass, fungal biomass,  
532 aboveground biomass, belowground respiration, heterotrophic respiration, gross  
533 primary productivity (GPP), litter decomposition, soil organic matter content (SOM),

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542 net nitrogen-mineralization, and soil and microbial nitrogen and phosphorus  
543 concentrations.

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544 To characterize the response of high-latitude soils to warming we collected  
545 data from studies that passively warmed soil using open top chambers (OTC) or  
546 greenhouses (OTG) and snow manipulation studies. We also collected data from  
547 studies that used incubations to increase temperature. We collected more than 2800  
548 entries from 53 field studies across 17 different high-latitude ecosystems. We  
549 present the data as a response ratio across all of the studies. We also sought to  
550 understand the influence of duration on certain responses, and where appropriate,  
551 data was further partitioned by experimental duration: short-term (< 2 yrs), long-  
552 term (> 5yrs) and intermediate (2 – 4 yrs).

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553 For nitrogen addition, we collected studies that applied nitrogen as either  
554 ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>) or nitrogen phosphorus potassium fertilizer (NPK).

555 We analyzed over 2,300 entries (i.e., individual measurements of each metric)  
556 across 37 nitrogen addition field studies from 14 geographically distinct sites (Table  
557 S1). We examined the influence of geography on the response of our data sets by  
558 partitioning the data between that collected from European and North American  
559 manipulation studies. The data were also temporally disaggregated in a similar  
560 manner as described above for the warming experiments.

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561 Data were extracted from figures using the Data Thief software (Tummers,  
562 2006). Comparison data were standardized to units of “g m<sup>-3</sup>” prior to calculating a  
563 response ratio. Bulk density measurements for the different soils were extracted  
564 from the published studies or through personal communication with the authors. In

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570 the cases where authors could not be contacted, bulk density was estimated using a  
571 previously published approach (Calhoun et al., 2001).

572

## 573 2.2 Meta analysis

574 Data were analyzed using the MetaWin 2.2 software package (Rosenberg et  
575 al., 2000), using the standard deviation (SD) reported from each individual  
576 observation. In the majority of cases, SD was calculated from the reported standard  
577 error and number of replicates. A response metric was calculated as the natural log  
578 of treatment group relative to a control:

$$\ln R = \ln \left( \frac{\bar{X}^T}{\bar{X}^A} \right)$$

579 Where  $\bar{X}^T$  and  $\bar{X}^A$  are the mean values for the treatment and ambient response  
580 variable, respectively. The sampling variance ( $V_{\ln R}$ ) was calculated as:

$$V_{\ln R} = \frac{(s^T)^2}{N^T (\bar{X}^T)^2} + \frac{(s^A)^2}{N^A (\bar{X}^A)^2}$$

581 Where  $s^T$  and  $s^A$  represent the normalized standard deviations around the mean  
582 values and  $N^T$  and  $N^A$  are the number of replicate studies from treatment and  
583 ambient experiments, respectively. The effect size for different response metrics  
584 was subsequently calculated using a weighted average value, where the weight for  
585 the  $i^{\text{th}}$  study is the reciprocal of its sampling variance.

586 A mixed model was used to calculate the cumulative differences in the  
587 response variables in treatment versus control plots. These cumulative differences  
588 were calculated for the overall dataset, and also after constraining the datasets to  
589 similar conditions and forcings (e.g., geographic location, magnitude of N added).

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590 When an effect size was drawn from a low number of contributing studies (< 15),  
591 the data was resampled (using 2500 iterations) by bootstrapping to give a  
592 conservative estimate of the confidence interval (CI). Data was also gathered on  
593 climate conditions (mean annual air temperature (MAT) and precipitation (MAP),  
594 and growing season mean air temperature (GSMT)) and experimental conditions  
595 (experimental duration and magnitude of warming or nitrogen added) for each site  
596 sampled. We used a regression analysis to examine whether variability in response  
597 variables (e.g., belowground respiration and microbial biomass) was due to spatial  
598 differences in climate or due to experimental manipulation (e.g., warming or  
599 nitrogen added).

600

### 601 2.3 CLM-BGC spin-up and experimental manipulation scenarios.

602 We simulated the ecosystem perturbation experiments using the community  
603 land model (CLM4.5) with two different representations of belowground  
604 biogeochemistry; a vertically resolved belowground module with similar  
605 biogeochemistry to the Century model (termed CLM-Century, (Koven et al., 2013),  
606 and the Carbon-Nitrogen biogeochemistry module (termed CLM-CN, (Thornton et al.,  
607 2007). CLM-Century and CLM-CN share the same formulation of aboveground  
608 biogeochemical processes and land biogeophysics, but differ in their representation  
609 of belowground carbon turnover and nitrogen cycling. For example, CLM-CN  
610 represents the belowground decomposition cascade as four discrete pools with  
611 faster turnover times than the three-pool approach used by CLM-Century (Koven et  
612 al., 2013). Furthermore, the nitrogen cycle of CLM-CN is much more open (i.e.,

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615 higher cycling rates and losses) than that of CLM-Century. Finally, CLM-CN does not  
616 resolve the vertical biogeochemical gradients characteristic of CLM-Century. [All](#)  
617 [simulations were run at a spatial resolution of 1.9° × 2.5°, using the Qian et al.,](#)  
618 [{Qian:2006wd} dataset for atmospheric forcing.](#) The models were spun up for 1500  
619 years to preindustrial equilibrium [following an improved spinup approach \(Koven](#)  
620 [et al., 2013\) that allows the models to reach equilibrium after 1000 years.](#)  
621 [Simulations were](#) then run from 1850 to 1979 under contemporary climate forcing  
622 before the onset of perturbation conditions over the following 21 years (from 1980  
623 to 2000). [Model vegetation was specified according to the MODIS vegetation](#)  
624 [continuous fields \(Oleson et al., 2013\).](#) Model simulations were parameterized to  
625 replicate the field experiments: the soil was warmed by scaling the aerodynamic  
626 resistance by a factor of 10, a value obtained by trial and error to achieve a desired  
627 warming of ~1 °C [\(in accordance with the average temperature increase noted for](#)  
628 [the experimental manipulations, see results section below\)](#), while keeping sufficient  
629 spatial variability of the warming. CLM forces the soil heat transport process  
630 through the residual flux from incoming radiation, latent heat, and sensible heat.  
631 Increasing aerodynamic resistance reduces the sensible and latent heat fluxes and  
632 warms the soil during the growing season. We tried warming the soil by increasing  
633 the surface air temperature (which is a diagnostic variable in CLM), but this  
634 approach violated CLM's surface energy budget and was therefore avoided.  
635 Furthermore, increasing aerodynamic resistance is more analogous to the approach  
636 of installing open-top chambers to warm the soil.

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640 Nitrogen was added in the form of  $\text{NH}_4\text{NO}_3$  at concentrations that replicated  
641 the very high concentrations of the nitrogen addition experiments (20, 40, 60, 80  
642 and 100  $\text{kg-N ha}^{-1} \text{ yr}^{-1}$ ). However, for comparison, we also simulated the model  
643 response to a range of nitrogen concentrations that reflect more realistic nitrogen  
644 deposition scenarios up to 2050 (0.2, 1.0, 2.0, 3.0  $\text{kg-N ha}^{-1} \text{ yr}^{-1}$ , (Galloway et al.,  
645 2004). To mimic the approach of most field studies, we began the perturbation  
646 (warming or nitrogen addition) when a given model grid was snow free for 7 days  
647 (< 1 mm standing stock) and ended after more than 7 days with standing snow (> 1  
648 mm standing stock).

649 Model output was collected for each site considered in the meta-analysis (Fig.  
650 1) using a 3×3 grid that surrounded the experimental manipulation site at the  
651 center. The mean and standard deviation (SD) of predictions from the 9 grid cells  
652 were then used to calculate the response ratios from that site. For coastal sites,  
653 some modeled grid cells were not on land due to model spatial resolution, and data  
654 statistics were therefore scaled with the actual number of data points accordingly.  
655 For all sites we took the mean and SD of the grid cells and analyzed the data using  
656 the meta-analysis approach applied to the observations and described above. Our  
657 model analysis was limited to the output from the surface soil (10 cm for CLM-  
658 Century and bulk prediction for CLM-CN, which represents approximately the top  
659 20 cm of soil) where the majority of the collected studies focused their  
660 measurements.

661

### 662 **3 Results.**

663 **3.1 Response of belowground C-cycling to warming**

664 On average, experimental warming increased soil temperatures by 1.4°C (±

665 0.7°C). Belowground respiration increased significantly under warming by 9% (±

666 5%) compared to the controls. This increase in belowground respiration was largely

667 driven by the response of European soils, where increase was 33% (± 11%) above

668 control soils. Conversely, belowground respiration from North American soils

669 showed a more modest, and non-significant, increase (2.5% ± 6.5%; Fig. 2a, S1b). It

670 is unlikely that this spatial difference is due to greater experimental warming of

671 European soils: passive warming increased soil temperatures by 1.4 ± 0.6 °C in

672 Europe and 1.3 ± 0.5 °C in North American experiments. A transient effect of

673 belowground respiration in high-latitude soils was also noted in the data set. Short

674 term experiments (< 2 years), showed a large significant increase (34.4% ± 16%) in

675 belowground respiration, which was not evident in studies lasting 2 – 4 years.

676 However, studies lasting ≥ 5 years also had significant increases in belowground

677 respiration. GPP increased significantly (11.8%) in warmed soils (Fig. 2a) and

678 showed a positive relationship with belowground respiration (Fig. 3).

679 Despite elevated GPP, litter decomposition declined significant by 9% (± 5%),

680 while SOM did not change significantly from control values (Fig. 2a). Both microbial

681 and fungal biomass increased non-significantly under warming: microbial biomass

682 increased 3.8% (± 12%) while fungal biomass increased by 11.5% (± 19%).

683 Under warming, soil nitrogen mineralization and soil nitrogen

684 concentrations both declined non-significantly (nitrogen mineralization: 7.6% ±

685 15%, soil nitrogen: 5.1% ± 9%) below the control soils. Soil phosphorus increased

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705 non-significantly above the control soils ( $12.5\% \pm 9\%$ , Fig. S1b). Finally, the use of  
706 the OTC and OTG to passively warm high-latitude soils significantly lowered soil  
707 moisture 8% ( $\pm 6\%$ ) below the control soils (Fig. S1b).

708 Modeled warming experiments increased soil temperature by  $1.21\text{ }^\circ\text{C} \pm$   
709  $0.47\text{ }^\circ\text{C}$  in CLM-CN and  $0.91\text{ }^\circ\text{C} \pm 0.35\text{ }^\circ\text{C}$  in CLM-Century. In response the two

710 models wach predicted a stronger relative and absolute increase in belowground

711 respiration compared with the observational data. The models predicted higher

712 litter decomposition in response to warming, which is in contrast with the

713 decreasing trend found in the observational data. Both models also predicted

714 increased nitrogen mineralization following warming, contrary to the observational

715 data. The relative changes in SOM under warming were consistent between the

716 model predictions and observations. Soil moisture increased non-significantly in

717 both models (CLM-CN:  $38\% \pm 42\%$ ; CLM-Century:  $7\% \pm 33\%$ ), in contrast to the

718 observations, but with a wide variability. In general, CLM-CN tended to predict a

719 much stronger temperature response than CLM-Century (Fig. 2a).

720

### 721 **3.2 Response of belowground carbon cycling to nitrogen addition**

722 The field experiments added an average of  $72\text{ kg-N ha}^{-1}\text{ yr}^{-1}$  ( $\pm 38\text{ kg-N ha}^{-1}$

723  $\text{yr}^{-1}$ ) of nitrogen to soils, with a range of  $1 - 100\text{ kg-N ha}^{-1}\text{ yr}^{-1}$ . This additional N

724 reduced belowground respiration and resulted in a larger sink for SOM, indicating a

725 negative feedback to atmospheric  $\text{CO}_2$  concentrations (Fig. 2b). Belowground

726 respiration in soils receiving additional nitrogen (in the form  $\text{NH}_4\text{NO}_3$ ) declined

727  $11.8\% (\pm 7\%)$ , significantly below control soils (Fig. 2b). This pattern was consistent

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737 for the two geographical regions examined and was not dependent on the duration  
738 of the experiment. Belowground respiration in European soils declined, non-  
739 significantly, by 7% ( $\pm 9.5\%$ ) below control soils (Fig. S1a). Belowground  
740 respiration in North American soils also declined significantly by 12.7% ( $\pm 9\%$ ).  
741 Belowground respiration showed a negative relationship with increasing soil  
742 nitrogen concentration (Fig. 4a). Linear regressions failed to uncover a significant  
743 relationship between the response of belowground respiration and climate (MAT,  
744 MAP) or experimental factors (experimental duration and magnitude of nitrogen  
745 added). Heterotrophic respiration showed no significant change under nitrogen  
746 addition; however, the data are highly variable ( $\pm 12\%$ ). Nitrogen addition resulted  
747 in a significant decline in litter decomposition (% mass loss/ yr<sup>-1</sup>) of 4.8% ( $\pm 3\%$ ),  
748 while SOM increased significantly 19.5 % ( $\pm 10\%$ ) in perturbed soils.

749       GPP increased significantly under nitrogen addition ( $44.3\% \pm 7.5\%$ )  
750 compared with the control soils (Fig. 2b). On average, aboveground biomass  
751 (vascular + non-vascular plants) non-significantly increased upon nitrogen addition  
752 ( $15\% \pm 22\%$ ). Vascular plant biomass increased significantly ( $33\% \pm 8\%$ ) over that  
753 of the control soils (Fig. S1b).

754       Overall, a non-significant increase in microbial biomass was observed for  
755 experimental soils (Fig. 2b), yet, declined with increasing concentrations of nitrogen  
756 added to the soil (Fig. 4b). When factoring in geographical location, microbial  
757 biomass in European soils increased significantly above the controls ( $17.5\% \pm 9\%$ ),  
758 but decreased non-significantly relative to control soils in North American soils (Fig.  
759 S1a). While different forms of nitrogen were applied in the experiments (e.g.,

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767 NH<sub>4</sub>NO<sub>3</sub> or NPK), the most significant factors, explaining 37 % of the variance in  
768 microbial biomass, were site-specific pH and mean annual temperature. Finally,  
769 fungal biomass increased significantly by 23% (± 20.5%) compared to the control  
770 soils.

771 For nitrogen perturbed CLM-CN and CLM-Century simulations we analyzed  
772 the relative response of variables complementary to the observational meta-  
773 analysis. Under nitrogen addition, the modeled response variables matched  
774 observations for only two parameters: GPP and SOM, and only at the lowest  
775 nitrogen addition concentrations (i.e., ≤ 1 kg-N ha<sup>-1</sup> yr<sup>-1</sup>, Fig. S3). Neither model  
776 accurately replicated the trend in the observed response of belowground  
777 respiration, litter decomposition, and nitrogen mineralization (Fig. 2b), while both  
778 models overestimated the response of heterotrophic respiration.

#### 780 4 Discussion

781 Accurate representation of the processes governing soil carbon cycling in high-  
782 latitude soils is crucial for reducing model uncertainty in energy and greenhouse gas  
783 feedbacks with climate. By comparing meta-analyses based on model output and  
784 observations, we show that two belowground biogeochemical representations in  
785 CLM4.5 are unable to adequately represent many of the observed high-latitude  
786 ecosystem responses to two important climate change variables: temperature and  
787 nitrogen availability. We focus our discussion on the potential reasons for the  
788 discrepancies in responses by highlighting: (1) the most important mechanisms  
789 currently missing from, or poorly represented in, the models; and (2) instances

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798 where deficiencies in the experimental approaches prohibits the data from being  
799 used for benchmarking the model. We also recommend further approaches to  
800 improve the mechanistic basis of the belowground biogeochemistry representation  
801 in ESMs.

802

#### 803 4.1 Response of belowground carbon cycling to warming

804 The observational meta-analysis suggests that elevated belowground  
805 respiration is balanced by elevated GPP (and associated increases in soil organic  
806 matter). We therefore conclude that the coupling of aboveground and belowground  
807 processes resulted in these soils being carbon neutral under modest (+ 1.3 °C)  
808 warming. The models also predicted no significant changes to belowground SOM  
809 content under warming due to concomitant increases in belowground respiration,  
810 and GPP. However, the magnitude of the modeled fluxes is many times larger than  
811 the observed fluxes. Therefore, the net impact of the manipulation on SOM was  
812 predicted by the models, but with incorrect mechanisms.

813 As a broader point, we believe this result illustrates a common problem  
814 among tests of land model performance, i.e., inferences of model fidelity based on  
815 comparisons solely with observations of emergent responses that has low signal to  
816 noise ratio. For example, it is insufficient to use of net ecosystem exchange (NEE) as  
817 a sole model benchmark (Schwalm et al., 2010), because it ignores that: (1) NEE is  
818 typically a small difference between ecosystem respiration and assimilation and (2)  
819 models separately represent these gross fluxes as being differently controlled by  
820 climate and antecedent system states. We contend that representing this type of

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850 emergent ecosystem net flux within the observational uncertainty gives little  
851 information as to whether the model is accurately representing the underlying  
852 mechanisms appropriately.

853

854 4.1.1 Nitrogen cycling under warming: Confronting the model outputs with  
855 observations showed a consistent overestimation of key variables in the model  
856 predictions (Fig. 2a). One potential reason for a larger modeled response is the  
857 approaches CLM-CN and CLM-Century take to representing the nitrogen cycle. The  
858 inclusion of nitrogen cycling in coupled carbon-nitrogen climate models is  
859 consistent with the idea that nitrogen is a significant determinant of carbon cycling  
860 in many ecosystems (Hungate, 2003; Vitousek and Howarth, 1991), and modeled  
861 nitrogen input, retention, and loss have been shown to have a large impact on  
862 ecosystem carbon sequestration (Thomas et al., 2013b; Zaehle and Dalmonech,  
863 2011). Moreover, data based modifications to ESM nitrogen cycling mechanisms  
864 may further improve the correspondence between observations and model output  
865 (Thomas et al., 2013a).

866 CLM-CN predicts much higher rates of nitrogen loss from denitrification than  
867 CLM-Century, and is therefore more responsive to changing nitrogen availability  
868 from inputs, mineralization, and losses. Under warming CLM-CN predicted a  
869 significant loss of soil nitrogen not predicted in CLM-Century, which has a more  
870 closed nitrogen cycle, possibly more representative of the nitrogen cycle in high-  
871 latitude soils (Barsdate and Alexander, 1975). Rates of nitrogen fixation, deposition  
872 and redox cycling (i.e., nitrification and denitrification) are low at high latitudes

874 [\(Cleveland et al., 1999; Giblin et al., 1991\)](#), and hydrological loss of nitrogen at the  
875 [beginning of the growing season is relatively large \(Harms and Jones, 2012; Jones et](#)  
876 [al., 2005\)](#). Mineralization is, therefore, the main source of nitrogen for plant and  
877 [microbial growth \(Shaver et al., 1992\)](#).

878 [Mineralization rates are controlled by the depolymerization of proteinaceous](#)  
879 [\(Jones et al., 2009; Schulten and Schnitzer, 1997\)](#), leading to the release of amino  
880 [acids \(Schimel and Bennett, 2004\) that are rapidly utilized by plants and microbes](#)  
881 [\(Kielland, 1994; Weintraub and Schimel, 2005\)](#). Ammonia is then released during  
882 [turnover of the dead microbial biomass. Depolymerization is the critical step in this](#)  
883 [process and, like organic matter decomposition, is dependent on microbial](#)  
884 [physiology and subject to the biotic and abiotic controls described above. Modeled](#)  
885 [nitrogen mineralization, however, increases under warming with a concomitant](#)  
886 [increase in soil nitrogen in the CLM-Century framework. CLM-CN, with its high rates](#)  
887 [of mineral nitrogen losses shows a very large decline in soil nitrogen, possibly](#)  
888 [rendering the above- and belowground communities nitrogen limited throughout.](#)  
889 [In our data analyses, nitrogen mineralization declined as microbial nitrogen \(i.e.,](#)  
890 [immobilization\) increased. The end result in both cases \(i.e., the models and](#)  
891 [observations\) is the potential limitation of plant growth over long time scales. Our](#)  
892 [data synthesis suggests that the release of nitrogen from increased decomposition is](#)  
893 [used to meet microbial demands or immobilized. Microbial immobilization is](#)  
894 [regulated by the stoichiometric imbalance between the substrate being](#)  
895 [depolymerized and the physiological nutrient demand. While analogous to the CUE,](#)  
896 [nitrogen use efficiency \(NUE\), which relates immobilization and mineralization to](#)

897 microbial growth {Mooshammer:2014ho}, is regulated independently in order to  
898 maintain cell stoichiometry. Some attempts have been made to incorporate NUE  
899 controls into ecosystem models (Manzoni and Porporato, 2009), but further  
900 experimental and modeling work is required to understand NUE's plasticity and  
901 impacts on soil carbon dynamics.

902  
903 4.1.2. Aboveground dynamics: The biogeochemical coupling between aboveground  
904 and belowground components of the ecosystem is crucial for understanding high-  
905 latitude carbon cycling under a changing climate. The meta-analysis of field  
906 measurements showed a general stimulation of aboveground activity under  
907 warming, while previous field studies have noted a shift in plant community  
908 composition with warming, favoring the establishment of deciduous shrubs and  
909 graminoids against mosses and lichens (Schuur et al., 2007; Sistla et al., 2013;  
910 Walker et al., 2006). This shift toward more woody plants changes the ecosystem  
911 carbon balance and nutrient dynamics (Jackson et al., 2002; Welker et al., 2004), as  
912 shrubs tend towards higher internal carbon allocation toward woody tissue, but  
913 also may increase belowground carbon allocation (as both litter and exudates)  
914 relative to mosses (Street et al., 2013). This change in belowground allocation may  
915 result in the observed relationship between GPP and belowground respiration (Fig.  
916 3), indicating a close coupling between these two processes. This positive  
917 relationship may develop due to higher rates of belowground labile root exudation,  
918 which may be respired directly by the plants themselves (Luo, 2007), or 'prime' the  
919 microbial community leading to the destabilization and decomposition of chemically

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935 complex SOM (Fontaine et al., 2004). Our data analysis cannot directly distinguish  
936 between the two pathways, although an observed drop in litter decomposition rates  
937 could indicate that the mineralization of plant exudates spurs the degradation of  
938 older SOM (Hartley et al., 2012), resulting in elevated belowground respiration rates,  
939 Further field studies and more data (e.g., radiocarbon measurements) are required  
940 to verify this conclusion.

941 Current models crudely represent above- and belowground biogeochemical  
942 coupling and do not represent some of the crucial roles plants play in soil carbon  
943 dynamics (Ostle et al., 2009; Schmidt et al., 2011). Of particular relevance to high-  
944 latitude ecosystems is the lack of any representation of cryptogams or bryophytes in  
945 CLM4.5. These plants contribute substantially to aboveground biomass and  
946 biogeochemical processes in tundra soils (Cornelissen et al., 2007; Elbert et al.,  
947 2012) and are clearly important for accurate simulations of tundra carbon dynamics.  
948 Few ESM land models (including CLM4.5) include dynamic vegetation, and when it  
949 is included, representation tends to be coarse (Ostle et al., 2009). Ongoing work will  
950 attempt to address some of these deficiencies, by including representations of  
951 aboveground ecosystem demography (Huntingford et al., 2008; Moorcroft et al.,  
952 2001), and soil carbon dynamics (Riley et al., 2014). Integration of these approaches  
953 into the CLM framework may improve the robustness of long-term tundra soil  
954 simulations and reduce uncertainty associated with the aboveground model  
955 response.

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**Deleted:** A comparison of the observational and modeled response to warming shows an overestimation by the models for a number of variables, and the opposite response sign for others (e.g., nitrogen mineralization). Below, we identify several areas of aboveground biogeochemistry that could constrain above and belowground responses to warming in high-latitude ecosystems.
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**Deleted:** The lack of vegetation dynamics precludes the impact of community shifts under a changing climate, and the resultant feedbacks to decomposition rates due to changes in litter quality or root depth (Cornwell et al., 2008). In addition, the models do not represent root exudates, which precludes the representation of priming of belowground communitie... [1]
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1010 | 4.1.3. Belowground Ecology: The observational data indicated elevated belowground  
 1011 | respiration under warming. The response of microbial heterotrophs to warming can  
 1012 | partially be explained by kinetic theory, whereby biochemical reaction rates  
 1013 | increase with increasing temperature (Davidson and Janssens, 2006). Hydrolytic  
 1014 | and oxidative extracellular enzymes, secreted to depolymerize complex organic  
 1015 | matter (Allison et al., 2010), are sensitive to temperature (German et al., 2012).  
 1016 | Structural modifications in cold ecosystems maximize their specific activity under in  
 1017 | situ temperatures relative to temperate ecosystems (Hochachka and Somero, 2002),  
 1018 | which may result in significantly enhanced activity under warming (Koch et al.,  
 1019 | 2007). This theory fits with the short-term (<2yr) data from the current meta-  
 1020 | analysis showing increasing belowground respiration despite no increase in  
 1021 | microbial biomass.

1022 |         However, we also identified a drop in belowground respiration in studies  
 1023 | lasting longer than 2 years and shorter than 5 years (Fig. S1b). Belowground  
 1024 | respiration has consistently been reported to decline under prolonged warming  
 1025 | (Rustad et al., 2001) and attributed to substrate limitation (Hartley et al., 2008) or a  
 1026 | community-level response of microbial populations to warmer temperatures  
 1027 | offsetting the kinetic response of individual microbes (Bradford, 2013; Bradford et  
 1028 | al., 2008). Given the increased GPP found in our meta-analysis, belowground  
 1029 | communities are unlikely to be substrate limited. Therefore, we hypothesize that the  
 1030 | community-level response is likely responsible for the drop in belowground  
 1031 | respiration under 2 - 5 years of warming.

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**Deleted:** Thermal respiratory acclimation has been demonstrated experimentally for plants (Atkin, 2003), fungi (Crowther and Bradford, 2013; Malcolm et al., 2008), and bacteria (Bradford et al., 2008). However, the physiological acclimation of individuals in an endemic community is likely to be outpaced by the rate of community turnover in soils undergoing experimental warming (Deslippe et al., 2012; Rinnan et al., 2008; Sistla et al., 2013). The ecological consequences of microbial community turnover are complex, but can alter the functional potential of soils, which in turn may alter the rate of organic matter breakdown and nutrient cycling.

1058 | The subsequent increase in belowground respiration, over prolonged  
1059 | warming (> 5 years) could represent either the decomposition of leaf litter driven  
1060 | by changes in microbial community composition, or thawing subsurface organic  
1061 | matter (Dorrepaal et al., 2009). This latter hypothesis is relevant to the long-term  
1062 | fate of high-latitude carbon. In the current analysis, NEE appears balanced, with no  
1063 | change in SOM. However, temporal patterns of vegetation response to warming  
1064 | show a transient response to warming, with nutrient limitation reducing plant  
1065 | productivity on longer time scales (Arft et al., 1999; Chapin and Shaver, 1996). It is  
1066 | possible, given the large nitrogen immobilization under warming, that belowground  
1067 | respiration may continue longer than productivity, unbalancing NEE and leading to  
1068 | net carbon loss.

1069 | Temperature is a key factor influencing biogeochemical mechanisms in the  
1070 | model. CLM models belowground respiration, using a static  $Q_{10}$  and fixed carbon use  
1071 | efficiencies, (CUE) for different SOM pools size. This approach may result in the large  
1072 | modeded increase in belowground respiration. In reality, both  $Q_{10}$  and CUE vary on  
1073 | spatial and temporal scales, and respond non-linearly to changes in temperature  
1074 | (Janssens & Pilegaard, 03; Sinsabaugh et al., 2013). Recent microbe-explicit models  
1075 | (MEMs) that consider basic microbial physiology (e.g., Lawrence et al., 2009)  
1076 | introduce direct biological control over soil carbon cycling and different conclusions  
1077 | on soil carbon pool size and dynamics under warming (Allison et al., 2010; Wieder  
1078 | et al., 2013). For example, by scaling the CUE value with temperature, in accordance  
1079 | with published observations (Luo et al., 2001; Melillo, 2002), the MEMs show a  
1080 | decline in soil carbon turnover under warming (Li et al., 2014; Wieder et al., 2013).

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Deleted: The long-term nature of above- and belowground response to warming is, therefore, an important research priority for future studies.

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11096 | Recent work using a MEM with explicit representation of internal physiology,  
 11097 | extracellular enzymes, and mineral surfaces (Tang & Riley 2014), demonstrates that  
 11098 | both decomposition temperature sensitivity and CUE are hysteretic and cannot  
 11099 | easily be represented by a simple function of soil temperature. However, it is also  
 11100 | important to note that microbial CUE is not solely temperature-dependent, and  
 11101 | other factors, some of which are already present in CLM-CN and CLM-Century  
 11102 | (including nutrient limitation, and soil moisture limitations), may uncouple growth  
 11103 | and respiration and change CUE (Manzoni et al., 2008; Sinsabaugh et al., 2013). The  
 11104 | predictions of the microbe-explicit models (MEM) provide further impetus for  
 11105 | greater representation of the structure and function of belowground biomass.

11106 | Other aspects of belowground ecology in high-latitude tundra that are not  
 11107 | included in the models can have a significant impact on the stability of soil carbon  
 11108 | (also see discussion below on barriers to benchmarking). For example, while there  
 11109 | is little evidence that fungal: bacterial ratios are altered by warming, either in our  
 11110 | observational meta-analysis or in previous work (Strickland and Rousk, 2010), the  
 11111 | community composition may change without altering fungal: bacterial ratios  
 11112 | (Strickland and Rousk, 2010). Certain traits that separate the main decomposing  
 11113 | functional guilds, such as biomass stoichiometry, nutrient use efficiency, substrate  
 11114 | utilization and response to environmental variables (e.g., temperature or soil  
 11115 | moisture) (Six et al., 2006) can bring about changes in the decomposition rates.  
 11116 | These factors are arguably more important than climate when modeling  
 11117 | decomposition at local and regional scales (Bradford et al., 2014).  
 11118 |

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1136 4.1.4 Litter Decomposition: Disagreement between the observations and model  
1137 predictions, was also noted for litter decomposition. Under warming, litter  
1138 decomposition declined in the observations, possibly contributing to SOM  
1139 accumulation, but increased in the models. In previous studies, the response of litter  
1140 decomposition, to warming was largely dependent on the method used to increased  
1141 soil temperature (Aerts, 2006). OTCs tend to warm the soil and reduce soil moisture,  
1142 limiting litter decomposition by saprotrophic fungi. Soil moisture in the models  
1143 showed a non-significant increase with warming as the permafrost began to thaw  
1144 (Fig. 2a). The difference between the observational meta-analysis and the models  
1145 represents a potentially confounding factor in using this data to benchmark the  
1146 model. A previous meta-analysis focused solely on litter decomposition in Arctic and  
1147 Alpine tundra found that warming induced a small increase in decomposition  
1148 provided sufficient soil moisture (Aerts, 2006). This response was not apparent in  
1149 our data syntheses, but suggests the model results, while overestimating litter  
1150 decomposition, were at least in the appropriate direction. Soil moisture is an  
1151 important controller on decomposition (Aerts, 2006; Hicks Pries et al., 2013).  
1152 However, changes to surface hydrology during permafrost thaw are dependent on  
1153 thermokarst formation and topological features of the landscape (Jorgenson and  
1154 Osterkamp, 2005) and may result in increased or decreased soil moisture. We  
1155 identify these issues as important for further experimental and modeling work in  
1156 order to better represent future changes in surface hydrology and the consequences  
1157 for litter decomposition,  
1158

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1171 | **4.2 Response of belowground carbon cycling to nitrogen addition**  
1172 | Our meta-analysis of field observations found that the addition of inorganic nitrogen  
1173 | to traditionally nitrogen limited ecosystems enhances the carbon sink, consistent  
1174 | with previous studies (Luo et al., 2012; McGuire et al., 2012). Interactions between  
1175 | the carbon and nitrogen cycles resulting in soil carbon accumulation in different  
1176 | ecosystems have been reported previously (Magnani et al., 2007; Thomas et al.,  
1177 | 2013b), and have been attributed to an increased carbon allocation to woody tissue  
1178 | (Ciais et al., 2008; Tummers, 2006) and reduction in the SOM decomposition rate  
1179 | (Olsson et al., 2005). Overall, our data-synthesis is largely consistent with the  
1180 | overarching conclusions of previous meta-analyses (Janssens et al., 2010; Knorr et  
1181 | al., 2005).

1182 | A question remains, however, about the value of the responses synthesized  
1183 | from studies that add fertilizer (NH<sub>4</sub>NO<sub>3</sub> or NPK) as a source of nitrogen far in  
1184 | excess of anticipated global change scenarios for high-latitude ecosystems. The  
1185 | average concentration of nitrogen added to the soils in the tundra studies (~ 72 kg  
1186 | ha<sup>-1</sup> yr<sup>-1</sup>) is extremely high when compared with (1) estimates of nitrogen fixation  
1187 | (< 10 kg ha<sup>-1</sup> yr<sup>-1</sup>, (Cleveland et al., 1999); (2) nitrogen deposition (both current  
1188 | rates of deposition 0.2 – 0.24 kg ha<sup>-1</sup> yr<sup>-1</sup>, (Jones et al., 2005) and projections of  
1189 | future deposition (Galloway et al., 2004)); and (3) potential nitrogen availability  
1190 | from organic matter mineralization under a warming climate (Harden et al., 2012).  
1191 | Consequentially, we question whether such data lends itself to understanding the  
1192 | response of the ecosystem to realistic chronic incremental changes in nitrogen

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1218 availability, and the benefit of benchmarking the ecosystem models against such a  
1219 dataset. On the other hand, if the models include the relevant underlying  
1220 mechanisms, then they should reproduce the field studies regardless of the amount  
1221 of nitrogen added. We give further examples below of where the high nitrogen  
1222 concentrations may confound the interpretation of the experiments with respect to  
1223 the model predictions.

1224  
1225 4.2.1 SOM dynamics: SOM accumulation under nitrogen addition experiments is a  
1226 common feature of both the field experiments and the model simulations. However,  
1227 the underlying mechanisms leading to SOM accumulation are very different, adding  
1228 uncertainty to the model predicted soil carbon fate over longer timescales. In both  
1229 versions of CLM, the alleviation of nitrogen limitation stimulates a number of  
1230 ecosystem processes including aboveground primary productivity, litter

1231 decomposition, and organic matter decomposition. The accumulation of SOM  
1232 indicates the stimulation of GPP and litter decomposition, (as a source into the SOM  
1233 pools) must outweigh losses from increased belowground respiration.

1234 The observations, on the other hand, show a significant decline in  
1235 belowground respiration and litter decomposition, under nitrogen addition.

1236 Belowground respiration depends on the decomposition and substrate utilization  
1237 capabilities of the microbial (i.e., bacterial and fungal) community to mineralize root  
1238 exudates and litter. A drop in belowground respiration, may, therefore, be  
1239 attributable to several mechanisms not included in either version of CLM. A recent  
1240 meta-analysis examined the response of Boreal forest ecosystems to added nitrogen

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1251 (Janssens et al., 2010), and concluded that the internal reallocation of carbon in  
1252 plants and trees reduced the rate of exudation to belowground ecosystems,  
1253 resulting in microbial biomass becoming carbon limited with a concomitant decline  
1254 in biomass and belowground respiration (Janssens et al., 2010). Our empirical data  
1255 shows increased GPP and vascular plant biomass, possibly indicating a reallocation  
1256 of newly fixed carbon in vascular plants (Ciais et al., 2008) and a drop in  
1257 belowground exudation.

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1258  
1259 4.2.2 Belowground Ecology: Overall, the current observational meta-analysis found a  
1260 non-significant increase in microbial biomass (i.e., bacterial and fungal) but a  
1261 significant increase in fungal biomass under nitrogen addition. This response  
1262 appears contrary to previous studies that have recorded a drop in microbial  
1263 biomass under nitrogen addition (Treseder, 2008), but in line with fertilization  
1264 studies in tundra ecosystems (Clemmensen et al., 2006). We also note that microbial  
1265 biomass (and belowground respiration) are inversely related to the amount of  
1266 nitrogen added to the soils (Fig. 4a, b). At low nitrogen concentrations microbial  
1267 community activity can be stimulated (Allison et al., 2009) and decomposition  
1268 elevated, as indicated by the models (Fig. 2b) and some of the observations (Fig. 4b).

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1269 Elevated nitrogen concentrations, however, have a negative impact on microbial  
1270 biomass (Treseder, 2008) and decomposition (Janssens et al., 2010). This response  
1271 can occur through the inhibition of lignin-degrading enzymes produced by  
1272 saprotrophic fungi (Sinsabaugh et al., 2002; but see Hobbie, 2008), or the increased  
1273 chemical recalcitrance of soil carbon undergoing condensation reactions with

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1283 inorganic nitrogen (Dijkstra et al., 2004), increasing the physical protection of  
 1284 organic matter from decomposition. Therefore, under the high nitrogen inputs used  
 1285 in the present field studies, the coupling between above- and belowground  
 1286 ecosystems can decrease belowground respiration and litter decomposition  
 1287 resulting in an accumulation of SOM.

1288 Whereas the warming meta-analysis yielded results that could be used to  
 1289 constrain model mechanisms, the same cannot be concluded for the nitrogen-  
 1290 addition studies due to the uncertainty of how high-latitude soils will respond to  
 1291 lower concentrations of nitrogen. However, we suggest two potential model changes  
 1292 that could rectify the different conclusions derived from the observations and  
 1293 models, (1) A dynamic vegetation approach sensitive to changes in nitrogen  
 1294 inventory could represent compositional changes across the tundra with important  
 1295 ramifications for root biomass, litter quality, and plant exudates that play a  
 1296 significant role in soil carbon dynamics (Aerts et al., 2005). (2) Representation of  
 1297 discrete belowground biomass functional groups (e.g., heterotrophic and fungal  
 1298 decomposers) alongside their dependencies on soil nitrogen may help to constrain  
 1299 the belowground response to nitrogen addition. Finally, while the model  
 1300 mechanisms should ideally be able to reproduce the observed response to high  
 1301 nitrogen loading, we believe that future manipulation studies in high-latitude soils  
 1302 that use realistic nitrogen additions would be more relevant for understanding the  
 1303 tundra soil response. For example, recent studies have added nitrogen to tundra  
 1304 soils at magnitudes one order of magnitude higher than measured concentrations  
 1305 {Lavoie:2011da} or guided by soil mineralization rates {Sistla:2012dq}. The

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1365 ecosystem response is therefore more likely to reflect future responses under  
1366 anticipated mineralization or deposition scenarios {Galloway:2004th}.

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#### 1368 **4.3 Barriers *and criteria* for successful experiment-based model benchmarking**

1369 While we were able to benchmark some aspects of the model predictions  
1370 using the observational meta-analysis, we acknowledge several concerns that may  
1371 have complicated the data-model comparison. First, no general protocol consistent  
1372 with field experiments is available for setting up model perturbations. Although  
1373 different land models have different structures and degrees of complexity, a  
1374 standard approach to establishing perturbations would be beneficial. In our model,  
1375 atmospheric warming resulted in unrealistic uniform soil warming across the study  
1376 domain and therefore underestimated the spatial heterogeneity found in passive  
1377 warming experiments (Bokhorst et al., 2012). On the other hand, solely reducing the  
1378 wind speed failed to alter the soil thermal regime, indicating a possible problem in  
1379 the formulation of CLM's surface boundary layer resistance. However, our approach  
1380 of warming via enhanced aerodynamics resistance is not transferable to models  
1381 using atmospheric temperature, rather than a surface energy balance scheme, to  
1382 force soil thermal dynamics.

1383 Therefore, criteria need to be established to ensure, regardless of the method  
1384 used, that the experimental manipulation is reproduced in the model with sufficient  
1385 fidelity that the predicted and observed responses can be reasonably compared. We  
1386 consider the criterion used here for the warming experiments (i.e., that the mean  
1387 predicted manipulation soil temperatures are not significantly different from the

1388 observations) to be a minimally acceptable criterion. Ideally, the predicted response  
1389 of soil temperature, soil moisture, and radiation under warming would emerge in a  
1390 statistically similar manner to the observations. In the current study, this criterion  
1391 was not met for soil moisture, where the observations found that soil moisture  
1392 declined (by  $8\% \pm 6\%$ ) under warming and the model predicted large increases  
1393 CLM-CN:  $38\% \pm 42\%$ ; CLM-Century:  $7\% \pm 33\%$ ). This may be an important given the  
1394 significant impacts moisture has on decomposition and nitrogen cycling.

1395 Second, the spatial discrepancy between the model predictions and  
1396 observational data is large. This mismatch arises from several sources, including  
1397 uncertainties: (1) in the climate and environmental forcing data used to drive the  
1398 models; (2) in soil and plant characterization; (3) caused by spatial heterogeneity in  
1399 the site and experimental manipulation (e.g., unequal heating within the open-top  
1400 chambers, energy leaking at the boundary with surrounding soil); and (4) in  
1401 accurate model characterization of the growing season.

1402 Third, while we acknowledge the complexity of interpreting single-factor  
1403 manipulation experiments, the multifaceted nature of climate change calls for more  
1404 multifactorial experiments and models that can reproduce any response. The few  
1405 studies we could find measuring the response of similar variables to combined  
1406 warming and nitrogen addition (e.g., Shaver et al., 1998) found an even larger  
1407 warming response than for the single-factor experiments. However, there were too  
1408 few studies measuring complementary variables to conduct a meta-analysis.

1409 Previous studies conducted in high-latitude soils have recorded a stronger response  
1410 of decomposition following perturbation by a combination of drivers (e.g., elevated

1411 temperature and CO<sub>2</sub>) than if those factors were considered in isolation (Fenner et  
1412 al., 2007). In contrast, Leuzinger et al. (Leuzinger et al., 2011) give several examples  
1413 where the opposite occurs: a combination of multiple drivers lessens the ecological  
1414 response relative to individual drivers. These contradictory results call for further  
1415 consideration of the impact of multiple drivers in high-latitude ecosystems that  
1416 might be used to benchmark model performance.

1417 Fourth, the field observational data lacks sufficient spatial coverage to  
1418 characterize high-latitude spatial heterogeneity accurately. There are many studies  
1419 that cluster in a few regions, represented in the model by only a few grid cells. While  
1420 we obtained some insights into the deficiencies of the model from this  
1421 benchmarking exercise, more work is required to develop confidence in our  
1422 conclusions given the spatial heterogeneity of high-latitude ecosystems.

1423

#### 1424 **4.4 Overall Recommendations**

1425 We have demonstrated here that despite some experimental drawbacks, the  
1426 underlying biogeochemical mechanisms of CLM-CN and CLM-Century are  
1427 insufficient to accurately reproduce the observations of a number of high-latitude  
1428 perturbation experiments. However, we can identify several metrics from the meta-  
1429 analyses, including nitrogen mineralization and litter decomposition, which may  
1430 serve as useful indices of model performance. The sign and magnitude of these  
1431 response ratios were incorrectly predicted by the models in under both warming  
1432 and nitrogen addition. This error in the sign of the response also occurred for  
1433 simulated belowground respiration under nitrogen addition, where the model was

1434 unable to capture the detrimental impact of very high nitrogen concentrations. In  
1435 contrast, the SOM response under temperature and nitrogen perturbations appears  
1436 to be a poor metric to benchmark the models, possibly owing to the large size and  
1437 undefined composition of the soil organic matter stock.

1438 Future development of biogeochemistry representation in CLM should focus  
1439 on improvements to the nitrogen cycle. Recent work has shown that specific  
1440 modifications to different nitrogen cycle pathways (e.g., redox cycling, plant-  
1441 microbial interactions) can improve the correspondence between model predictions  
1442 and observational data (Thomas et al., 2013a). Development should also may focus  
1443 on improved kinetics (e.g., equilibrium chemistry approximations, (Tang and Riley,  
1444 2013) to regulate competition for nutrients between biotic and abiotic sinks (e.g.,  
1445 plants, microbes, minerals) as an alternative to the current allocation schemes of  
1446 CLM-CN (Thornton et al., 2007). In addition, the integration of dissolved organic  
1447 nitrogen cycling as a nutrient source for microbes and plants appears to be an  
1448 important source of nitrogen in high-latitude soils (Hobbie et al., 2009; Weintraub  
1449 and Schimel, 2005). However, insufficient data were available to include DON as a  
1450 response factor in the meta-analysis.

1451 The lack of explicit coupling between plant functional types (PFT) and  
1452 belowground microbial ecosystems in the model fails to capture the importance of  
1453 this interaction for carbon and nutrients cycling and SOM stability. The PFT concept  
1454 could be further extended to characterize differential belowground carbon  
1455 allocation (Street et al., 2013). In addition, symbiotic relationships between  
1456 different plants and mycorrhizal fungi can increase nutrient acquisition (Hobbie et

1457 al., 2009), by facilitating nitrogen fixation (Nasto et al., 2014), and phosphorus  
1458 acquisition (Smith et al., 2011), thereby increasing photosynthetic rates (Jia et al.,  
1459 2004). Improving and expanding the definition of the PFT to include these  
1460 associations may serve to improve coupling between nutrient cycling with  
1461 belowground biogeochemistry.

1462 Finally, while the magnitudes of nitrogen added to tundra soils were very  
1463 high, the threshold relationship (Fig. 4) that describes the alleviation of nitrogen  
1464 limitation and stimulation of ecosystem processes at low concentrations from their  
1465 inhibition at high nitrogen concentrations has support from previous studies (Knorr  
1466 et al., 2005). However, mechanisms have not yet been integrated in the model to  
1467 capture this range of responses. The model should be able to reproduce the impact  
1468 of high nitrogen concentrations associated with agriculture soils, and more work is  
1469 required to further characterize this threshold effect. It is unlikely, however, that the  
1470 model-predicted linear relationship between nitrogen availability and ecosystem  
1471 processes will, in general, be true.

## 1473 **5 Summary and conclusions**

1474 We have shown that certain mechanisms poorly represented in land models,  
1475 as highlighted by ecological meta-analysis, can undermine conclusions regarding the  
1476 stability of high-latitude soil carbon. We found that two versions of CLM  
1477 biogeochemistry (1) poorly replicated coupling of the aboveground and  
1478 belowground components of the carbon cycle; (2) poorly represented nitrogen

1479 cycling; (3) inaccurately grouped belowground processes, and (4) insufficiently  
1480 represented plant community dynamics.  
1481 The use of a meta-analysis to benchmark models has a distinct advantage of  
1482 aggregating the response of a number of different climate change experiments  
1483 across spatial and temporal scales to converge upon an average ecosystem or biome  
1484 response. This aggregation reduces the weight that any one study has on the  
1485 development of a model benchmark metric. This approach is particularly valuable in  
1486 ecosystems in which a large number of studies have been performed (e.g.,  
1487 temperate systems, (Lu et al., 2013)). However, we also caution that the field  
1488 experiments used in a benchmarking meta-analysis must be carefully chosen. We  
1489 demonstrated the utility of benchmarking land models using studies and  
1490 measurements that attain a realistic ecosystem response to warming, and the  
1491 difficulties associated with comparing model performance against nitrogen addition  
1492 studies that do not replicate conditions under current, or anticipated future climate.

1493

#### 1494 **Author contribution**

1495 NJB and WJR designed the experiment. NJB develop the meta-analysis. JYT  
1496 developed model perturbation approach and carried out the simulations. NJB  
1497 analyzed the results and wrote the manuscript with input from WJR and JYT.

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1505 Modeling (RGCM) Program.  
1506

Nicholas Bouskill 11/6/14 9:11 PM

**Deleted:** While we were able to benchmark some aspects of the model predictions using the observational meta-analysis, we acknowledge several concerns that may have complicated the data-model comparison. First, the spatial discrepancy between the model output and observational data is large. This mismatch arises from several sources, including: (1) the uncertainties in the climate and environmental forcing data used to drive the models; (2) insufficient spatial resolution in the models preventing the representation of all field sites, particularly those in coastal regions (e.g., the Greenland sites); and (3) the lack of a simulation protocol determining the onset and completion of the growing season in the models. ... [7]

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1894 Figure 1: Study sites included in the meta-analysis.  
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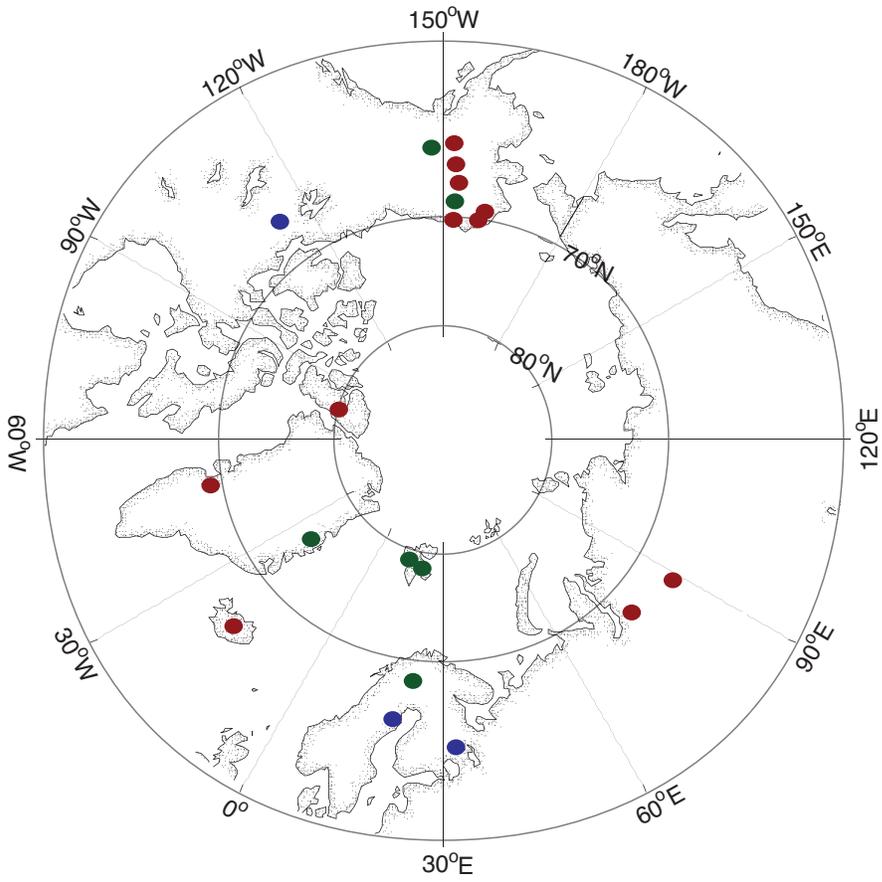
1896 Figure 2: Response ratio of select variables under (a) warming and (b) nitrogen  
1897 addition. The figures show the average response to perturbation derived from the  
1898 observations (blue circles or squares), CLM-CN (orange squares), and CLM-Century  
1899 (red squares). Also shown is the variance either side of the average. Under  
1900 circumstances where the variance could not fit on the axis, a numerical value  
1901 indicates the limits of variance. In figure 2b,  $R_B$  is given as the response to the  
1902 average nitrogen concentration and also to lower, more realistic concentrations  
1903 (represented by the green square). The modeled response in Figure 2b is the  
1904 collated response following the addition of low nitrogen concentrations (i.e., 0.2, 1.0,  
1905 2.0 and 3.0 kg-N ha<sup>-1</sup> yr<sup>-1</sup>) and high concentrations (20, 60 and 100 kg-N ha<sup>-1</sup> yr<sup>-1</sup>).  
1906 Note the axis change in fig. 2b following the break. The number of individual studies  
1907 and data points (in brackets) used in calculating the observation response ratio are  
1908 given in blue on the right-hand side of the figure.  
1909

1910 | Figure 3: Relationship between GPP and heterotrophic respiration in warmed plots.  
1911 Data points from the graph also represent the duration of warming. Each point  
1912 represents the effect size expressed as a percentage and the calculated bootstrapped  
1913 variance (across the x and y axis).

1914 Figure 4: The effect of increasing N-addition on (a) Belowground respiration, and  
1915 (b) microbial (i.e., bacterial + fungal) biomass.  
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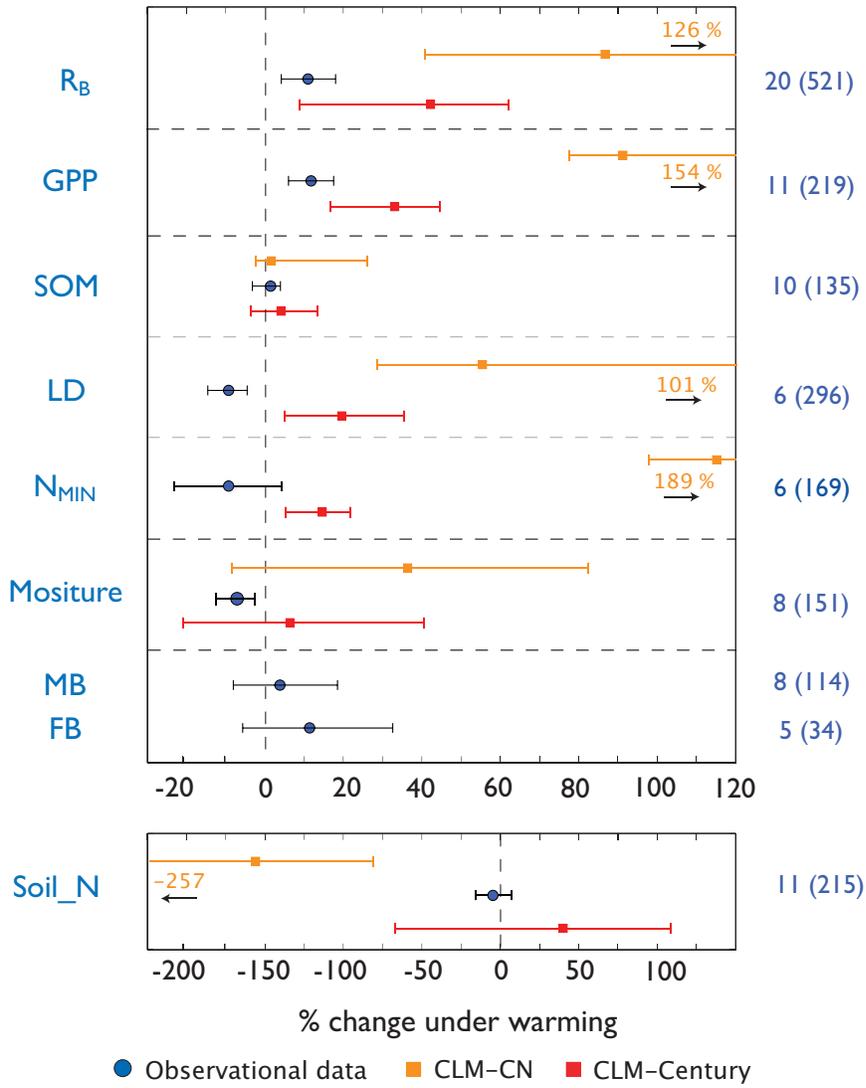
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● Nitrogen addition only    
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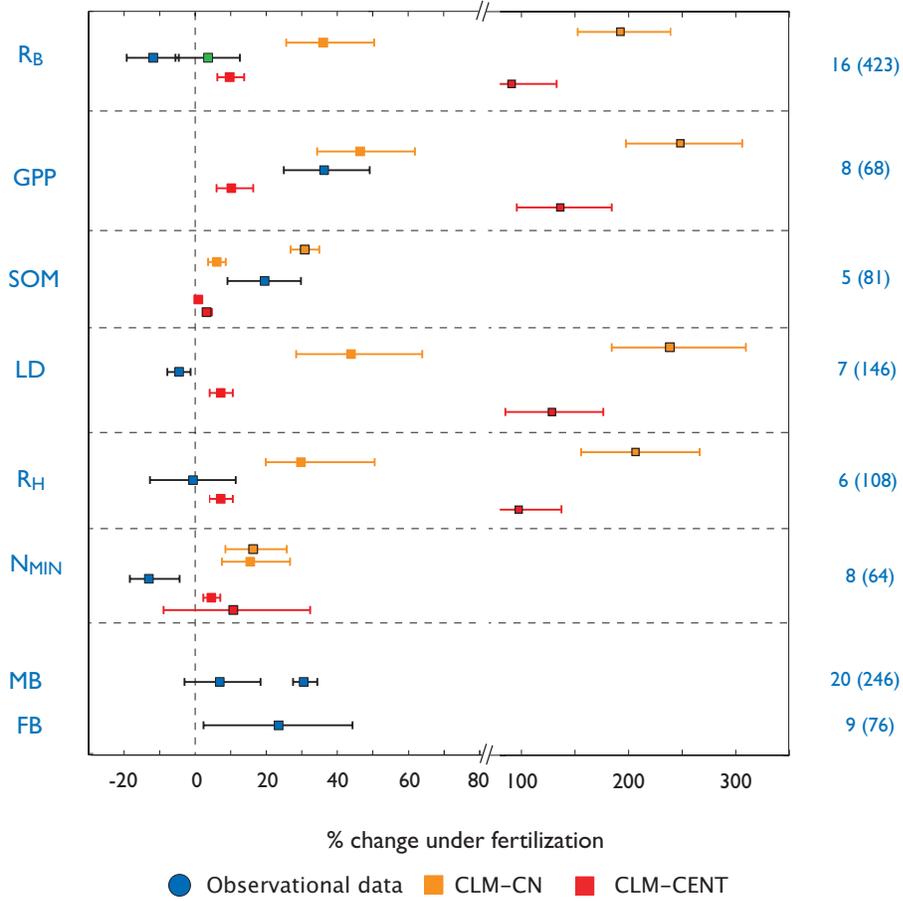
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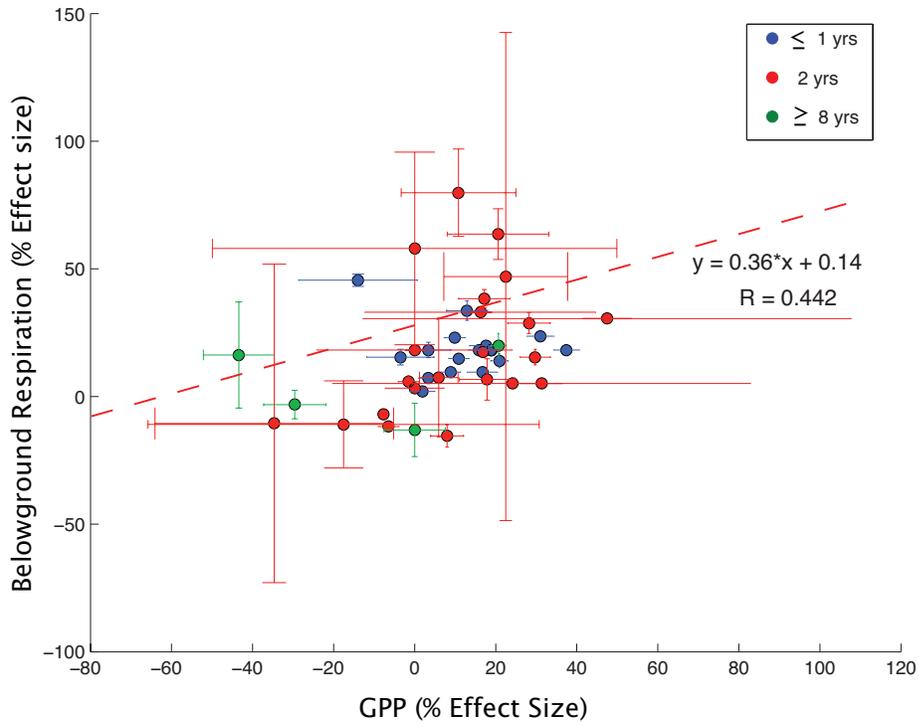
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Figure 2b

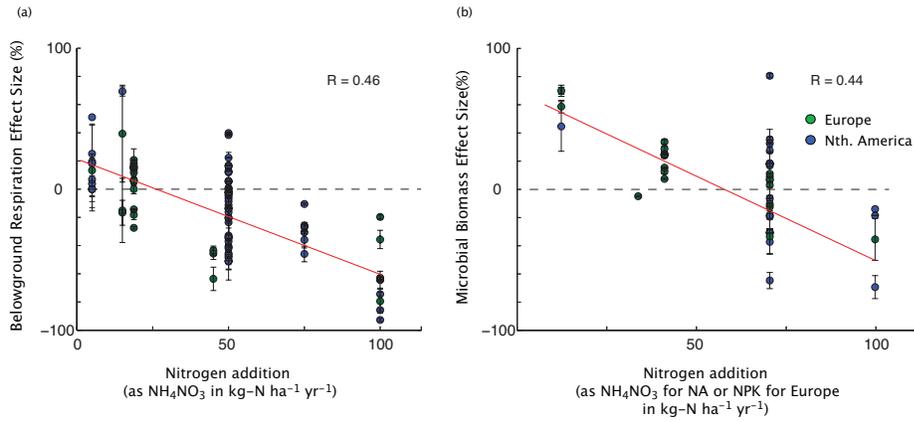
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Figure 3

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Figure 4