A summary of the key changes are as follows:

- Added literature summary table from 41.
- Added site summary table to the appendix (A2).
- Adjusted figure symbols, legend, layout in Figs. 2 & 3 as requested. We have also coloured forest PFT types in Fig. 4 to assist the reader.
- Added missing C4C category to fig. 1, A1 & A2.
- As we do not attempt to define C4 grass fractions at flux sites, we rename the grass PFT (GRA), where previously it had been labelled C3 Grass (C3G).
- Added additional sites that were mistakenly screened to Fig. 3. This does not alter the original patterns or conclusions drawn (see below).
- Corrected the number of sites and site-years reported in the methods. In the original submission these were calculated before we excluded mixed forest, wetland and unclassified PFTs and so did not match the total shown in Fig. 1.

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

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

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

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

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

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

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

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

To the route forward section, we have added: “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.”

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

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

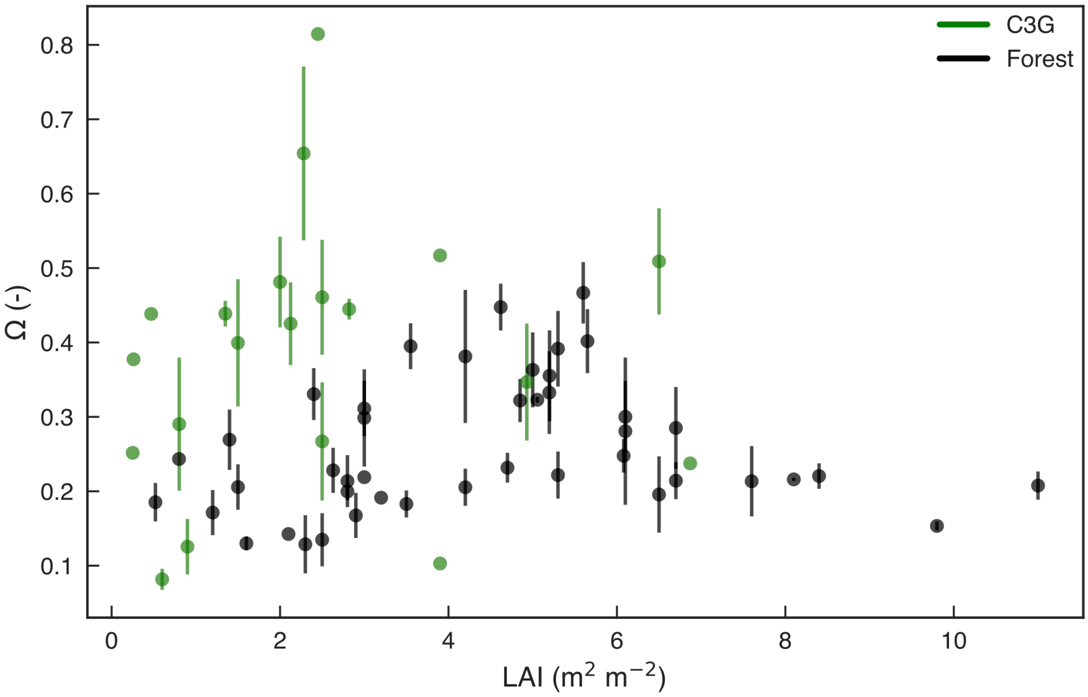
R: Further, I though the authors might have missed an opportunity to leverage the high-frequency data from FLUXNET to say something about temporal variation in decoupling over the course of a typical day.

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

We have added to the Route forward section: "In this study we examined the long-term average coupling factor. It may also be instructive to consider how estimated 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."

R: Finally, in paragraph 10, the authors state that LAI information for many sites is not available. Many FLUXNET sites have high-quality ground-based LAI measurements that are not reported to the network. Sometimes an email to the site PIs can turn up useful ancillary data.

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



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

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

Main Points:

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

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

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

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

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

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

R: (4) The FLUXNET La Thuile data used here is relatively outdated (from 2007) and only includes a limited number of sites (as Free and Fair use subset). Yet the newer and more extensive FLUXNET2015 dataset is available since late 2015 (same website as referred to in Methods section), but including many more sites and site years compared to the 2007 La Thuile dataset (~1000 vs. ~1500 site years), and also including a subset with a similar data policy (TIER1). I am wondering what the reasoning behind this choice of older dataset was and if the manuscript would not benefit from the larger sampling available in the newer dataset, particularly in terms of important PFTs (e.g. TRF) that were poorly represented in the 2007 dataset? It would also benefit the manuscript to have a table of the eventually retained sites (after data screening – see Section 2.1), their used site years and PFT etc. in the Appendix, something that is typically recommended when using the FLUXNET dataset.

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

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

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

To the end of the methods section we have added: “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.”

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

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

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

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

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

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

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

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

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

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

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

Specific Comments:

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

A: We have added: “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)”.

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

A: For each of the screening choices we have now added an explanation: “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 have also added to the methods: “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.”

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

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

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

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

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

A: We have removed “low”.

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

A: We have added the missing “global”.

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

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

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

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

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

A: We have removed “network”.

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

A: We have fixed the Knauer et al. reference

R: - Page 6, Line 32: "that" seems redundant here

A: We have removed "that".

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

A: See earlier response about FLUXNET 2015.

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

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

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

A: These data are not sufficient to probe the questions we posed, in many cases, particular with canopy/tower height, this information is simply not available at all sites (presumably this is covered by: (i) "At present only the variables of Site_General_Info and Disturbance_and_Management are made available; and (ii) "Additional BADM variables such as LAI, biomass measurements and soil characteristics will be added to the BADM files over time"). The LAI information is also problematic: we do not know how or when these data were measured (LAI-2000, hemispherical photography, other?), we do not know if they are LAI or really plant area index (i.e. not corrected for a woody component, or clumping), we do not know the sampling footprint these data represent and finally we cannot trace the origins of these data. For these reasons, we chose to instead analyse the decoupling in relation to precipitation (a proxy for LAI). We included a figure in response to reviewer 1 to demonstrate some agreement with our figure 3. However, due to the issues we raise above we feel it is more appropriate to stick with our analysis framework. If the reviewer wishes we could include this in the supplementary.

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

A: We have now added: “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, which would advance our understanding of the processes involved in scaling from the leaf to the canopy.”

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

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

R: - Figure 2: please consider (i) moving site names outside graph as axis caption (i.e. this is a categorical axis), (ii) separating the three groups a-c by vertical lines, (iii) removing selective ticks on x-axis OR adding one for every single site, and (iv) adding details on the meaning of the whiskers in the caption text.

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

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

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

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

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

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

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 CO_2. 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 41 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 forestsappear 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. We~~ 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 to a lesser extent, 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.

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, 1983; 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, Ω = ~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 Hyytiäläsite in Finland~~. Values are typically higher for deciduous broadleaved: Ω = 0.2-0.4 (Magnani et al., 1998; Wullschleger et al., 2000), evergreen broadleaved species: Ω = 0.4-0.9 ~~(Meinzer et al., 1997; Wullschleger et al., 1998; Cienciala et al., 2000)~~(Meinzer et al., 1997; W
, grasses: Ω = 0.8 (McNaughton and Jarvis, 1983), and crops: Ω = 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)~~(e.g. Stoy et al., 2006; Khatun et al., 2011).

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:

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

where ϵ = s / γ, 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 $^{-1}$)~~G_a (mol m^{-2} s^{-1}) is the aerodynamic conductance.

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:

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

where ~~G_a (mol m^{-2} s^{-1}) is the canopy aerodynamic conductance,~~ E (mol m^{-2} s^{-1}) is the canopy transpiration, ~~γ is the psychrometric constant (Pa K~~λ is the latent heat of vaporisation (J mol^{-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 (J kg^{-1} K^{-1}). At sites where values of G were not available, G was set to zero.

G_a was calculated following Thom (1975):

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

where the first term in the denominator of Eq. 3 represents the turbulent aerodynamic resistance (G_{am}), and the second term the canopy boundary layer component (G_b), $c = P / (R_{gas}\ T_k)$ is a conversion factor from units of m s^{-1} to mol m^{-2} s^{-1}, P is atmospheric pressure (Pa), R_{gas} is the gas constant (J mol^{-1} 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.

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.

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 fluxes using the Bowen-ratio method (each half-hourly LE and H flux) based on the available energy (Rn–G) on a longer time scale (three most productive months).

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 41 studies, in Tables 1 and 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 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 Ω = 0.21) as opposed to the literature review, which suggested ENF PFTs were the most coupled (mean Ω = 0.19). The FLUXNET data also indicated unexpectedly wide ranges for Ω within PFTs. For grasses, Ω ranged from 0.02–0.8; the number of low values was particular surprising, 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).~~

~~Among ENF sites, the range~~

The wide range in estimated values ~~shown in Fig. 1 was striking, extending from ∼~~for ENF sites was also striking; Ω extended from 0.05 to ~~∼0.4~~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 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 ~~C_3~~ grasses we found a significant relationship between 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 ~~C_3~~ 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, 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.

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 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 $\sim$~~0.4~~ 0.44 to $\sim$0.6) and ~~shrubs~~ deciduous broadleaved forests (Ω changed from $\sim$~~0.2 to $\sim$0.3~~0.31 to $\sim$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 41 literature studies, 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.

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 micro-climate (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 (see Knauer et al., 2017). 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 using the Bowen-ratio method based on the available energy (Rn–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 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 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 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~~$_a$~~$_b$ based on leaf size (Su et al., 2001). A more fundamental process understanding will require targeted G_s 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, 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-thuile-dataset/

Competing interests. The authors declare no competing financial interests.

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References

Ainsworth, E. and Rogers, A.: The response of photosynthesis and stomatal conductance to rising $[CO_2]$: mechanisms and environmental interactions, Plant, Cell and Environment, 30, 258–270, doi:10.1111/j.1365-3040.2007.01641.x, 2007.

Aires, L., Pio, C., and Pereira, J.: The effect of drought on energy and water vapour exchange above a mediterranean C3/C4 grassland in Southern Portugal, Agricultural and Forest Meteorology, 148, 565–579, 2008.

Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, Geoscientific Model Discussions, 4, 677–699, 2011.

Betts, R., Boucher, O., Collins, M., Cox, P., Falloon, P., Gedney, N., Hemming, D., Huntingford, C., Jones, C., Sexton, D., and Webb, M. J.: Projected increase in continental runoff due to plant responses to increasing carbon dioxide, Nature, 448, 1037–1041, 2007.

Black, T. A., Tanner, C., and Gardner, W.: Evapotranspiration from a snap bean crop, Agronomy Journal, 62, 66–69, 1970.

Bladon, K. D., Silins, U., Landhäusser, S. M., and Lieffers, V. J.: Differential transpiration by three boreal tree species in response to increased evaporative demand after variable retention harvesting, Agricultural and forest meteorology, 138, 104–119, 2006.

Bracho, R., Powell, T. L., Dore, S., Li, J., Hinkle, C. R., and Drake, B. G.: Environmental and biological controls on water and energy exchange in Florida scrub oak and pine flatwoods ecosystems, Journal of Geophysical Research: Biogeosciences, 113, 2008.

Brown, K. W.: Vegetation and the Atmosphere, chap. Sugar beet and potatoes, Academic Press, London, 1976.

Cao, L., Bala, G., Caldeira, K., Nemani, R., and Ban-Weiss, G.: Importance of carbon dioxide physiological forcing to future climate change, PNAS, 107, 9513–9518, doi:10.1073/pnas.0913000107, 2010.

Cienciala, E., Kučera, J., and Malmer, A.: Tree sap flow and stand transpiration of two Acacia mangium plantations in Sabah, Borneo, Journal of Hydrology, 236, 109–120, 2000.

Daudet, F., Le Roux, X., Sinoquet, H., and Adam, B.: Wind speed and leaf boundary layer conductance variation within tree crown: consequences on leaf-to-atmosphere coupling and tree functions, Agricultural and Forest Meteorology, 97, 171–185, 1999.

De Kauwe, M. G., Medlyn, B. E., Zaehle, S., Walker, A. P., Dietze, M. C., Hickler, T., Jain, A. K., Luo, Y., Parton, W. J., Prentice, I. C., Smith, B., Thornton, P. E., Wang, S., Wang, Y.-P., Wårlind, D., Weng, E., Crous, K. Y., Ellsworth, D. S., Hanson, P. J., Seok Kim, H., Warren, J. M., Oren, R., and Norby, R. J.: Forest water use and water use efficiency at elevated CO_2: a model-data intercomparison at two contrasting temperate forest FACE sites, Global Change Biology, 19, 1759–1779, doi:10.1111/gcb.12164, 2013.

De Kauwe, M. G., Kala, J., Lin, Y.-S., Pitman, A. J., Medlyn, B. E., Duursma, R. A., Abramowitz, G., Wang, Y.-P., and Miralles, D. G.: A test of an optimal stomatal conductance scheme within the CABLE land surface model, Geoscientific Model Development, 8, 431–452, doi:10.5194/gmd-8-431-2015, 2015.

Dekker, S. C., Groenendijk, M., Booth, B. B. B., Huntingford, C., and Cox, P. M.: Spatial and temporal variations in plant water-use efficiency inferred from tree-ring, eddy covariance and atmospheric observations, Earth System Dynamics, 7, 525–533, 2016.

Foken, T.: The energy balance closure problem: an overview, Ecological Applications, 18, 1351–1367, 2008.

Gaofeng, Z., Ling, L., Yonghong, S., Xufeng, W., Xia, C., Jinzhu, M., Jianhua, H., Kun, Z., and Changbin, L.: Energy flux partitioning and evapotranspiration in a sub-alpine spruce forest ecosystem, Hydrological processes, 28, 5093–5104, 2014.

Gedney, N., Cox, P., Betts, R., Boucher, O., Huntingford, C., and Stott, P.: Detection of a direct carbon dioxide effect in continental river runoff records, Nature, 439, 835–838, doi:10.1038/nature04504, 2006.

Goldberg, V. and Bernhofer, C.: Testing different decoupling coefficients with measurements and models of contrasting canopies and soil water conditions, in: Annales geophysicae: atmospheres, hydrospheres and space sciences, vol. 26, p. 1977, 2008.

Granier, A. and Bréda, N.: Modelling canopy conductance and stand transpiration of an oak forest from sap flow measurements, in: Annales des Sciences Forestieres, vol. 53, pp. 537–546, EDP Sciences, 1996.

Groenendijk, M., Dolman, A., van der Molen, M., Leuning, R., Arneth, A., Delpierre, N., Gash, J., Lindroth, A., Richardson, A., Verbeeck, H., et al.: Assessing parameter variability in a photosynthesis model within and between plant functional types using global Fluxnet eddy covariance data, Agricultural and Forest Meteorology, 151, 22–38, 2011.

Haijun, L., Cohen, S., Lemcoff, J. H., Israeli, Y., and Tanny, J.: Sap flow, canopy conductance and microclimate in a banana screenhouse, Agricultural and Forest Meteorology, 201, 165–175, 2015.

Hao, Y., Wang, Y., Huang, X., Cui, X., Zhou, X., Wang, S., Niu, H., and Jiang, G.: Seasonal and interannual variation in water vapor and energy exchange over a typical steppe in Inner Mongolia, China, Agricultural and Forest Meteorology, 146, 57–69, 2007.

Herbst, M.: Stomatal behaviour in a beech canopy: an analysis of Bowen ratio measurements compared with porometer data, Plant, Cell & Environment, 18, 1010–1018, 1995.

Hinckley, T., Brooks, J., Čermák, J., Ceulemans, R., Kučera, J., Meinzer, F., and Roberts, D.: Water flux in a hybrid poplar stand, Tree Physiology, 14, 1005–1018, 1994.

Huntingford, C. and Monteith, J.: The behaviour of a mixed-layer model of the convective boundary layer coupled to a big leaf model of surface energy partitioning, Boundary-Layer Meteorology, 88, 87–101, 1998.

Iida, S., Ohta, T., Matsumoto, K., Nakai, T., Kuwada, T., Kononov, A. V., Maximov, T. C., van der Molen, M. K., Dolman, H., Tanaka, H., et al.: Evapotranspiration from understory vegetation in an eastern Siberian boreal larch forest, Agricultural and Forest Meteorology, 149, 1129–1139, 2009.

Jacobs, C. and De Bruin, H.: The sensitivity of regional transpiration to land-surface characteristics: significance of feedback, Journal of Climate, 5, 683–698, 1992.

Jarvis, P.: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 273, 593–610, 1976.

Jarvis, P. and McNaughton, K.: Stomatal control of transpiration: Scaling up from leaf to region, Advances in Ecological Research, 15, 1–49, 1986.

Jarvis, P. G.: Attributes of Trees as Crop Plants, chap. Transpiration and assimilation of tree and agricultural crops: the omega factor, pp. 460–480, Institute of Terrestrial Ecology, 1985.

Jassal, R. S., Black, T. A., Spittlehouse, D. L., Brümmer, C., and Nesic, Z.: Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands, Agricultural and forest meteorology, 149, 1168–1178, 2009.

Khatun, R., Ohta, T., Kotani, A., Asanuma, J., Gamo, M., Han, S., Hirano, T., Nakai, Y., Saigusa, N., Takagi, K., et al.: Spatial variations in evapotranspiration over East Asian forest sites. I. Evapotranspiration and decoupling coefficient, Hydrological Research Letters, 5, 83–87, 2011.

Knauer, J., Zaehle, S., Medlyn, B., Reichstein, M., Williams, C. A., Migliavacca, M., De Kauwe, M. G., Werner, C., Keitel, C., Kolari, P., Limousin, J.-M., and Linderson, M.-J.: Towards physiologically meaningful water-use efficiency estimates from eddy covariance data, Global Change Biology, doi:10.1111/gcb.13893, 2017.

Köstner, B., Schulze, E.-D., Kelliher, F., Hollinger, D., Byers, J., Hunt, J., McSeveny, T., Meserth, R., and Weir, P.: Transpiration and canopy conductance in a pristine broad-leaved forest of Nothofagus: an analysis of xylem sap flow and eddy correlation measurements, Oecologia, 91, 350–359, 1992.

Kosugi, Y., Takanashi, S., Tanaka, H., Ohkubo, S., Tani, M., Yano, M., and Katayama, T.: Evapotranspiration over a Japanese cypress forest. I. Eddy covariance fluxes and surface conductance characteristics for 3years, Journal of Hydrology, 337, 269–283, 2007.

Kowalczyk, E. A., Wang, Y. P., Wang, P., Law, R. H., and Davies, H. L.: The CSIRO Atmosphere Biosphere Land Exchange (CABLE) model for use in climate models and as an offline model, Tech. Rep. CSIRO Marine and Atmospheric Research paper 013, CSIRO, CABLE model, 2006.

Kumagai, T., Saitoh, T. M., Sato, Y., Morooka, T., Manfroi, O. J., Kuraji, K., and Suzuki, M.: Transpiration, canopy conductance and the decoupling coefficient of a lowland mixed dipterocarp forest in Sarawak, Borneo: dry spell effects, Journal of Hydrology, 287, 237–251, 2004.

Launiainen, S.: Seasonal and inter-annual variability of energy exchange above a boreal Scots pine forest, Biogeosciences, 7, 3921–3940, 2010.

Law, B., Falge, E., Gu, L. v., Baldocchi, D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A., Falk, M., Fuentes, J., et al.: Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, Agricultural and Forest Meteorology, 113, 97–120, 2002.

Lee, X. and Black, T. A.: Atmospheric turbulence within and above a Douglas-fir stand. Part II: Eddy fluxes of sensible heat and water vapour, Boundary-Layer Meteorology, 64, 369–389, 1993.

Lin, Y.-S., Medlyn, B. E., Duursma, R. A., Prentice, I. C., Wang, H., Baig, S., Eamus, D., de Dios, V. R., Mitchell, P., Ellsworth, D. S., de Beeck, M. O., Wallin, G., Uddling, J., Tarvainen, L., Linderson, M.-L., Cernusak, L. A., Nippert, J. B., Ocheltree, T. W., Tissue, D. T., Martin-StPaul, N. K., Rogers, A., Warren, J. M., De Angelis, P., Hikosaka, K., Han, Q., Onoda, Y., Gimeno, T. E., Barton, C. V. M., Bennie, J., Bonal, D., Bosc, A., Low, M., Macinins-Ng, C., Rey, A., Rowland, L., Setterfield, S. A., Tausz-Posch, S., Zaragoza-Castells, J., Broadmeadow, M. S. J., Drake, J. E., Freeman, M., Ghannoum, O., Hutley, L. B., Kelly, J. W., Kikuzawa, K., Kolari, P., Koyama, K., Limousin, J.-M., Meir, P., Lola da Costa, A. C., Mikkelsen, T. N., Salinas, N., Sun, W., and Wingate, L.: Optimal stomatal behaviour around the world, Nature Climate Change, 5, 459–464, 2015.

Lindroth, A.: Aerodynamic and canopy resistance of short-rotation forest in relation to leaf area index and climate, Boundary-Layer Meteorology, 66, 265–279, 1993.

Loustau, D., Berbigier, P., Roumagnac, P., Arruda-Pacheco, C., David, J., Ferreira, M., Pereira, J., and Tavares, R.: Transpiration of a 64-year-old maritime pine stand in Portugal, Oecologia, 107, 33–42, 1996.

Magnani, F., Leonardi, S., Tognetti, R., Grace, J., and Borghetti, M.: Modelling the surface conductance of a broad-leaf canopy: effects of partial decoupling from the atmosphere, Plant, Cell & Environment, 21, 867–879, 1998.

Mahmood, K., Morris, J., Collopy, J., and Slavich, P.: Groundwater uptake and sustainability of farm plantations on saline sites in Punjab province, Pakistan, Agricultural Water Management, 48, 1–20, 2001.

Martin, P.: The significance of radiative coupling between vegetation and the atmosphere, Agricultural and Forest Meteorology, 49, 45–53, 1989.

Martin, T., Brown, K., Kučera, J., Meinzer, F., Sprugel, D., and Hinckley, T.: Control of transpiration in a 220-year-old Abies amabilis forest, Forest Ecology and Management, 152, 211–224, 2001.

McElwain, J. C. and Chaloner, W. G.: Stomatal density and index of fossil plants track atmospheric carbon dioxide in the Palaeozoic, Annals of Botany, 76, 389–395, 1995.

McNaughton, K. and Jarvis, P.: Water Deficits and Plant Growth, Vol. VII, chap. Predicting effects of vegetation changes on transpiration and evaporation, pp. 1–47, Academic Press, San Diego, 1983.

McNaughton, K. and Jarvis, P.: Effects of spatial scale on stomatal control of transpiration, Agricultural and Forest Meteorology, 54, 279–302, 1991.

Medlyn, B., Barton, C., Broadmeadow, M., Ceulemans, R., De Angelis, P., Forstreuter, M., Freeman, M., Jackson, S., Kellomaki, S., Laitat, E., Rey, A., Roberntz, P., Sigurdsson, B., Strassemeyer, J., Wang, K., Curtis, P., and Jarvis, P.: Stomatal conductance of forest species after long-term exposure to elevated $\mathrm{CO_2}$ concentration: a synthesis, New Phytologist, 149, 247–264, 2001.

Medlyn, B. E., De Kauwe, M. G., Lin, Y.-S., Knauer, J., Duursma, R. A., Williams, C. A., Arneth, A., Clement, R., Isaac, P., Limousin, J.-M., Linderson, M.-L., Meir, P., Martin-StPaul, N., and Wingate, L.: How do leaf and ecosystem measures of water-use efficiency compare?, New Phytologist, 2017.

Meinzer, F., Goldstein, G., Holbrook, N., Jackson, P., and Cavelier, J.: Stomatal and environmental control of transpiration in a lowland tropical forest tree, Plant, Cell &, Environment, 16, 429–436, 1993.

Meinzer, F., Andrade, J., Goldstein, G., Holbrook, N., Cavelier, J., and Jackson, P.: Control of transpiration from the upper canopy of a tropical forest: the role of stomatal, boundary layer and hydraulic architecture components, Plant, Cell & Environment, 20, 1242–1252, 1997.

Meirelles, M., Franco, A., Farias, S., and Bracho, R.: Evapotranspiration and plant–atmospheric coupling in a Brachiaria brizantha pasture in the Brazilian savannah region, Grass and Forage Science, 66, 206–213, 2011.

Mielke, M. S., Oliva, M., de Barros, N. F., Penchel, R. M., Martinez, C. A., and de Almeida, A. C.: Stomatal control of transpiration in the canopy of a clonal Eucalyptus grandis plantation, Trees-Structure and Function, 13, 152–160, 1999.

Miner, G. L., Bauerle, W. L., and Baldocchi, D. D.: Estimating the sensitivity of stomatal conductance to photosynthesis: A review, Plant, Cell & Environment, 2017.

Morison, J. I. L.: Sensitivity of stomata and water use efficiency to high $\mathrm{CO_2}$, Plant, Cell &, Environment, 8, 467–474, 1985.

Motzer, T., Munz, N., Küppers, M., Schmitt, D., and Anhuf, D.: Stomatal conductance, transpiration and sap flow of tropical montane rain forest trees in the southern Ecuadorian Andes, Tree Physiology, 25, 1283–1293, 2005.

Nicolás, E., Barradas, V., Ortuño, M., Navarro, A., Torrecillas, A., and Alarcón, J.: Environmental and stomatal control of transpiration, canopy conductance and decoupling coefficient in young lemon trees under shading net, Environmental and Experimental Botany, 63, 200–206, 2008.

Oleson, K. W., Lawrence, D. M., Bonan, G. B., Drewniak, B., Huang, M., Koven, C. D., Levis, S., Li, F., Riley, W. J., Subin, Z. M., Swenson, S. C., Thornton, P. E., Bozbiyik, A., Fisher, R., Heald, C. L., Kluzek, E., Lamarque, J.-F., Lawrence, P. J., Leung, L. R., Lipscomb, W., Muszala, S., Ricciuto, D. M., Sacks, W., Sun, Y., Tang, J., and Yang, Z.-L.: Technical Description of version 4.5 of the Community Land Model (CLM), NCAR Technical Note NCAR/TN-503+STR, National Center for Atmospheric Research. Climate and Global Dynamics Division, National Center for Atmospheric Research, P.O. Box 3000, Boulder, Colarado, 2013.

Raupach, M. and Finnigan, J.: 'Single-layer models of evaporation from plant canopies are incorrect but useful, whereas multilayer models are correct but useless': Discuss, Functional Plant Biology, 15, 705–716, 1988.

Raupach, M., Finkele, K., and Zhang, L.: SCAM (Soil-Canopy-Atmosphere Model): Description and comparison with field data, Aspendale, Australia: CSIRO CEM Technical Report, p. 81, 1997.

San José, J. J., Montes, R. A., and Florentino, A.: Water flux through a semi-deciduous forest grove of the Orinoco savannas, Oecologia, 101, 141–150, 1995.

Sánchez, J., Caselles, V., and Rubio, E.: Analysis of the energy balance closure over a FLUXNET boreal forest in Finland, Hydrology and Earth System Sciences, 14, 1487–1497, 2010.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J., Levis, S., Lucht, W., Sykes, M., Thonicke, K., and Venevski, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model, Global Change Biology, 9, 161–185, 2003.

Smith, D., Jarvis, P., and Odongo, J.: Management of windbreaks in the Sahel: the strategic implications of tree water use, Agroforestry systems, 40, 83–96, 1998.

Steduto, P. and Hsiao, T. C.: Maize canopies under two soil water regimes: III. Variation in coupling with the atmosphere and the role of leaf area index, Agricultural and Forest Meteorology, 89, 201–213, 1998.

Stoy, P., Katul, G., SIQUEIRA, M., JUANG, J., Novick, K., McCARTHY, H., Christopher Oishi, A., Uebelherr, J., KIM, H., and Oren, R.: Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US, Global Change Biology, 12, 2115–2135, 2006.

Su, Z., Schmugge, T., Kustas, W., and Massman, W.: An evaluation of two models for estimation of the roughness height for heat transfer between the land surface and the atmosphere, Journal of Applied Meteorology, 40, 1933–1951, 2001.

Takagi, K., Kimura, R., and Şaylan, L.: Variability of surface characteristics and energy flux patterns of sunn hemp (Crotalaria juncea L.) under well-watered conditions, Theoretical and applied climatology, 96, 261–273, 2009.

Tateishi, M., Kumagai, T., Suyama, Y., and Hiura, T.: Differences in transpiration characteristics of Japanese beech trees, Fagus crenata, in Japan, Tree physiology, 30, 748–760, 2010.

Thom, A. S.: Vegetation and the Atmosphere, chap. Momentum, Mass and Heat Exchange of Plant Communities, pp. 57–109, Academic Press, London, 1975.

Wever, L. A., Flanagan, L. B., and Carlson, P. J.: Seasonal and interannual variation in evapotranspiration, energy balance and surface conductance in a northern temperate grassland, Agricultural and Forest meteorology, 112, 31–49, 2002.

White, D., Beadle, C., and Worledge, D.: Control of transpiration in an irrigated Eucalyptus globulus Labill. plantation, Plant, Cell & Environment, 23, 123–134, 2000.

Whitehead, D., Jarvis, P. G., and Waring, R. H.: Stomatal conductance, transpiration, and resistance to water uptake in a Pinus sylvestris spacing experiment, Canadian Journal of Forest Research, 14, 692–700, 1984.

Williams, C. A., Reichstein, M., Buchmann, N., Baldocchi, D., Beer, C., Schwalm, C., Wohlfahrt, G., Hasler, N., Bernhofer, C., Foken, T., et al.: Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers, Water Resources Research, 48, 2012.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., et al.: Energy balance closure at FLUXNET sites, Agricultural and Forest Meteorology, 113, 223–243, 2002.

Wilson, K. B. and Baldocchi, D. D.: Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America, Agricultural and Forest Meteorology, 100, 1–18, 2000.

Wohlfahrt, G., Haslwanter, A., Hörtnagl, L., Jasoni, R. L., Fenstermaker, L. F., Arnone, J. A., and Hammerle, A.: On the consequences of the energy imbalance for calculating surface conductance to water vapour, Agricultural and forest meteorology, 149, 1556–1559, 2009.

Woodward, F. and Kelly, C.: The influence of CO2 concentration on stomatal density, New Phytologist, 131, 311–327, 1995.

Woodward, F. I., Smith, T. M., and Emanuel, W. R.: A global land primary productivity and phytogeography model, Global Biogeochemical Cycles, 9, 471–490, 1995.

Wullschleger, S. D., Meinzer, F., and Vertessy, R.: A review of whole-plant water use studies in tree, Tree physiology, 18, 499–512, 1998.

Wullschleger, S. D., Wilson, K. B., and Hanson, P. J.: Environmental control of whole-plant transpiration, canopy conductance and estimates of the decoupling coefficient for large red maple trees, Agricultural and Forest Meteorology, 104, 157–168, 2000.

Zeppel, M. and Eamus, D.: Coordination of leaf area, sapwood area and canopy conductance leads to species convergence of tree water use in a remnant evergreen woodland, Australian Journal of Botany, 56, 97–108, 2008.

Zhang, Z. Z., Zhao, P., McCarthy, H. R., Zhao, X. H., Niu, J. F., Zhu, L. W., Ni, G. Y., Ouyang, L., and Huang, Y. Q.: Influence of the decoupling degree on the estimation of canopy stomatal conductance for two broadleaf tree species, Agricultural and Forest Meteorology, 221, 230–241, 2016.

Zhou, L., Zhou, G., Liu, S., and Sui, X.: Seasonal contribution and interannual variation of evapotranspiration over a reed marsh (Phragmites australis) in Northeast China from 3-year eddy covariance data, Hydrological processes, 24, 1039–1047, 2010.

Zhu, P., Zhuang, Q., Ciais, P., Welp, L., Li, W., and Xin, Q.: Elevated atmospheric CO2 negatively impacts photosynthesis through radiative forcing and physiology-mediated climate feedback, Geophysical Research Letters, 2017.

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 - C_3 crops, C4C - C_4 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	0.42	0.23	0.21	0.8	4
C3C	0.4	0.28	0.2	0.59	2
C4C	0.58	—	—	—	1

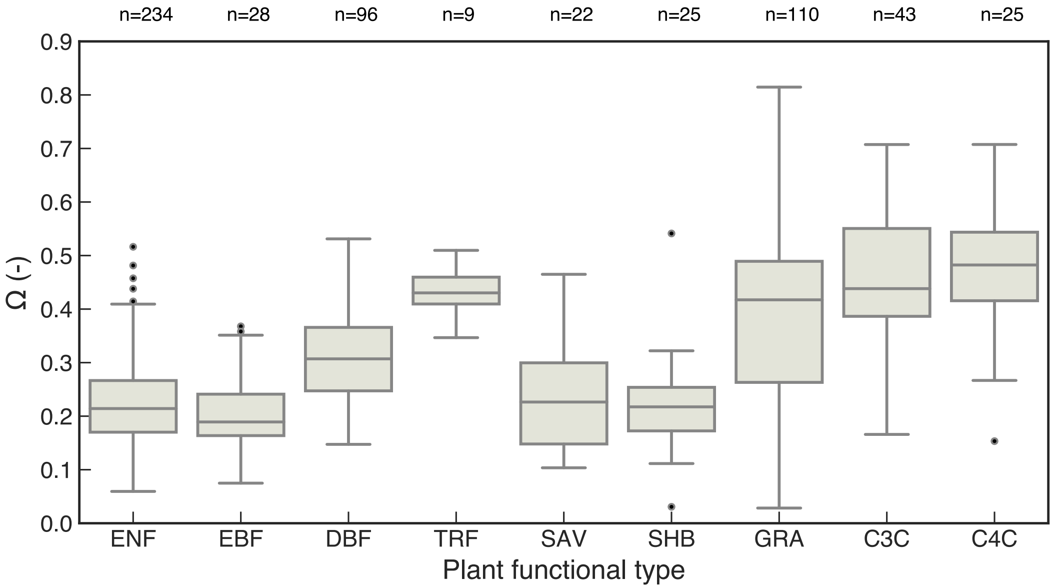

Figure 1. Box and whisker plot (line, median; box, inter-quartile range) showing the estimated ~~decoupling~~ coupling coefficient (Ω) from FLUXNET data, grouped by plant functional type. Whiskers extend to 1.5 times the inter-quartile range, with dots outside of the whiskers showing outliers. Plant 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 - ~~C_3 grass~~grasses, ~~C4G - C_4 grass,~~ C3C - C_3 crops, C4C - C_4 crops. Values of n indicate the number of site-years for FLUXNET.

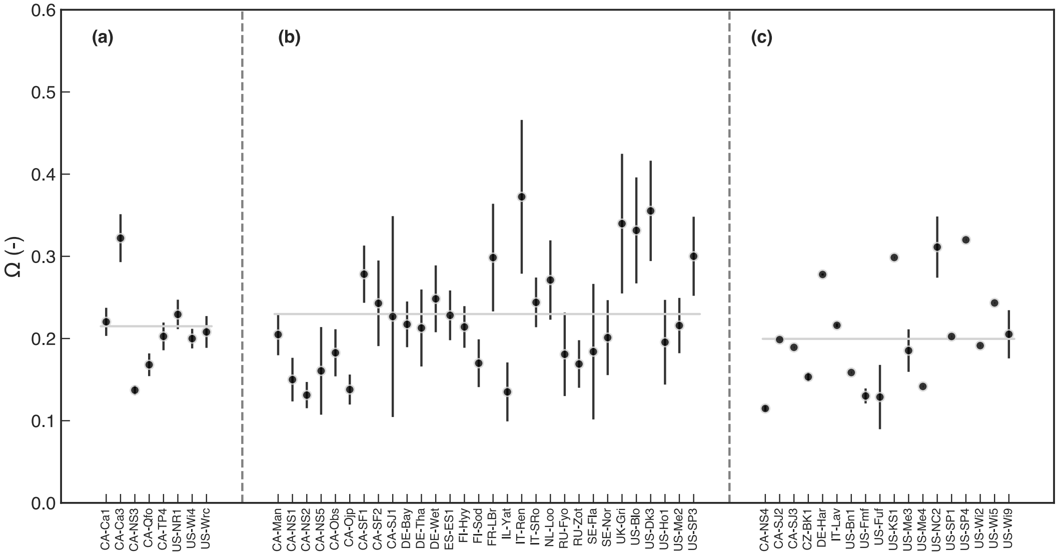

Figure 2. Values of the coupling coefficient (Ω) for sites from the evergreen needleleaf forests (ENF) plant functional type. Estimated values of Ω have been split into: (a) sites where the coefficient of variation (COV) is $< 20\%$; (b) sites where the COV is $> 20\%$; and (c) sites with only two years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

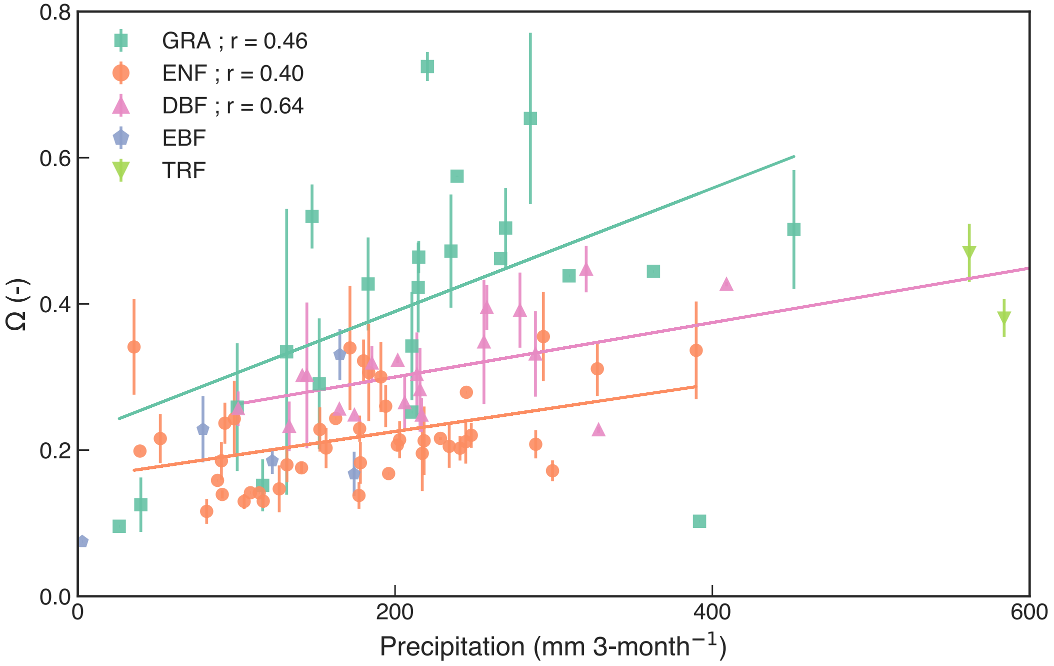

Figure 3. Values of the estimated coupling coefficient (Ω) for forest (ENF, EBF, DBF, TRF) vegetation and grasses as a function of precipitation in the three most productive months. Only data were 90% of the three most productive months were flagged as "good" are shown. Lines indicate statistically significant 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.

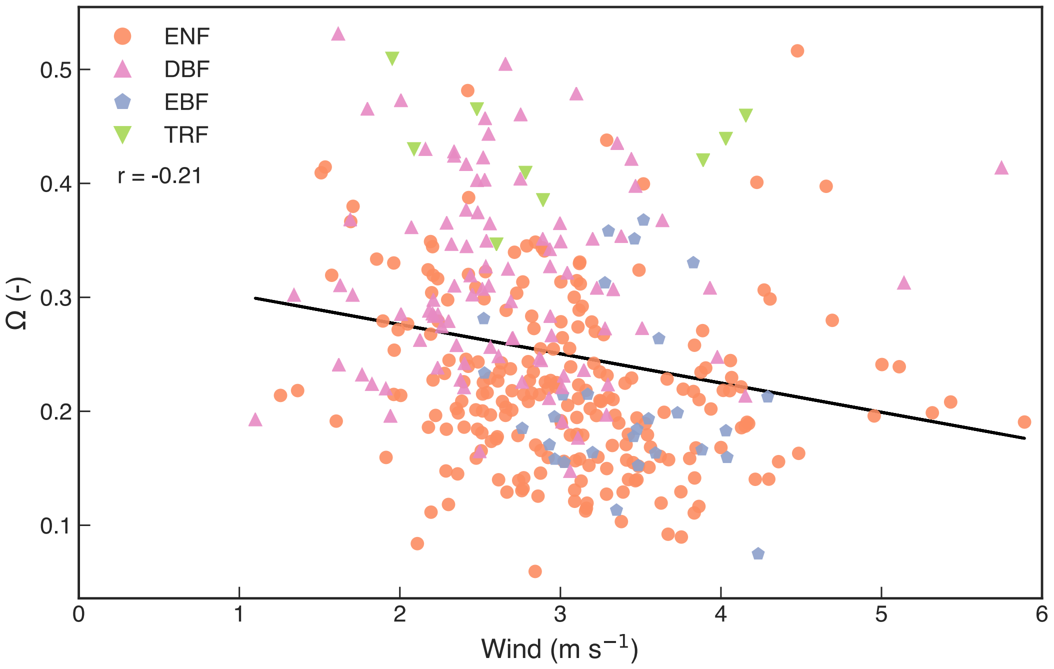

Figure 4. Values of the estimated coupling coefficient (Ω) for forest (ENF, EBF, DBF, TRF) vegetation as a function of wind speed. Line indicates statistically significant regression ($P < 0.05$), r is the correlation coefficient. Plant functional types are defined as: ENF - evergreen needle leaved forest,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

Appendix A

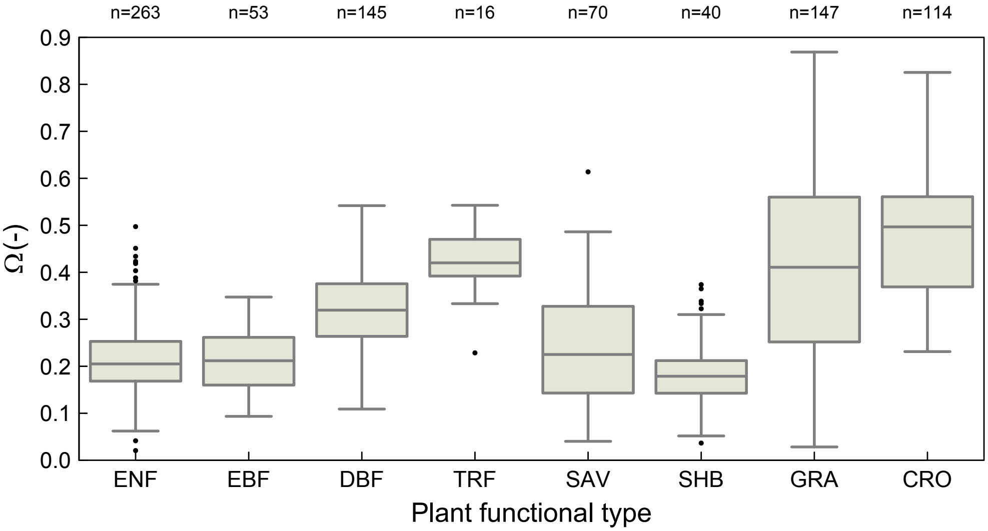

Figure A1. Box and whisker plot (line, median; box, inter-quartile range) showing the estimated coupling coefficient (Ω) from FLUXNET2015 data, grouped by plant functional type. Whiskers extend to 1.5 times the inter-quartile range, with dots outside of the whiskers showing outliers. Plant functional 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 - C_3 crops, C4C - C_4 crops. Values of n indicate the number of site-years for FLUXNET.

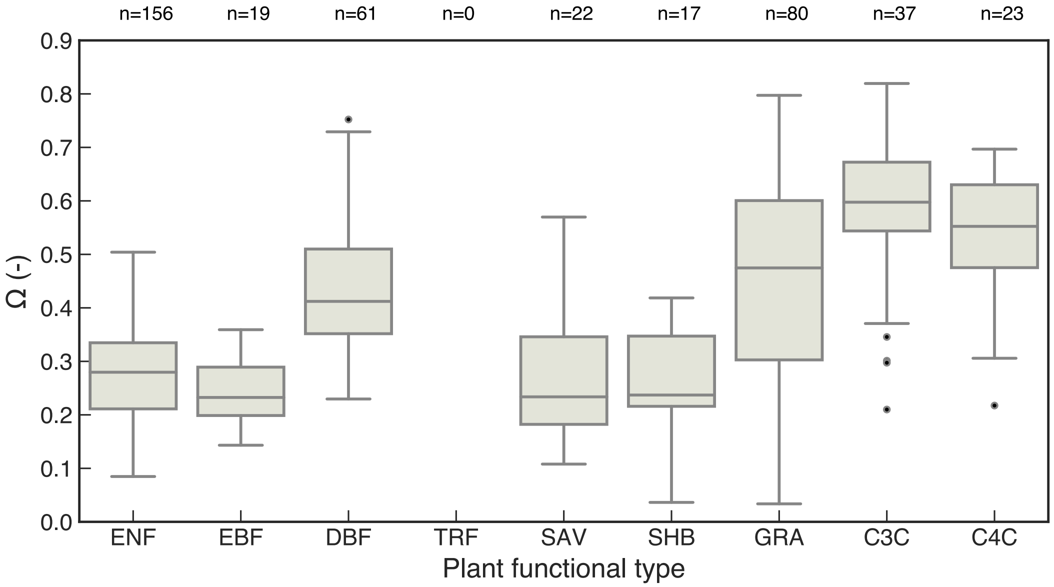

Figure A2. Box and whisker plot (line, median; box, inter-quartile range) showing the estimated coupling coefficient (Ω) from FLUXNET data, grouped by plant functional type. These data have been corrected for energy imbalance, adjusting the Bowen-ratio method by the imbalance across the three most productive 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 - C_3 crops, C4C - C_4 crops. Values of n indicate the number of site-years for FLUXNET.

Table A1: FLUXNET site years used in analysis.

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

Table A1 continued from previous page

Site ID	Years
CN-Du1	2005 2006
CN-Du2	2006
CN-HaM	2002 2003
CN-Xi1	2006
CN-Xi2	2006
CZ-BK1	2004 2005
CZ-BK2	2004
DE-Bay	1996 1997 1998 1999
DE-Geb	2004 2005 2006
DE-Gri	2005 2006
DE-Hai	2000 2001 2002 2003 2004 2005 2006
DE-Har	2005 2006
DE-Kli	2004 2005 2006
DE-Meh	2003 2004 2005 2006
DE-Tha	1996 1997 1998 1999 2000 2001 2002 2003 2004 2005
DE-Wet	2002 2003 2004 2005 2006
DK-Fou	2005
DK-Lva	2005
DK-Ris	2004
DK-Sor	2004 2005
ES-ES1	2000 2002 2003 2004 2005 2006
ES-ES2	2004 2005 2006
ES-LMa	2004 2005 2006
ES-VDA	2004 2005 2006
FI-Hyy	1998 1999 2000 2001 2002 2003 2004 2006
FI-Sod	2002 2003 2004 2005 2006
FR-Aur	2005
FR-Fon	2005 2006
FR-Gri	2005 2006
FR-Hes	1997 1998 1999 2000 2001 2002 2003 2004 2005 2006

Table A1 continued from previous page

Site ID	Years
FR-LBr	1996 1997 1998 2000 2003 2004 2005 2006
FR-Lam	2005
FR-Lq1	2005
FR-Lq2	2004 2005
FR-Pue	2000 2001 2002 2003 2004 2005 2006
GF-Guy	2004 2005 2006
HU-Bug	2002 2003 2004 2005 2006
HU-Mat	2004 2005 2006
ID-Pag	2002 2003
IE-Ca1	2004 2005 2006
IE-Dri	2004 2005
IL-Yat	2001 2002 2003 2006
IS-Gun	1996 1997 1998
IT-Amp	2002 2003 2004 2005 2006
IT-BCi	2005 2006
IT-Be2	2006
IT-Cas	2006
IT-Col	1998 1999 2004 2005 2006
IT-Cpz	1997 2000 2001 2002 2003 2004 2005 2006
IT-LMa	2004 2005 2006
IT-Lav	2004 2006
IT-MBo	2003 2004 2005 2006
IT-Mal	2004
IT-Noe	2004 2005 2006
IT-Non	2001 2002 2003 2006
IT-PT1	2003 2004
IT-Ren	2000 2001 2002 2003 2004
IT-Ro1	2000 2002 2003 2004 2005 2006
IT-Ro2	2004 2005 2006
IT-SRo	2000 2002 2003 2004 2005 2006

Table A1 continued from previous page

Site ID	Years
IT-Vig	2004
JP-Mas	2002 2003
NL-Ca1	2003 2004 2005 2006
NL-Hor	2006
NL-Lan	2005
NL-Loo	1996 1997 1998 1999 2001 2002 2003 2004 2006
PT-Esp	2002 2004 2006
PT-Mi1	2005
PT-Mi2	2004 2005 2006
RU-Cok	2005
RU-Fyo	1998 1999 2002 2003 2004 2005 2006
RU-Ha1	2003 2004
RU-Zot	2002 2003 2004
SE-Abi	2005
SE-Fla	1996 1997 1998 2001 2002
SE-Nor	1996 1997 1998 2005
UK-EBu	2004
UK-ESa	2004 2005
UK-Gri	1998 2000 2001 2006
UK-Ham	2004 2005
UK-Her	2006
UK-PL3	2005 2006
US-ARM	2003 2004 2005 2006
US-Aud	2002 2003 2004 2005 2006
US-Bar	2004 2005
US-Bkg	2004 2005 2006
US-Blo	1997 1998 1999 2000 2001 2002 2003 2004 2005
US-Bn1	2003
US-Bn2	2003
US-Bo1	1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

Table A1 continued from previous page

Site ID	Years
US-Bo2	2004 2005 2006
US-CaV	2004 2005
US-Dk1	2001 2002 2003 2004 2005
US-Dk2	2003 2004
US-Dk3	2001 2002 2003 2004 2005
US-FPe	2000 2001 2002 2003 2004 2005 2006
US-Fmf	2005 2006
US-Fuf	2005 2006
US-Fwf	2005 2006
US-Goo	2002 2003 2004 2005 2006
US-Ha1	1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2003 2005 2006
US-Ho1	1996 1997 1998 1999 2000 2001 2002 2003
US-IB1	2005 2006 2007
US-IB2	2004 2006 2007
US-KS1	2002
US-KS2	2002 2003 2004 2005 2006
US-MMS	2000 2001 2002
US-MOz	2004 2005 2006
US-Me2	2003 2004 2005
US-Me3	2004 2005
US-Me4	2000
US-NC2	2005 2006
US-NR1	1999 2000 2002 2003
US-Ne1	2001 2002 2003 2004 2005
US-Ne2	2001 2002 2003 2004 2005
US-Ne3	2001 2002 2003 2004
US-SO2	1997 1998 1999 2004 2005 2006
US-SO3	1997 1998 2005 2006
US-SP1	2005
US-SP3	1999 2000 2001 2002 2003 2004

Table A1 continued from previous page

Site ID	Years
US-SP4	1998
US-SRM	2004 2005 2006
US-Ton	2001 2002 2003 2004 2005 2006
US-UMB	1999 2000 2001 2002 2003
US-Var	2001 2002 2003 2004 2005 2006
US-WCr	1999 2000 2001 2002 2003 2004 2005 2006
US-Wi1	2003
US-Wi2	2003
US-Wi4	2003 2004 2005
US-Wi5	2004
US-Wi9	2004 2005
US-Wkg	2004 2005 2006
US-Wrc	1998 1999 2000 2001 2002 2004 2005 2006
VU-Coc	2001 2002 2003 2004

Table A2: Literature summary of decoupling coefficients. Where possible we have summarised data from the growing season during daylight hours. Where E is transpiration, G_a is the total aerodynamic conductance ($G_a = G_{am} + G_b$), G_{am} is the turbulent aerodynamic resistance, G_b is the canopy boundary layer conductance, G_s is the stomatal condutance, 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). 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 - C_3 crops, C4C - C_4 crops.

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

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PFT	Dominant species	Ω	Scale	Method	G_{am}	G_b	G_s	Reference
ENF	*Pinus elliotti*	0.43	Canopy	1	f(wind, roughness)	f(u_*)	Inverted PM, *E* from EC	Bracho et al. (2008)
ENF	*Pinus pinaster*	0.08	Stand	1	Empirical reln. between G_a & wind	—	Inverted PM, *E* from sap flow	Loustau et al. (1996)
ENF	*Pinus sylvestris*	0.1	Stand	1	f(wind, height)	—	Leaf gas exchange	Whitehead et al. (1984)
ENF	*Pinus sylvestris*	0.32	Canopy	1	f(wind, u_*)	—	Inverted PM, *E* from EC	Launiainen (2010)
ENF	*Pinus taeda*	0.25	Canopy	1	f(roughness, u_*)	f(characteristic leaf dimension, wind)	Bottom-up model: f(VPD, LAI & radiation)	Stoy et al. (2006)
ENF	*Pseudotsuga menziesii*	0.26	Canopy	1	f(wind, u_*)	—	Inverted PM, *E* from EC	Jassal et al. (2009)
ENF	*Pseudotsuga menziesii*	0.15	Canopy	1	f(wind, u_*)	—	Inverted PM, *E* from EC	Lee and Black (1993)
EBF	*Acacia ampliceps*	0.28	Stand	3	Empirical relationship between G_a & wind speed	—	Inverted (simplified) PM, *E* from sap flow	Mahmood et al. (2001)

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PFT	Dominant species	Ω	Scale	Method	G_{am}	G_b	G_s	Reference
EBF	*Azadirachta indica*	0.28	Tree	2	f(leaf temperature)	—	Inverted (Simplified) PM from sap flow	Smith et al. (1998)
EBF	*Citrus limon*	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	*Eucalyptus camaldulensis*	0.33	Stand	3	Empirical relationship between G_a & wind speed	—	Inverted (simplified) PM, *E* from sap flow	Mahmood et al. (2001)
EBF	*Eucalyptus crebra* F.Muell.	0.19	Canopy	1	f(wind, roughness)	—	Inverted PM, *E* from sap flow	Zeppel and Eamus (2008)
EBF	*Eucalyptus globulus*	0.63	Stand	1	TC – G_s	—	Simple gradient approach, *E* from sap flow	White et al. (2000)
EBF	*Eucalyptus grandis*	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	*Eucalyptus urophylla*	0.1	Stand	1	f(wind, roughness)	—	Inverted PM, *E* from sap flow	Zhang et al. (2016)

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

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

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PFT	Dominant species	Ω	Scale	Method	G_{am}	G_b	G_s	Reference
DBF	*Salix viminalis*	0.7	Canopy	1	Inverted PM when the canopy is wet	—	Inverted PM, *E* from sap flow	Lindroth (1993)
DBF	—	0.41	Canopy	1	Surface layer similarity	$f(u_*)$	Inverted PM, *E* using the Bowen ratio (EC)	Wilson and Baldocchi (200
TRF	*Anacardium excelsum*	0.75	Tree	2	TC – G_s	—	Leaf gas exchange	Meinzer et al. (1993)
TRF	*Cecropia longipes*	0.9	Tree	2	TC – G_s & stomatal conductance	—	Leaf gas exchange	Meinzer et al. (1997)
TRF	*Ficus insipida*	0.82	Tree	2	TC — G_s	—	Leaf gas exchange	Meinzer et al. (1997)
TRF	*Hedyosmum anisodorum* Todzia	0.37	Leaf	1	—	f(wind, leaf extension)	Leaf gas exchange	Motzer et al. (2005)
TRF	*Luehea seemannii*	0.88	Tree	2	TC – G_s	—	Leaf gas exchange	Meinzer et al. (1997)
TRF	*Naucleopsis* sp.	0.27	Leaf	1	—	f(wind, leaf extension)	Leaf gas exchange	Motzer et al. (2005)
TRF	*Psychotria brachiata* Ruiz & Pav.	0.27	Leaf	1	—	f(wind, leaf extension)	Leaf gas exchange	Motzer et al. (2005)

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

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PFT	Dominant species	Ω	Scale	Method	G_{am}	G_b	G_s	Reference
GRA	*Festuca arundinaria* Shreb.	0.34	Canopy	1	f(roughness, u_*)	f(characteristic leaf dimension, wind)	Bottom-up model: f(VPD, LAI & radiation)	Stoy et al. (2006)
GRA	*Phragmites australis*	0.48	Canopy	1	f(wind, u_*)	f(u_*)	Inverted PM, *E* from EC	Zhou et al. (2010)
GRA	—	0.45	Canopy	1	f(wind, u_*)	—	Inversion bulk transfer of sensible and latent heat (EC)	Goldberg and Bernhofer (2
GRA	—	0.49	Canopy	1	f(wind, u_*)	f(u_*)	Inverted PM, *E* from EC	Aires et al. (2008)
GRA	—	0.31	Canopy	1	f(wind, u_*)	f(u_*)	Inverted PM, *E* from EC	Hao et al. (2007)
GRA	—	0.21	Canopy	1	f(wind, u_*)	f(u_*)	Inverted PM, *E* from EC	Wever et al. (2002)
GRA	—	0.8	—	1	—	—	I—	McNaughton and Jarvis (1

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PFT	Dominant species	Ω	Scale	Method	G_{am}	G_b	G_s	Reference
C3C	*Crotalaria juncea*	0.59	Canopy	1	f(wind, roughness)	—	Inverted PM, *E* from Bowen Ratio energy balance method	Takagi et al. (2009)
C3C	*Musa sp.*	0.2	Stand	1	f(wind, characteristic leaf dimension, LAI)	—	Inverted PM, *E* from sap flow Ratio energy balance method	Haijun et al. (2015)
C4C	*Zea mays*	0.58	Canopy	1	f(wind, roughness)	$f(u_*)$	Inverted PM, *E* from Bowen Ratio energy balance method	Steduto and Hsiao (1998)