

1 A summary of the key changes are as follows:

- 2 - Added literature summary table from 40 studies covering 57 PFTs.
- 3 - Added site summary table to the appendix (A2).
- 4 - Adjusted figure symbols, legend, layout in Figs. 2 & 3 as requested. We have
- 5 also coloured forest PFT types in Fig. 4 to assist the reader.
- 6 - Added missing C4C category to fig. 1, A1 & A2.
- 7 - As we do not attempt to define C4 grass fractions at flux sites, we rename the
- 8 grass PFT (GRA), where previously it had been labelled C3 Grass (C3G).
- 9 - Added additional sites that were mistakenly screened to Fig. 3. This does not
- 10 alter the original patterns or conclusions drawn (see below).
- 11 - Corrected the number of sites and site-years reported in the methods. In the
- 12 original submission these were calculated before we excluded mixed forest,
- 13 wetland and unclassified PFTs and so did not match the total shown in Fig. 1.

14

1 We again thank the reviewer for their constructive comments and we address their
2 various concerns below. This version replaces our original response, updated with
3 specific changes where appropriate. Referee comments are highlighted in red, with
4 our response below in black in each case.

5 R: This paper leverages the new FLUXNET2015 dataset to estimate differences in the
6 decoupling coefficient across plant functional types, with some additional discussion
7 of how the coefficient varies in response to canopy structure and meteorological
8 condition. The work builds off a previous study that highlighted the decoupling
9 coefficient as a significant source of uncertainty in some model predictions (De
10 Kauwe et al. 2013). The authors report that evergreen forests are more decoupled than
11 previously thought, and that the decoupling of grasslands depends on mean annual
12 precipitation (among other results).

13
14 Overall, I think this analysis will be of interest to members of the observational and
15 modeling communities, and the article is generally well written and the figures are
16 clearly presented. I do have a few suggestions for the authors that would allow them
17 to bridge what I perceive to be a bit of a gap between the rationale/objective of the
18 paper and the interpretation of results.

19
20 First, the authors aimed to “examine if decoupling coefficients from FLUXNET were
21 consistent with the literature values.” However, the comparison of the decoupling
22 coefficients derived from FLUXNET data and literature values was largely
23 qualitative. The comparison would be more informative if values reported in the
24 literature (or assumed by the models) were presented alongside those derived from the
25 Flux data (for example, by including a bit more information in the box and whisker
26 plots of Figure 1).

27 A: To address the reviewer’s point about our comparison being qualitative, we have
28 now added a comprehensive literature review. We have summarised estimates of the
29 decoupling coefficient from across 40 studies, covering 57 PFTs. These results can be
30 seen in our new Table 1. On reflection however, we do not feel it is appropriate to add
31 this information to Fig 1. We feel that adding additional bars would give a false

32 equivalence, owing to the significantly smaller number of sites obtained from the
33 literature review.

34

35 We agree with the reviewer that information on what is currently assumed by models
36 would be a nice addition to the figure; however, this information is not available as it
37 is rarely (if ever) reported. We recommended this information be reported following
38 our analysis of several models in a recent model intercomparison (De Kauwe et al.
39 2013, Global Change Biology) but our insight into model assumptions is still limited
40 to the models considered there.

41

42 **R: Second, the authors aimed to “develop a benchmark metric against which to test**
43 **model assumptions about decoupling.” Presumably this “benchmark metric” is the**
44 **range of decoupling coefficients presented in the results. Would it be possible for the**
45 **authors to demonstrate, at least at a few sites, that using a decoupling coefficient**
46 **informed by the results of this study indeed improves agreement between the**
47 **predictions of at least one model, and observations (for example, flux tower**
48 **observations of ET)?**

49 **A:** Whilst we obviously see value in what the reviewer has suggested, we feel this is
50 actually a very separate piece of research. What we have aimed to do here was to raise
51 the issue again in the literature by developing a potential benchmarking metric (Fig.
52 1) for models. We have written this up as an “ideas and perspective” and not a full
53 research paper specifically for this reason. The next logical step would be to
54 determine what state-of-the-art models are currently assuming by comparison, but that
55 needs to be an exhaustive study. Little insight would be gained by playing with one
56 model quickly in isolation: models often get the right answers for the wrong reasons,
57 and we would want to guard against this.

58

59 To the route forward section, we have added: “The next steps involve determining
60 what models currently assume about the degree of coupling and then to determine
61 how flux-derived estimates of coupling would change model predictions.”

62

63 R: I was also curious about the author’s choice to limit the analysis to relatively
64 windy periods between 800 and 1600 hours. Coupling should be greater during these
65 condition when compared to relatively stable conditions, for example those
66 experienced from late evening to sunrise. Do the models similarly use a decoupling
67 coefficient that is most appropriate for those conditions, or do they perhaps employ a
68 lower value that is representative of daytime and nighttime periods (particularly if the
69 models run at a daily timestep)?

70 A: This is an interesting question. The simple answer is that we deemed daylight
71 hours and timesteps with $u^* < 0.25$ to be the period when stomatal control over
72 transpiration would be strongest. Additionally, we would assume that in more stable
73 conditions the errors in FLUXNET data would be greater (due to reduced turbulence),
74 so have avoided this period.

75

76 R: Further, I thought the authors might have missed an opportunity to leverage the
77 high-frequency data from FLUXNET to say something about temporal variation in
78 decoupling over the course of a typical day.

79 A: This also would be a valuable direction for further research. Decoupling factors are
80 not constant: both models and data will show variation during the course of the day.
81 Our goal here was simply to examine how long-term average decoupling factors
82 compare with literature values. Future more detailed work could examine the sub-
83 diurnal variation in both models and measurements.

84

85 We have added to the Route forward section: “In this study we examined the long-
86 term average coupling factor. It may also be instructive to consider how estimated
87 coupling factors change across the course of a day or within a season. However, it is
88 likely that such an approach may be more sensitive to noise in the fluxes as well as
89 events such as drought.”

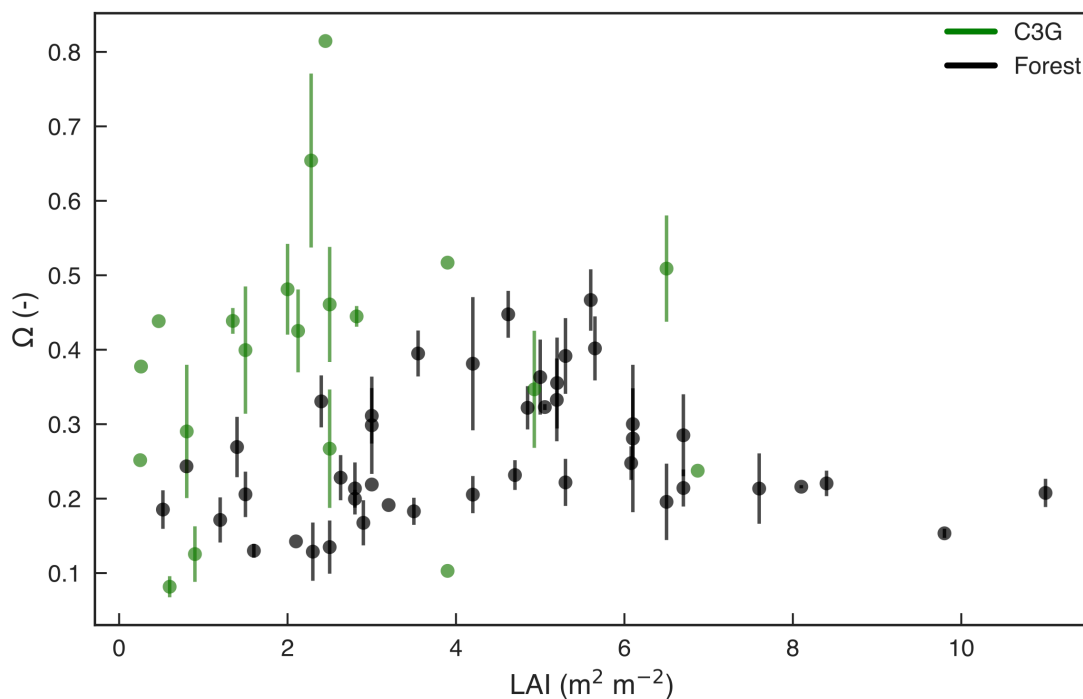
90

91 R: Finally, in paragraph 10, the authors state that LAI information for many sites is
92 not available. Many FLUXNET sites have high-quality ground-based LAI

93 measurements that are not reported to the network. Sometimes an email to the site PIs
94 can turn up useful ancillary data.

95 A: Firstly we note that the recommendation to email site PI's is unrealistic given our
96 analysis covered 164 sites. We did carry out the suggested analysis using an ancillary
97 file of LAI data from the FLUXNET sites. We have a number of concerns about
98 presenting these data however. The file we used is no longer available online, and we
99 have little information about what the data represent. We do not know how or when
100 these data were measured (LAI-2000, hemispherical photography, other?), we do not
101 know if they are LAI or really plant area index (i.e. not corrected for a woody
102 component, or clumping), we do not know the sampling footprint these data represent
103 and finally we cannot trace the origins of these data. For these reasons, we chose to
104 instead analyse the decoupling in relation to precipitation (a proxy for LAI). We show
105 the reviewer this figure below and as they can see there is some agreement with our
106 figure 3, but due to the issues we raise above we feel it is more appropriate to stick
107 with our analysis framework. If the reviewer wishes we could include this in the
108 supplementary.

109



110

111

112

1 We again thank the reviewer for their constructive comments and we address their
2 various concerns below. This version replaces our original response, updated with
3 specific changes where appropriate. Referee comments are highlighted in red, with
4 our response below in black in each case.

5 **R:** This manuscript presents results from a FLUXNET based analysis on vegetation-
6 atmosphere coupling of transpiration using the omega factor by Jarvis &
7 McNaughton. Aggregating daytime data during the peak growing season across plant
8 functional types (PFT), it was found that evergreen needleleaf forests (ENF) have a
9 lower degree of coupling, and that evergreen broadleaf forests (EBF) and shrubs were
10 more coupled than previously suggested in the literature. The manuscript concludes
11 that this decoupling analysis based on FLUXNET data can be used for benchmarking
12 to test models. The manuscript is overall well written (particularly the Discussion sec-
13 tion) and the presented research is of significant scientific interest to improve model
14 estimates of biosphere-atmosphere exchange. Nonetheless, I do have some concerns
15 regarding the argumentation and analysis presented here and would strongly
16 encourage the authors to consider the following points, before a revised manuscript
17 could be recommended for publication.

18

19 **Main Points:**

20 **R:** (1) While the manuscript is overall focused on the coupling of vegetation and
21 atmosphere regarding transpiration, the manuscript incoherently switches between the
22 use of the degree of coupling and decoupling, which all refer to omega values
23 between 0 and 1. Although this is linked to the original work by Jarvis &
24 McNaughton (i.e. the decoupling factor), it seems rather confusing for readers of this
25 manuscript and I would suggest using a consistent terminology throughout the
26 manuscript, e.g. the degree of coupling with high omega values referring to a lower
27 degree of coupling.

28 **A:** We are happy to switch our use of terminology to “degree of coupling”, noting that
29 these terms are used interchangeably widely across the literature.

30

31 R: (2) As the manuscript heavily relies on turbulence based measurements from
32 FLUXNET, there is a high chance that the coupling terminology might be misunder-
33 stood. It would help and strengthen the manuscript to more clearly differentiate in the
34 Introduction section, if your terminology of coupling is referring to turbulence
35 conditions above the plant canopy (e.g. quantified by u^* or σ_w) or to plant
36 physiological coupling at the leaf level or within the canopy, or between different
37 layers of the canopy such as in forests and woody shrublands. This seems also
38 important to differentiate between the leaf and ecosystem scale in this manuscript as
39 EC flux measurements are at the ecosystem scale, yet some of the presented concepts
40 here are referring to the stomatal coupling at the leaf scale (typically measured by leaf
41 chamber).

42 A: We do not fully follow the reviewer's lack of clarity on this issue. We define our
43 use clearly in equation 1, 2 and in particular 3 (which outlines the use of u^*). Our
44 approach following Jarvis & others and takes a big-leaf approach. We clearly address
45 potential issues in this approach in our Caveats section (2.3.1). The ecosystem scale is
46 an integration of the leaf-level processes and thus, reference to leaf / canopy processes
47 is appropriate.

48

49 R: (3) The manuscript currently relies substantially on comparisons of FLUXNET
50 derived values to the literature, yet the literature values are not presented and analysed
51 quantitatively. I would suggest considering a figure or table comparing both by PFT
52 and documenting details of the so heavily referred to values from the literature, e.g.
53 on how these were assessed/derived (single site/plant experiment, multiple sites,
54 cham- bers, EC, season etc) to give readers a better idea of their origin and meaning.
55 The manuscript draws substantial conclusions from the comparison to the literature
56 values and these needs to be justified accordingly in a quantitative way that is clearly
57 visualized.

58 A: We have now summarised the literature from 40 studies, covering 57 PFTs, in our
59 new table 1.

60

61 R: (4) The FLUXNET La Thuile data used here is relatively outdated (from 2007) and
62 only includes a limited number of sites (as Free and Fair use subset). Yet the newer

63 and more extensive FLUXNET2015 dataset is available since late 2015 (same website
64 as referred to in Methods section), but including many more sites and site years
65 compared to the 2007 La Thuile dataset (~1000 vs. ~1500 site years), and also
66 including a subset with a similar data policy (TIER1). I am wondering what the
67 reasoning behind this choice of older dataset was and if the manuscript would not
68 benefit from the larger sampling available in the newer dataset, particularly in terms
69 of important PFTs (e.g. TRF) that were poorly represented in the 2007 dataset? It
70 would also benefit the manuscript to have a table of the eventually retained sites (after
71 data screening – see Section 2.1), their used site years and PFT etc. in the Appendix,
72 something that is typically recommended when using the FLUXNET dataset.

73 A: We have added the list of the sites used in the analysis following screening to the
74 appendix.

75

76 The FLUXNET2015 release is being made progressively, and hence the data
77 available continue to change on a regular basis. When we originally carried out our
78 analysis, the quality assurance flags for latent heat flux were missing, meaning that
79 we could not carry out our analysis on the new release (a patch has now been
80 released). Owing to the fact that this dataset is still changing, and its properties have
81 not been explored or tested yet, we felt that it was more appropriate at this time to
82 work with the well-known and studied La Thuile dataset. We note that just because
83 there is a newer release, it does not invalidate the approach taken here. We are not the
84 only authors to continue to use the La Thuile data (see for example in Biogeosciences
85 discussions: Mahecha et al. 2017, doi:10.5194/bg-2017-130; Marcolla et al. 2017,
86 doi:10.5194/bg-2017-11).

87

88 We have run a similar analysis with the FLUXNET2015 dataset (see our new Figure
89 A1). Our conclusions are similar across the two datasets. In particular, the reviewer
90 highlighted the greater number of tropical sites, but as can be seen from our figure,
91 the change in site years is small (n=16 vs. n=9).

92

93 To the end of the methods section we have added: “We also replicated our analysis
94 using eddy covariance data taken from the FLUXNET2015 dataset
95 (<http://fluxnet.fluxdata.org/data/fluxnet2015-dataset>). Figure A1 is a replicate of Fig.
96 1 and shows the patterns we derived are robust across flux releases.”

97

98 R: (5) The manuscript correctly states (Section 2.3.1) that soil evaporation would bias
99 the coupling estimates, yet it is assumed that this only matters 24 hours after rainfall.
100 In fact soil evaporation is a substantial component of the measured ET at almost all
101 sites and except in closest canopy forests with high LAI, easily contributes up to 50%
102 of total ET, particularly in grasslands and shrublands. Consequently, the bias of soil
103 evaporation on the results of certain PFTs is likely much higher and this needs to be
104 addressed in the interpretation of the Results.

105 A: In fact, we screened data 48 hours after rainfall, not 24. There is a discrepancy in
106 our text where we mistakenly state 24 hours in the Caveats section, but 48 in the
107 method; we have fixed this error in the revised version. Of course, our choice of 48
108 hours is an assumption of the method, but as we highlighted in the Caveats section, it
109 is one that has been widely used (see Law et al., 2002; Groenendijk et al., 2011;
110 Dekker et al., 2016).

111

112 As suggested, we now highlight in our Caveats section to highlight the reviewer’s
113 point that this assumption may vary with PFT. However, it is not clear to us where the
114 reviewer’s soil evaporation figure of “easily up to 50%” originates; the literature we
115 have read points to transpiration accounting for between 60-80% of
116 evapotranspiration across the land surface (e.g. Miralles et al., 2011; Jasechko et al.,
117 2013; Schlesinger and Jasechko, 2014, but see Schlaepfer et al., 2014).

118

119 R: (6) The analysis on the controls of omega is largely focused on wind and
120 precipitation, yet soil moisture and VPD seem much better and more direct controls of
121 plant water stress affecting stomatal conductance. These data are available for most of
122 the sites in the FLUXNET dataset and I would encourage the authors to consider
123 extending their analysis to these controls, and linking these results to the recent
124 literature on stomatal conductance.

125 A: The effect of VPD is already accounted for through its use in equation 2. With
126 respect to the reviewer’s point about soil moisture, the focus of this manuscript was
127 on boundary layer controls on stomatal conductance. There is already ample literature
128 on drought and soil moisture.

129

130 Nevertheless, as requested by the reviewer, we did explore the soil moisture fields:

131 (1) We were unable to determine what depths “upper layer” and
132 “lower layer” refer to FLUXNET, or if these are consistent across
133 sites, we presume not?

134 (2) Setting an arbitrary threshold of acceptable data to be at least 20%
135 of a given year, we found that there were only 11 sites with data
136 from the upper layer and 9 sites with data from the lower layer.
137 These site numbers are reduced further to 7 and 5 for the lower and
138 upper layers, respectively, if one assumes sites: CA-NS1, CA-NS2,
139 CA-NS3, CA-NS4, CA-NS6 show (presumably close to) the same
140 information.

141

142 Given these stated reasons, we have not pursued any further analysis related to soil
143 moisture.

144

145 **R: Overall, I am aware of the length limitations of Opinion & Perspectives papers, yet**
146 **a full length manuscript might be more fitting for this study to sufficiently document**
147 **the analysis and the Conclusions that could be drawn from it.**

148 A: The main goal of this work was to document the degree of coupling observed at
149 FLUXNET sites and demonstrate how it differs from the literature. We feel that the
150 manuscript submission, even with the addition of the new summary table of literature
151 decoupling, sufficiently addresses this goal in its current form. The additions
152 requested by both reviewers do not appear to warrant a substantial extension in length
153 of the paper.

154

155 **Specific Comments:**

156 R: - Page 1, Line 19: please consider adding short explanation why Gs is reduced with
157 elevated CO₂.

158 A: We have added: “due to either a decrease in stomatal aperture with the reduced
159 photosynthetic demand for CO₂ and/or a change in stomatal density (McElwain and
160 Chaloner, 1995; Woodward and Kelly, 1995)”.

161

162 R: - It would help to add some details in Section 2.1. why the flux data were screened
163 this way and how this affects the interpretation of your Results. It would also be
164 helpful to specify that your analysis is presenting mean decoupling values during the
165 peak growing season somewhere in the Results.

166 A: For each of the screening choices we have now added an explanation: “Flux data
167 were first screened as follows: (i) data flagged as “good” (quality control flag
168 “fqcOK” = 1; Williams et al., 2012); (ii) data from the three most productive months,
169 to account for the different timing of summer in the Northern and Southern
170 hemispheres; (iii) daylight hours between 8 am and 4 pm, to account for periods when
171 the vegetation is photosynthesising; (iv) half-hours with precipitation, and the
172 subsequent 48 half-hours, were excluded to minimise the influence of soil evaporation
173 (Law et al., 2002; Groenendijk et al., 2011; Dekker et al., 2016); and (v) data with a
174 $u^* < 0.25$ were excluded to avoid conditions of low turbulence (Sánchez et al.,
175 2010).”

176

177 We have also added to the methods: “In our analysis we derived the average (three
178 most productive months) decoupling coefficient, as the focus of our manuscript was
179 on the spatial variability in coupling across FLUXNET. This is likely to be a metric
180 that can most readily be exploited to assess existing coupling assumptions in models.
181 Future analysis may wish to explore the temporal variability in this metric.”

182

183 R: Page 4, Line 29: why are open grasslands necessarily sites with low precipitation?

184 A: The reviewer is correct that the open grasslands are not necessarily sites with low
185 PPT. We have reworded this sentence to be: “The data suggest that for sites that are
186 likely to be more open grasslands (i.e. sites with a low precipitation)...”

187

188 R: - Page 4, Line 30: or are grasslands just more couple because of having just 1
189 canopy layer (compared to typically 2 in forest)?

190 A: This sentence refers to the fact that grasslands at low precipitation are more
191 coupled than grasslands at high precipitation; it does not compare grasslands with
192 forests. Forests are typically more coupled than grasslands.

193

194 R: - Page 5, Line 20: please consider removing “low” for consistency.

195 A: We have removed “low”.

196

197 R: - Page 5, Line 21: SDGVM = Sheffield Dynamic Global Vegetation Model (add
198 Global)

199 A: We have added the missing “global”.

200

201 R: - Page 5, Line 30: it seems incorrect to write “all” FLUXNET sites her, as you are
202 (i) only using a subset from the 2007 dataset and (ii) further reduce this subset by data
203 screening (see Section 2.1).

204 A: We have replaced “all” with “the 164 FLUXNET sites”.

205

206 R: - Page 5, Line 30: I would argue that “forest species” is not the correct term here as
207 you are referring to PFTs, not species groups, and the flux measurements are at the
208 ecosystem scale.

209 A: We have replaced “species” with “PFTs”.

210

211 R: - Page 5, Line 31: consider limiting “..the FLUXNET network..” to “FLUXNET”.

212 A: We have removed “network”.

213

214 R: - Page 6, Line 26-27: Ref. Knauer et al. missing in Reference list, and similarly the
215 incomplete citation of Knauer et al. in Line 31-32.

216 A: We have fixed the Knauer et al. reference

217

218 R: - Page 6, Line 32: “that” seems redundant here

219 A: We have removed “that”.

220

221 R: Section 2.3.1: what about the limitations arising from the use of an older dataset
222 (despite availability of newer dataset, which poorly represents some PFTs?)

223 A: See earlier response about FLUXNET 2015.

224

225 R: Page 7, Line 8-9: what about general variability of environmental conditions and
226 water availability?

227 A: We agree with the reviewer that anything that alters G_s and thus the ratio of G_s to
228 G_a, will also affect coupling. As previously stated, the focus of our analysis was on
229 boundary layer controls on stomatal conductance. We were interested in determining
230 if we could extract a metric related to coupling with which existing model
231 assumptions could be probed. As our interest was related to variability in space, we
232 feel our approach was the correct first step.

233

234 R: Page 7, Line 11: the BADM data of the new FLUXNET dataset is more extensive
235 than previously and includes details on canopy height and LAI for many sites

236 A: These data are not sufficient to probe the questions we posed, in many cases,
237 particular with canopy/tower height, this information is simply not available at all
238 sites (presumably this is covered by: (i) “At present only the variables of
239 Site_General_Info and Disturbance_and_Management are made available; and (ii)
240 “Additional BADM variables such as LAI, biomass measurements and soil
241 characteristics will be added to the BADM files over time”). The LAI information is
242 also problematic: we do not know how or when these data were measured (LAI-2000,

243 hemispherical photography, other?), we do not know if they are LAI or really plant
244 area index (i.e. not corrected for a woody component, or clumping), we do not know
245 the sampling footprint these data represent and finally we cannot trace the origins of
246 these data. For these reasons, we chose to instead analyse the decoupling in relation to
247 precipitation (a proxy for LAI). We included a figure in response to reviewer 1 to
248 demonstrate some agreement with our figure 3. However, due to the issues we raise
249 above we feel it is more appropriate to stick with our analysis framework. If the
250 reviewer wishes we could include this in the supplementary.

251

252 **R: Page 7, Line 16-17: please specify how process understanding from leaf to canopy**
253 **scale can be improved, if all the listed measurements are referring to the individual**
254 **plant and ecosystem scale. Furthermore, such targeted Gs measurements have been**
255 **performed at various sites already and it is not clear to me what new aspects the**
256 **authors are suggesting here.**

257 **A:** We have now added: “Recently, Medlyn et al. (2017) compared estimates of plant
258 water-use efficiency derived from leaf gas exchange data and eddy flux data for eight
259 sites where these measurements were acquired at the same point in time. They found
260 similarities for DBF and TRF PFTs, but differences for EBF and ENF PFTs. The
261 authors were unable to explain these scaling discrepancies. Further targeted
262 measurements campaigns at flux sites could lead to new knowledge, which would
263 advance our understanding of the processes involved in scaling from the leaf to the
264 canopy.”

265

266 **R: Figure 1: C4 PFTs in caption but not displayed in Figure? Please add missing data**
267 **or specify why these are not displayed. Ditto in Figure A1.**

268 **A:** We have added the missing C4C category that was mistakenly not previously
269 shown. For grasses, as we do not separate the C4 fraction (FLUXNET does not
270 provide enough information), we now label all grasses as GRA (i.e. not C3G).

271

272 **R: - Figure 2: please consider (i) moving site names outside graph as axis caption (i.e.**
273 **this is a categorical axis), (ii) separating the three groups a-c by vertical lines, (iii)**

274 removing selective ticks on x-axis OR adding one for every single site, and (iv)
275 adding details on the meaning of the whiskers in the caption text.

276 A: We have changed the figure as suggested and add the missing caption text.

277

278 R: - Figure 3: please consider changing the colours so that these are easier to differ-
279 entiate, and to change the symbols (i.e. different symbol for each PFT, and poten-
280 tially increasing size). It could also help to differentiate each regression line with
281 dashed/dotted display.

282 A: In revising the figure we realised that we had accidentally screened out some site
283 based on our calculation of precipitation in the most productive months. The new
284 relationships shown in Figure 3 between the decoupling coefficient and precipitation
285 are consistent with the original submission, although perhaps unexpectedly, including
286 more sites increases the variability in the relationship. We have amended the text
287 accordingly.

288

289 As requested we have attempted to make the figure easier to interpret: we have
290 removed the transparency to make the symbols bolder, we have used different symbol
291 types and simplified the legend.

292

293 R: Figure 4: why are the C3 grasses displayed in Fig. 3, yet not here? Also, what
294 about croplands? I would also suggest to consider add the slope values here and in
295 Fig. 3 for the regression lines.

296 A: The aim of figure 4 was to probe the relationship between wind speed and
297 coupling for forest PFTs. To make this distinction clearer, we have individually
298 coloured forest PFTs in the figure. We also add to the text: “For non-forest PFTs, we
299 did not find a significant relationship between wind speed and coupling.”

300

301

Ideas and perspectives: How coupled is the vegetation to the boundary layer?

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Abstract. Understanding the sensitivity of transpiration to stomatal conductance is critical to simulating the water cycle. This sensitivity is a function of the degree of coupling between the vegetation and the atmosphere, and is commonly expressed by the decoupling factor. The ~~level-of-decoupling~~ degree of coupling assumed by models varies considerably and has previously been shown to be a major cause for model disagreement when simulating changes in transpiration in response to elevated CO₂. The degree of coupling also offers us insight into how different vegetation types control transpiration fluxes, fundamental to our understanding of land–atmosphere interactions. To explore this issue, we ~~estimated the decoupling factor~~ combined an extensive literature summary from 40 studies, with estimates of the decoupling coefficient estimated from FLUXNET data, ~~finding~~. We found some notable departures from values previously reported in single site studies. ~~Evergreen needleleaf forests appear to be on the whole more decoupled than the literature suggests, whilst evergreen broadleaved forests and shrubs were considerably more coupled than is suggested in the literature or than would be predicted based on leaf size and plant stature.~~ There was large variability in estimated decoupling coefficients (range = 0.05–0.51) for evergreen needleleaf forests. A result that was broadly supported by our literature review, but contrasts with the early literature which suggests evergreen needleleaf forests are generally well-coupled. Estimates from FLUXNET indicated that evergreen broadleaved forests were the most tightly coupled, differing from our literature review, which instead suggested it was evergreen needleleaf forests. We also found that the assumption that grasses would be strongly decoupled (due to vegetation stature) was only true for high precipitation sites. These results were robust to assumptions about aerodynamic conductance and energy balance closure. Thus, these data form a benchmarking metric against which to test model assumptions about coupling. Our results identify a clear need to improve the quantification of the processes involved in scaling from the leaf to the whole ecosystem. Progress could be made with targeted measurement campaigns at flux sites, as well as ~~more~~ greater site characteristic information across the FLUXNET network.

20 1 Introduction

Predicting the response of transpiration to global change and the subsequent feedback to climate remains a major challenge for Earth system models (Zhu et al., 2017). Improving our understanding of how stomatal controls on transpiration vary between

vegetation types is fundamental to simulating land–atmosphere interactions. Experimental evidence strongly indicates that stomatal conductance (G_s) is generally reduced in response to elevated CO_2 (Morison, 1985; Medlyn et al., 2001; Ainsworth and Rogers, 2007), due to either a decrease in stomatal aperture with the reduced photosynthetic demand for CO_2 and/or a change in stomatal density (McElwain and Chaloner, 1995; Woodward and Kelly, 1995). In models, incorporating this leaf-level reduction in G_s , commonly results in predictions of decreased transpiration and increased runoff at global scales (Gedney et al., 2006; Betts et al., 2007; Cao et al., 2010). However, the magnitude of this effect varies strongly among models, because the sensitivity of transpiration to a change in G_s depends on the assumption made about the strength of coupling of the vegetation to the surrounding boundary layer (Jarvis and McNaughton, 1986; McNaughton and Jarvis, 1991; Jacobs and De Bruin, 1992) (McNaughton and Jarvis, 1983b; Jarvis and McNaughton, 1986; McNaughton and Jarvis, 1991; Jacobs and De Bruin, 1992). De Kauwe et al. (2013) identified differences in the degree of coupling to be a major cause of disagreement among 11 model predictions of transpiration in response to elevated CO_2 at two forest Free-Air CO_2 Enrichment (FACE) experiments in the USA. Consequently, resolving this discrepancy among models in their assumptions of vegetation-atmosphere coupling is key to reducing model uncertainty in future predictions of changes in transpiration.

The degree of coupling between vegetation and the atmosphere is commonly expressed by the decoupling factor (Ω ; Jarvis and McNaughton, 1986). If the decoupling factor is high, transpiration is more strongly controlled by incoming radiation and less by changes in G_s . Low stature-canopies, and species with large leaves, are expected to be more decoupled (high Ω), than tall-stature canopies, and species with small leaves. This occurs, because: (i) small-stature canopies decrease the surface roughness, and hence the aerodynamic conductance; and (ii) large leaves decrease the leaf boundary layer conductance. Both act to diminish the rate of exchange between the vegetation surface and the atmosphere. Other characteristics of the vegetation, including, foliage clumping, leaf shape, canopy density and the vertical canopy distribution, will also alter the coupling. Values given in the literature for coniferous forests are typically low, $\Omega = \sim 0.1-0.2$ (Whitehead et al., 1984; Jarvis, 1985; Lee and Black, 1993; Meinzer et al., 1993), ~~although Launiainen (2010) reported a higher summertime value (0.32) at the Hyttialäsäite in Finland.~~ Values are typically higher for deciduous broadleaved: $\Omega = 0.2-0.4$ (Magnani et al., 1998; Wullschleger et al., 2000), evergreen broadleaved species: $\Omega = 0.4-0.9$ (Meinzer et al., 1997; Wullschleger et al., 1998; Cienciala et al., 2000) (Meinzer et al., 1997; Wullschleger et al., 1998), grasses: $\Omega = 0.8$ (McNaughton and Jarvis, 1983a), and crops: $\Omega = 0.2-0.9$ (Black et al., 1970; Brown, 1976; Meinzer et al., 1993; Mielke et al., 1999). These literature estimates of the degree of ~~decoupling-coupling~~ are wide and thus, do not offer a clear constraint to models. Furthermore, methods to estimate Ω often differ across studies, which complicates interpretations about variation across plant functional types. Single studies, that have employed a consistent method to estimate Ω across multiple species are rare (e.g. Stoy et al., 2006).

There has been considerable recent effort to develop better global datasets of stomatal behaviour for use by the modelling community (Lin et al., 2015; ?) (Lin et al., 2015; Miner et al., 2017). However, constraining the coupling between stomatal conductance and transpiration is equally important. For example, De Kauwe et al. (2015) demonstrated modest changes in transpiration when using the Lin et al. (2015) dataset to constrain the parameterisation of G_s in the Community Atmosphere Biosphere Land Exchange (CABLE) land surface model. The CABLE model assumes a relatively **high-level-of-decoupling**

weak level of coupling (De Kauwe et al., 2013). It is likely that models that assume stronger coupling (e.g. the Joint UK Land Environment Simulator, JULES; Best et al., 2011) would obtain different results.

To shed new light on this important question of vegetation-atmosphere coupling, we used eddy-covariance data from FLUXNET to estimate the Ω coefficient for different plant functional types (PFTs). We aimed to: (i) examine if decoupling coefficients estimated from FLUXNET were consistent with literature values; and (ii) develop a benchmark metric against which to test model assumptions about coupling.

2 Materials and Methods

2.1 Flux Data

Half-hourly eddy covariance measurements of the exchange of carbon dioxide, energy and water vapour were obtained from the FLUXNET “La Thuile” Free and Fair dataset (<http://www.fluxdata.org>). We estimated the degree of decoupling (Jarvis and McNaughton, 1986) as:

$$\Omega = \frac{1 + \epsilon}{1 + \epsilon + \frac{G_a}{G_s}} \quad (1)$$

where $\epsilon = s / \gamma$, s is the slope of the saturation vapour pressure curve at air temperature (Pa K^{-1}), γ is the psychrometric constant (Pa K^{-1}) and λ is the latent heat of water vapour (J mol^{-1}).

We estimated values of G_s by inverting the Penman-Monteith equation using measured latent heat (LE) flux for all datasets where the net radiation (R_n ; W m^{-2}) and the frictional velocity (u_* ; m s^{-1}) were available:

$$G_s = \frac{G_a \gamma \lambda E}{s(R_n - G) - (s + \gamma)\lambda E + G_a M_a c_p D} \quad (2)$$

where G_a ($\text{mol m}^{-2} \text{s}^{-1}$) is the canopy aerodynamic conductance, E ($\text{mol m}^{-2} \text{s}^{-1}$) is the canopy transpiration, γ is the psychrometric constant (Pa K^{-1}), D (Pa) is the vapour pressure deficit, G (W m^{-2}) is the soil heat flux, M_a (kg mol^{-1}) is molar mass of air, c_p is the heat capacity of air ($\text{J kg}^{-1} \text{K}^{-1}$). At sites where values of G were not available, G was set to zero.

G_a was calculated following Thom (1975):

$$G_a = \frac{c}{\frac{u}{u_*^2} + 6.2u_*^{-\frac{2}{3}}} \quad (3)$$

where $c = P / (R_{\text{gas}} T_k)$ is a conversion factor from units of m s^{-1} to $\text{mol m}^{-2} \text{s}^{-1}$, P is atmospheric pressure (Pa), R_{gas} is the gas constant ($\text{J mol}^{-1} \text{K}^{-1}$), T_k is the air temperature in Kelvin, and u (m s^{-1}) is the wind speed.

In our analysis we derived the average (three most productive months) decoupling coefficient, as the focus of our manuscript was on the spatial variability in coupling across FLUXNET. This is likely to be a metric that can most readily be exploited to assess existing coupling assumptions in models. Future analysis may wish to explore the temporal variability in this metric.

The approach we have taken (similar to Jarvis and McNaughton, 1986) ignores differences between canopy and air temperature (radiative coupling) within the canopy (see Martin, 1989). However, correcting for the longwave radiative conductance (G_r) most impacts vegetation with the weakest control on transpiration the most and as a result, this assumption has little impact on the [decoupling degree of coupling](#) range for forest species, but may be a factor for other species.

5 Flux data were first screened as follows: (i) data flagged as “good” ([quality control flag “fqcOK” = 1; Williams et al., 2012](#)); (ii) data from the three most productive months, to account for the different timing of summer in the Northern and Southern hemispheres; (iii) daylight hours between 8 am and 4 pm, [to account for periods when the vegetation is photosynthesising](#); (iv) half-hours with precipitation, and the subsequent 48 half-hours, were excluded [to minimise the influence of soil evaporation](#) ([Law et al., 2002; Groenendijk et al., 2011; Dekker et al., 2016](#)); and (v) data with a $u_* < 0.25$ were excluded to avoid conditions of low turbulence (Sánchez et al., 2010). [We also excluded sites classified as mixed-forest, permanent wetlands or those where the PFT was unclassified.](#)

Pressure was estimated using the hypsometric equation based on site elevation data. Where site elevation information was missing, values were gap-filled using the 30-arc second (~1 km) global digital elevation model GTOPO30 data from the United States Geological Survey (USGS). After filtering, ~~175 sites and 634~~ [164 sites and 592](#) site-years remained.

15 We also tested the sensitivity of estimated values to: (i) errors in G_a ; and (ii) errors due to a lack of energy balance closure. First, we increased/decreased estimated values of G_a by 30% to examine the sensitivity of G_s values inverted from the Penman-Monteith equation. Secondly, following recommendations by Wohlfahrt et al. (2009), we tested the sensitivity of our results to energy balance closure, by correcting the Bowen-ratio (each half-hourly LE and H flux) based on the available energy ($R_n - G$) on a longer time scale (three most productive months).

20 [We also replicated our analysis using eddy covariance data taken from the FLUXNET2015 dataset](#) (<http://fluxnet.fluxdata.org/data/fluxnet2015-dataset>). [Figure A1 is a replicate of Fig. 1 and shows the patterns we derived are robust across flux releases.](#)

2.2 Results

[We summarised previously reported estimates of the decoupling coefficient from 40 studies, covering 57 PFTs, in Tables 1 and](#)
25 [A2](#). Broadly speaking, estimated decoupling coefficients [from FLUXNET \(Fig. 1\)](#) differed among PFTs in line with [previous](#) literature values ([Fig. Tables 1 and A2](#)) and in line with expectations related to vegetation roughness and/or stature. Evergreen needleleaf forests (ENF), which have small leaves, were [in general](#) tightly coupled (low Ω), while deciduous broadleaved forests ~~and~~, tropical rain forest (large leaves), ~~and~~ C_3 -grasses and crops (small stature), had [greater levels of decoupling a](#)
[lower degree of coupling](#) (higher Ω). However, ~~the low decoupling coefficient for there were some notable departures from~~
30 [expectations. Estimates derived from FLUXNET indicated that](#) evergreen broadleaf forests ~~(despite their large leaves and rough canopy structure)~~, as well as the range of decoupling coefficients for C_3 -grasses, were surprising. ~~The high level of coupling from sites with shrubs was also unexpected~~ were the most coupled PFT (mean $\Omega = 0.21$) as opposed to the literature review, which suggested ENF PFTs were the most coupled (mean $\Omega = 0.19$). The FLUXNET data also indicated unexpectedly wide ranges for Ω within PFTs. For grasses, Ω ranged from 0.02–0.81; the number of low values was particular suprising, given

the expectation that shorter stature vegetation would be more decoupled. Across PFTs, the range of decoupling factors was less than that typically cited in the literature. The median value for ENF is above 0.2, in contrast to the range suggested by Jarvis (1985) (0.1–0.2), while the median value for broadleaf forests and crops is below 0.5, which is towards the lower end of previously quoted ranges (0.2–0.9) (Meinzer et al., 1993, 1997; Wullschleger et al., 1998; Cienciala et al., 2000).

5 Among ENF sites, the range in estimated values shown in Fig. 1 was striking, extending from ~~The wide range in estimated~~ values for ENF sites was also striking; Ω extended from 0.05 to ~~-0.40~~ 0.51. To attempt to better understand this range ~~better~~, we first separated ENF sites into: (a) sites with a low inter-annual coefficient of variation (20%), indicating consistent year-to-year estimates of ~~decoupling~~ the degree of coupling; (ii) sites with a coefficient of variation > 20%, indicating sites with year-to-year variability in coupling; and (iii) sites with only two years of data. This separation was intended to rule out sampling

10 issues. Figure 2 shows that the variability in the estimated decoupling coefficient cannot be explained by sampling bias, with significant site-to-site variability, irrespective of the inter-annual variability.

We then probed these results for relationships with site variables, by testing to see if: (i) sites with higher precipitation (in the three most productive months) were more decoupled, where precipitation was assumed to be a proxy for leaf area index (LAI)/productivity; or (ii) windy sites were more coupled. For ~~C₃~~ C₃-grasses we found a significant relationship between

15 the degree of ~~decoupling~~ coupling and precipitation (Fig. 3). The data suggest that ~~in~~ for sites that are likely to be more open grasslands (i.e. sites with a low precipitation) the vegetation is very coupled to the atmosphere, with a high level of stomatal control. This relationship between ~~decoupling~~ the degree of coupling and precipitation ($r=0.77$ 0.46) explains the high variability in estimated decoupling coefficients for ~~C₃~~ C₃-grasses shown in Fig. 1. The prediction that grasses would be ~~strongly decoupled~~ weakly coupled due to small vegetation stature only holds true at sites with high 3-month precipitation,

20 which are presumably sites with high LAI. We also found a significant relationship for ENF sites ($r=0.46$ 0.40), and deciduous broadleaved forests ($r=0.63$ 0.64) suggesting that ~~decoupling increased~~ the degree of coupling declined with canopy density. We also found evidence of a weak negative relationship ($r=-0.21$) between wind speed and the degree of coupling for forest sites, i.e. windier sites tended to be more coupled (Fig 4). For non-forest PFTs, we did not find a significant relationship between wind speed and coupling.

25 Finally, we examined sensitivity of our results to potential errors. We tested whether our results were sensitive to different estimates of G_a and whether our estimates of G_s were sensitive to energy imbalance. We found that the broad pattern of our results in Fig. 1 was insensitive to errors in G_a . Increasing or decreasing G_a by 30%, led to the median decoupling coefficient ~~increasing or decreasing~~ decreasing or increasing by roughly 0.05 for evergreen broadleaf forest (EBF) sites for example. However, we did find that our results were sensitive to a correction for the lack of energy balance closure. Figure ~~S1~~ A2 shows

30 that attempting to correct for a lack of closure leads to sites becoming ~~more decoupled~~ less coupled, but does not shift the between-PFT differences in ~~decoupling~~ the degree of coupling. The largest changes were for C3 crops (Ω changed from ~~~0.4~~ 0.44 to ~~~0.6~~) and ~~shrubs~~ deciduous broadleaved forests (Ω changed from ~~~0.2~~ to ~0.30 0.31 to ~~~0.41~~).

2.3 Discussion

Correctly characterising the sensitivity of transpiration to G_s is critical for simulating the water cycle, particularly for future projections of the terrestrial biosphere where it is widely expected that G_s will decrease in response to increasing atmospheric CO_2 . The parameterisation of this crucial link between leaf- and canopy-scale water fluxes has been largely ignored in model studies addressing the impact of elevated CO_2 (Betts et al., 2007; Cao et al., 2010; Zhu et al., 2017). Resulting projections of changes in transpiration and associated fluxes (e.g. runoff, precipitation) are likely to be model-specific, with large uncertainty among models (De Kauwe et al., 2013). Model studies rarely provide information about the degree of ~~decoupling-coupling~~ assumed within the model. The range of assumptions commonly incorporated in models include: (i) coupling is a function of roughness length (determined by vegetation height), e.g. JULES; (ii) coupling is a function of leaf size, e.g. CLM (the Community Land Model; Oleson et al., 2013); (iii) coupling is affected by within canopy turbulence, e.g. CABLE (Raupach et al., 1997; Kowalczyk et al., 2006); (iv) some combination of all three, e.g. CABLE/CLM; (v) coupling is not sensitive to ~~low-wind-speeds~~ wind speed (i.e. wind speed is fixed to 5 m s^{-1}), e.g. SDGVM (~~Sheffield dynamic-vegetation-model; Woodward et al., 1995~~) (Sheffield Dynamic Global Vegetation Model; Woodward et al., 1995); or (vi) models that use an alternative to the Penman-Monteith equation, e.g. LPJ (Lund-Potsdam-Jena family of models; Sitch et al., 2003). This family of models use an empirically calibrated hyperbolic function of canopy conductance (Huntingford and Monteith, 1998) and the implied level of coupling depends on how this function is parameterised.

Understandably, the pioneering work of ~~Jarvis and colleagues (e.g. Jarvis and McNaughton, 1986)~~ Jarvis and McNaughton (1986) is widely cited when issues of coupling are discussed in the literature. However, many of the earlier estimates of coupling ~~are~~ they summarised were taken from single sites and thus ~~do~~ does not necessarily reflect the diversity of global vegetation. In this study we have ~~leveraged data from FLUXNET to estimate decoupling factors across a wide range of sites. Unlike previous studies that have collated estimates of coupling across studies (e.g. Jarvis and McNaughton, 1986), in which methods to estimate coupling may have differed~~ summarised 40 literature studies, covering 57 PFT, in combination with estimates of the decoupling coefficient from 164 sites and 592 site-years from FLUXNET. Our literature summary (Tables 1 and A2) highlights the diversity of approaches used to determine Ω . In contrast, we have applied a consistent methodology across all the 164 FLUXNET sites. For forest ~~species~~ PFTs, our results point to a ~~greater level of decoupling~~ weaker level of coupling than is often assumed. Notably, ENF species were found to be less coupled ~~across the FLUXNET network than work by Jarvis and others suggested~~ (mean $\Omega = 0.21$; range = 0.05–0.51) across FLUXNET than summarised in Jarvis and McNaughton (1986) ($\Omega = 0.1$). Our estimate derived from FLUXNET was supported by our wider literature summary (n=13). We found that the often assumed ~~high degree of decoupling~~ low degree of coupling for grasses is likely to only be true for high precipitation (and presumably high LAI) sites; low precipitation sites were strongly coupled. A further plausible explanation is that these drier sites are limited by available soil moisture, with lower G_s resulting in a high degree of coupling. We could not easily explain the coupling values estimated for evergreen broadleaf forests, which were estimated to be more coupled than evergreen needleleaf forests; a break from theoretical understanding developed from vegetation roughness and/or stature. Finally, grouping the data by PFTs also highlighted marked within-PFT variation in the degree of coupling.

As land models move towards more realistic representations of the variability of stomatal conductance (De Kauwe et al., 2015), informed by leaf-level syntheses (Lin et al., 2015; ?; De Kauwe et al., 2015)(Lin et al., 2015; Miner et al., 2017), it is also important that they accurately simulate the coupling between vegetation and the atmosphere. Without this focus, any efforts to improve the realism at the leaf-scale will not be reflected in improvements in simulated transpiration at the canopy scale.

5 2.3.1 Caveats

One criticism of the approach taken here is that we have assumed a big-leaf approximation to estimate vegetation ~~decoupling~~ the degree of coupling (see Raupach and Finnigan, 1988). It is of course likely that variation within a canopy in terms of microclimate (i.e. vapour pressure deficit, irradiance, temperature), as well as how stomata respond, may invalidate this approach. Use of a big-leaf approximation could be a possible explanation for the surprisingly ~~low level of decoupling~~ high level of coupling found in evergreen broadleaf forests, although it would appear unlikely given the ~~higher level of decoupling~~ weaker level of coupling found for deciduous broadleaved and tropical rainforest species.

We found high variation in the estimated ~~decoupling~~ coupling factor both across sites and within sites. Two assumptions we make with respect to the flux data could explain this variation. Firstly, we excluded data ~~for 24 hours after rainfall following rainfall (48 hours)~~ (Law et al., 2002; Groenendijk et al., 2011; Dekker et al., 2016) to minimise the effects of soil evaporation. Clearly, if soil evaporation is still a component of the LE flux after this point it would introduce error to our estimates. This assumption may also vary with PFT. Secondly, flux towers commonly do not close the energy balance (Foken, 2008; Wilson et al., 2002). Our use of the inverted Penman-Monteith equation implies that we are attributing any errors due to energy imbalance to the sensible heat flux. Additionally, where data on the soil heat flux were missing, we assumed there was no storage. Correcting for these issues is not straightforward as it requires determining which flux is the source of the error (see Wohlfahrt et al., 2009, for a detailed discussion). We followed recommendations by Wohlfahrt et al. (2009) and tested the sensitivity of our results to energy balance closure, by correcting the Bowen-ratio based on the available energy ($R_n - G$). Whilst we did find some sensitivity in our results (particularly for C3 crops and ~~shrubs~~ deciduous broadleaved forests), it did not change the ordering of ~~decoupling~~ coupling factors between PFTs, or explain the unexpected high level of ~~decoupling~~ coupling for EBF sites.

Finally, we estimated the canopy aerodynamic conductance (G_a) using an empirical equation following Thom (1975). ~~Knauer et al. (in review)~~ Knauer et al. (2017) tested the impact on different methods of estimating G_a from flux data on estimates of the stomatal slope parameter (the sensitivity of stomatal conductance to assimilation). They found that correcting G_a for atmospheric instabilities only led to small increases in estimates of G_a during daytime growing conditions. They also found that a more physically-based representation of G_a (Su et al., 2001), led to lower estimate of G_a at two EBF flux sites, and higher estimates of G_a at another EBF and a deciduous broadleaved site. We tested the sensitivity of our results to a change in G_a of the order shown by ~~Knauer et al. and found that~~ Knauer et al. (2017) and found the patterns in ~~decoupling~~ coupling to be robust across PFTs.

2.3.2 Route forward

Estimates of ~~decoupling-coupling~~ from ecosystem scale flux data are directly relevant for models. We previously speculated (De Kauwe et al., 2013) that discrepancies among models in ~~decoupling-coupling~~ might be resolved by examining eddy covariance data. The range in ~~decoupling-coupling~~ factors we have estimated from the FLUXNET data provides an overall
5 constraint on the ~~level-of-decoupling-degree of coupling~~ that should be assumed in models, as well as an indication of the appropriate degree of variability in ~~decoupling-coupling~~ across PFTs and rainfall regimes. The next steps involve determining what models currently assume about the degree of coupling and then to determine how flux-derived estimates of coupling would change model predictions.

In this study we examined the long-term average coupling factor. It may also be instructive to consider how estimated
10 coupling factors change across the course of a day or within a season. However, it is likely that such an approach may be more sensitive to noise in the fluxes as well as events such as drought.

Our results also identify a clear need to better understand leaf-to-atmosphere coupling. We need to better understand why ~~decoupling-coupling~~ factors vary within PFTs. There are a number of plausible explanations, such as drought, diversity of vegetation within a flux footprint, data issues, and it is likely that more detailed site-specific insight will be required to move
15 forward. To assist in better understanding patterns, we will need greater detail in terms of ancillary data from FLUXNET sites. We attempted to probe our results with respect to canopy height and LAI, but for many sites this information was not available. Other potentially useful information would include leaf size, stem density and crown length, and whether canopy height is static or increasing. These data would facilitate more sophisticated approaches to be explored, for example stability corrections and/or estimates of G_a based on leaf size (Su et al., 2001). A more fundamental process understanding will require targeted G_s
20 measurements throughout the canopy, alongside corresponding sap flux measurements in forests and chamber measurements in grasslands. ~~Targeted measurements~~ Recently, Medlyn et al. (2017) compared estimates of plant water-use efficiency derived from leaf gas exchange data and eddy flux data for eight sites where these measurements were acquired at the same point in time. They found similarities for DBF and TRF PFTs, but differences for EBF and ENF PFTs. The authors were unable to explain these scaling discrepancies. Further targeted measurements campaigns at flux sites could lead to new knowledge,
25 which would advance our understanding of the processes involved in scaling from the leaf to the canopy.

Code availability. All code is freely available from: https://github.com/mdekauwe/flux_decoupling

Data availability. All Eddy covariance data are available from: <http://fluxnet.fluxdata.org/data/la-thuille-dataset/>

Competing interests. The authors declare no competing financial interests.

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Table 1: Literature summary of decoupling coefficients, see Table A2 for summaries of individual studies. Plant functional types (PFT) are defined as: ENF - evergreen needle leaved forest, EBF - evergreen broadleaved forest, DBF - deciduous broadleaved forest, TRF - tropical rain forest, SAV - savanna, SHB - shrub, GRA - grasses, C3C - C₃ crops, C4C - C₄ crops.

PFT	Mean	Standard Deviation	Min	Max	Number of studies
ENF	0.19	0.1	0.06	0.43	13
EBF	0.26	0.13	0.1	0.63	12
DBF	0.36	0.18	0.1	0.7	11
TRF	0.57	0.28	0.25	0.9	11
SAV	0.14	—	—	—	1
SHB	0.27	0.19	0.13	0.4	2
GRA	0.33	0.1	0.21	0.45	4
C3C	0.4	0.28	0.2	0.59	2
C4C	0.58	—	—	—	1

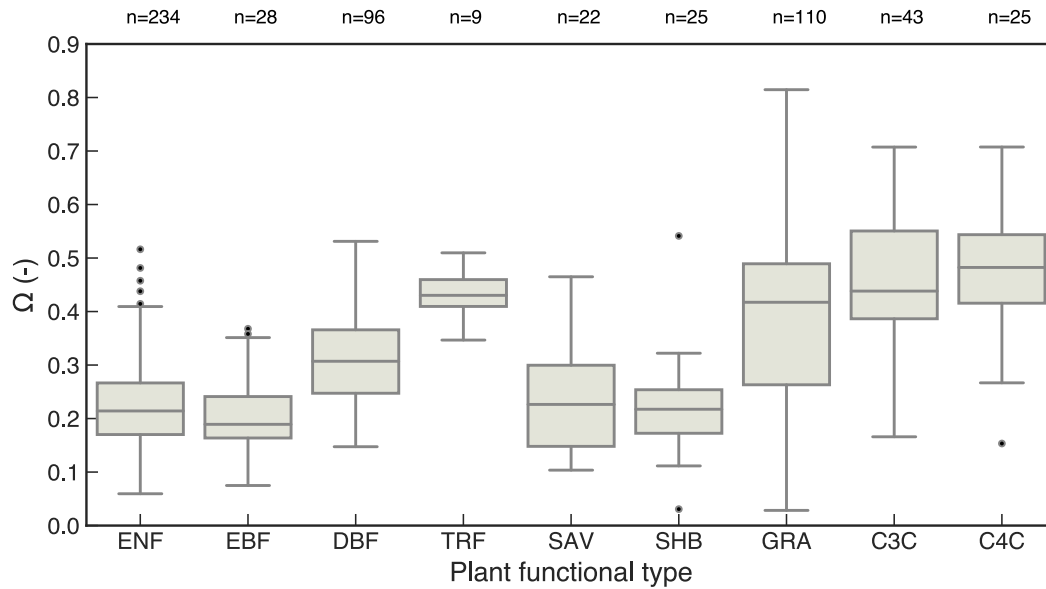


Figure 1. Box and whisker plot (line, median; box, inter-quartile range) showing the estimated ~~decoupling-coupling~~ coefficient (Ω) from FLUXNET data, grouped by plant functional type. Whiskers extend to 1.5 times the inter-quartile range, with dots outside of the whiskers showing outliers. Plant functional types are defined as: ENF - evergreen needle leaved forest, EBF - evergreen broadleaved forest, DBF - deciduous broadleaved forest, TRF - tropical rain forest, SAV - savanna, SHB - shrub, ~~C3G-GRA~~ - ~~C₃-grassgrasses~~, ~~C4G-C₄grass~~, C3C - C₃ crops, C4C - C₄ crops. Values of n indicate the number of site-years for FLUXNET.

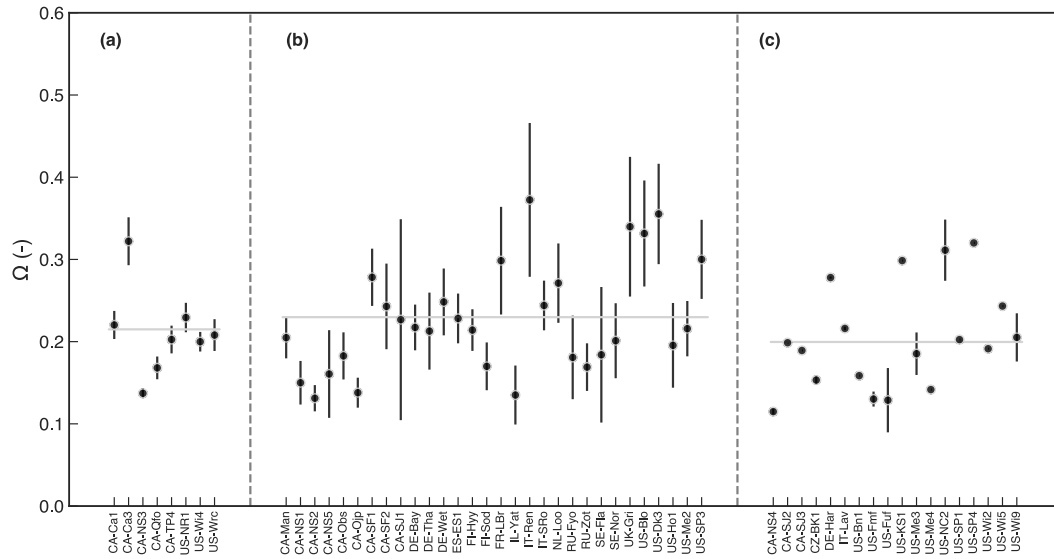


Figure 2. Values of the coupling coefficient (Ω) for sites from the evergreen needleleaf forests (ENF) plant functional type. Estimated values of Ω have been split into: (a) sites where the coefficient of variation (COV) is < 20%; (b) sites where the COV is > 20%; and (c) sites with only two years of data. Site errorbars represent one standard deviation (site year variation) in estimated Ω values. Solid horizontal grey lines show overall mean coupling coefficients.

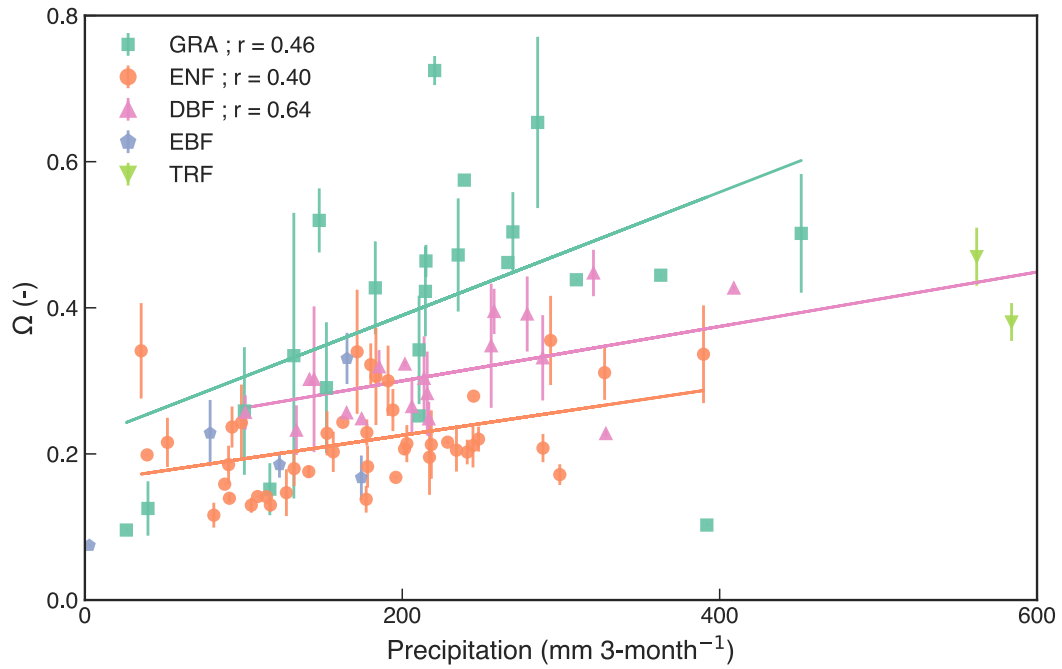


Figure 3. Values of the estimated coupling coefficient (Ω) for forest (ENF, EBF, DBF, TRF) vegetation and grasses as a function of precipitation in the three most productive months. Only data where 90% of the three most productive months were flagged as “good” are shown. Lines indicate statistically significant regressions ($P < 0.05$). Plant functional types are defined as: GRA - grasses, ENF - evergreen needle leaved forest, EBF - evergreen broadleaved forest, DBF - deciduous broadleaved forest and TRF - tropical rain forest.

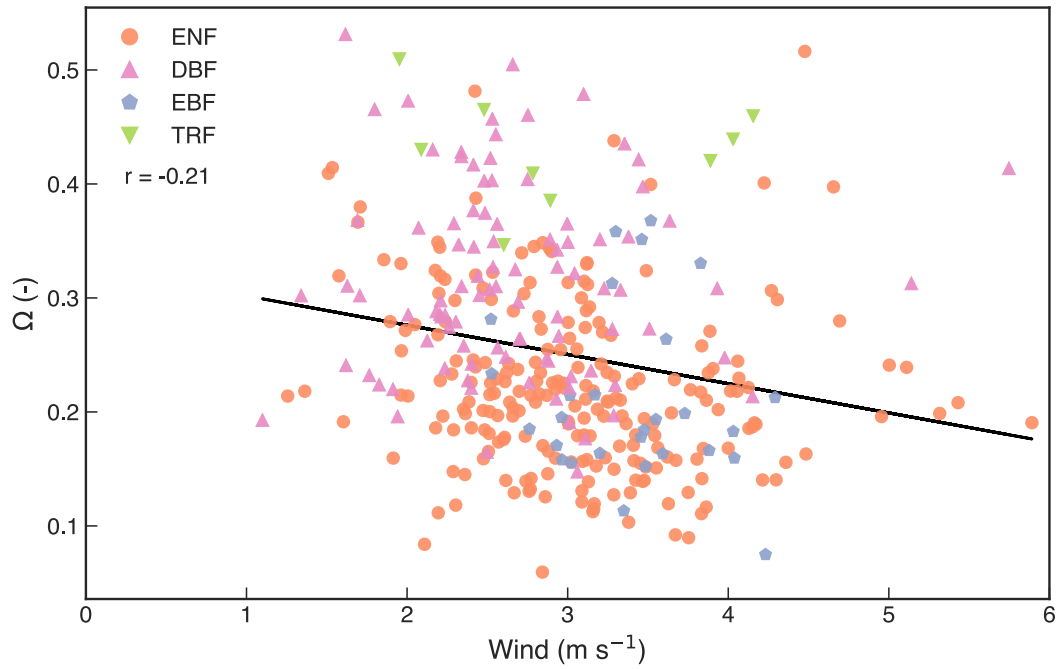


Figure 4. Values of the estimated coupling coefficient (Ω) for forest (ENF, EBF, DBF, TRF) vegetation as a function of wind speed. Line indicates statistically significant regression ($P < 0.05$), r is the correlation coefficient. Plant functional types are defined as: ENF - evergreen needle leaved forest, EBF - evergreen broadleaved forest, DBF - deciduous broadleaved forest, TRF - tropical rain forest.

Appendix A

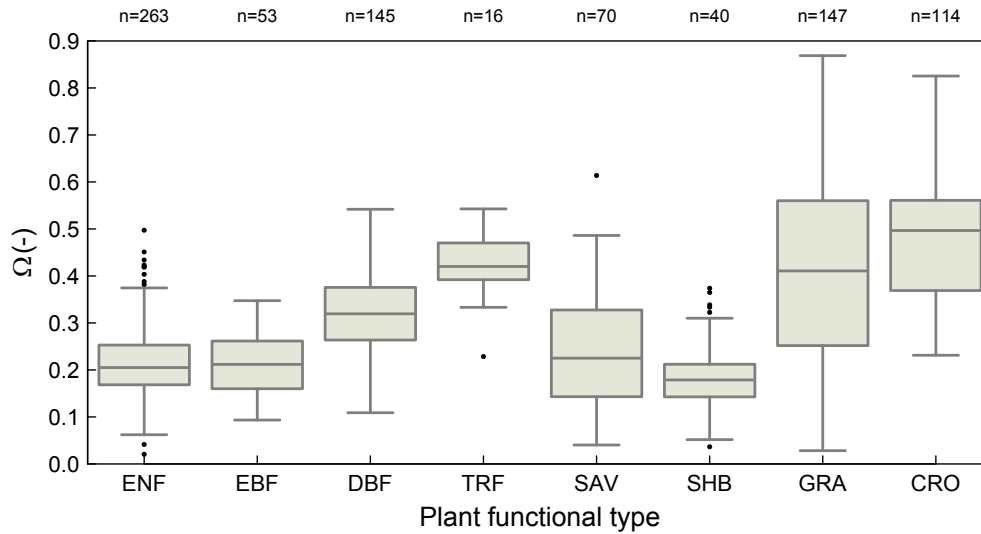


Figure A1. Box and whisker plot (line, median; box, inter-quartile range) showing the estimated coupling coefficient (Ω) from FLUXNET2015 data, grouped by plant functional type. Whiskers extend to 1.5 times the inter-quartile range, with dots outside of the whiskers showing outliers. Plant functional types are defined as: ENF - evergreen needle leaved forest, EBF - evergreen broadleaved forest, DBF - deciduous broadleaved forest, TRF - tropical rain forest, SAV - savanna, SHB - shrub, GRA - grasses, C3C - C₃ crops, C4C - C₄ crops. Values of n indicate the number of site-years for FLUXNET.

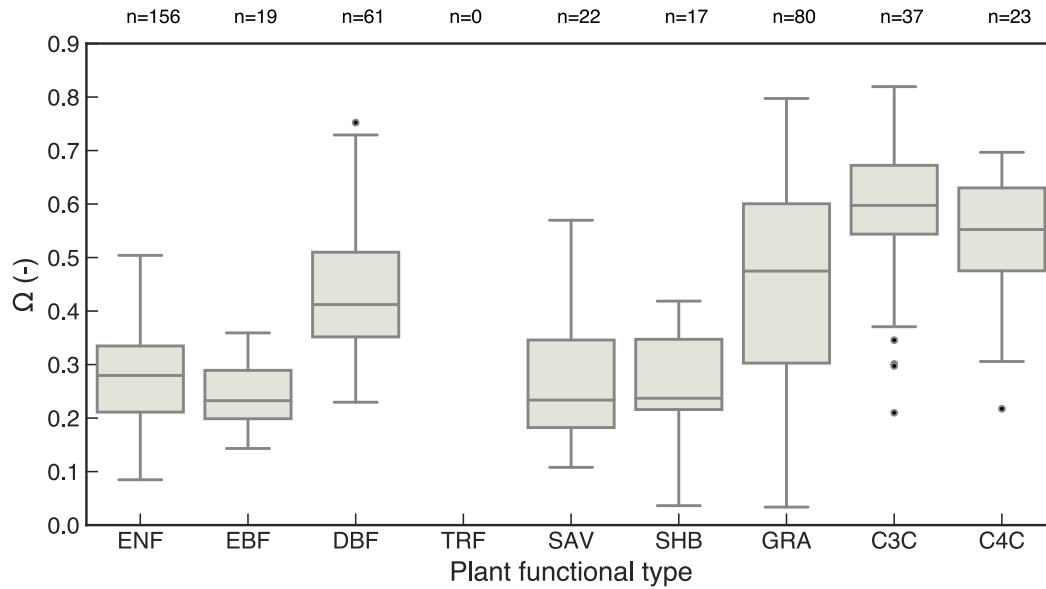


Figure A2. Box and whisker plot (line, median; box, inter-quartile range) showing the estimated coupling coefficient (Ω) from FLUXNET data, grouped by plant functional type. These data have been corrected for energy imbalance, adjusting the Bowen-ratio by the imbalance across the three most productive months. Whiskers extend to 1.5 times the inter-quartile range, with dots outside of the whiskers showing outliers. Plant functional types are defined as: ENF - evergreen needle leaved forest, EBF - evergreen broadleaved forest, DBF - deciduous broadleaved forest, TRF - tropical rain forest, SAV - savanna, SHB - shrub, GRA - grasses, C3C - C₃ crops, C4C - C₄ crops. Values of n indicate the number of site-years for FLUXNET.

Table A1: FLUXNET site years used in analysis.

<u>Site ID</u>	<u>Years</u>
<u>AT-Neu</u>	<u>2002 2003 2004 2005</u>
<u>AU-How</u>	<u>2001 2002 2003 2004 2006</u>
<u>AU-Tum</u>	<u>2001 2002 2003 2004 2005 2006</u>
<u>AU-Wac</u>	<u>2005 2006 2007</u>
<u>BE-Lon</u>	<u>2004 2005 2006</u>
<u>BW-Ghg</u>	<u>2003</u>
<u>BW-Ghm</u>	<u>2003</u>
<u>BW-Ma1</u>	<u>1999 2000 2001</u>
<u>CA-Ca1</u>	<u>1998 1999 2000 2001 2002 2003 2004 2005</u>
<u>CA-Ca3</u>	<u>2001 2002 2003 2004 2005</u>
<u>CA-Let</u>	<u>1998 1999 2000 2001 2002 2003 2004 2005</u>
<u>CA-Man</u>	<u>1994 1995 1997 1998 1999 2000 2001 2002 2003</u>
<u>CA-NS1</u>	<u>2002 2003 2004</u>
<u>CA-NS2</u>	<u>2002 2003 2004 2005</u>
<u>CA-NS3</u>	<u>2001 2002 2004 2005</u>
<u>CA-NS4</u>	<u>2003 2004</u>
<u>CA-NS5</u>	<u>2001 2002 2003 2004 2005</u>
<u>CA-NS6</u>	<u>2001 2002 2003 2004 2005</u>
<u>CA-Oas</u>	<u>1997 1999 2000 2001 2002 2003 2004 2005</u>
<u>CA-Obs</u>	<u>1999 2000 2001 2002 2003 2004 2005</u>
<u>CA-Ojp</u>	<u>1999 2000 2001 2002 2003 2004 2005</u>
<u>CA-Qfo</u>	<u>2003 2004 2005 2006</u>
<u>CA-SF1</u>	<u>2003 2004 2005</u>
<u>CA-SF2</u>	<u>2003 2004 2005</u>
<u>CA-SJ1</u>	<u>2003 2004 2005</u>
<u>CA-SJ2</u>	<u>2005</u>
<u>CA-SJ3</u>	<u>2005</u>
<u>CA-TP4</u>	<u>2003 2004 2005</u>
<u>CG-Tch</u>	<u>2006</u>
<u>CH-Oe1</u>	<u>2003 2004 2005</u>
<u>CN-Du1</u>	<u>2005 2006</u>
<u>CN-Du2</u>	<u>2006</u>

Table A1 continued from previous page

<u>Site ID</u>	<u>Years</u>
<u>CN-HaM</u>	<u>2002 2003</u>
<u>CN-Xi1</u>	<u>2006</u>
<u>CN-Xi2</u>	<u>2006</u>
<u>CZ-BK1</u>	<u>2004 2005</u>
<u>CZ-BK2</u>	<u>2004</u>
<u>DE-Bay</u>	<u>1996 1997 1998 1999</u>
<u>DE-Geb</u>	<u>2004 2005 2006</u>
<u>DE-Gri</u>	<u>2005 2006</u>
<u>DE-Hai</u>	<u>2000 2001 2002 2003 2004 2005 2006</u>
<u>DE-Har</u>	<u>2005 2006</u>
<u>DE-Kli</u>	<u>2004 2005 2006</u>
<u>DE-Meh</u>	<u>2003 2004 2005 2006</u>
<u>DE-Tha</u>	<u>1996 1997 1998 1999 2000 2001 2002 2003 2004 2005</u>
<u>DE-Wet</u>	<u>2002 2003 2004 2005 2006</u>
<u>DK-Fou</u>	<u>2005</u>
<u>DK-Lva</u>	<u>2005</u>
<u>DK-Ris</u>	<u>2004</u>
<u>DK-Sor</u>	<u>2004 2005</u>
<u>ES-ES1</u>	<u>2000 2002 2003 2004 2005 2006</u>
<u>ES-ES2</u>	<u>2004 2005 2006</u>
<u>ES-LMa</u>	<u>2004 2005 2006</u>
<u>ES-VDA</u>	<u>2004 2005 2006</u>
<u>FI-Hyy</u>	<u>1998 1999 2000 2001 2002 2003 2004 2006</u>
<u>FI-Sod</u>	<u>2002 2003 2004 2005 2006</u>
<u>FR-Aur</u>	<u>2005</u>
<u>FR-Fon</u>	<u>2005 2006</u>
<u>FR-Gri</u>	<u>2005 2006</u>
<u>FR-Hes</u>	<u>1997 1998 1999 2000 2001 2002 2003 2004 2005 2006</u>
<u>FR-LBr</u>	<u>1996 1997 1998 2000 2003 2004 2005 2006</u>
<u>FR-Lam</u>	<u>2005</u>
<u>FR-Lq1</u>	<u>2005</u>
<u>FR-Lq2</u>	<u>2004 2005</u>

Table A1 continued from previous page

<u>Site ID</u>	<u>Years</u>
<u>FR-Pue</u>	<u>2000 2001 2002 2003 2004 2005 2006</u>
<u>GF-Guy</u>	<u>2004 2005 2006</u>
<u>HU-Bug</u>	<u>2002 2003 2004 2005 2006</u>
<u>HU-Mat</u>	<u>2004 2005 2006</u>
<u>ID-Pag</u>	<u>2002 2003</u>
<u>IE-Cal</u>	<u>2004 2005 2006</u>
<u>IE-Dri</u>	<u>2004 2005</u>
<u>IL-Yat</u>	<u>2001 2002 2003 2006</u>
<u>IS-Gun</u>	<u>1996 1997 1998</u>
<u>IT-Amp</u>	<u>2002 2003 2004 2005 2006</u>
<u>IT-BCi</u>	<u>2005 2006</u>
<u>IT-Be2</u>	<u>2006</u>
<u>IT-Cas</u>	<u>2006</u>
<u>IT-Col</u>	<u>1998 1999 2004 2005 2006</u>
<u>IT-Cpz</u>	<u>1997 2000 2001 2002 2003 2004 2005 2006</u>
<u>IT-LMa</u>	<u>2004 2005 2006</u>
<u>IT-Lav</u>	<u>2004 2006</u>
<u>IT-MBo</u>	<u>2003 2004 2005 2006</u>
<u>IT-Mal</u>	<u>2004</u>
<u>IT-Noe</u>	<u>2004 2005 2006</u>
<u>IT-Non</u>	<u>2001 2002 2003 2006</u>
<u>IT-PT1</u>	<u>2003 2004</u>
<u>IT-Ren</u>	<u>2000 2001 2002 2003 2004</u>
<u>IT-Ro1</u>	<u>2000 2002 2003 2004 2005 2006</u>
<u>IT-Ro2</u>	<u>2004 2005 2006</u>
<u>IT-SRo</u>	<u>2000 2002 2003 2004 2005 2006</u>
<u>IT-Vig</u>	<u>2004</u>
<u>JP-Mas</u>	<u>2002 2003</u>
<u>NL-Cal</u>	<u>2003 2004 2005 2006</u>
<u>NL-Hor</u>	<u>2006</u>
<u>NL-Lan</u>	<u>2005</u>
<u>NL-Loo</u>	<u>1996 1997 1998 1999 2001 2002 2003 2004 2006</u>

Table A1 continued from previous page

<u>Site ID</u>	<u>Years</u>
<u>PT-Esp</u>	<u>2002 2004 2006</u>
<u>PT-Mi1</u>	<u>2005</u>
<u>PT-Mi2</u>	<u>2004 2005 2006</u>
<u>RU-Cok</u>	<u>2005</u>
<u>RU-Fyo</u>	<u>1998 1999 2002 2003 2004 2005 2006</u>
<u>RU-Ha1</u>	<u>2003 2004</u>
<u>RU-Zot</u>	<u>2002 2003 2004</u>
<u>SE-Abi</u>	<u>2005</u>
<u>SE-Fla</u>	<u>1996 1997 1998 2001 2002</u>
<u>SE-Nor</u>	<u>1996 1997 1998 2005</u>
<u>UK-EBu</u>	<u>2004</u>
<u>UK-ESa</u>	<u>2004 2005</u>
<u>UK-Gri</u>	<u>1998 2000 2001 2006</u>
<u>UK-Ham</u>	<u>2004 2005</u>
<u>UK-Her</u>	<u>2006</u>
<u>UK-PL3</u>	<u>2005 2006</u>
<u>US-ARM</u>	<u>2003 2004 2005 2006</u>
<u>US-Aud</u>	<u>2002 2003 2004 2005 2006</u>
<u>US-Bar</u>	<u>2004 2005</u>
<u>US-Bkg</u>	<u>2004 2005 2006</u>
<u>US-Blo</u>	<u>1997 1998 1999 2000 2001 2002 2003 2004 2005</u>
<u>US-Bn1</u>	<u>2003</u>
<u>US-Bn2</u>	<u>2003</u>
<u>US-Bo1</u>	<u>1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007</u>
<u>US-Bo2</u>	<u>2004 2005 2006</u>
<u>US-CaV</u>	<u>2004 2005</u>
<u>US-Dk1</u>	<u>2001 2002 2003 2004 2005</u>
<u>US-Dk2</u>	<u>2003 2004</u>
<u>US-Dk3</u>	<u>2001 2002 2003 2004 2005</u>
<u>US-FPe</u>	<u>2000 2001 2002 2003 2004 2005 2006</u>
<u>US-Fmf</u>	<u>2005 2006</u>
<u>US-Fuf</u>	<u>2005 2006</u>

Table A1 continued from previous page

<u>Site ID</u>	<u>Years</u>
<u>US-Fwf</u>	<u>2005 2006</u>
<u>US-Goo</u>	<u>2002 2003 2004 2005 2006</u>
<u>US-Ha1</u>	<u>1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2003 2005 2006</u>
<u>US-Ho1</u>	<u>1996 1997 1998 1999 2000 2001 2002 2003</u>
<u>US-IB1</u>	<u>2005 2006 2007</u>
<u>US-IB2</u>	<u>2004 2006 2007</u>
<u>US-KS1</u>	<u>2002</u>
<u>US-KS2</u>	<u>2002 2003 2004 2005 2006</u>
<u>US-MMS</u>	<u>2000 2001 2002</u>
<u>US-MOz</u>	<u>2004 2005 2006</u>
<u>US-Me2</u>	<u>2003 2004 2005</u>
<u>US-Me3</u>	<u>2004 2005</u>
<u>US-Me4</u>	<u>2000</u>
<u>US-NC2</u>	<u>2005 2006</u>
<u>US-NR1</u>	<u>1999 2000 2002 2003</u>
<u>US-Ne1</u>	<u>2001 2002 2003 2004 2005</u>
<u>US-Ne2</u>	<u>2001 2002 2003 2004 2005</u>
<u>US-Ne3</u>	<u>2001 2002 2003 2004</u>
<u>US-SO2</u>	<u>1997 1998 1999 2004 2005 2006</u>
<u>US-SO3</u>	<u>1997 1998 2005 2006</u>
<u>US-SP1</u>	<u>2005</u>
<u>US-SP3</u>	<u>1999 2000 2001 2002 2003 2004</u>
<u>US-SP4</u>	<u>1998</u>
<u>US-SRM</u>	<u>2004 2005 2006</u>
<u>US-Ton</u>	<u>2001 2002 2003 2004 2005 2006</u>
<u>US-UMB</u>	<u>1999 2000 2001 2002 2003</u>
<u>US-Var</u>	<u>2001 2002 2003 2004 2005 2006</u>
<u>US-WCr</u>	<u>1999 2000 2001 2002 2003 2004 2005 2006</u>
<u>US-Wi1</u>	<u>2003</u>
<u>US-Wi2</u>	<u>2003</u>
<u>US-Wi4</u>	<u>2003 2004 2005</u>
<u>US-Wi5</u>	<u>2004</u>

Table A1 continued from previous page

<u>Site ID</u>	<u>Years</u>
<u>US-Wi9</u>	<u>2004 2005</u>
<u>US-Wkg</u>	<u>2004 2005 2006</u>
<u>US-Wrc</u>	<u>1998 1999 2000 2001 2002 2004 2005 2006</u>
<u>VU-Coc</u>	<u>2001 2002 2003 2004</u>

Table A2: Literature summary of decoupling coefficients. Where possible we have summarised data from the growing season during daylight hours. Plant functional types (PFT) are defined as: ENF - evergreen needle leaved forest, EBF - evergreen broadleaved forest, DBF - deciduous broadleaved forest, TRF - tropical rain forest, SAV - savanna, SHB - shrub, GRA - grasses, C3C - C₃ crops, C4C - C₄ crops. Where E is transpiration, u_* is the frictional velocity, EC is eddy covariance, PM is Penman-Monteith, R_{tot} is the total resistance, R_a is the aerodynamic resistance, PAR is Photosynthetically Active Radiation and TC is the total conductance. The simple gradient approach refers to an estimation of G_s from vapour pressure deficit, pressure, and transpiration. Method refers to the approach to estimating Ω : (1) - default, as in this manuscript (amphistomatous vegetation); (2) hypostomatous vegetation; and (3) accounting for radiative coupling following Martin (1989).

PFT	Dominant species	Ω	Scale	Method	G_a	G_b	G_s	Reference
ENF	<i>Abies amabilis</i>	0.18	Stand	2	f(wind, roughness, radiation)	f(wind)	Inverted PM with sap flow	Martin et al. (2001)
ENF	<i>Callitris glaucophylla</i> J.Thompson	0.15	Canopy	1	f(wind, roughness)	---	Inverted PM, E from sap flow	Zeppel and Eamus (2008)
ENF	<i>Chamaecyparis obtusa</i>	0.21	Canopy	1	f(wind, u_*)	---	Inverted PM, E from EC	Kosugi et al. (2007)
ENF	<i>Picea glauca</i>	0.4	Stand	1	f(wind, u_*)	---	Simplified PM with sap flow	Bladon et al. (2006)
ENF	<i>Picea abies</i>	0.19	Canopy	1	Inversion bulk transfer of sensible heat (EC)	---	Inversion bulk transfer of sensible and latent heat (EC)	Goldberg and Bernhofer (2002)
ENF	<i>Picea crassifolia</i>	0.06	Canopy	1	f(wind, u_*)	---	Inverted PM, E from EC	Gaofeng et al. (2014)
ENF	<i>Pinus elliotti</i>	0.43	Canopy	1	f(wind, roughness)	f(u_*)	Inverted PM, E from EC	Bracho et al. (2008)

Table A2 continued from previous page

<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
<u>ENF</u>	<u><i>Pinus pinaster</i></u>	<u>0.08</u>	<u>Stand</u>	<u>1</u>	<u>Empirical reln. between G_a & wind</u>	<u>—</u>	<u>Inverted PM, E from sap flow</u>	<u>Loustau et al. (1996)</u>
<u>ENF</u>	<u><i>Pinus sylvestris</i></u>	<u>0.1</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, height)</u>	<u>—</u>	<u>Leaf gas exchange</u>	<u>Whitehead et al. (1984)</u>
<u>ENF</u>	<u><i>Pinus sylvestris</i></u>	<u>0.32</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>—</u>	<u>Inverted PM, E from EC</u>	<u>Launiainen (2010)</u>
<u>ENF</u>	<u><i>Pinus taeda</i></u>	<u>0.25</u>	<u>Canopy</u>	<u>1</u>	<u>f(roughness, u_*)</u>	<u>f(characteristic leaf dimension, wind)</u>	<u>Bottom-up model: f(VPD, LAI & radiation)</u>	<u>Stoy et al. (2006)</u>
<u>ENF</u>	<u><i>Pseudotsuga menziesii</i></u>	<u>0.26</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>—</u>	<u>Inverted PM, E from EC</u>	<u>Jassal et al. (2009)</u>
<u>ENF</u>	<u><i>Pseudotsuga menziesii</i></u>	<u>0.15</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>—</u>	<u>Inverted PM, E from EC</u>	<u>Lee and Black (1993)</u>
<u>EBF</u>	<u><i>Acacia ampliceps</i></u>	<u>0.28</u>	<u>Stand</u>	<u>3</u>	<u>Empirical relationship between G_a & wind speed</u>	<u>—</u>	<u>Inverted (simplified) PM, E from sap flow</u>	<u>Mahmood et al. (2001)</u>
<u>EBF</u>	<u><i>Azadirachta indica</i></u>	<u>0.28</u>	<u>Tree</u>	<u>2</u>	<u>f(leaf temperature)</u>	<u>—</u>	<u>Inverted (Simplified) PM from sap flow</u>	<u>Smith et al. (1998)</u>

Table A2 continued from previous page

<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
EBF	<i>Citrus limon</i>	0.12	Stand	1	f(wind, u_*)	—	$R_{tot} - R_a, R_{tot}$ from simplified PM, E from sap flow	Nicolás et al. (2008)
EBF	<i>Eucalyptus camaldulensis</i>	0.33	Stand	3	Empirical relationship between G_a & wind speed	—	Inverted (simplified) PM, E from sap flow	Mahmood et al. (2001)
EBF	<i>Eucalyptus crebra</i> F.Muell.	0.19	Canopy	1	f(wind, roughness)	—	Inverted PM, E from sap flow	Zeppel and Eamus (2008)
EBF	<i>Eucalyptus globulus</i>	0.63	Stand	1	TC - G_s	—	Simple gradient approach, E from sap flow	White et al. (2000)
EBF	<i>Eucalyptus grandis</i>	0.28	Stand	1	f(wind, u_*)	—	$R_{tot} - R_a, R_{tot}$ from simplified PM, E from sap flow	Mielke et al. (1999)
EBF	<i>Eucalyptus urophylla</i>	0.1	Stand	1	f(wind, roughness)	—	Inverted PM, E from sap flow	Zhang et al. (2016)

Table A2 continued from previous page

<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
<u>EBF</u>	<u><i>Nothofagus fusca</i></u>	<u>0.24</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>—</u>	<u>Stomatal conductance from gas exchange upscaled by leaf area</u>	<u>Köstner et al. (1992)</u>
<u>EBF</u>	<u><i>Quercus</i></u>	<u>0.3</u>	<u>Canopy</u>	<u>1</u>	<u>f(roughness, u_*)</u>	<u>f(characteristic leaf dimension, wind)</u>	<u>Bottom-up model: f(VPD, LAI & PAR)</u>	<u>Stoy et al. (2006)</u>
<u>EBF</u>	<u><i>Schima superba</i></u>	<u>0.22</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>—</u>	<u>Inverted PM, E from sap flow</u>	<u>Zhang et al. (2016)</u>
<u>EBF</u>	<u><i>Vaccinium vitis-idaea</i></u>	<u>0.2</u>	<u>Canopy (understorey only)</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>—</u>	<u>Inverted PM, E from EC</u>	<u>Iida et al. (2009)</u>
<u>DBF</u>	<u><i>Acer rubrum</i></u>	<u>0.23</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>f(u_*)</u>	<u>Inverted PM, E from sap flow</u>	<u>Wullschleger et al. (2000)</u>
<u>DBF</u>	<u><i>Betula papyrifera</i></u>	<u>0.36</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>—</u>	<u>Simplified PM from sap flow</u>	<u>Bladon et al. (2006)</u>

Table A2 continued from previous page

<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
<u>DBF</u>	<u><i>Fagus sylvatica</i></u>	<u>0.28</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>f(leaf size)</u>	<u>Bottom-up model: f(VPD, maximum G_s, temperature and radiation)</u>	<u>Magnani et al. (1998)</u>
<u>DBF</u>	<u><i>Fagus crenata</i></u>	<u>0.3</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>f(characteristic leaf dimension, wind)</u>	<u>Inverted PM, E from sap flow</u>	<u>Tateishi et al. (2010)</u>
<u>DBF</u>	<u><i>Fagus sylvatica</i></u>	<u>0.2</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>—</u>	<u>Inverted PM, E from the Bowen ratio</u>	<u>Herbst (1995)</u>
<u>DBF</u>	<u><i>Juglans regia</i></u>	<u>0.37</u>	<u>Tree</u>	<u>2</u>	<u>—</u>	<u>f(leaf temperature, roughness)</u>	<u>Modelled following Jarvis (1976) and upscaled</u>	<u>Daudet et al. (1999)</u>
<u>DBF</u>	<u><i>Populus balsamifera</i></u>	<u>0.4</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>—</u>	<u>Simplified PM with sap flow</u>	<u>Bladon et al. (2006)</u>
<u>DBF</u>	<u><i>Populus trichocarpa x P. deltoides</i></u>	<u>0.66</u>	<u>Canopy</u>	<u>3</u>	<u>TC - G_s</u>	<u>—</u>	<u>Simple gradient approach, E from sap flow</u>	<u>Hinckley et al. (1994)</u>
<u>DBF</u>	<u><i>Quercus petraea</i></u>	<u>0.1</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>—</u>	<u>Inverted PM, E from EC</u>	<u>Granier and Bréda (1996)</u>

Table A2 continued from previous page

<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
<u>DBF</u>	<u><i>Salix viminalis</i></u>	<u>0.7</u>	<u>Canopy</u>	<u>1</u>	<u>Inverted PM when the canopy is wet</u>	<u>—</u>	<u>Inverted PM, E from sap flow</u>	<u>Lindroth (1993)</u>
<u>DBF</u>	<u>—</u>	<u>0.41</u>	<u>Canopy</u>	<u>1</u>	<u>Surface layer similarity</u>	<u>$f(u_*)$</u>	<u>Inverted PM, E using the Bowen ratio (EC)</u>	<u>Wilson and Baldocchi (2000)</u>
<u>TRF</u>	<u><i>Anacardium excelsum</i></u>	<u>0.75</u>	<u>Tree</u>	<u>2</u>	<u>TC – G_s</u>	<u>—</u>	<u>Leaf gas exchange</u>	<u>Meinzer et al. (1993)</u>
<u>TRF</u>	<u><i>Cecropia longipes</i></u>	<u>0.9</u>	<u>Tree</u>	<u>2</u>	<u>TC – G_s & stomatal conductance</u>	<u>—</u>	<u>Leaf gas exchange</u>	<u>Meinzer et al. (1997)</u>
<u>TRF</u>	<u><i>Ficus insipida</i></u>	<u>0.82</u>	<u>Tree</u>	<u>2</u>	<u>TC – G_s</u>	<u>—</u>	<u>Leaf gas exchange</u>	<u>Meinzer et al. (1997)</u>
<u>TRF</u>	<u><i>Hedyosmum anisodorum</i> <i>Todzia</i></u>	<u>0.37</u>	<u>Leaf</u>	<u>1</u>	<u>—</u>	<u>$f(\text{wind, leaf extension})$</u>	<u>Leaf gas exchange</u>	<u>Motzer et al. (2005)</u>
<u>TRF</u>	<u><i>Luehea seemanii</i></u>	<u>0.88</u>	<u>Tree</u>	<u>2</u>	<u>TC – G_s</u>	<u>—</u>	<u>Leaf gas exchange</u>	<u>Meinzer et al. (1997)</u>
<u>TRF</u>	<u><i>Naucleopsis</i> sp.</u>	<u>0.27</u>	<u>Leaf</u>	<u>1</u>	<u>—</u>	<u>$f(\text{wind, leaf extension})$</u>	<u>Leaf gas exchange</u>	<u>Motzer et al. (2005)</u>
<u>TRF</u>	<u><i>Psychotria brachiata</i> Ruiz & Pav.</u>	<u>0.27</u>	<u>Leaf</u>	<u>1</u>	<u>—</u>	<u>$f(\text{wind, leaf extension})$</u>	<u>Leaf gas exchange</u>	<u>Motzer et al. (2005)</u>

Table A2 continued from previous page

<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
<u>TRF</u>	<u><i>Ruagea cf. pubescens</i> H. Karst.</u>	<u>0.25</u>	<u>Leaf</u>	<u>1</u>	<u>—</u>	<u>f(wind, leaf extension)</u>	<u>Leaf gas exchange</u>	<u>Motzer et al. (2005)</u>
<u>TRF</u>	<u><i>Spondias mombin</i></u>	<u>0.9</u>	<u>Tree</u>	<u>2</u>	<u>TC — G_s</u>	<u>—</u>	<u>Leaf gas exchange</u>	<u>Meinzer et al. (1997)</u>
<u>TRF</u>	<u><i>Trichilia guianensis</i> Klotzsch</u>	<u>0.43</u>	<u>Leaf</u>	<u>1</u>	<u>—</u>	<u>f(wind, leaf extension)</u>	<u>Leaf gas exchange</u>	<u>Motzer et al. (2005)</u>
<u>TRF</u>	<u>—</u>	<u>0.43</u>	<u>Canopy</u>	<u>1</u>	<u>TC — G_a — f(wind, u_*)</u>	<u>—</u>	<u>Inverted PM, E from EC</u>	<u>Kumagai et al. (2004)</u>
<u>SAV</u>	<u>—</u>	<u>0.14</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>—</u>	<u>Inverted PM, E from EC</u>	<u>San José et al. (1995)</u>
<u>SHB</u>	<u><i>Quer juliflora</i></u>	<u>0.13</u>	<u>Stand</u>	<u>3</u>	<u>Empirical relationship between G_a & wind speed</u>	<u>—</u>	<u>Inverted (simplified) PM, E from sap flow</u>	<u>Mahmood et al. (2001)</u>
<u>SHB</u>	<u><i>Quercus sp.</i></u>	<u>0.4</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>f(u_*)</u>	<u>Inverted PM, E from EC</u>	<u>Bracho et al. (2008)</u>
<u>GRA</u>	<u><i>Brachiaria brizantha</i></u>	<u>0.5</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>f(u_*)</u>	<u>Inverted PM, E from EC</u>	<u>Meirelles et al. (2011)</u>

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<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
<u>ENF</u>	<u><i>Festuca arundinaria</i> Shreb.</u>	<u>0.34</u>	<u>Canopy</u>	<u>1</u>	<u>f(roughness, u_*)</u>	<u>f(characteristic leaf dimension, wind)</u>	<u>Bottom-up model: f(VPD, LAI & radiation)</u>	<u>Stoy et al. (2006)</u>
<u>GRA</u>	<u><i>Phragmites australis</i></u>	<u>0.48</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>f(u_*)</u>	<u>Inverted PM, E from EC</u>	<u>Zhou et al. (2010)</u>
<u>GRA</u>	<u>—</u>	<u>0.45</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>—</u>	<u>Inversion bulk transfer of sensible and latent heat (EC)</u>	<u>Goldberg and Bernhofer (2002)</u>
<u>GRA</u>	<u>—</u>	<u>0.49</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>f(u_*)</u>	<u>Inverted PM, E from EC</u>	<u>Aires et al. (2008)</u>
<u>GRA</u>	<u>—</u>	<u>0.31</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>f(u_*)</u>	<u>Inverted PM, E from EC</u>	<u>Hao et al. (2007)</u>
<u>GRA</u>	<u>—</u>	<u>0.21</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, u_*)</u>	<u>f(u_*)</u>	<u>Inverted PM, E from EC</u>	<u>Wever et al. (2002)</u>
<u>C3C</u>	<u><i>Crotalaria juncea</i></u>	<u>0.59</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>—</u>	<u>Inverted PM, E from Bowen Ratio energy balance method</u>	<u>Takagi et al. (2009)</u>

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<u>PFT</u>	<u>Dominant species</u>	<u>Ω</u>	<u>Scale</u>	<u>Method</u>	<u>G_a</u>	<u>G_b</u>	<u>G_s</u>	<u>Reference</u>
<u>C3C</u>	<u><i>Musa sp.</i></u>	<u>0.2</u>	<u>Stand</u>	<u>1</u>	<u>f(wind, characteristic leaf dimension, LAI)</u>	<u>—</u>	<u>Inverted PM, E from sap flow Ratio energy balance method</u>	<u>Haijun et al. (2015)</u>
<u>C4C</u>	<u><i>Zea mays</i></u>	<u>0.58</u>	<u>Canopy</u>	<u>1</u>	<u>f(wind, roughness)</u>	<u>f(u*)</u>	<u>Inverted PM, E from Bowen Ratio energy balance method</u>	<u>Steduto and Hsiao (1998)</u>