

1 **Response to reviewer 1**

2

3 We thank the reviewer for their constructive comments and we address their various concerns
4 below.

5

6 In revision, we have now fixed the WUE bug (see below) and this now allows us to
7 investigate both the carbon and the water simulations by CABLE. We now very clearly
8 demonstrate that models need to implement different sensitivities to water stress at xeric sites,
9 otherwise models will underestimate carbon and water fluxes during drought. Finally,
10 following the reviewer's suggestion we have restructured the results to make the text clearer
11 for the reader.

12

13

14 **The focus of the paper is on modelling drought impacts on ecosystem gas exchanges,**
15 **with the hypothesis that species respond differently to drought. While interesting for the LSM**
16 **community, the hypothesis is somewhat trivial to ecologists, who know species behave**
17 **differently in respect of drought.**

18 It is one thing to 'know' that there are differences among species in response to drought; it is
19 another thing entirely to quantify these differences and use them to attempt to predict drought
20 impacts on forests at landscape scales. The question addressed in our work is whether or not
21 these differences among species in sensitivity actually matter when simulating land surface
22 fluxes. This is a far from a trivial question.

23 There are two important points to make here:

24 1. The current state-of-the-art in terms of drought modelling (not just LSMs), assumes
25 PFTs have similar responses to drought. For a given location, differences in wilting
26 point and field capacity are a function of soil texture and as such, different PFT
27 occurring on the same soil type would have an identical limitation to gas exchange
28 during drought (assuming both PFTs transpired the same amount of water). Other
29 models, CABLE included, also assume differences among PFTs in terms of rooting

30 depth; however, these differences are often very small. Thus, the approach taken in
31 this paper, testing empirical drought sensitivities into CABLE, is highly novel.

32 2. Implementing a species-dependent response to drought is a non-trivial problem. As we
33 demonstrate in figure 2, the relationship between soil water content and soil water
34 potential is highly non-linear. The consequence of this nonlinearity is that whether a
35 model assumes gas exchange is limited by soil texture, or a species-dependent water
36 potential, can sometimes have very little effect on modelled fluxes. The importance of
37 species-level differences in response to drought for vegetation fluxes depends on the
38 water potential a plant “sees”. In this paper we tested three alternative approaches to
39 determining this water potential. Our results have implications for the wider modelling
40 community. For example, we demonstrated that the approach implemented within the
41 CLM (one of our tested approaches), likely fails to capture drought responses despite
42 depending on water potential, rather than soil texture.

43

44

45 The approach is to try three different parameterisations, and also three different root uptake
46 models, and evaluate model outputs against 5 flux sites over a European drought. The core
47 output of the paper is table 4, where a range of statistics are applied to the comparison of
48 observation and fluxes.

49

50 I remain to be convinced of a main conclusion – that there is high drought sensitivity at
51 northern sites. The hypothesis testing is not robust. I worry that there are a range of alternative
52 model tweaks that could get similar improvements in the flux comparison. We really need
53 further independent checks on model outputs using other data streams, for example local LAI
54 data, biomass increments, soil moisture time series etc.

55 As the reviewer does not elaborate specifically on why they are not convinced the northern
56 (or most mesic) sites can be characterised as having high drought sensitivity, it is difficult to
57 address this point. Nevertheless, we have improved our justification of the rationale behind
58 this hypothesis in the introduction: “*We hypothesised that drought sensitivity would increase
59 with latitude, as sites transitioned from xeric to mesic. We hypothesised that trees at more
60 mesic sites, with a greater abundance of available water than at xeric sites, would be more*

61 *vulnerable to shorter duration droughts and thus have higher drought sensitivity (or lower*
62 *resistance to drought). Therefore, accounting for this latitudinal gradient in drought*
63 *sensitivity would improve the performance of CABLE.”*

64

65 We agree with the reviewer that it is certainly possible that “alternative model tweaks” may
66 result in improved model-data agreement. Such tweaks may include adjusting the site texture
67 or root depth (both which would change access to soil water), but we would suggest these
68 kinds of tweaks would need to be carried out on a site-to-site basis. It would be (highly)
69 unlikely that a single adjustment would improve the model across all 5 sites (as our changes
70 do). In fact, Ukkola et al. 2015 (Hydrol. Earth Syst. Sci. Discuss., 12, 10789–10825)
71 demonstrate this very point using the CABLE model across 20 flux tower sites. They found
72 that the effect of adjusting soil properties had a limited ability to improve model-data
73 mismatch, with improvements limited to individual sites. In the paper we are instead taking an
74 evidence-based approach to model development, rather than tweaking individual parameters
75 to improve data-model mismatch and then attributing improvement to this property.

76

77 Consequently, we disagree that the hypothesis testing is not robust, we have tested the new
78 model simulations with the most direct data stream available – fluxes of latent heat and flux-
79 derived GPP from the 5 flux tower sites. Ideally, we would of course have liked to use
80 additional data streams to test model improvement. In fact, we make this very point in the
81 discussion: “*Access to water by deep roots could be a potential alternative explanation for the*
82 *low drought sensitivity that we inferred at the southernmost (xeric) site, Espirra. Here the*
83 *dominant species is not native to the region, but rather a plantation of blue gum (Eucalyptus*
84 *globulus), a species that is generally found to have high, not low, drought sensitivity (White*
85 *1996; Mitchell et al. 2014). Many eucalypts have a deep rooting strategy (Fabiao et al.*
86 *1987), suggesting a possible alternative explanation for drought tolerance at this site. More*
87 *in-depth study of fluxes and soil moisture patterns at this site would be needed to determine*
88 *the role of rooting depth.”*

89

90 Unfortunately none of the reviewer’s suggested alternative data streams are appropriate for
91 model testing at this scale. With respect to LAI, see our extended comment below. Changes in

92 biomass increment are a function of drought impacts on growth and carbon allocation as well
93 as gas exchange, and are only available at longer time scales (e.g. annually) giving relatively
94 little information to constrain the models. With respect to soil moisture data: datasets of deep
95 soil water layers (CABLE simulates depths up to 4.6 m) are rarely measured, and if they are,
96 are not freely available. Satellite derived estimates of soil moisture content only extend to the
97 very top few centimetres (<10 cm) and so do not allow us to test deep soil water access
98 appropriately. Hence, currently available soil moisture information is of limited use in
99 constraining drought responses.

100

101

102 We know that the PFT approach is a weakness due to its one-size-fits-all approach, and
103 therefore finer scales of parameterisation will help. The problem is to figure out how to make
104 that happen in a tractable and robust manner, and this paper is not written in a way to tackle
105 that problem.

106 We agree that our paper does not solve the problem, but we do believe that we take a very
107 important first step towards tackling it, which is to explore whether or not finer scales of
108 parameterisation would actually make a difference to land surface simulations. As discussed
109 above, this is not a given. We demonstrate that differential sensitivity to drought can be
110 important in determining drought responses. In the discussion we propose some potential
111 ways forward for implementing within-PFT variability in modelled responses to drought:
112 *“Global vegetation models would require a more sophisticated approach that relates drought*
113 *sensitivity to the climate of each pixel. One potential solution would be to develop an*
114 *empirical correlation between drought sensitivity and a long-term moisture index (e.g. the*
115 *ratio of mean precipitation to the equilibrium evapotranspiration; Cramer and Prentice,*
116 *1988; Gallego-Sala et al. 2010). Previous studies have demonstrated the feasibility of linking*
117 *model parameters that determine plant water use strategy to such a moisture index in global*
118 *simulations (Wang et al. 2014; De Kauwe et al. 2015). Such an approach would require a*
119 *concerted effort to collate appropriate data, as there are few compilations to date of traits*
120 *related to drought sensitivity (but see Manzoni et al. 2011; Zhou et al. 2013). Another, more*
121 *challenging, alternative, would be to develop optimization hypotheses that can predict*
122 *vegetation drought sensitivity from climate (e.g. Manzoni et al. 2014).”*

123

124

125 **The existence of a model bug is another major concern that undermines confidence.**

126 Both reviewers have raised an issue with respect to our section outlining the water use
127 efficiency (WUE) bug and the ensuing analysis. We acknowledge therefore that we were not
128 clear enough in our original text.

129

130 The bug *only* affected the modelled fluxes of gross primary productivity during periods of
131 drought: *all* water fluxes were correctly simulated (at all times). During periods where there
132 was an inadequate soil water supply to meet the atmospheric demand for simulated
133 transpiration, transpiration was reduced to the available amount of water in the root zone. To
134 maintain a coupled carbon and water cycle, photosynthesis should also be reduced, but
135 wasn't. This has the effect of producing erroneously high WUE during periods of extreme
136 water limitation, i.e. free carbon in exchange for water might be another way to interpret this.
137 It was for this reason we chose to focus *all* of our analysis on latent heat and transpiration and
138 *not* on gross primary productivity. Nevertheless, we did originally show the gross primary
139 productivity fluxes so that the readers could judge for themselves the erroneously increased
140 water use efficiency during drought (i.e. the effect of the bug).

141

142 We have now fixed the bug (here we acknowledge assistance of Ying-Ping Wang and
143 Vanessa Haverd of CSIRO), and so we now remove all text that referred to this from the
144 manuscript. Hopefully this should allay any concerns the reviewers have about the impact of
145 the bug on any of our results. We do note that part of the fix requires changing the method of
146 root extraction in the standard version of the model. Consequently, as well as reducing
147 erroneously high GPP during drought, there are also small changes in the latent heat fluxes.

148

149

150 **Abstract The text is not clear about what drought response is analysed – is it C cycle, water**
151 **cycle, energy balance?**

152 We agree with the reviewer, this was not clear. We have amended the text to say: “*We tested*
153 *whether variable drought sensitivities are needed to explain the observed large-scale patterns*
154 *of drought impact on the carbon, water and energy fluxes*”

155

156

157 **Introduction:**

158 **The focus of the final paragraph is on improving CABLE too much. The text should develop**
159 **knowledge of broader interest than for a single model user group.**

160 We respectfully disagree. The point of this paragraph was to set out exactly what was done in
161 terms of this paper. It is important therefore to be explicit and describe the changes that were
162 made to CABLE. We do broaden the implications of the results in what we consider to be the
163 appropriate place, which is the discussion text.

164

165

166 **Methods:**

167 **p. 12355 l. 10. “Optimally” needs to be defined carefully – what is optimised, over what time**
168 **scale? This stomatal model is a modification of a well used empirical model (Ball Berry) and**
169 **this should be stated.**

170 The stomatal model used here should not be regarded as a ‘modification’ of an existing
171 empirical model. The model, as derived by Medlyn et al. (2011), follows the theory of
172 optimal stomatal behaviour and is functionally equivalent to the Ball-Berry model, but with
173 the advantage that biological meaning can be associated with the model parameters.

174

175 We defined what we mean by “optimally”:

176 “*We build on the work by De Kauwe et al. (2015), who introduced a new g_s scheme into*
177 *CABLE. In this scheme, stomata are assumed to behave optimally; that is, when plants*
178 *maximise carbon gain, whilst simultaneously minimising water loss over short time periods*
179 *(i.e. a day) (Cowan and Farquhar, 1977) leading to the following formulation of g_s (Medlyn*

180 *et al. 2011)*”

181

182

183 p. 12356. Sensitivity of V_{cmax} and J_{max} to predawn water potential There is not consistent
184 evidence that these parameters are related to soil conditions as specified here. For instance,
185 Wright et al. (2013) show that these parameters are higher or unchanged in a temperate forest
186 growing in droughted conditions compared to well watered conditions. It is premature to
187 construct global parameterisations on this assumption when it does not hold across all species.

188 We tend to disagree that this is premature. The evidence would appear to us to be reasonably
189 clear that there are changes in apparent V_{cmax} in response to drought in the majority of cases
190 where this has been examined (Cornic et al. 1989; Epron and Dreyer 1992; Medrano et al.
191 1997; Parry et al. 2002 Keenan et al. 2009; Egea et al. 2011; Zhou et al. 2013). The Wright et
192 al. study cited would appear to be an exception rather than the rule. Furthermore, we highlight
193 to the reviewer that there are a number of existing models that *only* limit gas exchange via
194 reducing the V_{cmax} (J_{max}), for example CLM4.

195

196

197 p. 12357 l. 5. Constant J_{max}/V_{cmax} ratio is assumed Misson et al. (2006) hypothesized that
198 J_{max} is more sensitive to low water availability than V_{cmax} , so drought conditions may also
199 lead to a decrease in the J_{max}/V_{cmax} ratio. Data from Wright et al. (2013) support this
200 hypothesis.

201 We agree with the reviewer that such a hypothesis, i.e. that J_{max} is more sensitive than V_{cmax} is
202 potentially an interesting hypothesis to test in a model. We should clarify, the model assumes
203 a constant J_{max}/V_{cmax} ratio; we did not specifically add this for the purposes of this study. As
204 such, in this paper we were only testing an equal reduction in both properties. A logical
205 follow-on to this work would be to examine the impacts of such a hypothesis, but this is
206 outside the scope of this current study and we leave this to other interested researchers.

207

208

209 1. 8. Refers to eqn 6, but is this an error?

210 We thank the reviewer for spotting this mistake. It has now been corrected.

211

212

213 **Model Simulations:**

214 **The models are run with MODIS LAI as a driver – but there is a problem in that MODIS LAI**
215 **contains significant biases when used at site (flux tower) scale. Thus the LAI drivers used are**
216 **unlikely to be correct, and this will lead to model biases. This issue needs to be addressed.**

217 We agree with the reviewer that the prescribed MODIS LAI may not be a true reflection of
218 observed site dynamics. However, there is unfortunately no practical alternative. Measured
219 site LAI would need be collected at the necessary temporal and/or spatial resolution to force a
220 LSM (i.e. daily to monthly and 1 km²). Such measurements may have been made at a small
221 subset of sites but are not freely available. Hence, the most practical solution is to use MODIS
222 data, as is commonly done when simulating flux sites with land surface models.

223

224 CABLE, similar to other models, does have the means to dynamically simulate LAI, but there
225 is no reason to expect this would out-perform MODIS. We address the issue that because the
226 model prescribes LAI (as is standard among LSMs), it likely misses the effect of canopy
227 defoliation in the discussion text: “*During droughts, plants are often observed to shed their*
228 *leaves as a self-regulatory mechanism to reduce water losses (Tyree et al., 1993; Jonasson et*
229 *al., 1997; Bréda 20 et al., 2006). During the 2003 heatwave, at Hesse an early reduction of*
230 *approximately 1.7 m² m⁻² was observed, similarly at Brasschaat there was a observed*
231 *reduction of 0.8 m² m⁻² and at Tharandt needle-litter was increased during September until*
232 *November, with LAI estimated to be 0.9 m² m⁻² lower (Bréda et al., 2006; Granier et al.,*
233 *2007). In contrast, models typically fix turnover rates for leaves and as such this feedback is*
234 *largely absent from models. During periods of water stress, models do simulate an indirect*
235 *reduction in LAI via down-regulated net primary productivity; however this feedback is much*
236 *slower than is commonly observed. Not accounting for the canopy scale feedback will result*
237 *in models over-estimating carbon and water fluxes and thus losses in θ during drought.”*

238

239 Ultimately the aim of this study is not to address how well CABLE simulates LAI and we do
240 acknowledge that errors here will impact on simulations during drought (see above); however,
241 it is by no means the main cause for data-model mismatch during drought periods.

242

243

244 **Why are these species (Quercus, Cedrus) chosen? Why not use the species that are found at**
245 **the flux sites (Table 2)? A consistent approach would be more valuable.**

246 The simple answer is that the data required to parameterise the model for the actual site
247 species are not available. This issue is directly related to the reviewer's original point that "*the*
248 *hypothesis is somewhat trivial to ecologists, who know species behave differently in respect of*
249 *drought*" – and yet there are relatively few data currently available with which one could
250 parameterise such a model. Instead, the approach we have taken is a parsimonious one: we
251 have taken a range of different species sensitivities to soil moisture from a recent meta-
252 analysis. We explain in the discussion that in the absence of more appropriate site level data:
253 "*One potential solution would be to develop an empirical correlation between drought*
254 *sensitivity and a long-term moisture index (e.g. the ratio of mean precipitation to the*
255 *equilibrium evapotranspiration; Cramer and Prentice, 1988; Gallego-Sala et al., 2010).*
256 *Previous studies have demonstrated the feasibility of linking model parameters that determine*
257 *plant water use strategy to such a moisture index in global simulations (Wang et al., 2014; De*
258 *Kauwe et al., 2015). Such an approach would require a concerted effort to collate*
259 *appropriate data, as there are few compilations to date of traits related to drought sensitivity*
260 *(but see Manzoni et al., 2011; Zhou et al., 2013). Another, more challenging, alternative,*
261 *would be to develop optimization hypotheses that can predict vegetation drought sensitivity*
262 *from climate (e.g. Manzoni et al., 2014)."*

263

264

265 **Water use efficiency bug I appreciate the openness of the authors on this issue. But**

266 **I remain unclear on the implications of the bug and to what degree it invalidates the**
267 **conclusions of the paper. Is photosynthesis over-estimated during drought? – this would seem**
268 **to indicate that the paper must only focus on water and energy responses to drought. The**

269 authors seem to suggest that root water supply is always sufficient to meet demand, and so
270 transpiration is never down-regulated – but I am confused as I would suggest that water
271 limitation is a definition of drought, and that water limitation must have occurred in Europe in
272 2003 due to high demand by plants and low rainfall. This issue needs much more clarity if the
273 paper is to be useful.

274 See earlier response.

275

276

277 **Results:**

278 The opening of the results should be targeted towards key knowledge, rather than a bland
279 listing of tables and figures.

280 This section needs sub-headings to provide structure. It is hard to see what has been learned.
281 We need clear statements.

282 We thank the reviewer for these suggestions. We have restructured the results accordingly.

283

284

285 **When referring to GPP, be clear whether this is flux-derived or model-derived.**

286 We agree with the reviewer this information was unclear. In the methods we now clarify this:
287 “Model simulations were compared to measured latent heat flux at each of the FLUXNET
288 sites. In addition, simulated GPP was compared to flux derived (site modelled) GPP. These
289 flux GPP estimates are calculated from the measured net ecosystem exchange (NEE) of
290 carbon between the atmosphere and the vegetation/soil, and the modelled ecosystem
291 respiration (R_{eco}), where GPP is calculated as $NEE + R_{eco}$.” Throughout the text we refer to
292 “observed” GPP as flux-derived GPP.

293

294

295 **P 12361. “CTRL simulation” repeated**

296 We thank the reviewer for spotting this mistake; it has now been corrected.

297

298

299 The discussion here on the WUE bug just confused me further. I don't know what we can
300 learn from these simulations when a bug is complicating matters so much.

301 We have addressed this issue above.

302

303

304 There are simulations for sand and clay soils. Why not use an appropriate soil
305 parameterisation for the site in question? This would target the analysis more effectively. At
306 present the comparison across soil texture is confusing.

307 It is possible that the reviewer has confused the results of figure 2, with subsequent model
308 simulations carried out with CABLE? In figure 2, we have picked two extremes out of the soil
309 texture continuum simulated by CABLE and shown, in an idealised way, how the model
310 simulates the reduction of photosynthesis with decreasing soil water content. In the remaining
311 figures, where CABLE is run at the different flux tower sites we do not assume a sand or clay
312 soil texture, rather, we use the representative soil texture class as given by Zobler (1999) for
313 the corresponding site pixel.

314

315

316 We are given three statistical outputs (RMSE, NSE, R), but the text focuses on RMSE alone,
317 and the main conclusion re trait changes N-S is derived from RMSE. What is the point of the
318 other stats? It seems to me they do not support the conclusions about N-S trait changes
319 derived from RMSE.

320 We provided a range of statistical characteristics of model-data performance for the readers
321 benefit. Our feeling was that if we had only provided RMSE, it is likely another reviewer may
322 have requested additional statistics. We disagree that the statistics contradict the RMSE; the
323 NSE values unsurprisingly show the same mesic-xeric transition as the RMSE. The Pearson's
324 correlation coefficient does show a different story, but this is unsurprising as this is showing
325 the linear correlation between the model and the observations. As such, as long as the model

326 and observed change in the same direction a high correlation will be obtained, but this does
327 not strictly tell us whether the error is smaller or larger, hence the focus on the more
328 meaningful RMSE statistic.

329

330

331 **Discussion:**

332 **4.1 This section is well written and interesting. The modelling is used to advance**
333 **understanding of root zone effects on drought. But this issue needs to be better introduced in**
334 **the results section.**

335 We have an entire section of the methods dedicated to testing root zone weighting, page
336 123570-123571. In the results section, figure 2 explores the effect of root zone effects on
337 drought. Given the reviewers comment above in regards to texture (which we address), we
338 think it is possible that the reviewer misunderstood the purpose of this figure. Hopefully it
339 will now be clearer that we link to these issues earlier in the manuscript.

340

341

342 **The rest of the discussion drifts away from the experiment and the detail of the research**

343 **– the focus is lost and an array of topics related to model application are raised.**

344 **These do not seem pertinent to the paper. There is no final concluding paragraph to emphasise**
345 **the key learnings.**

346 The discussion text in section 4.3 is relevant to the wider issues of modelling drought, many
347 of the topics explored in this section link back to other areas of the manuscript. Section 4.3
348 addresses four areas: (i) rooting depth, (ii) leaf shedding, (iii) stomatal vs mesophyll
349 responses and (iv) soil heterogeneity. The assumption of rooting depth is an important issue,
350 as it will of course impact upon the incurred drought stress of the model and is not a uniform
351 assumption across models. We also make the point that this could be an alternative
352 explanation for the results at the Espirra site (see above). The reviewer had asked previously
353 about errors that may come from using MODIS LAI; the leaf shedding section addresses this

354 issue. In response to the reviewer’s comment, these paragraphs have been shortened and re-
355 focused.

356 The final paragraph is a summary of the key learnings of the paper.

357

358

359 **Figures and Tables Table 3. Adjust column headers to add a delta term to each for clarity.**
360 **Some statistics describing the variation in the deltas should be added.**

361 We have added this information.

362

363

364 **Figure 1. Why not also show the 2002 data?**

365 In short, because 2002 did not experience a drought and this paper is focussed on the drought
366 of 2003. We show the departure from 2002, which characterises the severity of the drought in
367 Table 2. Overall, we would argue little would be gained by adding additional figures showing
368 responses in a non-drought year. Furthermore, on all plots we show a line representing “no
369 drought”, which depicts an approximation to the size of the drought in 2003.

370

371

372 **Figure 2. Legend not clear – explain panels a b and c.**

373 We have improved the explanation of this figure.

374

375

376 **Fig 3-7. There is a lot of information in the figures, but it is hard to extract, so their value is**
377 **not clear. Presenting a large number of time-series output of models in this unstructured**
378 **manner is not really helpful. Pick which panels are important and discuss them properly.**

379 We disagree the figures were unstructured: they are ordered to show a mesic-xeric transition
380 between sites, detailing the impact of the different drought sensitivities and different methods
381 to obtain soil water potential (SWP) at each site. On each panel we show the observed, control

382 simulations and three different drought sensitivities. We do not see any other way to
383 succinctly display this information. Hopefully with the new restructuring of the text, it will be
384 clearer to the reviewer.

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408 **Response to reviewer 2**

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410 We thank the reviewer for their constructive comments and we address their various concerns
411 below.

412

413 In revision, we have now fixed the WUE bug (see below) and this now allows us to
414 investigate both the carbon and the water simulations by CABLE. We now very clearly
415 demonstrate that models need to implement different sensitivities to water stress at xeric sites,
416 otherwise models will underestimate carbon and water fluxes during drought. Finally, we
417 have restructured the results to make the text clearer for the reader.

418

419

420 *De Kauwe and others explore drought parameterization in the CABLE model. An alternate
421 drought formulation is found to improve modeled GPP and LE across five European flux sites
422 in response to the 2003 drought.*

423

424 *The paper as written is interesting and complete but in many cases must be revised for clarity.
425 The choice of sites is poorly described, as is the justification for the drought schemes chosen.
426 The tendency to describe the gradient of sites as north/south rather than xeric/mesic is
427 distracting. That being said, the results are logical with a simple and clear message that will
428 benefit global model development. I recommend publication following (many) minor
429 revisions.*

430 Forested sites in Europe were selected from those available through the Protocol for the
431 Analysis of Land Surface models (PALS; <http://pals.unsw.edu.au>; Abramowitz, 2012). These
432 data have previously been pre-processed and quality controlled for use within the LSM
433 community. We have clarified the text: *“To assess the performance of the CABLE model both
434 with and without the new drought scheme, we selected a gradient of five forested Fluxnet
435 (<http://www.fluxdata.org/>) sites across Europe (Table 2) from those available through the
436 Protocol for the Analysis of Land Surface models (PALS; pals.unsw.edu.au; Abramowitz,
437 2012). These data have previously been pre-processed and quality controlled for use within*

438 *the LSM community. Consequently, all site-years had near complete observations of key*
439 *meteorological drivers (as opposed to significant gap-filled periods).”*

440

441 As for the description of sites, we have followed the reviewer’s suggestion and replaced
442 north/south with mesic/xeric. We have also changed the paper title to reflect this change as
443 well.

444

445

446 *The introduction is well-written and well-cited but could use improvement. The passage ‘Our*
447 *ability to model drought effect on vegetation function is currently limited’ is vague. Some*
448 *drought responses are simulated very well, others poorly, and the challenge remains to model*
449 *drought response well, all the time.*

450 We have clarified this sentence: *“Our ability to model drought effect on vegetation function*
451 *(carbon and water fluxes) is currently limited (Galbraith et al. 2010; Egea et al. 2011; Powell*
452 *et al. 2013).”*

453

454

455 *The following paragraph discusses the Galbraith results, then the Powell results, then the*
456 *Galbraith results again.*

457 We have now combined both sections of text that referred to the Galbraith paper.

458

459

460 *A good argument that PFTs are insufficient to capture the range in drought responses. It*
461 *would be even better to give examples within PFTs that differ with respect to their isohydric*
462 *or anisohydric behavior. In this case, might the behavior of species in a PFT average out or*
463 *would all different species (or groups thereof) emerge to become important?*

464 We thank the reviewer for this suggestion and have amended the text: *“Such an approach*
465 *ignores experimental evidence of the range of sensitivities to drought among vegetation types,*
466 *which would fall within a single PFT group (Choat et al. 2012; Limousin et al. 2013; Zhou et*

467 *al. 2014; Mitchell et al., 2014; Mencuccini et al. 2015). For example, Turner et al. (1984)*
468 *found contrasting responses in leaf water potential to increasing vapour pressure deficit,*
469 *ranging from isohydric to anisohydric, among a group of woody and herbaceous species.*
470 *Similarly, Zhou et al. (2014) found that in a dry-down experiment, European sapling species*
471 *originating from more mesic environments were more sensitive to water stress (more rapid*
472 *reduction of photosynthesis and stomatal conductance) than species from more xeric regions.*
473 *However, it is not known whether observed differences in the response to soil moisture deficit*
474 *among species are important in determining fluxes at large scales.”*

475

476

477 *The need to test drought parameterizations across sites is described nicely. What was not*
478 *described well is the justification for the hypothesis that drought sensitivity would increase as*
479 *a function of latitude. First and foremost, latitude is only ever a correlate of something else*
480 *like temperature or daylength. If this justification is improved, the manuscript would be more*
481 *compelling.*

482 *We have now added additional text to clarify this: “We hypothesised that drought sensitivity*
483 *would increase as sites transitioned from xeric to mesic. We hypothesised that trees at more*
484 *mesic sites, with a greater abundance of available water than at xeric sites, would be more*
485 *vulnerable to shorter duration droughts, and thus have higher drought sensitivity (or lower*
486 *resistance to drought). Therefore, accounting for this latitudinal gradient in drought*
487 *sensitivity would improve the performance of CABLE.”*

488

489

490 *It may be argued that the optimal stomatal function framework falls victim to the*
491 *simultaneous need for plants to not succumb to hydraulic stress (e.g. Sperry 2004). That being*
492 *said, optimization theory is important to consider in models although for the case of drought it*
493 *might be superseded by hydraulic considerations, which are described nicely in equations 3-5.*
494 *In other words, the model as written incorporates optimal stomatal behavior and conductance,*
495 *but it is able to simulate tree death?*

496 CABLE, similar to many other LSMs does not directly simulate tree mortality: instead only
497 accounting for reductions in productivity.

498

499

500 It would be good to cite the work of Katul, Leuning, and Oren (2003) with respect to the
501 coupling of hydraulic and photosynthetic parameters; I believe this is the original reference
502 for this notion.

503 Much as we like the paper by Katul et al., in this paper we are not discussing the hydraulic
504 constraints to transpiration so it does not seem relevant to cite this paper.

505

506

507

508 Why were the three approaches on page 9 tested? Are they meant to simulate a gradient of
509 complexity from simple to complex?

510 The three tested approaches were selected as plausible ways to appropriately weight soil water
511 potential in a model. They were not intended to span a complexity gradient. Rather, we started
512 with M1; finding it was too strongly weighted to the top soil we tried M2; finding that was too
513 strongly weighted towards the lower soil we tried M3 which uses dynamic weighting. We
514 have added further text, similar to that found in the discussion section 4.1, which should better
515 explain the logic behind our selected approaches: “*We tested three potential approaches for*
516 *weighting in this paper:*

517 (i) *Using the root-biomass weighted θ and converting this to Ψ_s using Eq. (8). Such*
518 *an approach is often favoured by models, following experimental evidence that*
519 *plants preferentially access regions in the root zone where water is most freely*
520 *available (Green and Clothier 1995; Huang et al. 1997).*

521 (ii) *Taking the integrated θ over the top 5 soil layers (1.7 m depth) and converting this*
522 *to Ψ_s using Eq. (8). This method assumes the plant effectively has access to an*
523 *entire “bucket” of soil water. This approach is often favoured by “simpler” forest*
524 *productivity models (e.g. Landsberg and Waring, 1997).*

525 (iii) Weighting the average Ψ_S for each of the six soil layers by the weighted soil-to-
526 root conductance to water uptake of each layer, following Williams et al. (1996;
527 2001). The total conductance term depends the combination of a soil component
528 (R_S) and a root component (R_r). R_S is defined as (Gardner, 1960):

$$R_S = \frac{\ln\left(\frac{r_s}{r_r}\right)}{2\pi l_r D G_{soil}} \quad (6)$$

529 where r_s is the mean distance between roots (m), r_r is the fine root radius (m), D
530 is the depth of the soil layer, G_{soil} is the soil conductivity ($\text{mmol m}^{-1} \text{s}^{-1} \text{MPa}^{-1}$)
531 which depends on soil texture and soil water content, l_r is the fine root density
532 (mm^{-3}). R_r is defined as:

$$R_r = \frac{R_r^*}{FD} \quad (7)$$

533 where R_r^* is the root resistivity (MPa s g mmol^{-1}), F is the root biomass per unit
534 volume (g m^{-3}). This method weights Ψ_S to the upper soil layers when the soil is
535 wet, but shifts towards layer lowers as the soil dries, due to the lower soil
536 hydraulic conductance (e.g. Duursma et al. 2011).”

537

538 I like the honesty of section 2.3.1. That being said, is the problem simply and conveniently
539 avoided in this case? How is a reader to know that it does not factor into the results?

540

541

542 Both reviewers have raised an issue with respect to our section outlining the water use
543 efficiency (WUE) bug and the ensuing analysis. We acknowledge therefore that we were not
544 clear enough in our original text.

545

546 The bug *only* affected the modelled fluxes of gross primary productivity during periods of
547 drought: *all* water fluxes were correctly simulated (at all times). During periods where there
548 was an inadequate soil water supply to meet the atmospheric demand for simulated
549 transpiration, transpiration was reduced to the available amount of water in the root zone. To

550 maintain a coupled carbon and water cycle, photosynthesis should also be reduced, but
551 wasn't. This has the effect of producing erroneously high WUE during periods of extreme
552 water limitation, i.e. free carbon in exchange for water might be another way to interpret this.
553 It was for this reason we chose to focus *all* of our analysis on latent heat and transpiration and
554 *not* on gross primary productivity. Nevertheless, we did originally show the gross primary
555 productivity fluxes so that the readers could judge for themselves the erroneously increased
556 water use efficiency during drought (i.e. the effect of the bug).

557

558 The bug has now been fixed. We thank Vanessa Haverd and Ying-Ping Wang of CSIRO for
559 their assistance with this fix. Following the fix, we have removed all text referred to the bug
560 from the manuscript. Hopefully this change should allay the reviewers' concerns about the
561 impact of the bug on our results. We do note that part of the fix requires changing the method
562 of root extraction in the standard version of the model. Consequently, as well as reducing
563 erroneously high GPP during drought, there were small changes in the latent heat fluxes as
564 well.

565

566

567 **Section 2.4 could use expansion to justify the choice of the 5 sites. Why were they chosen?**

568 We have clarified the selection choice as stated in our comment above.

569

570

571 **The results section is succinct. Note that RMSE has units.**

572 We have added the missing units throughout.

573

574

575 **Also, back to the question about why the three different drought parameterizations were**
576 **chosen, were the first two straw men or are these common in LSMs for simulating drought?**

577 No, these are not straw men; they are common approaches in LSMs. With the additional
578 information added to the methods as per the reviewer's earlier comment, this should now be
579 clearer.

580

581

582 Per the comments above regarding latitude, the first sentence of the discussion sounds more
583 robust with mesic species exhibiting higher drought sensitivity than xeric ones for which one
584 can assume that plants have adapted. That being said, there must be some good references for
585 this basic concept. In the first paragraph of the discussion the authors move back to this
586 north/south framework rather than the wet/dry framework, which is perhaps additionally
587 surprising from a group from Australia.

588 As suggested we have replaced the latitude text and added appropriate references.

589

590

591 In section 4.1 I wouldn't say that pot moisture is necessarily uniform but rather the
592 relationship between active root area and the moisture profile does not match what is
593 commonly observed in the field.

594 The text has been modified to read: "*in which it is fair to assume that the soil moisture*
595 *content is relatively uniform and fully explored by roots. In contrast, soil moisture content*
596 *and rooting depth in the field typically have strong vertical profiles.*"

597

598

599 Interestingly, section 4.1 provides much of the justification for choosing the different
600 weighting schemes that was lacking above. Regarding the comment about plant traits and
601 drought sensitivity at the bottom of page 18, not the TRY database?

602 Whilst the TRY database does have a great deal of useful information on plant traits, it does
603 not contain the necessary information to parameterise a model like the one considered in this
604 manuscript. The sensitivity of gas exchange to drought is not one of the traits compiled in the
605 database.

606

607

608 On page 20 line 19, the 'drought-deciduous' concept could be introduced more clearly.

609 We have amended the text to: "*During droughts, plants are often observed to shed their*
610 *leaves. This is a self-regulatory mechanism to reduce water losses (Tyree et al. 1993;*
611 *Jonasson et al. 1997; Bréda et al. 2006).*"

612

613

614 The following sentence could use re-working: Overall however, there remains a tendency to
615 trade mechanistic realism is often traded for present day accuracy,

616 We have removed this text.

617

618

619 From Table 1 the sites go at least as far maritime/continental as they do 'north/south'.

620 See comment below.

621

622

623 A relatively far northern site wasn't chosen. Just another reason to couch things in terms of
624 water availability rather than latitude.

625 As suggested, we have changed all site descriptions to mesic/xeric, rather than north/south.

626 We did not use a far northern site as the 2003 heatwave did not extend into the far north, as
627 far as we are aware.

628

629

630 In figure 1 (and figures 3-7), how was transpiration measured?

631 In these figures transpiration was not measured (note there is no black line to indicate
632 observations), instead only the observed LE fluxes are shown.

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References Sperry J.S. (2004). Coordinating stomatal and xylem functioning: an evolutionary perspective. *New Phytologist*, 162, 568-570.

658 **Do land surface models need to include differential plant**
659 **species responses to drought? Examining model**
660 **predictions across a mesic-xeric gradient in Europe.**

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662 **M. G. De Kauwe¹, S.-X. Zhou^{1,2}, B. E. Medlyn^{1,3}, A. J. Pitman⁴, Y.-P. Wang⁵, R. A.**
663 **Duursma³ and I. C. Prentice^{1,6}**

664

665 [1]{Macquarie University, Department of Biological Sciences, New South Wales 2109,
666 Australia.}

667 [2] {CSIRO Agriculture Flagship, Waite Campus, PMB 2, Glen Osmond, SA 5064,
668 Australia.}

669 [3]{Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag
670 1797, Penrith, NSW, Australia}

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671 [4]{Australian Research Council Centre of Excellence for Climate Systems Science and
672 Climate Change Research Centre, UNSW, Sydney, Australia}

673 [5]{CSIRO Ocean and Atmosphere Flagship, Private Bag #1, Aspendale, Victoria 3195,
674 Australia}

675 [6]{AXA Chair of Biosphere and Climate Impacts, Grand Challenges in Ecosystems and
676 the Environment and Grantham Institute – Climate Change and the Environment,
677 Department of Life Sciences, Imperial College London, Silwood Park Campus, Buckhurst
678 Road, Ascot SL5 7PY, UK}

679

680

681 Correspondence to: M. G. De Kauwe (mdekauwe@gmail.com)

682

683

686 **Abstract**

687 Future climate change has the potential to increase drought in many regions of the globe,
688 making it essential that land surface models (LSMs) used in coupled climate models,
689 realistically capture the drought responses of vegetation. Recent data syntheses show that
690 drought sensitivity varies considerably among plants from different climate zones, but state-
691 of-the-art LSMs currently assume the same drought sensitivity for all vegetation. We tested
692 whether variable drought sensitivities are needed to explain the observed large-scale patterns
693 of drought impact on the carbon, water and energy fluxes. We implemented data-driven
694 drought sensitivities in the Community Atmosphere Biosphere Land Exchange (CABLE)
695 LSM and evaluated alternative sensitivities across a latitudinal gradient in Europe during the
696 2003 heatwave. The model predicted an overly abrupt onset of drought unless average soil
697 water potential was calculated with dynamic weighting across soil layers. We found that high
698 drought sensitivity at the most mesic sites, and low drought sensitivity at the most xeric sites,
699 was necessary to accurately model responses during drought. Our results indicate that LSMs
700 will over-estimate drought impacts in drier climates unless different sensitivity of vegetation
701 to drought is taken into account.

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717 **1 Introduction**

718 Changes in regional precipitation patterns with climate change are highly uncertain (Sillmann
719 et al. 2014), but are widely expected to result in a change in the frequency, duration and
720 severity of drought events (Allen et al. 2010). Drought is broadly defined, but for plants is a
721 marked deficit of moisture in the root zone which results from a period of low rainfall and/or
722 increased atmospheric demand for evapotranspiration. Recently, a series of high-profile
723 drought events (Ciais et al. 2005; Fensham et al. 2009; Phillips et al. 2009; Lewis et al. 2011)
724 and associated tree mortality (Breshears et al. 2005; van Mantgem et al. 2009; Peng et al.
725 2011; Anderegg et al. 2013), have occurred across the globe and these events have led to
726 debate as to whether incidence of drought are increasing (Allen et al. 2010; Dai et al. 2013,
727 but see Sheffield et al. 2012). Drought and any ensuing vegetation mortality events have the
728 potential to change land ecosystems from a sink to source (Lewis et al. 2011), and the
729 dominant mechanisms governing the ecosystem responses to drought can vary from reducing
730 stomatal conductance (Xu and Baldocchi, 2003) to increasing tree mortality (Lewis et al.
731 2011) and changing community species composition (Nepstad et al. 2007).

732

733 | Our ability to model drought effect on vegetation function (carbon and water fluxes) is
734 currently limited (Galbraith et al. 2010; Egea et al. 2011; Powell et al. 2013). Remarkably,
735 given the importance of correctly capturing drought impacts on carbon and water fluxes, land
736 surface models (LSMs) designed for use in climate models have rarely been benchmarked
737 against extreme drought events. Mahfouf et al. (1996) compared summertime crop
738 transpiration from 14 land surface schemes, finding that only half of the models fell within the
739 uncertainty range of the observations. They attributed differences among models to the
740 various schemes used by models to represent transpiration processes (e.g. soil water stress
741 function, different number of soil layers) and variability in the initial soil water content at the
742 start of the growing season which relates to variability in the way bare soil evaporation and
743 drainage are represented among different models. Galbraith et al. (2010) showed that a set of
744 dynamic global vegetation models (DGVMs) were unable to capture the 20–30% reduction in
745 biomass due to drought during a set of throughfall exclusion experiments in the Amazon.

746 | Galbraith et al. (2010) attributed model variability during drought to: changes in autotrophic
747 respiration, (which was not supported by the data), model insensitivity to observed leaf area
748 reductions, and the use of different empirical functions to down-regulate productivity during

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Moved down [2]: Similarly, Powell et al. (2013) demonstrated that a group of five models were unable to predict drought-induced reductions in aboveground biomass (~20%) in two large-scale Amazon experiments.

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759 water stress. The models ~~differed~~ both in terms of time-scale of the application of this
760 function (sub-diurnal vs. daily) and whether it ~~was~~ used to down-regulate net photosynthesis
761 or the maximum rate of Rubisco activity, V_{cmax} . ~~Similarly, Powell et al. (2013) demonstrated~~
762 ~~that a group of five models were unable to predict drought-induced reductions in aboveground~~
763 ~~biomass (~20%) in two large-scale Amazon experiments.~~ Gerten et al. (2008) compared the
764 effect of adjusting precipitation regimes on simulated net primary productivity (NPP) by four
765 ecosystem models across a range of hydroclimates. They found a consistent direction of
766 change (in terms of NPP) with different scenarios across models but found that the seasonal
767 evolution of soil moisture ~~differed~~ ~~among~~ the models.

768

769 In order for models to better capture realistic responses during drought, they need to draw
770 more closely on experimental data (see Chaves et al. 1993 for a review). One key observation
771 is that there is a continuum of species responses to soil moisture deficit, ranging from
772 isohydric (stomata close rapidly during drought, maintaining a minimum leaf water potential,
773 Ψ_l) to anisohydric (stomata remain open during drought, which allows Ψ_l to decrease)
774 hydraulic strategies (Tardieu and Simonneau, 1998; Klein, 2014). These differences are
775 widely observed and are thought to be important in determining resilience to drought
776 (McDowell et al. 2008; Mitchell et al. 2013; Garcia-Forner et al. 2015). Many traits, including
777 hydraulic conductivity, resistance to cavitation, turgor loss point, stomatal regulation and
778 rooting depth, contribute to these differences. Systematic differences in the response of leaf
779 gas exchange to soil moisture potential have been observed among species originating from
780 different hydroclimates (Zhou et al. 2013), with species from mesic environments showing
781 stronger stomatal sensitivity to drought than species from xeric environments. Currently,
782 these environmental gradients in species behaviour are not captured in LSMs, which typically
783 assume static plant functional type (PFT) parameterisations. This is in part because
784 historically the data required to describe these attributes have not been available at the global
785 scale, but also due to the necessity of simplification required to run global climate model
786 simulations. ~~Species with a PFT~~ are assumed to have similar or identical sensitivities to
787 drought. Such an approach ignores experimental evidence of the range of sensitivities to
788 drought among ~~species~~ (Choat et al. 2012; Limousin et al. 2013; Zhou et al. 2014; Mitchell et
789 al., 2014; Mencuccini et al. ~~2015~~). ~~For example, Turner et al. (1984) found contrasting~~
790 ~~responses in leaf water potential to increasing vapour pressure deficit, ranging from isohydric~~

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802 to anisohydric, among a group of woody and herbaceous species. Similarly, Zhou et al. (2014)
803 found that in a dry-down experiment, European sapling species originating from more mesic
804 environments were more sensitive to water stress (more rapid reduction of photosynthesis and
805 stomatal conductance) than species from more xeric regions. However, it is not known
806 whether observed differences in the response to soil moisture deficit among species are
807 important in determining fluxes at large scales.

808

809 In this study we test whether differences in species' responses to drought are needed to
810 capture drought responses on a continental scale. We built on recent changes to the stomatal
811 conductance (g_s) scheme (De Kauwe et al. 2015) within the Community Atmosphere
812 Biosphere Land Exchange (CABLE) LSM (Wang et al. 2011), by implementing a new
813 formulation for drought impacts based on plant ecophysiological studies for 31 species (Zhou
814 et al. 2013; 2014). We obtained three parameterisations for drought response from these
815 studies, characterising low, medium and high sensitivities to drought. We then applied
816 CABLE to simulate responses to an extreme meteorological event, the European 2003
817 heatwave, at five eddy covariance sites covering a latitudinal gradient, transitioning from
818 mesic sites at the northern extreme to xeric at the southern sites. Observations show that there
819 was a significant impact of drought on ecosystem fluxes at these sites (Ciais et al. 2005; Schär
820 et al. 2005). We note that models have been applied to simulate drought effects on
821 productivity (net primary production) and leaf area at individual sites (Ciais et al. 2005;
822 Fischer et al. 2007; Granier et al. 2007; Reichstein et al. 2007) but have not been used to
823 examine whether alternative parameterisations are needed to capture drought responses across
824 sites. We therefore tested how well CABLE was able to simulate the impact of drought on
825 carbon and water fluxes at these sites using alternative parameterisations for drought
826 sensitivity. We hypothesised that drought sensitivity would increase as sites transitioned from
827 xeric to mesic. We hypothesised that trees at more mesic sites, with a greater abundance of
828 available water than at xeric sites, would be more vulnerable to shorter duration droughts, and
829 thus have higher drought sensitivity (or lower resistance to drought). Therefore, accounting
830 for this latitudinal gradient in drought sensitivity would improve the performance of CABLE.

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834 2 Methods

835 2.1 Model description

836 CABLE represents the vegetation using a single layer, two-leaf canopy model separated into
837 sunlit and shaded leaves (Wang and Leuning, 1998), with a detailed treatment of within
838 canopy turbulence (Raupach 1994; Raupach et al. 1997). Soil water and heat conduction is
839 numerically integrated over six discrete soil layers following the Richards equation and up to
840 three layers of snow can accumulate on the soil surface. A complete description can be found
841 in Kowalczyk et al. (2006) and Wang et al. (2011). CABLE has been used extensively for
842 both offline (Abramowitz et al. 2008; Wang et al. 2011; De Kauwe et al. 2015) and coupled
843 simulations (Cruz et al. 2010; Pitman et al. 2011; Mao et al. 2011; Lorenz et al. 2014) within
844 the Australian Community Climate Earth System Simulator (ACCESS, see
845 <http://www.accessimulator.org.au>; Kowalczyk et al. 2013); a fully coupled earth system
846 model. The source code can be accessed after registration at <https://trac.nci.org.au/trac/cable>.

848 2.2 Representing drought stress within CABLE.

849 We build on the work by De Kauwe et al. (2015), who introduced a new g_s scheme into
850 CABLE. In this scheme, stomata are assumed to behave optimally; that is, stomata are
851 regulated to maximise carbon gain whilst simultaneously minimising water loss, over short
852 time periods (i.e. a day) (Cowan and Farquhar, 1977) leading to the following formulation of
853 g_s (Medlyn et al. 2011)

$$g_s = g_0 + 1.6 \left(1 + \frac{g_1}{\sqrt{D}} \right) \frac{A}{C_s} \quad (1)$$

854 where A is the net assimilation rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$), C_s ($\mu\text{mol mol}^{-1}$) and D (kPa) are the CO_2
855 concentration and the vapour pressure deficit at the leaf surface, respectively, and g_0 (mol m^{-2}
856 s^{-1}), and g_1 are fitted constants representing the residual stomatal conductance when A reaches
857 zero, and the slope of the sensitivity of g_s to A , respectively. The model was parameterised for
858 different PFTs using data from Lin et al. (2015) (see De Kauwe et al. 2015).

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862 In the standard version of CABLE, drought stress is implemented as an empirical scalar (β)
 863 that depends on soil moisture content, weighted by the fraction of roots in each of CABLE's
 864 six soil layers:

$$\beta = \sum_{i=1}^n f_{root,i} \frac{\theta_i - \theta_w}{\theta_{fc} - \theta_w}; \beta \in [0,1] \quad (2)$$

865 where θ_i is the volumetric soil moisture content ($\text{m}^3 \text{m}^{-3}$) in soil layer i , θ_w is the wilting point
 866 ($\text{m}^3 \text{m}^{-3}$), θ_{fc} is the field capacity ($\text{m}^3 \text{m}^{-3}$) and $f_{root,i}$ is the fraction of root mass in soil layer
 867 i . The six soil layers in CABLE have depths 0.022 m, 0.058 m, 0.154 m, 0.409 m, 1.085 m
 868 and 2.872 m. The factor β is assumed to limit the slope of the relationship between stomatal
 869 conductance (g_s , $\text{mol m}^{-2} \text{s}^{-1}$; Leuning 1995) by acting as a modifier on the parameter g_1 .

870 In this study, we introduced a new expression for drought sensitivity of gas exchange, based
 871 on the work of Zhou et al. (2013, 2014). In this model, both g_1 and the photosynthetic
 872 parameters V_{cmax} and J_{max} are assumed to be sensitive to pre-dawn leaf water potential, but
 873 this sensitivity varies across species. There is considerable evidence that both g_1 and V_{cmax} are
 874 sensitive to soil moisture (Keenan et al. 2009; Egea et al. 2011; Flexas et al. 2012; Zhou et al.
 875 2013). There is also widespread evidence that plants more directly respond to water
 876 potential rather than water content (Comstock and Mencuccini 1998; Verhoef and Egea,
 877 2014).

878

879 Zhou et al. (2013) extended the optimal stomatal model of Medlyn et al. (2011) by fitting an
 880 exponential function to relate g_1 to pre-dawn leaf water potential (Ψ_{pd}):

$$g_1 = g_{1wet} \times \exp(b\Psi_{pd}) \quad (3)$$

881 where g_{1wet} is fitted parameter representing plant water use under well watered conditions (i.e.
 882 when $\Psi_{pd} = 0$) and b is a fitted parameter representing the sensitivity of g_1 to Ψ_{pd} . Species
 883 with different water use strategies can be hypothesised to differ in not only their g_1 parameter
 884 under well-watered conditions, g_{1wet} (see Lin et al. 2015), but also with the sensitivity to Ψ_{pd} ,
 885 b . Zhou et al. (2013) also advanced a non-stomatal limitation to the photosynthetic
 886 biochemistry, which describes the apparent effect of water stress on V_{cmax} :

$$V_{cmax} = V_{cmax,wet} \frac{1 + \exp(S_f \Psi_f)}{1 + \exp(S_f (\Psi_f - \Psi_{pd}))} \quad (4)$$

887 where $V_{cmax,wet}$ is the V_{cmax} value in well watered conditions, S_f is a sensitivity parameter
 888 describing the steepness of the decline with water stress, Ψ_f is the water potential at which
 889 Ψ_{pd} decreases to half of its maximum value. As with g_1 , it is hypothesised that in the same
 890 way species vary in their V_{cmax} values in well-watered conditions ($V_{cmax,wet}$), they would also
 891 differ in their sensitivity of down-regulated V_{cmax} with water stress (Zhou et al. 2014). In
 892 CABLE, as there is a constant ratio between the parameters J_{max} and V_{cmax} , the parameter J_{max}
 893 is similarly reduced by drought.

894

895 To implement Eq. (6) in CABLE we first had to convert soil moisture content (θ) to pre-dawn
 896 leaf water potential (Ψ_{pd}). We did so by assuming that overnight Ψ_{pd} and Ψ_s equilibrate
 897 before sunrise, thus ignoring any night-time transpiration (Dawson et al. 2007). Following
 898 [Campbell](#) (1974), we related θ to Ψ_s in each soil layer by:

$$\Psi_{s,i} = \Psi_e \left(\frac{\theta_i}{\theta_{sat}} \right)^{-k} \quad (5)$$

899 where Ψ_e is the air entry water potential (MPa) and k (unitless) is an empirical coefficient
 900 which is related to the soil texture. Values for Ψ_e and b are taken from CABLE's standard
 901 lookup table following Clapp and Hornberger (1978). We then needed to obtain a
 902 representative weighted estimate of Ψ_s across CABLE's soil layers. We tested three potential
 903 approaches for weighting in this paper:

- 904 (iv) Using the root-biomass weighted θ and converting this to Ψ_s using Eq. [\(8\)](#),
 905 [hereafter denoted M1. Such an approach is often favoured by models, following](#)
 906 [experimental evidence that plants preferentially access regions in the root zone](#)
 907 [where water is most freely available \(Green and Clothier 1995; Huang et al. 1997\).](#)
 908 (v) Taking the integrated θ over the top 5 soil layers (1.7 m depth) and converting this
 909 to Ψ_s using Eq. [\(8\)](#), [hereafter denoted M2](#). This method assumes the plant
 910 effectively has access to an entire "bucket" of soil water. [This approach is often](#)
 911 [favoured by "simpler" forest productivity models \(e.g. Landsberg and Waring,](#)
 912 [1997\).](#)

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916 (vi) Weighting the average Ψ_s for each of the six soil layers by the weighted soil-to-
917 root conductance to water uptake of each layer, following Williams et al. (1996;
918 2001), hereafter denoted M3. The total conductance term depends the combination
919 of a soil component (R_s) and a root component (R_r). R_s is defined as (Gardner,
920 1960):

$$R_s = \frac{\ln\left(\frac{r_s}{r_r}\right)}{2\pi l_r D G_{soil}} \quad (6)$$

921 where r_s is the mean distance between roots (m), r_r is the fine root radius (m), D
922 is the depth of the soil layer, G_{soil} is the soil conductivity ($\text{mmol m}^{-1} \text{s}^{-1} \text{MPa}^{-1}$)
923 which depends on soil texture and soil water content, l_r is the fine root density
924 (mm^{-3}). R_r is defined as:

$$R_r = \frac{R_r^*}{FD} \quad (7)$$

925 where R_r^* is the root resistivity (MPa s g mmol^{-1}), F is the root biomass per unit
926 volume (g m^{-3}). This method weights Ψ_s to the upper soil layers when the soil is
927 wet, but shifts towards layer lowers as the soil dries, due to the lower soil
928 hydraulic conductance (e.g. Duursma et al. 2011).

929

930 2.3 Model simulations

931 During 2003, Europe experienced an anomalously dry summer, amplified by a combination of
932 a preceding dry spring and high summer temperatures (Ciais et al. 2005; Schär et al. 2005).
933 Summer temperatures were recorded to have exceeded the 30-year June-July-August (JJA)
934 average by 3°C (Schär et al. 2005). Consequently we choose to focus our model comparisons
935 on this period, in particular the period between June and September 2003.

936

937 At each of the five Fluxnet sites we ran three sets of simulations:

- 938 - A control simulation (“CTRL”), representing CABLE version 2.0.1.
- 939 - Three simulations to explore the new drought model using a “high” (*Quercus robur*),
940 “medium” (*Quercus ilex*) and “low” (*Cedrus atlantica*) sensitivity to soil moisture.

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943 Parameter values were obtained from the meta-analysis by Zhou et al. (2013; 2014)
944 and are given in Table 1. For each of these simulations we also tested the three
945 different methods of obtaining Ψ_5 as described above.

946 - A “no drought” simulation in which any transpired water was returned to the soil. By
947 comparing this simulation with either the control or any of the new drought model
948 simulations (high, medium, low), a guide to the magnitude of the drought should be
949 apparent.

950

951 Model parameters were not calibrated to match site characteristics; instead default PFT
952 parameters were used for each site. Although CABLE has the ability to simulate full carbon,
953 nitrogen and phosphorus biogeochemical cycling, this feature was not activated for this study,
954 instead only the carbon and water cycle were simulated. For all simulations, leaf area index
955 (LAI) was prescribed using CABLE’s gridded monthly LAI climatology derived from
956 Moderate-resolution Imaging Spectroradiometer (MODIS) LAI data (Knyazikhin et al. 1998;
957 1999) and the g_s scheme following Medlyn et al. (2011; see De Kauwe et al. 2015) was used
958 throughout. All model simulations were spun-up by repeating the meteorological forcing site
959 data until soil moisture and soil temperatures reached equilibrium (as we were ignoring the
960 full biogeochemical cycling in these simulations).

961

962 2.4 Datasets used

963 To assess the performance of the CABLE model both with and without the new drought
964 scheme, we selected a gradient of five forested Fluxnet (<http://www.fluxdata.org/>) sites across
965 Europe (Table 2) from those available through the Protocol for the Analysis of Land Surface
966 models (PALS; pals.unsw.edu.au; Abramowitz, 2012). These data have previously been pre-
967 processed and quality controlled for use within the LSM community. Consequently, all site-
968 years had near complete observations of key meteorological drivers (as opposed to significant
969 gap-filled periods).

970

971 Model simulations were compared to measured latent heat and flux-derived gross primary
972 productivity (GPP) at each of the FLUXNET sites. Flux-derived GPP estimates are calculated

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976 | from the measured net ecosystem exchange (NEE) of carbon between the atmosphere and the
977 | vegetation/soil, and the modelled ecosystem respiration (R_{eco}), where GPP is calculated as
978 | $NEE + R_{eco}$.

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990 **3 Results**

991 Severity of the 2003 drought

992 Table 3 summarises summer differences in rainfall, air temperature, GPP and LE between
993 2002 and 2003 across the five sites covering the latitudinal gradient from mesic to xeric sites
994 across Europe. Whilst the impact of the 2003 heatwave varied between sites, every site was
995 warmer and drier in 2003. Similarly, GPP was lower at every site except Espirra, and LE was
996 lower at three of the sites (Hesse, Roccarespampani and Castelporziano) in 2003 than in 2002.

998 Simulated fluxes during drought from the standard model

999 Figure 1 shows a site-scale comparison between standard CABLE (CTRL) transpiration (E),
1000 flux derived GPP, and the observed LE at the five sites. Table 4 and 5 shows a series of
1001 summary statistics (Root Mean Squared Error (RMSE), Nash-Sutcliffe efficiency (NSE),
1002 Pearson's correlation coefficient (r) between modelled and observed GPP and LE. An
1003 indication of the severity of the drought can be obtained by comparing the difference between
1004 the "No drought" and the CTRL simulation.

1006 For the two more mesic sites (Tharandt and Hesse), the CTRL simulation generally matched
1007 the trajectory of the observed LE, but displayed systematic periods of over-estimation (i.e.
1008 under-estimated the drought effect). By contrast, in the three more xeric sites
1009 (Roccarespampani, Castelporziano and Espirra), the reverse was true: the CTRL simulations
1010 descended into drought stress much more quickly than the observed fluxes. This rapid drought
1011 progression was particularly evident around day of year 155 at the Roccarespampani site.
1012 Across all sites, agreement with observed LE fluxes was generally poor (RMSE = 21.25 W m⁻²
1013 to 38 W m⁻²; NSE = -8.95 to 0.15). This outcome is partly a result of the high soil
1014 evaporation around mid-spring, which results in CABLE simulating very large LE fluxes
1015 during this period.

1017 At Tharandt, Hesse and Roccarespampani, simulated GPP systematically underestimated the
1018 flux-derived peak GPP, particularly evident before day of year 180. Transitioning to the more
1019 xeric sites (Roccarespampani, Castelporziano and Espirra), simulated GPP was apparently too

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Deleted: LE and GPP. An indication of the severity of the drought can be obtained by looking at the difference between the "No drought" and the CTRL simulation. For the two northernmost sites (Tharandt and Hesse), the CTRL simulation, the CTRL simulation generally matches the trajectory of the observed LE, but displays systematic periods of over-estimation (i.e. under-estimating the drought effect). By contrast, in the three southernmost sites (Roccarespampani, Castelporziano and Espirra), the reverse is true: the CTRL simulations descend into drought stress much more quickly than the observed fluxes. This rapid drought progression is particularly evident around day of year 155 at the Roccarespampani site. Across all sites, the CTRL simulations agree more closely with the observed fluxes in terms of GPP (NSE = -0.64 to -0.61; r = 0.71 to 0.84), rather than LE (NSE = -8.55 to -0.04; r = 0.14 to 0.70). The better prediction of GPP than LE is partly explained by the WUE bug that we identified in the methods section (2.3). The CTRL simulations over-predict the sensitivity of the LE fluxes to drought, but do not down-regulate the GPP at the same time, resulting in closer agreement with the observed for GPP (essentially compensating for CABLE's over-sensitivity of GPP to drought). The second part of the explanation relates to soil evaporation. Around mid-spring, CABLE simulates very large LE fluxes that are not evident in the E fluxes. This over-evaporation of soil water results in model-observation divergence in LE fluxes, which is not evident in the model-observation GPP comparison

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1063 sensitive to water stress, contributing to a poor agreement with flux-derived data (RMSE =
1064 2.22 g C m⁻² to 3.03 g C m⁻²; NSE = -2.67 to 0.42).

1065

1066 Theoretical behaviour of new drought scheme

1067 We now consider the implementation of the new drought model and the three sensitivity
1068 parameterisations. Figure 2a shows how leaf-level photosynthesis is predicted to decline
1069 (using Eqs. 3 and 4) in the new drought model with increasing water stress (more negative
1070 Ψ_s). The different sensitivities to drought are clearly visible, with the three parameterisations
1071 representing a spectrum of behaviour ranging from high to low drought sensitivity. Figures 2b
1072 and c show how the new drought model compares to the standard CABLE (CTRL; using Eq.
1073 2) model on a sandy and clay soil type. The CTRL model is seen to most closely match the
1074 high sensitivity simulation on a sandy soil, but it predicts an earlier descent into drought
1075 stress. By contrast on the clay soil, the new medium and high sensitivity simulations
1076 encompass the predictions from the CTRL model. The new drought model and
1077 parameterisations afford a more flexible sensitivity to the down-regulation of photosynthesis
1078 with drought, which is particularly evident in the low sensitivity simulation.

1079

1080 Impact of new drought scheme on modelled LE

1081 Figures 3–7 show the same site comparisons as Fig. 1, but with the addition of the new
1082 drought model and the three different ways (M1-3) in which Ψ_s can be averaged over the soil
1083 profile. Across all sites it is clear that using M1, the new drought model behaves in much the
1084 same way as the CTRL simulation. The explanation is that weighting Ψ_s by the fraction of
1085 roots in each layer, results in water being principally extracted from the top three shallow
1086 layers (Supplementary figures S1–S5). Consequently, small changes in θ result in a rapid
1087 decline in Ψ_s (owing to the non-linear relationship between θ and Ψ_s , Fig. 1), which causes
1088 an unrealistically abrupt shutdown of transpiration. M2 showed a greater separation between
1089 the three sensitivity parameterisations than method one. The greater separation is most
1090 evident at the xeric sites; the model performs particularly well at Espirra (LE RMSE < 16 W
1091 m⁻² vs. CTRL RMSE = 35.31 W m⁻²) and to a lesser extent at Castelporziano (LE low
1092 sensitivity RMSE = 19 72 W m⁻² vs. CTRL RMSE = 31 76 W m⁻²). Nevertheless, at the two
1093 mesic sites, the model completely underestimates the size of the drought, as a result of using a

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1104 large soil water bucket (1.7 m) to calculate Ψ_s . M3 in combination with the new drought
 1105 model generally performed the best across all the sites, as it allows CABLE to simulate a
 1106 more gradual reduction of fluxes during drought. At Roccarespampani a medium drought
 1107 sensitivity performed best at reproducing the observed LE (CTRL RMSE = 38.0 W m^{-2} vs.
 1108 18.27 W m^{-2}), whilst at Espirra (CTRL RMSE = 35.31 W m^{-2} vs. 15.40 W m^{-2}) the low
 1109 sensitivity performed best. At Castelporziano, both low (CTRL RMSE = 31.76 W m^{-2} vs.
 1110 20.41 W m^{-2}) and medium sensitivity (LE RMSE = 20.47 W m^{-2}) performed well. In contrast,
 1111 at the two mesic sites, a high drought sensitivity performed best, although at both Hesse (LE
 1112 CTRL RMSE = 21.25 W m^{-2} vs. 25.90 W m^{-2}) and Tharandt (LE CTRL RMSE = 28.5 W m^{-2}
 1113 vs. 28.82 W m^{-2}), the new drought model performed marginally worse than the CTRL.

1114

1115 Impact of new drought scheme on modelled GPP

1116 At the more xeric sites, there were noticeable improvements in simulated GPP during the
 1117 drought period. Similar to the LE result, across all sites M3 worked best: using a medium
 1118 drought sensitivity at both Roccarespampani (CTRL RMSE = $2.49 \text{ g C m}^{-2} \text{ d}^{-1}$ vs. $1.73 \text{ g C m}^{-2} \text{ d}^{-1}$)
 1119 and Castelporziano (CTRL RMSE = $2.22 \text{ g C m}^{-2} \text{ d}^{-1}$ vs. $0.95 \text{ g C m}^{-2} \text{ d}^{-1}$), and a low
 1120 sensitivity at Espirra (CTRL RMSE = $3.03 \text{ g C m}^{-2} \text{ d}^{-1}$ vs. $1.43 \text{ g C m}^{-2} \text{ d}^{-1}$). At the mesic end
 1121 of the gradient, a medium sensitivity at Hesse (CTRL RMSE = $2.85 \text{ g C m}^{-2} \text{ d}^{-1}$ vs. 2.71 g C
 1122 $\text{m}^{-2} \text{ d}^{-1}$) and a medium or high sensitivity at Tharandt worked best; although using either
 1123 sensitivity performed slightly worse than the CTRL (CTRL RMSE = $2.06 \text{ g C m}^{-2} \text{ d}^{-1}$ vs. \geq
 1124 $2.23 \text{ g C m}^{-2} \text{ d}^{-1}$).

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1155 **4 Discussion**

1156 Experimental data suggest that plants exhibit a continuum of drought sensitivities, with
1157 species originating in more mesic environments showing higher sensitivity than species from
1158 more xeric environments, (Bahari et al. 1985; Reich and Hinckley, 1989; Ni and Pallardy,
1159 1991; Zhou et al. 2014). We investigated whether variable drought sensitivity improves the
1160 ability of the CABLE LSM to reproduce observed drought impacts across a latitudinal
1161 gradient. We found that, at the mesic sites, a high drought sensitivity was required; moving
1162 southwards towards more xeric sites, the sensitivity parameterisation transitioned to a medium
1163 and finally to a low drought sensitivity. This work demonstrates the importance of
1164 understanding how plant traits vary with climate across the landscape. However, our analysis
1165 also highlighted the importance of identifying which soil layers matter most to the plant: our
1166 results depended strongly on how we weighted soil moisture availability through the profile.

1167

1168 *Weighting soil moisture availability*

1169 Commonly, empirical dependences of gas exchange on soil moisture content or potential
1170 (Eqns 3, 4) are estimated from pot experiments (e.g. Zhou et al. 2013; 2014), in which it is
1171 fair to assume that the soil moisture content is relatively uniform, and fully explored by roots.
1172 In contrast, soil moisture content and rooting depth in the field typically have strong vertical
1173 profiles. Thus, to implement such equations in a land surface model requires that we specify
1174 how to weight the soil layers to obtain a representative value of whole-profile θ or Ψ_s . In this
1175 study we tested three potential implementations. Our first approach was to weight each layer
1176 by root biomass. Evidence suggests that plants preferentially access regions in the root zone
1177 where water is most freely available (Green and Clotheir 1995; Huang et al. 1997). Hence,
1178 many models follow this approach: for example, the original version of CABLE weighted soil
1179 moisture content by root biomass (Eqn 2) while the Community Land Model (CLM)
1180 estimates a water stress factor based on a root-weighted Ψ_s , using a PFT-defined minimum
1181 and maximum water potential (Oleson et al. 2013). However, we found that this approach
1182 performed poorly. We observed an ‘on-off’ behaviour in response to drought, which occurs
1183 because the behaviour of the model is driven by the top soil layers, whose total soil moisture
1184 content is relatively small and root biomass is relatively high, and can be depleted rapidly,
1185 leading to a sudden onset of severe drought. Many other LSMs show this abrupt effect of

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1191 drought (Egea et al., 2011; Powell et al., 2013). Powell et al. (2013) found that four models
1192 (CLM version 3.5, Integrated Biosphere Simulator version 2.6.4 (IBIS), Joint UK Land
1193 Environment Simulator version 2.1 (JULES), and Simple Biosphere model version 3 (SiB3))
1194 implement abrupt transitions of this kind. We also found that with this weighting of soil
1195 layers, there was little effect of variable drought sensitivity: the depletion of soil moisture
1196 content of the top layers is so rapid that there is little difference between low and high
1197 sensitivities to drought. Such an outcome suggests that there is little adaptive significance of
1198 drought sensitivity, which seems unlikely. A further implication of using a root-weighted
1199 function to calculate Ψ_S is that two distinctly different scenarios, a soil that has been very wet
1200 but experienced a short dry period, allowing the topsoil to dry, and a soil that has had a
1201 prolonged period of drought but experienced a recent rainfall event, would have similar
1202 impacts on gas exchange. Again, this outcome seems unlikely.

1203

1204 We tested a second implementation in which soil moisture potential was calculated from the
1205 moisture content of the entire rooting zone (top five soil layers = 1.7 m). Such an approach is
1206 commonly used in forest productivity models (e.g. Landsberg and Waring, 1997). However,
1207 this approach severely underestimates drought impacts because the moisture content of the
1208 total soil profile is so large, meaning that it is rarely depleted enough to impact on gas
1209 exchange.

1210

1211 In reality, plant water uptake shifts lower in the profile as soil dries out (e.g. Duursma et al.
1212 2011). Thus, in our third implementation, we tested an approach in which the weighting of
1213 soil layers moves downwards as drought progresses. This approach is effectively similar to
1214 that used by the soil–plant–atmosphere (SPA) model (Williams et al. 1996; 2001), in which
1215 soil layers are weighted by their soil-to-root conductance, which declines as the moisture
1216 content declines. Of the three approaches we tested, this method performed best, allowing
1217 CABLE to replicate the observations across the latitudinal mesic to xeric gradient. This
1218 dynamic weighting of Ψ_S may partially explain previous good performance by SPA in other
1219 model inter-comparisons focussed on drought (e.g. Powell et al. 2013). Recently, Bonan et al.
1220 (2014) tested the suitability of using a model that considers optimal stomatal behaviour and
1221 plant hydraulics (SPA; Williams et al. 1996) for earth system modelling, and demonstrated

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1224 marked improvement over the standard model during periods of drought stress. We thus
1225 suggest that models using a soil moisture stress function to simulate drought effects on gas
1226 exchange should consider a dynamic approach to weighting the contribution of different soil
1227 layers.

1228

1229 We note that this issue is related to another long-standing problem for LSMs: that of
1230 determining the vertical distribution of root water uptake (e.g. Feddes et al., 2001; Federer et
1231 al., 2003; Kleidon and Heimann, 1998, 2000). In the standard version of CABLE, water
1232 uptake from each soil layer initially depends on the fraction of root biomass in each layer, but
1233 moves downwards during drought as the upper layers are depleted. It is possible that changes
1234 to the weighting of soil moisture in determining drought sensitivity should also be
1235 accompanied by changes to the distribution of root water uptake, but we did not explore this
1236 option here. Li et al. (2012) previously tested an alternative dynamic root water uptake
1237 function (Lai and Katul, 2000) in CABLE, but found little improvement in predicted LE
1238 during seasonal droughts without also considering a mechanism for hydraulic redistribution.
1239 Further work should evaluate models not only against LE fluxes, but also against
1240 measurements of soil moisture profiles. Many experimental sites now routinely install
1241 multiple soil moisture sensors (e.g. direct gravimetric sampling, neutron probes, time domain
1242 reflectometry), which provide accurate insight into root water extraction and hydraulic
1243 redistribution, even down to considerable depths (>4 m). These data have thus far been
1244 underutilised for model improvement, but should be a priority for reducing the uncertainty in
1245 soil moisture dynamics.

1246

1247 *Incorporating different sensitivities to drought*

1248 Using the third and best method to calculate overall Ψ_s , we found that varying drought
1249 sensitivity across sites enabled the model to better capture drought effects across the
1250 mesic/xeric gradient, with a high drought sensitivity implied in mesic sites and a low drought
1251 sensitivity implied in xeric sites. These results should not be surprising, given the increasing
1252 amount of experimental evidence suggesting that drought sensitivity varies among species
1253 and across climates (e.g. Engelbrecht and Kursar, 2003; Engelbrecht et al. 2007; Skelton et al.
1254 2015). In contrast to these data, most LSMs assume a single parameterisation for drought

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1258 sensitivity, which is typically based on mesic vegetation. Our results suggest that such a
1259 parameterisation is very likely to overstate the impacts of drought on both carbon and water
1260 fluxes in drier regions.

1261
1262 Our work thus underlines a need to move beyond models that implement drought sensitivity
1263 through a single PFT parameterisation. In order to capture the observed variability in plant
1264 responses to drought, models need to consider a continuum of sensitivities. It is, of course,
1265 challenging to implement such a continuum in a global vegetation model. In this study, we
1266 used a simple site-specific approach in which we selected three sets of model parameters from
1267 a meta-analysis by Zhou et al. (2013; 2014), allowing us to characterise a range of plant
1268 responses to drought. Global vegetation models would require a more sophisticated approach
1269 that relates drought sensitivity to the climate of each pixel. One potential solution would be to
1270 develop an empirical correlation between drought sensitivity and a long-term moisture index
1271 (e.g. the ratio of mean precipitation to the equilibrium evapotranspiration; Cramer and
1272 Prentice, 1988; Gallego-Sala et al. 2010). Previous studies have demonstrated the feasibility
1273 of linking model parameters that determine plant water use strategy to such a moisture index
1274 in global simulations (Wang et al. 2014; De Kauwe et al. 2015). Such an approach would
1275 require a concerted effort to collate appropriate data, as there are few compilations to date of
1276 traits related to drought sensitivity (but see Manzoni et al. 2011; Zhou et al. 2013). Another,
1277 more challenging, alternative, would be to develop optimization hypotheses that can predict
1278 vegetation drought sensitivity from climate (e.g. Manzoni et al. 2014).

1279 | ▲
1280 *Further model uncertainties*

1281 Whilst this work advances the ability of LSMs to simulate drought, it does not address all
1282 processes needed to correctly capture drought impacts. Other issues to consider include: (i)
1283 rooting depth; (ii) leaf shedding; (iii) soil evaporation; and (iv) soil heterogeneity, among
1284 others.

1285
1286 Here we have assumed that all sites had the soil depth (4.6 m), with rooting depth distributed
1287 exponential through the profile, as is commonly used in LSMs. However, this assumption
1288 may be incorrect. Access to water by deep roots could be a potential alternative explanation

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1289 | for the low drought sensitivity that we inferred at the southernmost (xeric) site, Espirra. Here
1290 | the dominant species is not native to the region, but rather a plantation of blue gum
1291 | (*Eucalyptus globulus*), a species that is generally found to have high, not low, drought
1292 | sensitivity (White 1996; Mitchell et al. 2014). Many eucalypts have a deep rooting strategy
1293 | (Fabiao et al. 1987), suggesting a possible alternative explanation for drought tolerance at this
1294 | site. More in-depth study of fluxes and soil moisture patterns at this site would be needed to
1295 | determine the role of rooting depth.

1296

1297 | During droughts, plants are often observed to shed their leaves. This is a self-regulatory
1298 | mechanism to reduce water losses (Tyree et al. 1993; Jonasson et al. 1997; Bréda et al. 2006).
1299 | During the 2003 heatwave at Hesse, an early reduction of approximately $1.7 \text{ m}^2 \text{ m}^{-2}$ was
1300 | observed. Similarly, at Brasschaat there was a observed reduction of $0.8 \text{ m}^2 \text{ m}^{-2}$ and at
1301 | Tharandt needle-litter was increased during September until November, with LAI estimated to
1302 | be $0.9 \text{ m}^2 \text{ m}^{-2}$ lower (Bréda et al. 2006; Granier et al. 2007). In contrast, models typically fix
1303 | turnover rates for leaves and as such this feedback is largely absent from models. During
1304 | periods of water stress, models do simulate an indirect reduction in LAI via down-regulated
1305 | net primary productivity, but this feedback is much slower than is commonly observed. Not
1306 | accounting for this canopy-scale feedback will result in models over-estimating carbon and
1307 | water fluxes and thus losses in θ during drought.

1308

1309 | Existing models also disagree as to the mechanism by which to down-regulate productivity
1310 | during periods of water stress (De Kauwe et al. 2013). In the standard version of CABLE,
1311 | only the slope of the relationship between g_s and A is reduced by water stress. The SPA model
1312 | behaves similarly. In contrast, JULES (Clark et al. 2011) and the Sheffield Dynamic Global
1313 | Vegetation Model (SDGVM; Woodward and Lomas, 2004), down-regulate the
1314 | photosynthetic capacity via the biochemical parameters V_{cmax} and J_{max} (maximum electron
1315 | transport rate). Here, we assumed that water stress affects both the slope of g_s - A and the
1316 | biochemical parameters V_{cmax} and J_{max} , supported by results from Zhou et al. (2013, 2014).
1317 | We did not evaluate this assumption against the eddy flux data. However, previous studies
1318 | have also suggested that both effects are needed to explain responses of fluxes during drought
1319 | (Keenan et al. 2010).

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1330 Finally, although models do have the capacity to simulate vertical variations in θ , they do not
1331 always **represent** horizontal sub-grid scale variability. This assumption is likely to contribute
1332 to the abruptness of modelled transitions from well-watered to completely down-regulated
1333 carbon and water fluxes. Earlier work by Entekhabi and Eagleson (1989), and models such as
1334 the variable infiltration capacity (VIC) model (Liang et al. 1994), and most recently Decker
1335 2015 (submitted) have attempted to address this issue by employing statistical distributions to
1336 approximate horizontal spatial heterogeneity in soil moisture (see also Crow and Wood,
1337 2002). These parsimonious approaches typically require few parameters, making them
1338 attractive in the LSM context and potentially suitable for modelling ecosystem and
1339 hydrological responses to drought (Luo et al. 2013).

1340

1341 *Testing models against extreme events*

1342 **In conclusion, we** have used a model evaluation against flux measurements during a large-
1343 scale heatwave event to make significant progress in modelling of drought impacts. While
1344 model evaluation against data is now commonplace (Prentice et al. 2015) and has recently
1345 been extended to formal benchmarking, particularly in the land surface community
1346 (Abramowitz, 2005; Best et al. 2015), many of these benchmarking indicators are based on
1347 seasonal or annual outputs and thus miss the opportunity to examine model performance
1348 during extreme events. **Model projections under future climate change require good**
1349 mechanistic representations of the impacts of extreme events. However, **responses to extreme**
1350 **events are rarely evaluated** and there is therefore an urgent need to orient model testing to
1351 periods of extremes. To that end, precipitation manipulation experiments (e.g. Nepstad et al.
1352 2002; Hanson et al. 2003; Pangle et al. 2012) represent a good example of a currently under-
1353 exploited avenue (but see Fisher et al. 2007; Powell et al. 2013) that could be used for model
1354 evaluation and/or benchmarking (Smith et al. 2014). However, we urge that these exercises do
1355 not focus solely on overall model performance, but also test the realism of individual model
1356 assumptions (Medlyn et al. 2015).

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Deleted: Furthermore, the key weakness of model evaluation in its current inception is the focus on tests that aim to identify the best overall model performance; this applies particularly to land surface schemes. This is something the benchmarking approach used by Abramowitz (2005) and Best et al., (2015) seek to avoid by testing model performance against empirical benchmarks. Overall however, there remains a tendency to trade mechanistic realism is often traded for present day accuracy, with limited real improvement in model structure.

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1919 **Figure Captions**

1920 Figure 1: A comparison of the observed (OBS) and modelled (CTRL) Latent Heat (LE) and
1921 transpiration (E) at five Fluxnet sites during 2003. The data have been smoothed with a 5-day
1922 moving window to aid visualisation.

1923
1924 Figure 2: Modelled impact of drought on the assimilation rate (A), shown as (a) a function of
1925 volumetric soil moisture content (θ) and (b) soil water potential (Ψ_s) for a sand and clay soil.

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1927 Figure 3: A comparison of the observed (OBS) and modelled latent Heat (LE) and
1928 transpiration (E) at the Tharandt site during 2003. Simulations show the control (CTRL) and
1929 the three drought sensitivities to drought (high, medium, low) based on Zhou et al. (2013;
1930 2014) and three different methods to calculate soil water potential (Ψ_s). The data have been
1931 smoothed with a 5-day moving window to aid visualisation.

1932

1933 Figure 4: A comparison of the observed (OBS) and modelled latent Heat (LE) and
1934 transpiration (E) at the Hesse site during 2003. Simulations show the control (CTRL) and the
1935 three drought sensitivities to drought (high, medium, low) based on Zhou et al. (2013; 2014)
1936 and three different methods to calculate soil water potential (Ψ_s). The data have been
1937 smoothed with a 5-day moving window to aid visualisation.

1938

1939 Figure 5: A comparison of the observed (OBS) and modelled latent Heat (LE) and
1940 transpiration (E) at the Roccarespampani site during 2003. Simulations show the control
1941 (CTRL) and the three drought sensitivities to drought (high, medium, low) based on Zhou et
1942 al. (2013; 2014) and three different methods to calculate soil water potential (Ψ_s). The data
1943 have been smoothed with a 5-day moving window to aid visualisation.

1944

1945 Figure 6: A comparison of the observed (OBS) and modelled latent Heat (LE) and

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1973 | transpiration (E) at the Castelporziano Fluxnet site during 2003. Simulations show the control
1974 | (CTRL) and the three drought sensitivities to drought (high, medium, low) based on Zhou et
1975 | al. (2013; 2014) and three different methods to calculate soil water potential (Ψ_s). The data
1976 | have been smoothed with a 5-day moving window to aid visualisation.

1977

1978 | Figure 7: A comparison of the observed (OBS) and modelled latent Heat (LE) and
1979 | transpiration (E) at the Espirra site during 2003. Simulations show the control (CTRL) and the
1980 | three drought sensitivities to drought (high, medium, low) based on Zhou et al. (2013; 2014)
1981 | and three different methods to calculate soil water potential (Ψ_s). The data have been
1982 | smoothed with a 5-day moving window to aid visualisation.

1983

1984 | Supplementary Figure 1: Simulated soil water content of each of CABLE's six layers for the
1985 | control (CTRL), and three drought sensitivities (high, medium, low) based on Zhou et al.
1986 | (2013; 2014) at the Tharandt site. The grey shading highlights the heatwave period between
1987 | the 1st of June and the 31st of August. The data have been smoothed with a 5-day moving
1988 | window to aid visualisation.

1989 | Supplementary Figure 2: Simulated soil water content of each of CABLE's six layers for the
1990 | control (CTRL), and three drought sensitivities (high, medium, low) based on Zhou et al.
1991 | (2013; 2014) at the Hesse site. The grey shading highlights the heatwave period between the
1992 | 1st of June and the 31st of August. The data have been smoothed with a 5-day moving
1993 | window to aid visualisation.

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1996 | Supplementary Figure 3: Simulated soil water content of each of CABLE's six layers for the
1997 | control (CTRL), and three drought sensitivities (high, medium, low) based on Zhou et al.
1998 | (2013; 2014) at the Roccarespampani site. The grey shading highlights the heatwave period
1999 | between the 1st of June and the 31st of August. The data have been smoothed with a 5-day
2000 | moving window to aid visualisation.

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2012

2013 Supplementary Figure 4: Simulated soil water content of each of CABLE's six layers for the
2014 control (CTRL), and three drought sensitivities (high, medium, low) based on Zhou et al.
2015 (2013; 2014) at the Castelporziano site. The grey shading highlights the heatwave period
2016 between the 1st of June and the 31st of August. The data have been smoothed with a 5-day
2017 moving window to aid visualisation.

2018

2019 Supplementary Figure 5: Simulated soil water content of each of CABLE's six layers for the
2020 control (CTRL), and three drought sensitivities (high, medium, low) based on Zhou et al.
2021 (2013; 2014) at the Espirra site. The grey shading highlights the heatwave period between the
2022 1st of June and the 31st of August. The data have been smoothed with a 5-day moving
2023 window to aid visualisation.

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2033 Table 1. Baseline parameter values used to represent the three sensitivities: “high” (*Quercus*
 2034 *robur*), “medium” (*Quercus ilex*) and “low” (*Cedrus atlantica*) to drought stress. Parameter
 2035 values are taken from Zhou et al. (2013; 2014).

Sensitivity	b	S_f	Ψ_f
High	1.55	6.0	-0.53
Medium	0.82	1.9	-1.85
Low	0.46	5.28	-2.31

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2037 Table 2: Summary of flux tower sites.

Site	PFT	Dominant species	Latitude	Longitude	Country	Sand/Silt/Clay Fraction
Tharandt	ENF	<i>Picea abies</i>	50°58' N	13°34' E	Germany	0.37/0.33/0.3
Hesse	DBF	<i>Fagus sylvatica</i>	48°40' N	7°05' E	France	0.37/0.33/0.3
Roccarespampani	DBF	<i>Quercus cerris</i>	42°24' N	11°55' E	Italy	0.6/0.2/0.2
Castelporziano	EBF	<i>Quercus ilex</i>	41°42' N	12°22' E	Italy	0.6/0.2/0.2
Espirra	EBF	<i>Eucalyptus globulus</i>	38°38' N	8°36' W	Portugal	0.37/0.33/0.3

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2046 Table 3: Mean change in climate and fluxes between 2002 and 2003 covering the period
2047 between June and September.

Site	Precipitation (mm month ⁻¹)	Air temperature (° C)	GPP (g C m ⁻² month ⁻¹)	LE (W m ⁻²)
Tharandt	-115.57	1.45	-38.45	0.52
Hesse	-49.20	2.98	-123.38	-11.90
Roccarespampani	-87.36	2.18	-71.94	-6.17
Castelporziano	-20.31	4.57	-49.73	-6.47
Espirra	-14.45	1.77	28.46	22.83

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2053 Table 4: Summary statistics of modelled and observed LE at the five FLUXNET sites during the main drought period (1st of June – 31st
 2054 August, 2003). For each site the best performing model simulation has been highlighted in bold.

Site	Ψ_s Method	Root Mean Squared Error (RMSE; $W m^{-2}$)				Nash-Sutcliffe efficiency (NSE)				Pearsons's correlation coefficient (r)			
		CTRL	High	Medium	Low	CTRL	High	Medium	Low	CTRL	High	Medium	Low
Tharandt	1	21.25	24.64	26.57	29.55	-0.70	-1.28	-1.65	-2.28	0.69	0.73	0.73	0.70
	2		34.59	36.20	36.97		-3.50	-3.93	-4.14		0.58	0.56	0.55
	3		25.90	29.39	32.26		-1.52	-2.25	-2.94		0.72	0.67	0.63
Hesse	1	28.50	36.22	41.59	51.49	0.15	-0.37	-0.81	-1.77	0.68	0.66	0.74	0.79
	2		52.60	59.87	63.46		-1.89	-2.75	-3.21		0.80	0.75	0.71
	3		28.82	45.32	56.46		0.13	-1.15	-2.33		0.79	0.84	0.77
Roccarespampini	1	38.00	48.41	40.98	34.27	-0.34	-1.17	-0.55	-0.09	0.67	0.52	0.67	0.81
	2		31.62	22.81	26.81		0.08	0.52	0.34		0.83	0.84	0.79
	3		45.12	18.27	29.50		-0.88	0.69	0.20		0.67	0.85	0.81
Castelporziano	1	31.76	38.77	40.54	40.40	-8.95	-13.82	-15.21	-15.10	0.18	-0.08	0.01	0.06
	2		31.04	27.19	19.72		-8.50	-6.29	-2.84		0.47	0.54	0.57
	3		39.17	20.47	20.41		-14.40	-3.13	-3.11		-0.02	0.55	0.61
Espirra	1	35.31	41.52	40.97	33.87	-3.35	-5.02	-4.86	-3.01	0.42	0.32	0.59	0.70
	2		15.58	13.82	13.84		0.15	0.33	0.33		0.77	0.74	0.73

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2319 Table 5: Summary statistics of modelled and observed GPP at the five FLUXNET sites during the main drought period (1st of June – 31st

2320 August, 2003). For each site the best performing model simulation has been highlighted in bold.

Site	Ψ_5 Method	Root Mean Squared Error (RMSE; $\text{g C m}^{-2} \text{d}^{-1}$)				Nash-Sutcliffe efficiency (NSE)				Pearsons's correlation coefficient (r)			
		CTRL	High	Medium	Low	CTRL	High	Medium	Low	CTRL	High	Medium	Low
Tharandt	1	2.06	2.27	2.07	2.10	0.33	0.19	0.33	0.31	0.80	0.71	0.66	0.61
	2		2.25	2.29	2.30		0.20	0.18	0.17		0.52	0.51	0.50
	3		2.23	2.12	2.20		0.22	0.30	0.25		0.66	0.59	0.55
Hesse	1	2.85	3.57	2.48	2.94	0.48	0.18	0.60	0.44	0.79	0.78	0.78	0.71
	2		2.65	3.22	3.47		0.55	0.33	0.22		0.75	0.67	0.62
	3		3.51	2.71	3.24		0.21	0.53	0.32		0.83	0.75	0.66
Roccarespampani	1	2.49	3.70	2.69	2.38	0.42	-0.28	0.32	0.47	0.85	0.64	0.82	0.87
	2		2.12	1.47	2.84		0.58	0.80	0.24		0.92	0.91	0.87
	3		3.74	1.73	3.08		-0.31	0.72	0.11		0.84	0.91	0.85
Castelporziano	1	2.22	3.46	3.64	3.76	-2.16	-6.71	-7.51	-8.08	0.55	-0.18	0.07	0.13
	2		2.65	1.84	1.22		-3.52	-1.17	0.04		0.63	0.63	0.81
	3		3.71	0.95	1.46		-7.82	0.42	-0.37		0.05	0.81	0.84
Espirra	1	3.03	4.39	4.33	3.72	-2.67	-6.72	-6.51	-4.55	0.74	0.58	0.53	0.67
	2		1.92	1.46	1.34		-0.48	0.14	0.28		0.80	0.81	0.81
	3		4.70	2.01	1.43		-7.84	-0.62	0.18		0.34	0.74	0.78

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Water use efficiency bug

During the course of these simulations we identified a bug in the way CABLE calculates carbon and water fluxes during drought. If CABLE is unable to meet atmospheric demand for water, it down-regulates transpiration to match the available supply from the soil; however, CABLE does not in turn down-regulate photosynthesis sufficiently to match this reduced water flux. Consequently, during periods of extreme drought CABLE's decoupling of the water and carbon cycles, results in very high water use efficiency (WUE). Fixing this issue is not straightforward because of the way the model solves for multiple components at once (e.g. C_i , A_n , D , leaf temperature, etc.) and is thus beyond the scope of this work. Crucially, the issue only relates to an over-estimation of photosynthesis during drought; the transpiration and latent heat fluxes are both calculated correctly and thus does not preclude useful assessment of the standard CABLE model. The issue arises because the estimated β using Eq. (2) does not sufficiently limit carbon and water fluxes during periods of water stress. In the new drought model the drought sensitivities are stronger, and so we do not reach this scenario for which root water supply is insufficient to meet demand (requiring down-regulation of transpiration).

Losses via soil evaporation play an important role in determining drought depth, particularly at sites with low LAI. Here we identified an early-season over-estimation of soil evaporation in CABLE that was apparent across all of the European flux tower sites. Alternative soil schemes have been tested within CABLE, for example the SLI soil model adjusts the soil boundary layer resistance and adds a litter layer (Haverd and Cuntz, 2010). A new hydrological model has been developed by Decker 2015 (submitted) that includes lateral flows, sub-grid scale soil moisture variability, groundwater and a replacement formulation of soil evaporation. This improved the simulation of total evaporation in CABLE but still lacks the drought responses discussed here and therefore is unlikely to solve the problems identified. Overall, it is likely that LSMs will require a simultaneous development of the hydrological and ecological parameterizations, something that is unfortunately rare in land surface modelling where the objectives are linked with global climate modelling.

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Haverd, V. and Cuntz, M.: Soil–Litter–Iso: A one-dimensional model for coupled transport of heat, water and stable isotopes in soil with a litter layer and root extraction, J. Hydrol., 388, 438–455, 2010.

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Figure 1

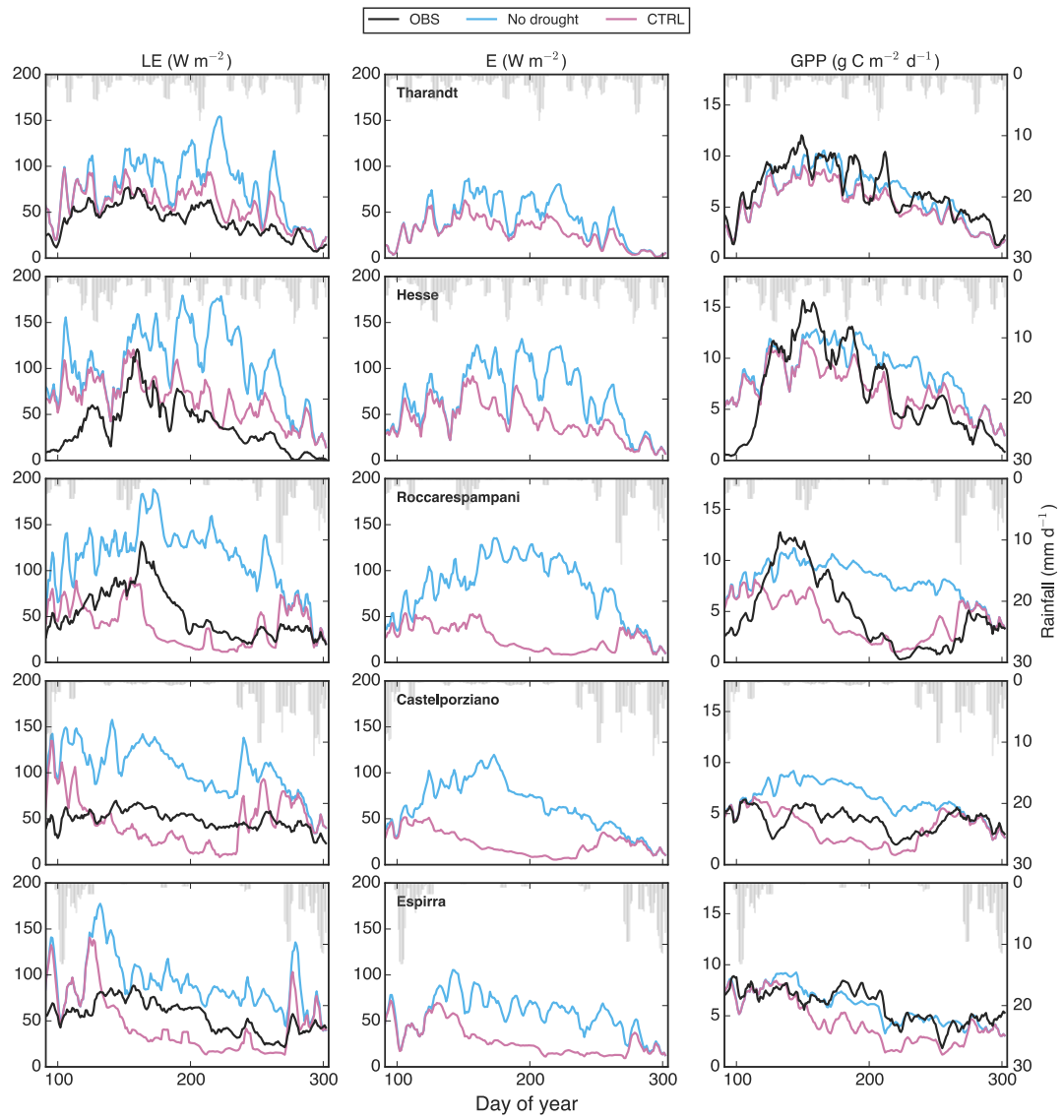


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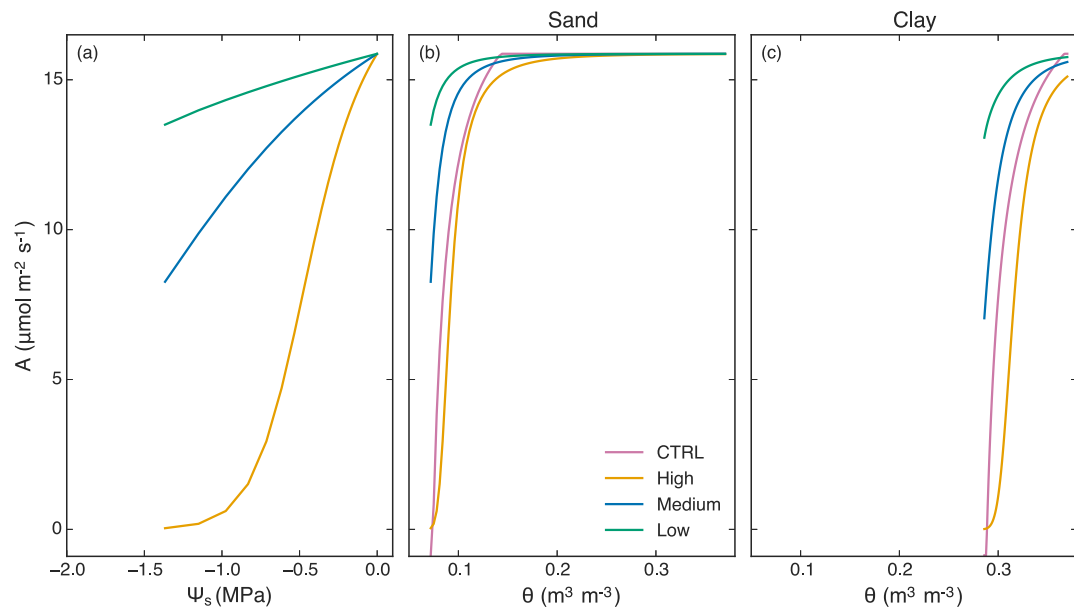


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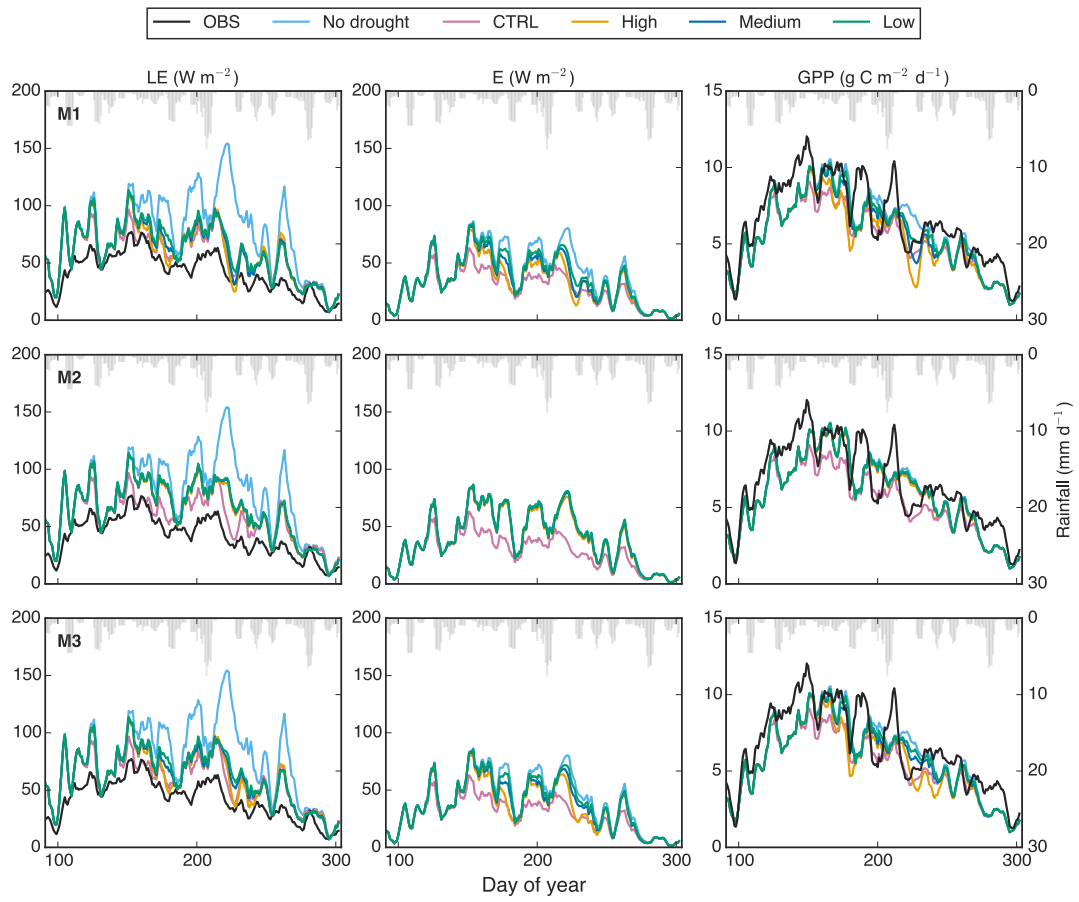


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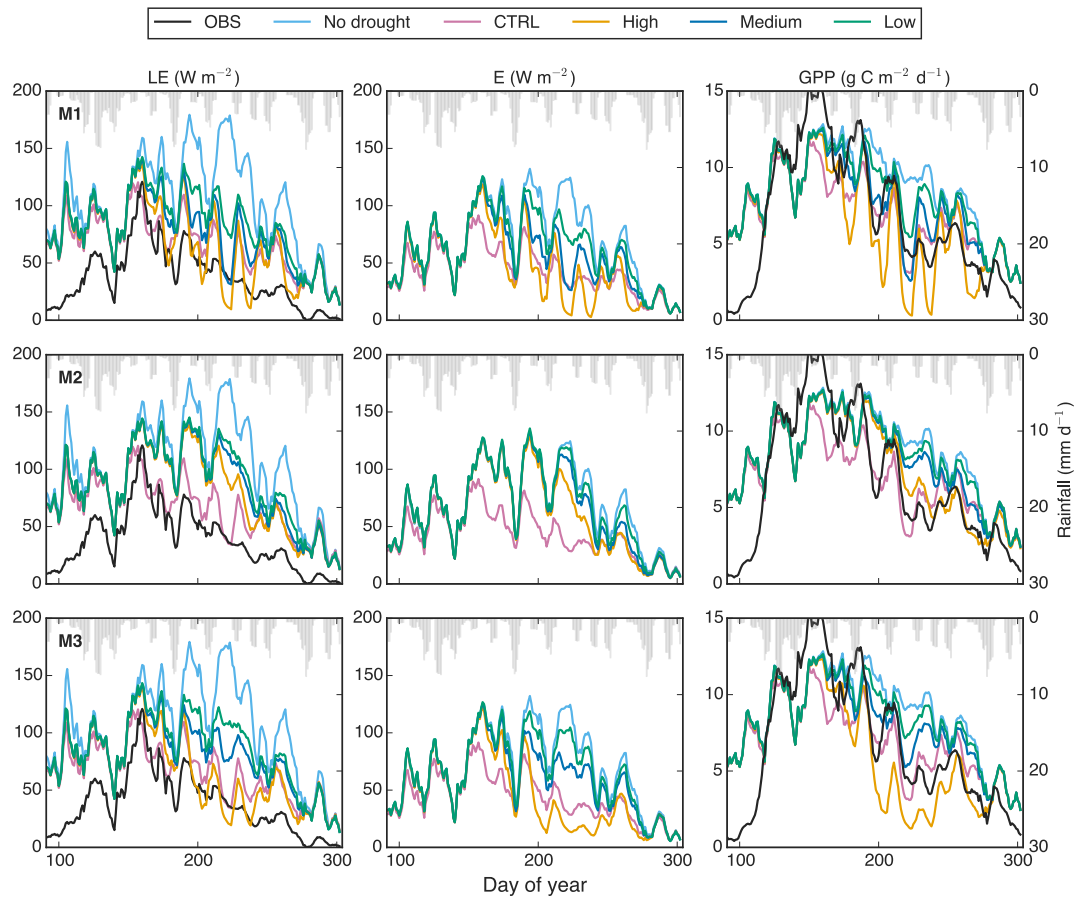


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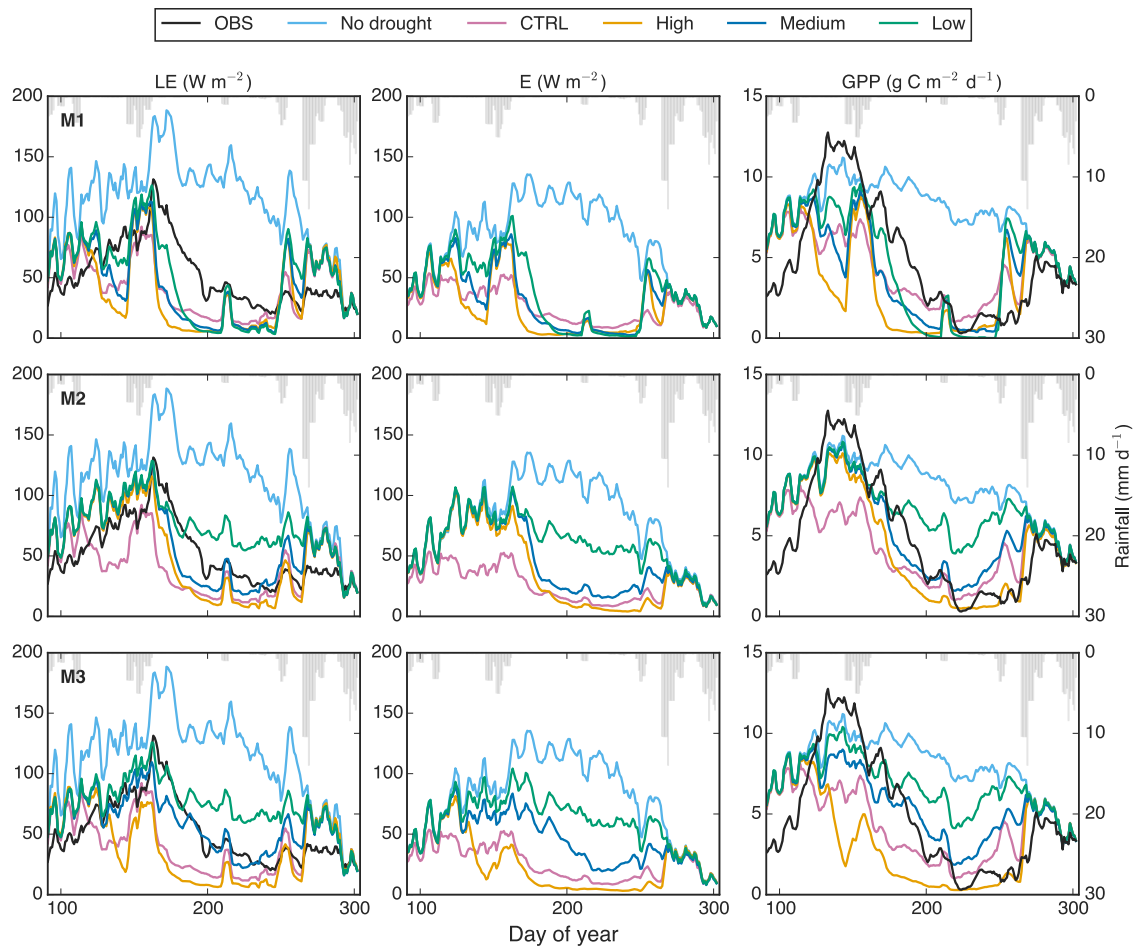


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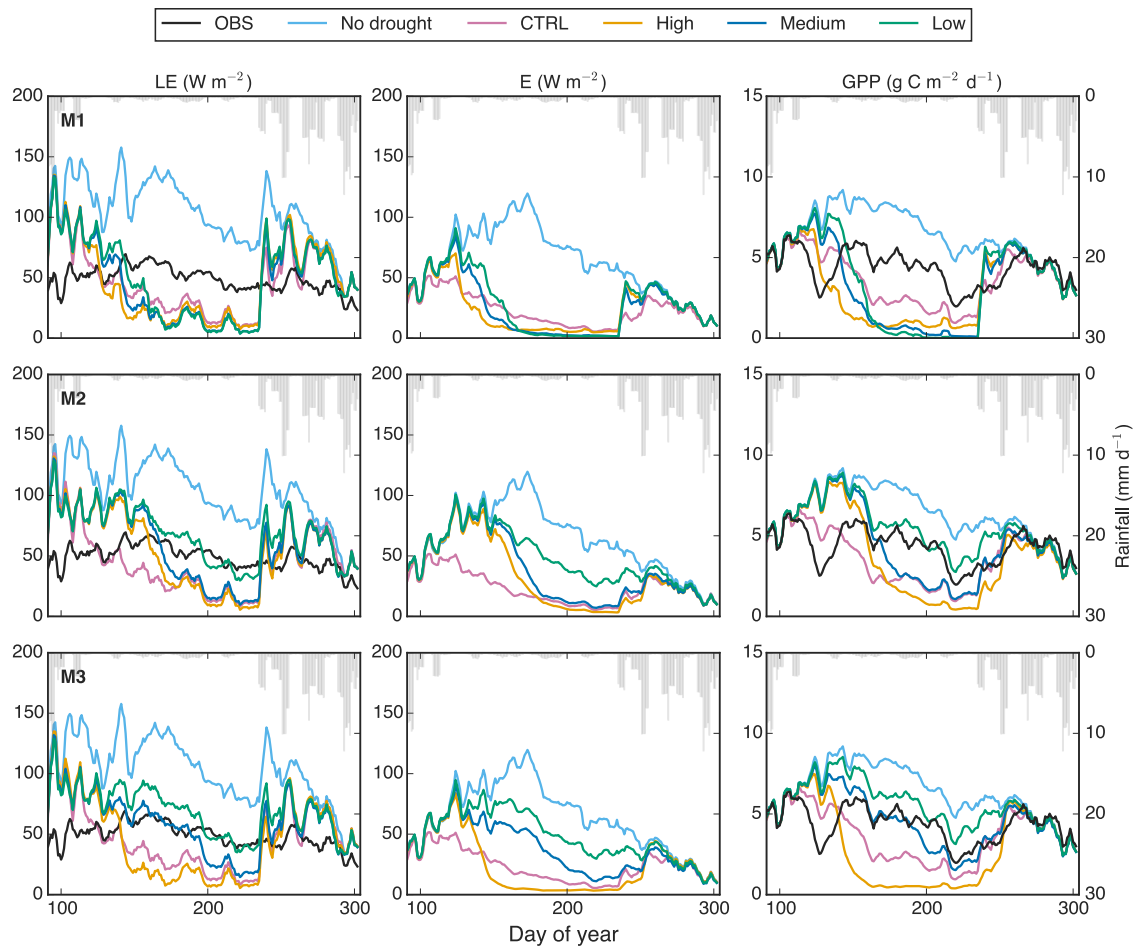


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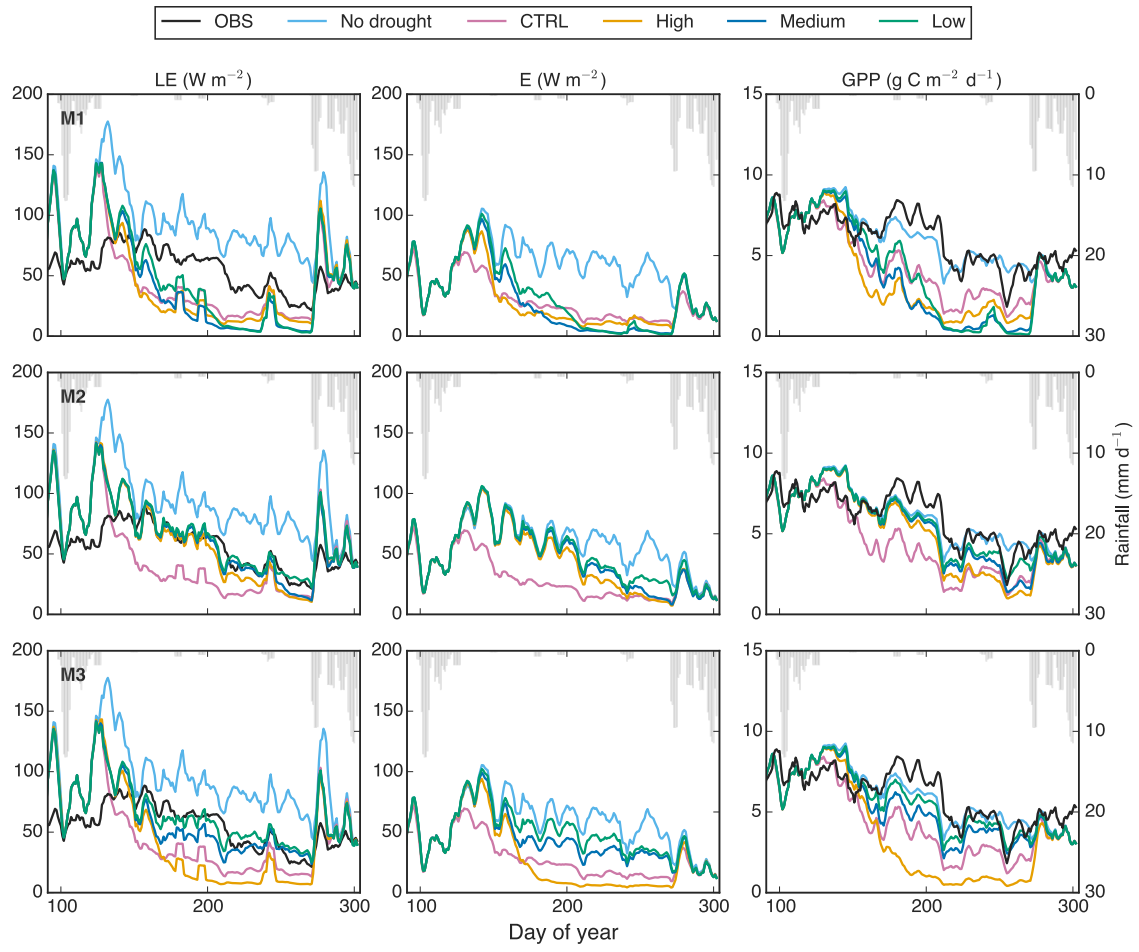


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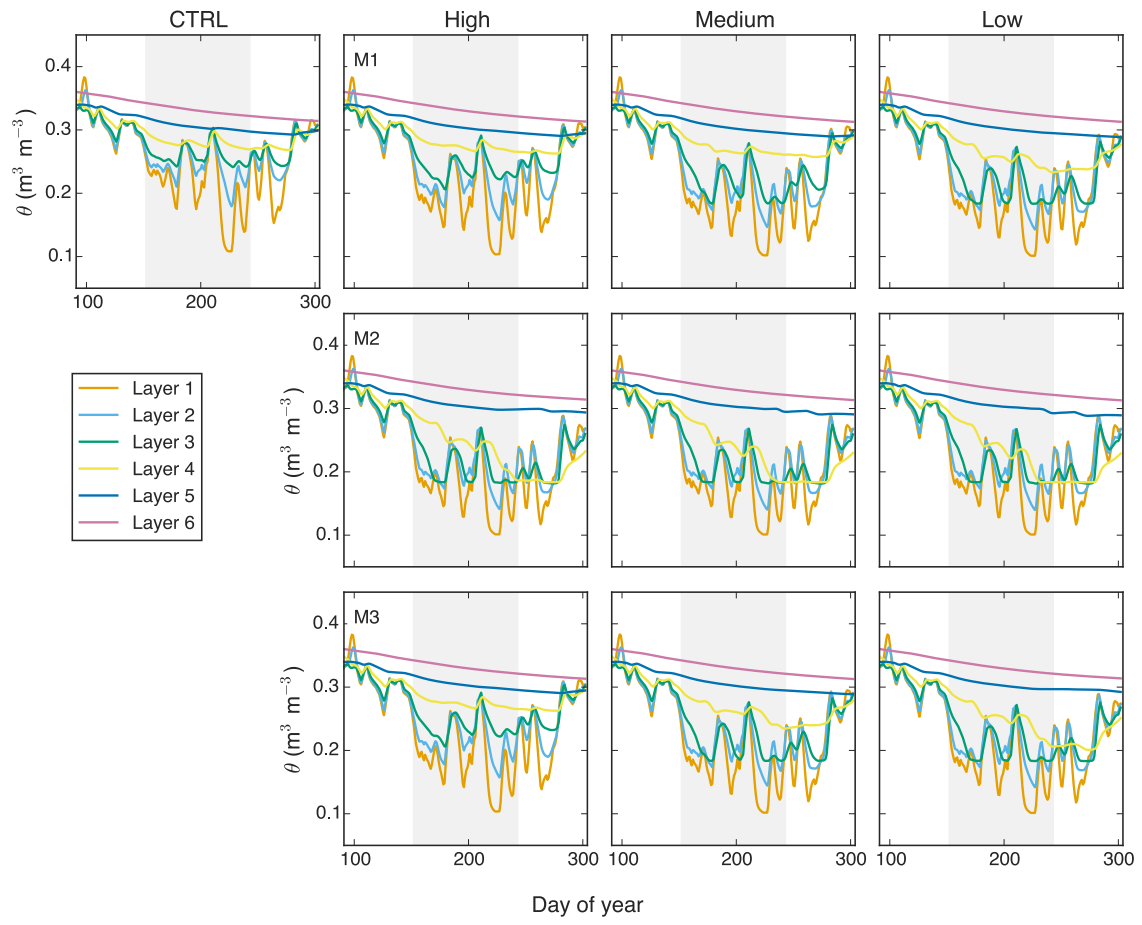


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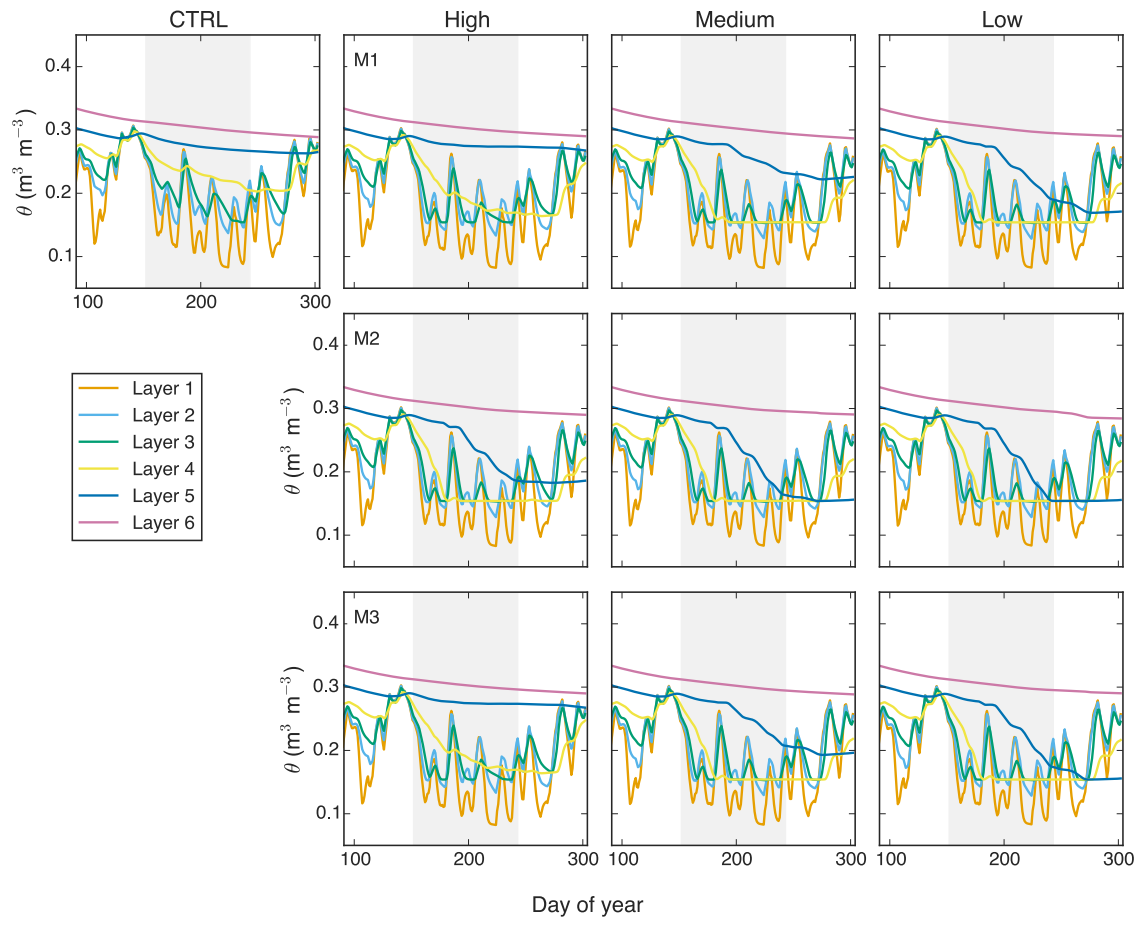


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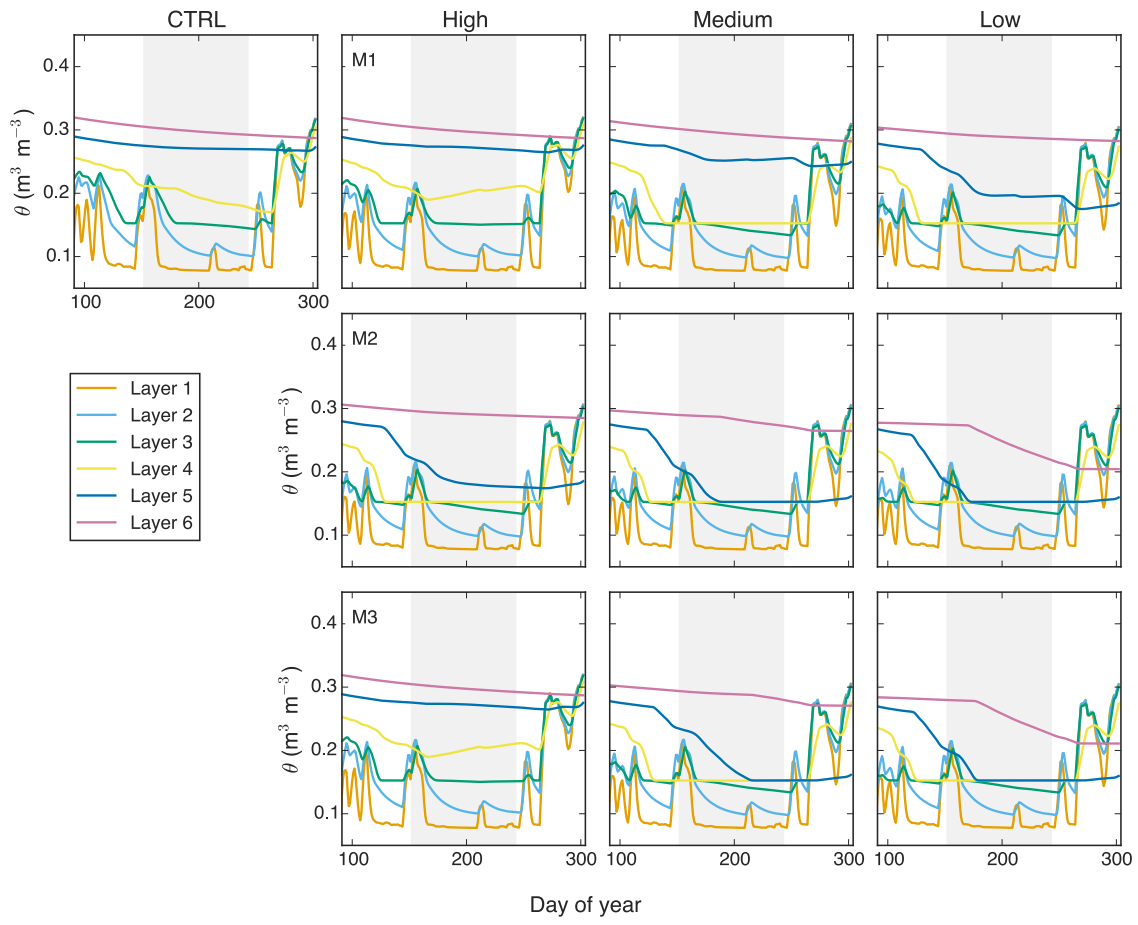


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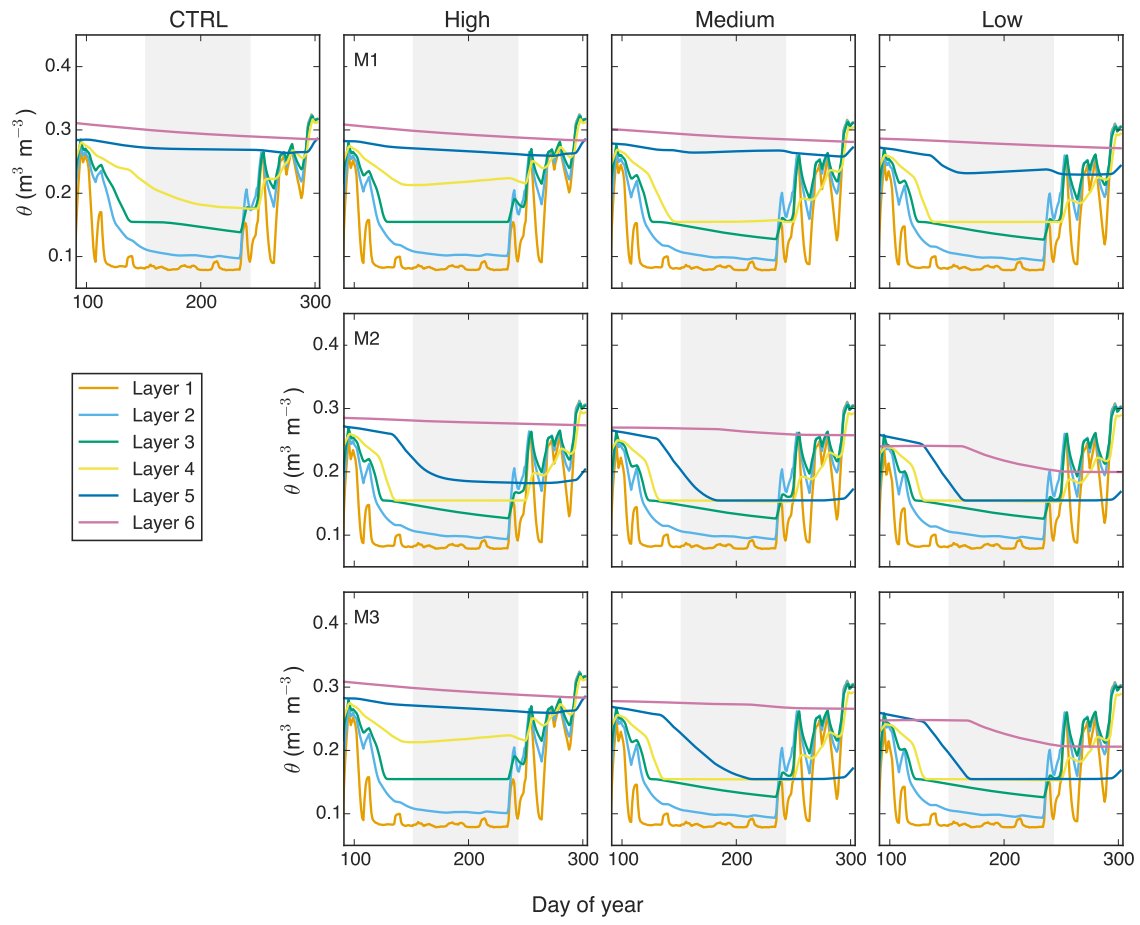


Figure S5

