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### Title

Inter-annual variability of net and gross ecosystem carbon fluxes: A review

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2 Inter-Annual Variability of Net and Gross Ecosystem Carbon Fluxes: A Review

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25



26 **Abstract**

27 As the lifetime of regional flux networks approach twenty years, there is a growing number of papers  
28 that have published long term records (5 years or more) of net carbon fluxes between ecosystems and  
29 the atmosphere. Unanswered questions from this body of work are: 1) how variable are carbon fluxes  
30 on a year to year basis?; 2) what are the biophysical factors that may cause interannual variability  
31 and/or temporal trends in carbon fluxes?; and 3) how does the biophysical control on this **carbon flux**  
32 variability differ by climate and ecological spaces? To address these questions, we surveyed published  
33 data from 59 sites that reported on five or more years of continuous measurements, yielding 544 site-  
34 years of data.

35 We found that the standard deviation of the interannual variability in net ecosystem carbon exchange  
36 ( $162 \text{ gC m}^{-2} \text{ y}^{-1}$ ) is large relative to its population mean ( $-200 \text{ gC m}^{-2} \text{ y}^{-1}$ ). Broad-leaved evergreen forests  
37 and crops experienced the greatest absolute variability in interannual net carbon exchange (greater than  
38  $\pm 300 \text{ gC m}^{-2} \text{ y}^{-1}$ ) and boreal evergreen forests and maritime wetlands were among the least variable  
39 (less than  $\pm 40 \text{ gC m}^{-2} \text{ y}^{-1}$ ).

40 A disproportionate fraction of the yearly variability in net ecosystem exchange was associated with  
41 biophysical factors that modulated ecosystem photosynthesis rather than ecosystem respiration. Yet,  
42 there was appreciable and statistically significant covariance between ecosystem photosynthesis and  
43 respiration. Consequently, biophysical conditions that conspired to increase ecosystem photosynthesis  
44 to from one year to the next were associated with an increase in ecosystem respiration, and vice versa;  
45 on average, the year to year change in respiration was 40% as large as the year to year change in  
46 photosynthesis. The analysis also identified sets of ecosystems that are on the verge of switching from  
47 being carbon sinks to carbon sources. These include sites in the Arctic tundra, the evergreen forests in  
48 the Pacific northwest and some grasslands, where year to year changes in respiration are outpacing  
49 those in photosynthesis.

50 While a select set of climatic and ecological factors (e.g. light, rainfall, temperature, phenology) played  
51 direct and indirect roles on this variability, their impact differed conditionally, as well as by climate and  
52 ecological spaces. For example, rainfall had both positive and negative effects. Deficient rainfall caused  
53 a physiological decline in photosynthesis in **temperate and semi-arid regions**. Too much rain, in the  
54 humid tropics, limited photosynthesis by limiting light. In peatlands and tundra, excess precipitation  
55 limited ecosystem respiration when it raised the water table to the surface. For deciduous forests,  
56 warmer temperatures lengthened the growing season, increasing photosynthesis, but this effect also  
57 increased soil respiration.

58 Finally, statistical analysis was performed to evaluate the detection limit of trends; we computed the  
59 confidence intervals of trends in multi-year carbon fluxes that need to be resolved to conclude whether  
60 the differences are to be attributed to randomness or biophysical forcings. Future studies and reports  
61 on interannual variations need to consider the role of the duration of the time series on random errors  
62 when quantifying potential trends and extreme events.

63

64 **Introduction**

65 Scientists have been making direct, quasi-continuous and long term eddy covariance measurements of  
66 net and gross carbon exchange between ecosystems and the atmosphere at solitary sites since the early  
67 1990s (Black et al., 1996; Greco and Baldocchi, 1996; Saigusa et al., 2005a; Valentini et al., 1996; Wofsy  
68 et al., 1993). This set of early studies was influential because it gave the community confidence that  
69 eddy covariance measurements could be made on a quasi-continuous basis to produce annual budgets  
70 of carbon and water fluxes between ecosystems and the atmosphere. Starting in the late 1990s, a set  
71 of regional and global networks of eddy covariance flux measurements stations were formed, with the  
72 launching of the Euroflux, AmeriFlux, AsiaFlux and FLUXNET networks (Aubinet et al., 2000; Baldocchi et  
73 al., 2001; Yamamoto et al., 2005). Today, the sustained operation of many of these networks is  
74 providing us with many time series exceeding a decade in length, and some that are approaching twenty  
75 years in duration.

76 One of the overarching goals and aspirations of the flux networks was to collect time series long enough  
77 to assess the biophysical factors that may cause interannual variability and/or detect temporal trends in  
78 carbon fluxes. Until recently, too few of the time series from published eddy covariance study sites have  
79 been long enough to separate natural variability and emerging trends from sampling and measurement  
80 errors, as these sampling errors sum to the order of 20 to 50 gC m<sup>-2</sup> y<sup>-1</sup> (Elbers et al., 2011; Hollinger et  
81 al., 2004; Richardson et al., 2007).

82  
83 There are many possible climatic, physiological and ecological reasons why ecosystem-atmosphere  
84 carbon fluxes may experience different degrees of interannual variability. To find the best and most  
85 pertinent explanations for carbon flux variability, it is important to examine the modulation of the gross  
86 flux components that are combined to form the net carbon flux. From first principles, we know that net  
87 ecosystem carbon exchange of an ecosystem ( $N_E$ ) consists of three constituent fluxes--gross  
88 photosynthesis (assimilation), autotrophic (plant) respiration ( $R_a$ ) and heterotrophic (microbial) ( $R_h$ )  
89 respiration.

90 Gross photosynthesis (G) of an ecosystem is sensitive to a different set of anomalous weather and  
91 climate variability than ecosystem respiration (Frank et al., 2015). Weather and climatic based  
92 explanations for year to year changes in carbon assimilation start with variability in clouds and  
93 precipitation and their impact on such primary drivers of assimilation, such as light, temperature,  
94 humidity deficits and soil moisture (Law et al., 2002; van Dijk et al., 2005; Yi et al., 2010). The  
95 combination of clouds, rain/drought, sunlight, and humidity can interact to either promote or retard  
96 photosynthesis. Wetter years will be associated with less sunlight, which may reduce photosynthesis,  
97 compared to a baseline (Zeri et al., 2014). And, drier years will be associated with more sunlight, which  
98 may increase photosynthesis up to a point; greater **deficits in** humidity and soil moisture will cause  
99 stomatal closure and reduce photosynthesis (Reichstein et al., 2007; Wolf et al., 2016). Photosynthesis  
100 responds to changes in temperature in a non-linear, quadratic fashion that is highly plastic (Baldocchi et  
101 al., 2001; Way and Yamori, 2014); some warming increases photosynthesis, too much warming is  
102 deleterious and the optimal temperature are known to acclimate with mean growing season  
103 temperature. Temperature can also influence ecosystem photosynthesis through phenology (Baldocchi  
104 et al., 2005; Richardson et al., 2010); the timing of phenological events is generally associated with  
105 temperature sums (Kramer et al., 2000). Timing of leaf out affects the length of the growing season,  
106 which in turn, can modulate seasonally-integrated photosynthesis (Gu et al., 2003). Plant and soil

107 respiration, on the other hand, tends to: 1) increase exponentially with temperature, given sufficient soil  
108 moisture (Atkin et al., 2005; Xu and Qi, 2001); 2) decline if soils are too dry or wet and 3) scale with  
109 carbon inputs into the rhizosphere from plant photosynthesis (Baldocchi, 2008).

110 In some regions, seasonal variations in climatic drivers, rather than variations in mean annual climate  
111 conditions, may be more important modulators in yearly summed carbon fluxes. For example, in cold  
112 regions the presence or absence of snow can have major impact on the amount of soil respiration during  
113 the winter (Monson et al., 2006a). In Mediterranean climate, the amount of rain during the spring  
114 growing season is more important than annual precipitation (Allard et al., 2008; Ma et al., 2007; Thomas  
115 et al., 2009); excess winter rain may run off and not contribute to the amount of water stored in the  
116 rhizosphere.

117 There can also be a disproportionate effect of 'hot moments' on the annual sums of net carbon fluxes.  
118 An analysis, using seven years of data from eight forested AmeriFlux sites, discovered that year to year  
119 differences in annual carbon fluxes were best described by the number of hours that short term fluxes  
120 exceeded a specified percentile (Zscheischler et al., 2016).

121 Year to year changes in the structural and functional traits of an ecosystem can also explain a significant  
122 portion of interannual variability in net and gross carbon fluxes (Richardson et al., 2007; van Dijk et al.,  
123 2005). For example, variations in leaf area index affect light capture and the surface area of the sources  
124 and sinks. With regards to functional traits, changes in the nitrogen supply will alter photosynthetic  
125 capacity and seasonally integrated photosynthesis (Reichstein et al., 2014). Changes in basal rates in soil  
126 and root respiration can occur through differences in leaf litter fall (Granier et al., 2008) and  
127 photosynthetic activity (Tang et al., 2005).

128 In the case of agriculture, management practices and cropping choices can be important factors that  
129 modulate gross and net carbon fluxes (Baker and Griffis, 2009; Dold et al., 2017; Knox et al., 2016;  
130 Suyker and Verma, 2010); the alternating choice of a C<sub>4</sub> (maize) vs C<sub>3</sub> (soybean) crop or decisions to  
131 irrigate or whether or not to till the soils affects annually integrated carbon fluxes on a year to year  
132 basis. For natural ecosystems, disturbance by fire, logging, insects and disease are other exogenous  
133 factors that can introduce year to year variations in net and gross carbon fluxes (Amiro et al., 2010; Clark  
134 et al., 2010; Dore et al., 2012; Frank et al., 2014).

135 Long term carbon flux measurements are needed to capture the rare extreme events that may have a  
136 detrimental or beneficial impact on an ecosystem (Frank et al., 2015). To capture information on the  
137 occurrence of rare droughts or variability in rain associated with *El Nino* and *La Nina* one may need 7  
138 years of data, or more (Chen et al., 2009b; Wharton and Falk, 2016). Time since disturbance can also  
139 cause long term fluxes to differ on a year by year basis, as the greening of the landscape will cause  
140 photosynthesis to outpace respiration after x number of years (Amiro et al., 2010; Odum, 1969). Legacy  
141 effects can modulate year to year carbon fluxes, especially in wetlands and grasslands. For example,  
142 years with excessive vegetation will produce plenty of dead standing mass which will compete with live  
143 vegetation the next year for photons (Ma et al., 2016; Rocha et al., 2008). There also may be legacy  
144 effects following the return to normal conditions after an excessive drought if there is much plant, stem,  
145 shoot or root mortality.

146 Superimposed on the decadal record are trends in carbon dioxide and temperature, as the Earth  
147 experiences global change (Keenan et al., 2013; Schimel et al., 2015). Before we can detect whether or

148 not there are emerging trends in net ecosystem fluxes based on these chronic forcings we must  
149 understand the sources of natural variability and whether or not measurement uncertainty is greater or  
150 less than certain figures of merit. Finally, the duration of the time series must exceed a certain time  
151 threshold to be able to reduce measurement and sampling errors to an acceptable level and to be able  
152 to separate measurement and sampling errors from climatic and ecological sources of variation (Keenan  
153 et al., 2012).

154 Today, we are reaching a milestone where a large and diverse number of eddy covariance studies have  
155 been operating for more than a decade; more than 250 sites have been operating for 10 or more years  
156 (Chu et al., 2017; Pastorello et al., 2016). Subsequently, a growing and critical number of studies have  
157 been published in the peer review literature documenting the results from these long-term flux  
158 observations. Hence, we are at a juncture when this literature merits distillation and review. This  
159 review is intended to provide guidelines for future synthesis studies on interannual variability that are  
160 expected to be generated by the newest version of the FLUXNET database (Pastorello et al., 2016).

161  
162 To perform this review, we harvested information from the suite of published carbon flux studies that  
163 report on long term measurements; they ranged between 5 and 18 years in duration. We divided the  
164 review into three sections. Part one is a panoramic view of interannual variability, which was  
165 conducted by examining the compiled dataset as an ensemble. Here we address the following  
166 questions: how variable is net ecosystem carbon exchange ( $N_E$ ) and its constituent components, gross  
167 ecosystem photosynthesis ( $G$ ) and ecosystem respiration ( $R_e$ ), on quasi-decadal time scales?; To what  
168 degree is interannual variability in net ecosystem carbon exchange imposed by modulation of ecosystem  
169 photosynthesis, and respiration, or by random noise and errors associated with the summation of hourly  
170 fluxes to annual time scales?; and do legacy or lag effect arise when looking at the lag autocorrelation  
171 functions of long time series? In part two, we examine lessons learned about interannual variability by  
172 dividing the database into major climate and ecological groups. In this section we address such  
173 questions as: which biophysical (weather vs ecological) forcings are most responsible to year to year  
174 variations in net and gross carbon fluxes?; do the controlling biophysical factors differ by climate and  
175 ecological space?; and where is year to year variability in  $N_E$  the greatest and least?. In part three, we  
176 draw upon the lessons learned and synthesize the findings. We ask if the published data records are  
177 long enough to detect trends given uncertainty in long term measurements? And, if so are temporal  
178 trends in carbon fluxes in a warmer world with more  $CO_2$  detectable?

179

## 180 **Methods and Data**

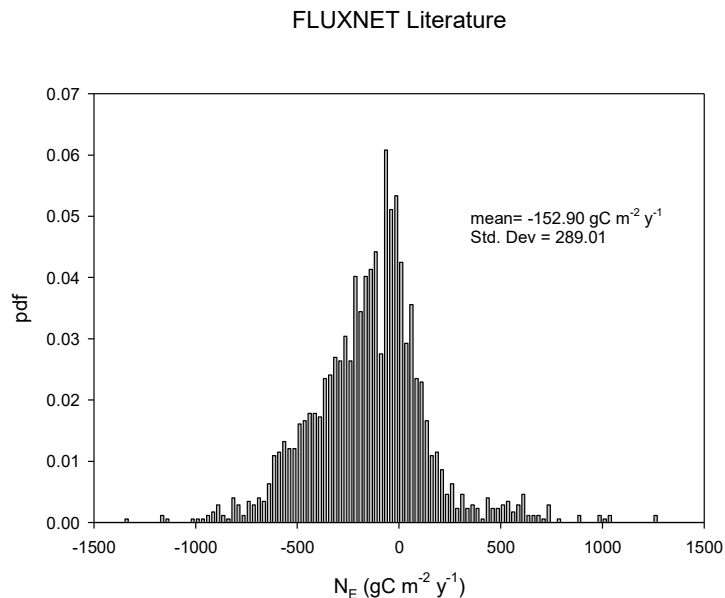
181 Data used in this analysis are derived from an updated compilation of published data (Baldocchi, 2003;  
182 Baldocchi, 2008) that used the eddy covariance method to measure net ecosystem exchange ( $N_E$ ).  
183 Negative values for net ecosystem exchange indicate a loss of carbon from the atmosphere, and a gain  
184 by the ecosystem. The interpretation of net ecosystem exchange was predicated on the inference of  
185 gross canopy photosynthesis ( $G$ ) and ecosystem respiration ( $R_e$ ) on annual time scales. Values of  $G$  and  
186  $R_e$  were derived from conditional sampling of net carbon fluxes during day and night periods. For this  
187 analysis, we assigned positive signs for the values of  $G$  and  $R_e$ , so  $N_E$  equals  $R_e$  minus  $G$ . As we write this  
188 review, the literature database has 1781 site years of data published, recorded from more than 270  
189 locations world-wide.

190 To produce daily and annually integrated carbon fluxes, missing values of the respective flux  
191 components were filled with data-derived, empirical algorithms (Reichstein et al., 2005). The most

192 prominent gap filling methods used by the scientific community include artificial neural networks, look-  
193 up tables or mean diel patterns (Falge et al., 2001; Moffat et al., 2007).

194 Because  $G$  and  $R_e$  are derived from  $N_E$  there has been some concern about errors from spurious  
195 correlation (Lasslop et al., 2010; Vickers et al., 2009). In a previous paper, we addressed this topic by  
196 testing the hypothesis that separate day/night and dormant/growing season sampling of carbon fluxes  
197 reduces spurious correlation when gross carbon fluxes are computed on annual time scales. Using data  
198 from a suite of FLUXNET field sites, we found that spurious correlations between derived gross carbon  
199 fluxes and net carbon exchange are generally small and most of the correlations between  $G$  and  $R_e$  at  
200 annual time scales were statistically true (Baldocchi et al., 2015). For background, we present the  
201 statistical distribution of annual sums of net and gross carbon fluxes in the database. Figure 1 shows the  
202 histogram of the published annual sums of net ecosystem exchange of carbon dioxide. This histogram  
203 indicates that ninety-five percent of the data resides between -748 and 482  $\text{gC m}^{-2} \text{y}^{-1}$ . The mean of the  
204 distribution is  $-153 \text{ gC m}^{-2} \text{y}^{-1}$  and its standard deviation is  $289 \text{ gC m}^{-2} \text{y}^{-1}$ .

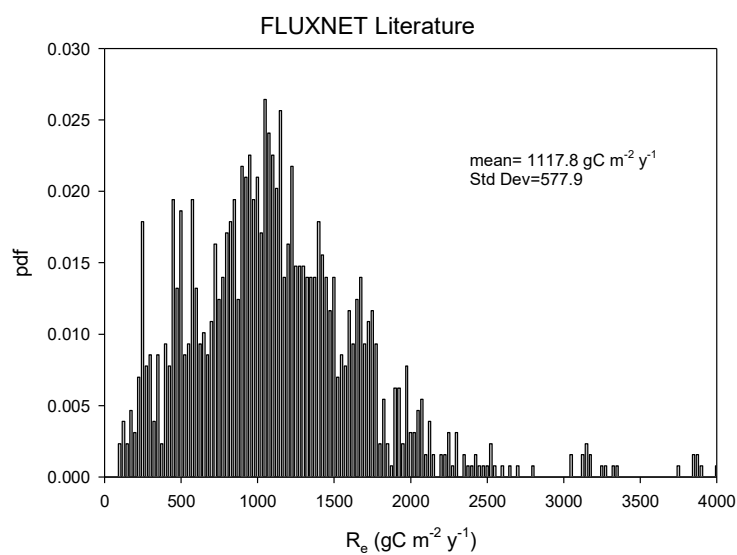
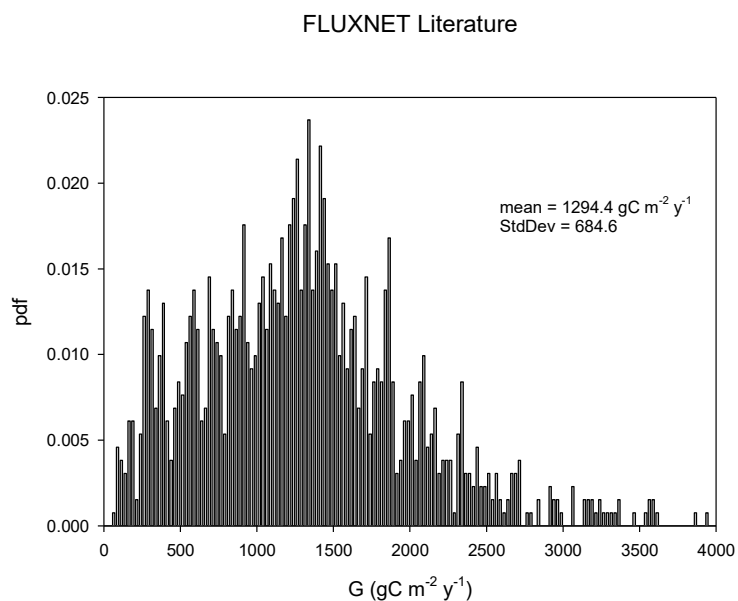
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206

207 Figure 1 Histogram of published values of net ecosystem carbon exchange,  $N_E$ , derived from annual long  
208 studies using the eddy covariance method. The histogram is based on 1781 site years of data. The y axis  
209 represents the probability density function, pdf.

210 Histograms for data associated with gross ecosystem photosynthesis ( $G$ ) and ecosystem respiration ( $R_e$ )  
211 are shown in Figure 2. Figure 2a shows that ninety-five percent of the data for  $G$  reside between 176  
212 and  $2919 \text{ gC m}^{-2} \text{y}^{-1}$  and that the histogram possesses a mean equal to  $1294 \text{ gC m}^{-2} \text{y}^{-1}$  and a standard  
213 deviation equal to  $684 \text{ gC m}^{-2} \text{y}^{-1}$ . Figure 2b shows that ninety-five percent of the data for  $R_e$  are  
214 confined between 219 and  $2511 \text{ gC m}^{-2} \text{y}^{-1}$ . This distribution possesses a mean of  $1117 \text{ gC m}^{-2} \text{y}^{-1}$  and a  
215 standard deviation of  $578 \text{ gC m}^{-2} \text{y}^{-1}$ . With the majority of flux sites in the temperate zone, these  
216 histograms tend to have long tails, and are biased from an under representation of measurements in the  
217 tropics which have larger values of  $G$  and  $R_e$  (Beer et al., 2010).



219

220 Figure 2 a) Histograms of published values of ecosystem photosynthesis (G) at annual time scales,  
 221 reported in the literature; b) histogram of published values of ecosystem respiration (R<sub>e</sub>) at annual time  
 222 scales, reported in the literature. These gross carbon fluxes were derived from eddy covariance  
 223 measurements of net ecosystem carbon exchange. The y axes represent the probability density  
 224 function, pdf.

225 For this analysis, we drew on data from 59 study sites that reported 5 or more years of flux data,  
 226 yielding 544 site years of data (Table 1). This dataset comprised of 5 studies with 15 or more years  
 227 reported; the longest published study has 18 years of observations (Froelich et al., 2015). We also  
 228 analyzed 18 studies with ten to 15 years of data and 36 studies with 5 to 10 years of data. The cut-off at  
 229 5 years may be viewed as arbitrary, but given that the majority of relatively long term studies are of this  
 230 duration it is worth including these studies for the sake of this review. Later in the paper we will address

231 the question 'how long is long enough?', with regards of the detection limit of year to year variations in  
232 annual carbon fluxes from random noise.

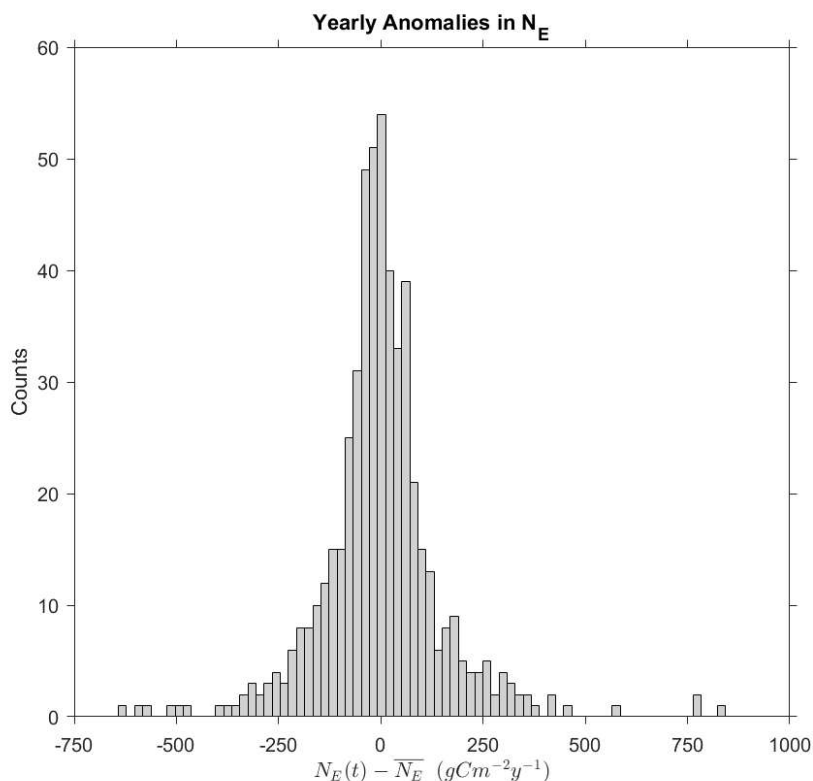
### 233 **Panoramic View of Interannual Variability**

234 The first query of the long-term database is: how variable are net and gross carbon fluxes on a year to  
235 year basis? If variability is low, we may have ample information to describe the carbon balance of  
236 these ecosystems. But, if interannual variability is great, we may need longer datasets to capture and  
237 explain the sources of this temporal variation.

238 We inspected the anomalies from the annual mean of each of the 59 time-series and plotted the  
239 histogram. For net ecosystem carbon exchange, the histogram was non-Gaussian (Figure 3); its  
240 distribution was peaked and positively skewed. The statistics for this distribution of anomalies  
241 possessed a standard deviation equal to  $162 \text{ gC m}^{-2} \text{ y}^{-1}$ , a skewness equal to 0.833 and a kurtosis equal  
242 to 12.5. Ninety-five percent of the data were bound between -317 and  $328 \text{ gC m}^{-2} \text{ y}^{-1}$ . Given the  
243 population mean of  $N_e$  around  $-200 \text{ gC m}^{-2} \text{ y}^{-1}$  (Figure 1), we conclude that the interannual variability of  
244 net ecosystem carbon exchange is very large. The high variability of net carbon fluxes has implications  
245 the uncertainty bounds of data used to benchmark carbon cycle models and on setting the probability  
246 distribution of priors used for Bayesian models (Zobitz et al., 2011).

247

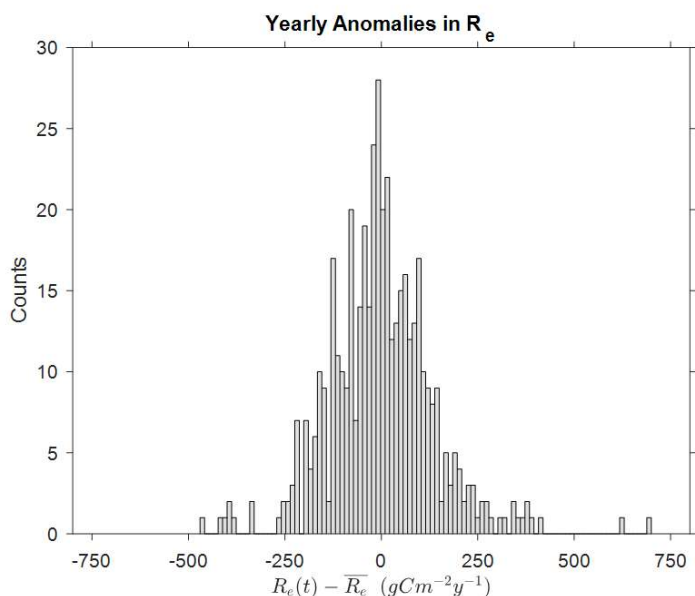
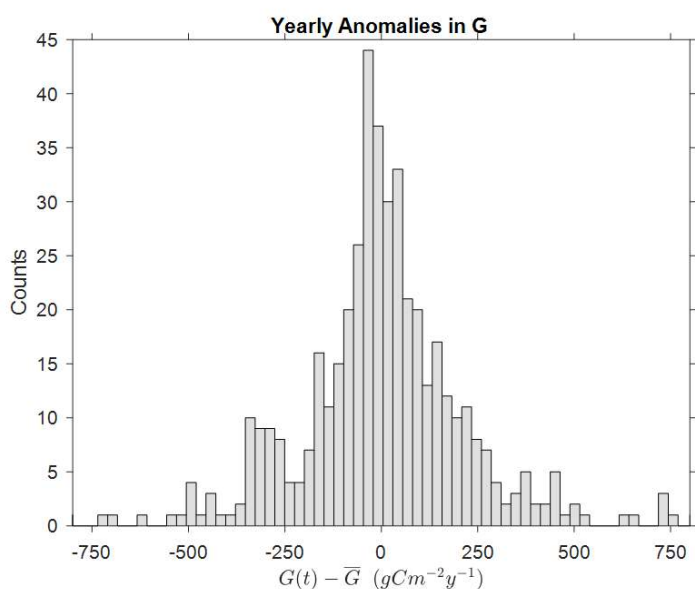
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249

250 Figure 3 Histogram of yearly anomalies in net ecosystem carbon exchange from the literature data pool  
251 of 544 site years of data. Anomalies were computed with regards to the annual mean of each time  
252 series in the database.

253 Variations in  $N_E$  can be due to large excursions in  $G$  or  $R_e$  or some combination of the two. In Figure 4a  
254 we examine the histogram of yearly anomalies in mean annual fluxes of gross photosynthesis. The  
255 standard deviation of interannual anomalies in  $G$  was  $230 \text{ gC m}^{-2} \text{ y}^{-1}$ , which was equivalent to 17.8% of  
256 population mean of  $G$  (Figure 2a). The skewness was -0.326, and its kurtosis was 8.51. Ninety-five  
257 percent of the interannual anomalies in the histogram for anomalies in  $G$  ranged between -475 and 468  
258  $\text{gC m}^{-2} \text{ y}^{-1}$ . In comparison, 95% of the anomalies in  $R_e$ , showed in Figure 4b, ranged between -243 and  
259  $308 \text{ gC m}^{-2} \text{ y}^{-1}$ . This distribution possessed a standard deviation of  $137 \text{ gC m}^{-2} \text{ y}^{-1}$ , which was equivalent  
260 to 12.6% of population mean of  $R_e$  (Figure 2b). The skewness was 0.472, and its kurtosis was 5.75.





262

263 Figure 4 Histogram of yearly anomalies in a) gross primary production, or photosynthesis (G) and b)  
264 ecosystem respiration,  $R_e$ . These data are derived literature data pool of 454 site years of data.  
265 Anomalies were computed with regards to the mean of each time series in the database.

266 The next question we explore are the degrees that the variances of inter-annual variations in  $N_E$  are  
267 associated with variances in G or  $R_e$ ? We can define the variance in net ecosystem exchange ( $N_E$ ) as the  
268 sum of the variance in gross canopy photosynthesis (G) and ecosystem respiration ( $R_e$ ), minus two times  
269 the covariance between G and  $R_e$  (Lasslop et al., 2010):

270 
$$\sigma_{N_E}^2 = \sigma_G^2 + \sigma_{R_e}^2 - 2\text{cov}(G, R_e) \quad (1)$$

271 In addition, one can express the covariance between G and  $R_e$  as a product of the respective standard  
272 deviations and the correlation coefficient ( $r_{GR_e}$ )

273 
$$\text{cov}(G, R_e) = \overline{G'R_e'} = r_{GR_e} \sigma_G \sigma_{R_e} \quad (2)$$

274 The interpretation of the sources of variance in  $N_E$  can be complicated by how the constituent terms  
275 add, covary and subtract with one another.

276 Normalizing the population of the mean of the constituent variances in Equation 1 we find that the  
277 variance in G is about twice the variance of  $N_E$  and that the variance in  $R_e$  is about 76% of the variance of

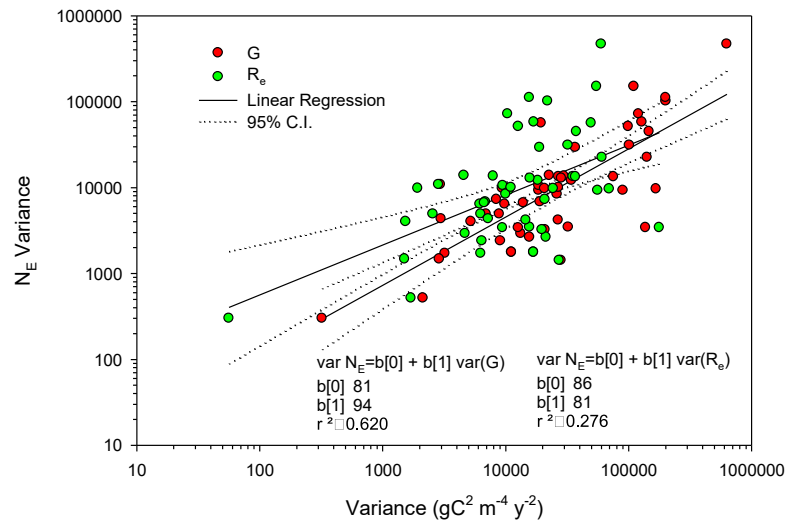
278  $N_E$ ;  $\frac{\sigma_G^2}{\sigma_{N_E}^2}$  equaled 2.038 and  $\frac{\sigma_{R_e}^2}{\sigma_{N_E}^2}$  equaled 0.767. The covariance between G and  $R_e$  interact to reduce

279 the variance in  $N_E$  by about 176%; the term,  $\frac{-2r_{GR_e}\sigma_G\sigma_{R_e}}{\sigma_{N_E}^2}$ , equaled -1.763. From these ratios one can

280 conclude that the direct contribution of the variance in G on the variance in  $N_E$  was about 2.65 times  
281 greater than the impact of the variance in  $R_e$ .

282 We dive deeper into the database by examining the relationship between the variances in  $N_E$ , computed  
283 for each site, and the terms in Equation 1 (Figure 5). The slope of the linear regression between the  
284 variances of G and  $N_E$  (0.794) was greater than the slope between the variances of  $R_e$  and  $N_E$  (0.58).  
285 Moreover, a lower portion of the variance in  $N_E$  was explained by the variance in  $R_e$  ( $r^2 = 0.276$ ) than by  
286 the variance in G ( $r^2 = 0.620$ ). While we conclude that a greater fraction of the variance in  $N_E$  is  
287 explained by the variance in G than the variance in  $R_e$ , it is clear that the magnitude of the variance of  $N_E$   
288 was conditional on the values of the variances of G and  $R_e$ . For example, when the variance in  $N_E$  was  
289 relatively low (e.g.  $1000 \text{ gC}^2 \text{ m}^{-4} \text{ y}^{-2}$ ) the variance in G equaled  $1487 \text{ gC}^2 \text{ m}^{-4} \text{ y}^{-2}$  and the variance in  $R_e$   
290 equaled  $271 \text{ gC}^2 \text{ m}^{-4} \text{ y}^{-2}$ . When the variance in  $N_E$  was at the midpoint of the data population ( $27,844 \text{ gC}^2$   
291  $\text{m}^{-4} \text{ y}^{-2}$ ), the variance in G was  $98,198 \text{ gC}^2 \text{ m}^{-4} \text{ y}^{-2}$  and the variance in  $R_e$  was  $83,246 \text{ gC}^2 \text{ m}^{-4} \text{ y}^{-2}$ . Finally,  
292 variance in  $N_E$  equaled  $38,125 \text{ gC}^2 \text{ m}^{-4} \text{ y}^{-2}$  when these variance terms were identical ( $145,989 \text{ gC}^2 \text{ m}^{-4} \text{ y}^{-2}$ ).

293

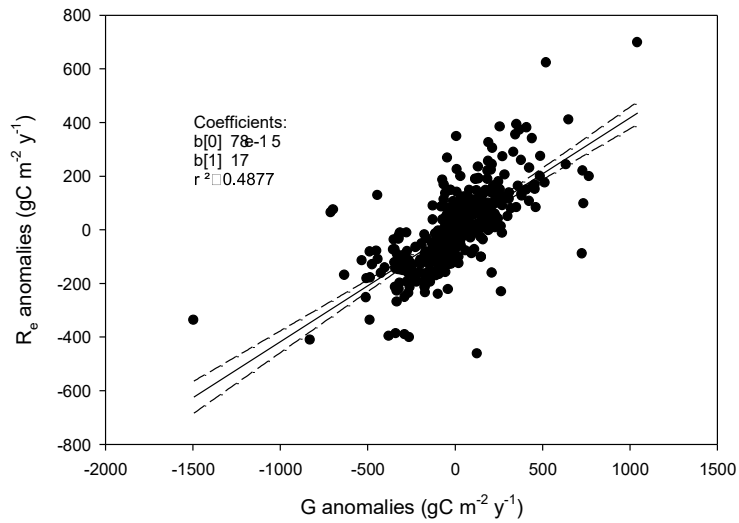


294

295 Figure 5 The regression between the variance in net ecosystem exchange ( $N_E$ ) and gross photosynthesis  
 296 (G) and ecosystem respiration ( $R_e$ ). Regression coefficients are for the log transform of  $\log(y) = b(0) + b(1)$   
 297  $\log(x)$ .

298 The degree with which anomalies in G and  $R_e$  covary with one another, as expressed in Equation 2, is  
 299 inspected in Figure 6. If the correlation between G and  $R_e$  is small, then the third term on the right-  
 300 hand side of Equation 1 may be small. Conversely, if the correlation between G and  $R_e$  is great, this third  
 301 term can offset sources of variance with the individual terms. Anomalies in  $R_e$  are about 42% as large as  
 302 anomalies in G. Moreover, there was a larger than expected degree of decoupling between anomalies  
 303 in G and  $R_e$ , as the coefficient of determination ( $r^2$ ) indicates that only 49% of the variation in  $R_e$  are  
 304 explained by G.

305

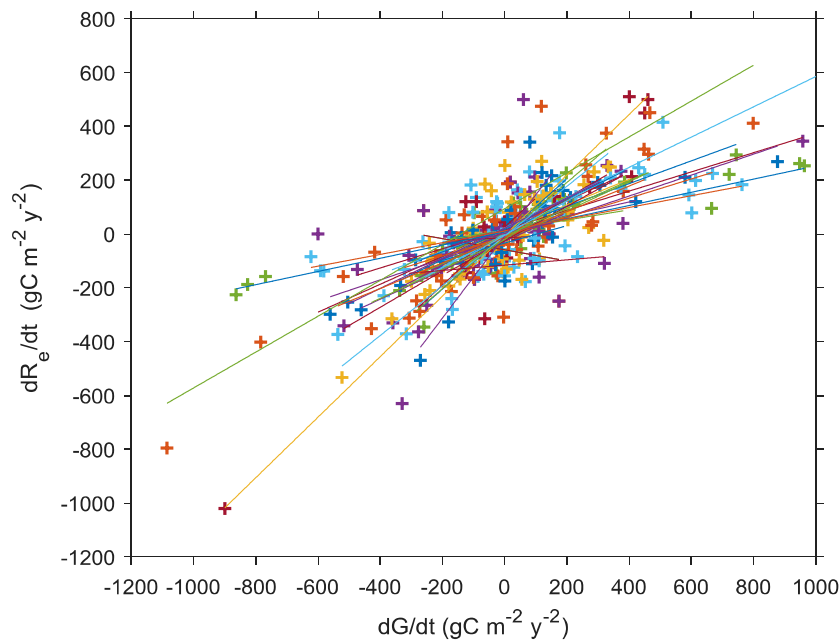


306

307 Figure 6 Examination of the covariance between ecosystem photosynthesis (G) and respiration ( $R_e$ ).  
 308 Plotted here are the yearly anomalies with the long term means of the data.

309 With longer datasets, we can inspect the degree of year to year coupling between G and  $R_e$  that spans a  
 310 spectrum of climates and ecosystem types (Figure 7),  $dG/dt$  and  $dR_e/dt$ . We observe a positive slope  
 311 between year to year changes in G and  $R_e$ , which is consistent with an earlier report using a smaller data  
 312 set consisting of shorter time series (Baldocchi, 2008). In sum, conditions that will cause G to increase  
 313 from year 1 to year 2 will be accompanied by a proportional, but smaller (49%), increase in  $R_e$ .  
 314 Conversely, conditions that lead G to decrease from year 1 to year 2 will be associated with a  
 315 compensating decrease in  $R_e$ . Hence, interannual variations in  $N_E$  have the potential to be more  
 316 sensitive to climate and weather anomalies that drive photosynthesis than respiration. This is a key  
 317 lesson in searching for attributions causing variations in  $N_E$  under extreme climate events.

318



319

320 Figure 7 Relation between year to year changes in gross ecosystem photosynthesis ( $dG/dt$ ) vs ecosystem  
 321 respiration ( $dR_e/dt$ ). The slope of the population is 0.494, the intercept is -1.137 and  $r^2$  equals 0.552,  $N =$   
 322 398. Color codes indicate data points from each study.

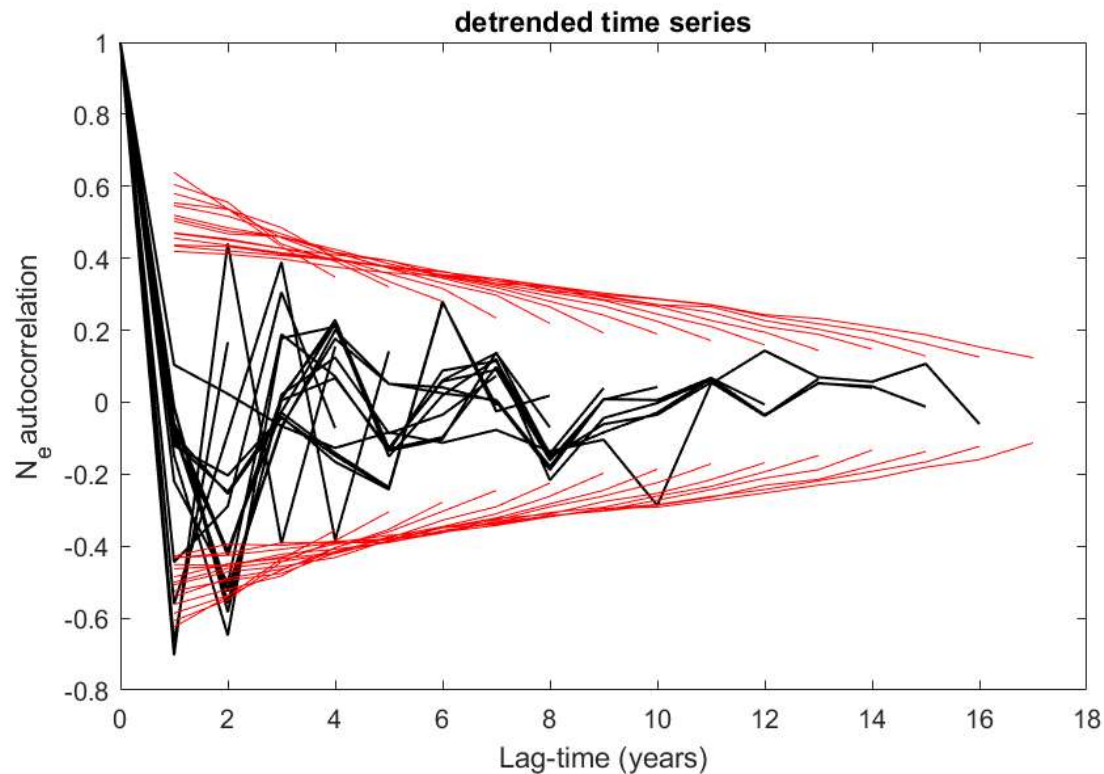
323 Contained within Figure 7 are four sets of data where year to year changes in  $R_e$  were equal or greater  
 324 than year to year changes in  $G$ . The evergreen conifer forests in the Pacific northwest (Wind River,  
 325 Campbell River), a deciduous beech forest in Denmark, and a grassland in North Carolina, which was in  
 326 the initial stage of post agricultural succession, fell into this category. Also noteworthy were data from  
 327 two other grasslands that had slopes close to one. These included a grassland in California and a  
 328 sphagnum, grass bog in Scotland. Signals emerging from these data suggest that sites associated with  
 329 two functional types (evergreen, humid conifer forests and grasslands) may be more vulnerable to  
 330 switching from being carbon sources to sinks with further perturbations in carbon fluxes from factors  
 331 like climatic and environmental change.

332 With regards to weather and climate, we know there is some degree of persistence in the system; there  
 333 is a high likelihood that today's weather will be the same tomorrow, and next year (Rybski et al., 2006).  
 334 The next question we ask is to what degree is there persistence in net carbon fluxes, from one year to  
 335 the next. We can investigate this by calculating and plotting the lag autocorrelation coefficients for each  
 336 of the detrended time series (Figure 8).

337 We see several types of behavior. Overall, it took between one-half to five years for the lagged  
 338 autocorrelation coefficients to cross zero. Of this population, we found one set of sites that became  
 339 negatively ( $< -0.5$ ) correlated with itself after a one-year lag; these correlation coefficients are  
 340 significantly different than zero, as determined from the 95% confidence interval of a random time  
 341 series. The implication of these negative lag correlation coefficients indicates a highly oscillatory  
 342 behavior in the net carbon fluxes from year to year. Sites in this category included an alpine meadow, a  
 343 sub-tropical forest, evergreen oak woodlands, a grassland, temperate evergreen forests and a deciduous  
 344 forest. The third feature in Figure 8 relates to decadal time scales. We found that the lag correlations

345 were generally not significantly different from zero, as detected by the band of the 95% confidence  
346 interval that was produced by a random time series. So, at this time we are unable to detect any world-  
347 wide variability in carbon fluxes that are at the time scales of El Nino's and La Nina's. Only one case  
348 experienced a relatively strong negative autocorrelation **at the time scale of a decade**; this occurrence  
349 was from the 18 year long record at the deciduous forest in Ontario, Canada. Its ten-year lag  
350 autocorrelation equaled -0.28, which was just inside the associated value of the 95% confidence interval  
351 (-0.29).

352



353

354 Figure 8 Lagged auto-correlation function for net ecosystem exchange at the 59 sites listed in Table 1.  
355 Each line denotes results from time series of one site study. To detect if the lag correlation values were  
356 significantly different from zero we performed a set of auto-correlation computations on a set of  
357 random numbers of progressive lengths (5 to 18). From these computations, we computed the 95%  
358 confidence intervals of lag correlations from an repeated ensemble (5000) of calculations, as shown with  
359 the red lines.

### 360 **Lessons Learned from Ecological and Climate Regions**

361 In this section, we divide the database into the dominant ecological and climatic regions of the world.  
362 We then distill which set of climate/ecological forcings and circumstances are responsible for driving  
363 carbon flux interannual variability in these regions. We also inspect the data to determine if any trends  
364 in carbon fluxes are being detected in our changing world? One of the lessons to emerge from the  
365 following analysis will be that there are a variety of explanations for interannual variability of carbon  
366 fluxes, and they differ region by region.

367 *Boreal Evergreen Forests*

368 Boreal evergreen forests thrive in the circumpolar latitude belt between 50 and 70 degrees of North  
369 America, Scandinavia, and Asia. They comprise of trees on the order of 10 m tall and establish canopies  
370 that possess a leaf area index on the order of 3 to 4 m<sup>2</sup> m<sup>-2</sup> (Bonan and Shugart, 1989; Luysaert et al.,  
371 2007).

372 Across the boreal forest, the interannual standard deviation of net carbon fluxes was relatively modest,  
373 less than 50 gC m<sup>-2</sup> y<sup>-1</sup> (Dunn et al., 2007; Ilvesniemi et al., 2009; Richardson et al., 2007; Soloway et al.,  
374 2017; Ueyama et al., 2014), compared to data from many other climate and ecological spaces shown in  
375 Figure 5 and Table 1.

376 In Finland, links between climate and year to year variability in net and gross carbon fluxes were not  
377 clear and only explained a small fraction of the variability in annual net ecosystem exchange (Ilvesniemi  
378 et al., 2009). However, the start of the growing season was best associated with air temperature and  
379 the end of the growing season was best described by day length (Suni et al., 2003). In contrast, an  
380 analysis of 15 years of data from a boreal deciduous and an evergreen forest in Saskatchewan and  
381 Manitoba, Canada, respectively, revealed that interannual variability in net carbon exchange was best  
382 explained by the interval of the dates in autumn when net carbon uptake and gross ecosystem  
383 photosynthesis ceased, a period called the 'autumn interval' (Wu et al., 2012). At these Canadian sites,  
384 there was no significant relationship between net carbon uptake and the spring interval between when  
385 ecosystem photosynthesis and net carbon uptake commenced. Another analysis of data from the  
386 mature (160 year-old) black spruce forest, in Manitoba, Canada, revealed the net ecosystem carbon  
387 exchange switched back and forth from being a carbon source or sink (Dunn et al., 2007; Soloway et al.,  
388 2017). In general, year to year variations in net carbon exchange were attributed to variations in air  
389 temperature, soil moisture, water balance and summer solar radiation. More specifically, warming and  
390 thawing of the soil caused ecosystem respiration to lag ecosystem photosynthesis. In these wet and  
391 cold boreal ecosystems, a shallow water table would suppress respiration and favor photosynthesis,  
392 causing the system to be a small carbon sink. Converse conditions would cause the ecosystem to be a  
393 carbon source.

394 For a boreal spruce forest growing in Alaska, interannual variation in net carbon exchange was forced  
395 mainly by changes in ecosystem respiration, which was being pushed by autumnal warming (Ueyama et  
396 al., 2014). At the southern fringe of the boreal zone, in Maine, United States, 40% of the variance in net  
397 ecosystem exchange was due to environmental drivers and 55% was due to biotic factors (Richardson et  
398 al., 2007).

399 Disturbance also plays a role in interannual variation of carbon fluxes in the boreal region (Amiro et al.,  
400 2010; Goulden et al., 2011). Following recovery from logging, a boreal forest in Canada will continue to  
401 be a carbon source for 10 years. Afterwards, it becomes carbon neutral and later a carbon sink  
402 (Coursolle et al., 2012).

403 None of these long-term studies identified the presence or absence of winter snow as a modulating  
404 factor, explicitly. However, Monson et al. (2006b) reported that winter respiration of an alpine forest,  
405 which is an elevated version of a boreal forest, depends upon the state of the snow pack. Soil  
406 temperatures are colder when the snow pack is shallow, which reduces soil respiration. And, a recent

407 regional analysis inferred that a decrease in winter respiration from declining snow pack explains an  
408 enhancement in the carbon sink of northern forests (Yu et al., 2016).

#### 409 *Temperate Evergreen Forests*

410 Temperate evergreen forests span a wide range of climate and soil conditions and are often intensively  
411 managed (Jarvis and Leverenz, 1983). On average, temperate evergreen forests maintain closed  
412 canopies with high leaf area indices ( $7 \pm 3 \text{ m}^2 \text{ m}^{-2}$ ), tall trees ( $20 \pm 12 \text{ m}$ ) and large amounts of  
413 standing biomass ( $14,934 \pm 13,562 \text{ gC m}^{-2}$ ) (Luyssaert et al., 2007). Temperate evergreen forests living  
414 in the humid Pacific northwest of North America possess some of the greatest biomass, highest leaf area  
415 index and the longest living trees. Conifer forests in the southern United States and Europe are  
416 intensively managed and logged at specific time intervals. Hence, long term carbon fluxes often include  
417 additional variability due to disturbance (Bracho et al., 2012; Dore et al., 2012). In addition, evergreen  
418 forests, with longer growing seasons, tend to grow on poorer soils, compared to deciduous forests.

419 There exist two sets of long term carbon flux studies in the wet humid, temperate zone of western  
420 North America (Krishnan et al., 2009; Wharton and Falk, 2016). One nine year study in British Columbia  
421 over a relatively young (58 year old) Douglas fir (*Pseudotsuga menziesii*) forest concluded that the major  
422 drivers of interannual variability of annual carbon fluxes were annual and spring air temperatures and  
423 water deficits during the late summer and autumn (Chen et al., 2009b; Krishnan et al., 2009). This forest  
424 was a strong net carbon sink ( $-356 \pm 51 \text{ gC m}^{-2} \text{ y}^{-1}$ ). The other study presented 13 years of data from an  
425 old age Douglas fir forest (Wharton and Falk, 2016). The net carbon budget was near zero,  $-32 \pm 84 \text{ gC}$   
426  $\text{m}^{-2} \text{ y}^{-1}$ . The interannual variability of net ecosystem exchange of the old Douglas fir forest growing in  
427 Washington was 64% greater than that of the younger forest growing in British Columbia. With this  
428 comparison, we start to see evidence for the effect of stand age on interannual variability of carbon  
429 fluxes of these temperate rain forests.

430 While the Pacific northwest is wet and receives ample rainfall, it experiences relatively dry summer  
431 growing seasons (Lassoie et al., 1985). Hence, year to year differences in net carbon exchange are  
432 strongly affected by spring temperature and late summer water deficits (Chen et al., 2009b; Krishnan et  
433 al., 2009). On a seasonal basis, light explained 85% of the variability in monthly ecosystem  
434 photosynthesis and temperature explained 91% of the variation in monthly ecosystem respiration. In  
435 sum, net carbon exchange was highest when precipitation was normal and air temperature was  
436 'optimally' warm and lowest during the warmest and driest years. Variability of net and gross carbon  
437 fluxes in this region are closely linked to the El Nino-Southern Oscillation (ENSO), and the Pacific North  
438 American (PNA) and Pacific Decadal Oscillations; the old-age forest was a stronger sink during the  
439 favorable climate conditions of La Nina and was either a source or near neutral during El Nino years  
440 (Wharton and Falk, 2016).

441 Ponderosa pine (*Pinus ponderosa*) thrive in semi-arid mountain regions from east side of the Cascade  
442 mountains in Oregon, through the Sierra Nevada mountains of California and Nevada and into northern  
443 Arizona. The carbon budget of these forests is often disturbed by fire and logging. Two sets of studies  
444 have produced long term records on net and gross carbon exchange of these forests (Dore et al., 2010;  
445 Thomas et al., 2009). In both instances year to year variations in net ecosystem exchange, as quantified  
446 by the standard deviation, were on the order of  $100 \text{ gC m}^{-2} \text{ y}^{-1}$ , indicating a highly variable ecosystem.

447 For a 90 years old ponderosa pine stand in Oregon, mean net ecosystem carbon exchange was  $-464 \pm$   
448  $116 \text{ gC m}^{-2} \text{ y}^{-1}$  over seven years. Interannual variation in growing season length of the hydro-ecological  
449 year could be as large as 45 days (Thomas et al., 2009). However available soil water was the main factor  
450 modulating net and gross carbon fluxes on a year to year basis. This team concludes that variability in  
451 annual ecosystem photosynthesis, which is modulated by available soil water, drives the interannual  
452 variability in net ecosystem carbon exchange. In Arizona, disturbance by fire and thinning were factors  
453 driving interannual variability in net and gross carbon fluxes of another ponderosa pine forest (Dore et  
454 al., 2012).

455 Slash pine (*Pinus elliotii*) forests in Florida experience relatively frequent logging cycles (20 to 25 years).  
456 An 11 year study across the disturbance and recovery time history was the most variable in the record  
457 ( $111 \pm 683 \text{ gC m}^{-2} \text{ y}^{-1}$ ) in this database. The forest lost between 800 and 1250  $\text{gC m}^{-2} \text{ y}^{-1}$  during the first  
458 3 years after disturbance, was carbon neutral after 5 years and was a strong sink ( $-400$  to  $-700 \text{ gC m}^{-2} \text{ y}^{-1}$ )  
459 thereafter (Bracho et al., 2012). Aggrading leaf area index was a dominant factor driving this forest  
460 from a large carbon source to sink. Across the data base that was inspected this site possessed the  
461 greatest year to year variability in  $N_E$ . In comparison, the mid-rotation stand had a negative NEE value of  
462  $-669 \pm 98 \text{ gC m}^{-2} \text{ y}^{-1}$  over 9 years.

463 For forests growing in Europe, we find that a 100 years old spruce forest (*Picea abies*) in Germany is one  
464 of the more productive of those surveyed, but its net ecosystem carbon exchange is highly variable; its  
465 mean net ecosystem exchange over 10 years was  $-550 \pm 91 \text{ gC m}^{-2} \text{ y}^{-1}$  (Grunwald and Bernhofer,  
466 2007). High variation in net and gross carbon fluxes was attributed to a wide span of rainfall (500 to  
467  $1000 \text{ mm y}^{-1}$ ) and mean annual air temperature (6 to 9 C) during the duration of the time series at this  
468 continental site. Carbon uptake was greatest during the warm and relatively wet years and least during  
469 the warm and driest years. The wettest year depressed net carbon uptake, which is expected due to  
470 light limitations by clouds.

#### 471 *Temperate Deciduous Forests*

472 The geographic band for temperate deciduous forests range between 30 and 50 degrees across North  
473 America, Europe and Asia (Barnes, 1991; Hicks and Chabot, 1985). These forests rely on a substantial,  
474 but not excessive amount of rainfall (800 to 1400 mm per year), survive cold winters down to about -20  
475 C and can withstand warm summer temperatures up to the low 30s (Baldocchi and Xu, 2005). These  
476 forest tend to be tall ( $19 \pm 7 \text{ m}$ ) and possess a closed canopy with high leaf area index ( $6 \pm 3 \text{ m}^2 \text{ m}^{-2}$ )  
477 (Luyssaert et al., 2007).

478 Temperate deciduous forests are one of the ecosystems with the largest number of long term eddy  
479 covariance, carbon flux measurement studies (Froelich et al., 2015; Granier et al., 2008; Herbst et al.,  
480 2015; Novick et al., 2015; Pilegaard et al., 2011; Saigusa et al., 2005b; Shao et al., 2014; Sulman et al.,  
481 2016; Urbanski et al., 2007; Wilkinson et al., 2012; Wilson and Baldocchi, 2001). Interannual variation  
482 of  $N_E$  among this climate and functional type is relatively large. On average, the standard deviation of  
483 interannual  $N_E$  of these datasets is close to  $\pm 100 \text{ gC m}^{-2} \text{ y}^{-1}$  (Table 1).

484 The longest published time series of  $N_E$  comes from the mixed forest near Borden, Ontario, Canada, and  
485 is 18 years long (Froelich et al., 2015). At this site, the mean  $N_E$  was  $-177 \pm 115 \text{ gC m}^{-2} \text{ y}^{-1}$ . The authors  
486 reported that light and temperature were the main meteorological factors forcing interannual variation  
487 in carbon fluxes. Net carbon exchange also correlated well with length of growing season, which ranged



488 between 111 and 164 days per year. At this site a small trend in  $N_E$  was reported ( $15 \text{ gC m}^{-2} \text{ y}^{-2}$ ) and was  
489 attributed to slow long term warming ( $0.09 \text{ C y}^{-1}$ ).

490 Harvard Forest, in Massachusetts, USA, was the first locale at which the first long term carbon fluxes  
491 were measured (Wofsy et al., 1993), and is the source of the longest measured time series. This team's  
492 analysis of 13 years of measurements found that uptake rates doubled as the forest aged from 75 to 110  
493 years (Urbanski et al., 2007); they concluded that tree biomass, successional changes in forest  
494 composition and disturbance were dominant factors driving interannual and decadal variations in net  
495 carbon exchange. Length of the growing season and deepness of winter snow has also been identified  
496 as a factor affecting net carbon exchange at this site (Goulden et al., 1996).

497 Three long term studies come from beech forests growing across Europe and differing in age (Granier et  
498 al., 2008; Herbst et al., 2015; Pilegaard et al., 2011). Each experienced different sources of variation.  
499 Over an 80 to 90 year old beech forest in Denmark, a trend  $N_E$  measured was detected; it increased  $23$   
500  $\text{gC m}^{-2} \text{ y}^{-2}$  as the length of the growing season increased 1.9 days per year across a 13 year period  
501 (Pilegaard et al., 2011). In comparison, a 40 year old beech forest in France experienced high variability  
502 in  $N_E$  due to length of the growing season and the duration of soil water deficits (Granier et al., 2008).  
503 This forest was thinned, but this thinning did not change photosynthesis markedly and year to year  
504 changes in ecosystem respiration were not linked to climate forcings. In Germany, an unmanaged beech  
505 forest with trees up to 250 years old was compared with a managed beech forest with trees averaging  
506 130 years old (Herbst et al., 2015). Average net carbon exchange of the two forests did not differ.  
507 However, this team found that interannual variability of  $N_E$  was greater for the managed, than the  
508 unmanaged, forest ( $119$  vs  $70 \text{ gC m}^{-2} \text{ y}^{-1}$ ). The lowest years of carbon uptake occurred when fruit  
509 production was greatest. In addition, the old age, unmanaged forest suffered more from the 2003  
510 drought/heat spell and no trend in  $N_E$  was detected, in contrast to the beech forest in Denmark.

511 An 80 year old deciduous forest in the United Kingdom was highly productive ( $-486 \text{ gC m}^{-2} \text{ y}^{-1}$ ) and  
512 experienced moderate ( $\pm 73 \text{ gC m}^{-2} \text{ y}^{-1}$ ) variability over 12 years (Wilkinson et al., 2012).  
513 At this site year to year differences in the growing season was small and stable ( $165 \pm 6$  days).  
514 Interannual variations in sunlight modulated carbon fluxes at this site most (variations in radiation  
515 accounted for 46% of the variation in  $N_E$ ). Insect infestations were another source of variation. This is a  
516 natural and possible source of variation in carbon fluxes that would be missed with shorter term studies.

517 In Japan, interannual variability in net carbon exchange of a temperate deciduous forest was strongly  
518 associated with spring air temperature and the timing of leaf out (Saigusa et al., 2005a); it was also  
519 reported that the occurrence of *El Nino* favored earlier leaf emergence. On the other hand, the effect of  
520 the monsoon on clouds and summer solar radiation did not have a discernable effect on interannual  
521 variation in net carbon exchange.

522 In sum, length of growing season is a dominant factor affecting  $N_E$  across much of the deciduous forest  
523 biome. Deciduous forests tend to optimize the length of growing season by leafing out when soil  
524 temperature matches mean annual air temperature (Baldocchi et al., 2005). If the plants leaf out too  
525 early they are susceptible to damage by late freeze or frost events (Gu et al., 2008). In contrast, if they  
526 are too conservative and leaf out too late they have a shorter period to accumulate carbon.

527 *Evergreen Broadleaved Forests*

528 Evergreen broadleaved forests thrive where there is no frost or freezing (Woodward, 1987). Examples  
529 include the tropical forests of South America, Africa and Asia, subtropical forests, like the eucalyptus  
530 forests of Australia, and the evergreen oaks of zones with Mediterranean type climates.

531 Temperature is mostly invariant in the tropics. So year to year differences in rainfall and sunlight tend  
532 to have the greatest impact on interannual carbon fluxes (Araújo, 2002; Goulden et al., 2004; Wu et al.,  
533 2016; Yan et al., 2013; Zeri et al., 2014). Often tropical forests are light limited due to the presence of  
534 clouds and frequent rain, so there can be an unexpected consequence with mild drought, more light and  
535 photosynthesis.

536 Six years of carbon flux observations from a southwestern Amazonian forest encountered two years of  
537 severe drought and one year of flooding (Zeri et al., 2014). At this site, carbon fluxes tend to be highest  
538 at the end of the dry season when sunlight is ample and diffuse light increases light use efficiency. This  
539 site is noteworthy for the observation of a lack of synchrony between monthly rainfall and carbon  
540 uptake. Consequently, legacy effects of the 2005 drought were noted the year after; this year the forest  
541 was a carbon source even though gross photosynthesis remained relatively high ( $2000 \text{ gC m}^{-2} \text{ y}^{-1}$ ).

542 In another part of the Amazon, near Santarem, Brazil, it was found that hourly variations in solar  
543 radiation, diffuse light fraction and vapor pressure deficits could account for 75% of the variability in  
544 ecosystem photosynthesis (Wu et al., 2016). When carbon fluxes were aggregated into daily, monthly  
545 and annual integrals, these variables explained a progressively smaller fraction of variability in  
546 photosynthesis (down to 3%). Instead, biological factors, such as light use efficiency and phenology, had  
547 a larger (63%) explanatory power.

548 Across Asia, tropical forests assimilate carbon at greater rates and with greater interannual variability (-  
549  $397 \pm 94 \text{ gC m}^{-2} \text{ y}^{-1}$ ) than sub-tropical forests ( $-166 \pm 49 \text{ gC m}^{-2} \text{ y}^{-1}$ ) (Yan et al., 2013). Rainfall is the  
550 fundamental driver of carbon exchange of tropical and sub-tropical forests and best explained  
551 interannual variability in  $N_E$ . The sub-tropical forest was a carbon sink during wet and dry seasons. In  
552 contrast, the tropical forest was a carbon source during the wet season, when ecosystem respiration  
553 outpaced carbon assimilation. Drought reduced wet season respiration, enabling the tropical forest to  
554 be a stronger carbon sink during the dry years.  
555

556 Two papers reported on measurements from eucalypt forests, a natural stand in Australia (van Gorsel et al.  
557 et al., 2013) and a plantation in Portugal (Rodrigues et al., 2011). Ten years of carbon flux measurements  
558 over a native eucalypt stand revealed that extended clouds during wet periods and extended dry  
559 periods both reduced carbon uptake (van Gorsel et al., 2013). Drought also promoted an insect attack,  
560 which caused the forest to become a carbon source. Large year to year variations in rainfall (between  
561  $370$  and  $750 \text{ mm y}^{-1}$ ) at a Portuguese eucalypt plantation caused this stand to switch back and forth  
562 from being a strong sink ( $-865 \text{ gC m}^{-2} \text{ y}^{-1}$ ) to being carbon neutral ( $-11 \text{ gC m}^{-2} \text{ y}^{-1}$ ) (Rodrigues et al., 2011).

563 As has been shown with shorter time series, evergreen broad-leaved forests in semi-arid regions, like  
564 Australia, or Mediterranean climates, like France, Italy and Portugal can experience variability by the  
565 amount of rain during the wet growing season (Allard et al., 2008; Pereira et al., 2007). And, drought  
566 stress reduces ecosystem photosynthesis more than respiration.

567 *Grasslands*

568 Grasslands are associated intermediate rainfall conditions that are too dry to sustain forests and too wet  
569 for deserts (Woodward, 1987). While grasslands thrive across wide swaths of North and South America  
570 and Eurasia, long term published data come only from the Mediterranean climate of California and the  
571 benign maritime climates of the British Isles.

572 Based on 15 years of data, an annual grassland in California, with a winter and spring growing season  
573 experienced reduced photosynthesis during the wettest years (Ma et al., 2016). This system also  
574 experienced legacy effects on ecosystem respiration. Consider a year with high biomass production. A  
575 large fraction of this biomass will persist and be present the next growing season. This dead biomass  
576 will compete for photons with emerging sprouts and reduce their carbon assimilation.

577 Grass grows nearly year-round in Ireland. Management, in terms of grazing and harvesting, were among  
578 the more dominant factors affecting carbon fluxes in this maritime climate where environmental  
579 conditions were often not limiting (Peichl et al., 2012).

580 *Semi-Arid Savanna*

581 Semi-arid ecosystems can be viewed as natural models for a future world that is drier and warmer, as  
582 these system experience much year to year variability in rainfall (30 to 40% coefficient of variation),  
583 compared to more humid and mesic climate zones (Fatichi et al., 2012). Semi-arid savannas tend to be  
584 about 12 +/- 8 m tall and support an open canopy (leaf area index equals 3.5 +/- 1.2) (Luyssaert et al.,  
585 2007; Sankaran et al., 2005).

586 Savanna woodlands in regions with Mediterranean climates, cool, wet winters and hot dry summers,  
587 year to year variations are mostly driven by the amount of rain during the spring (Allard et al., 2008; Ma  
588 et al., 2016; Ma et al., 2007). Both G and  $R_{eco}$  increased linearly with increasing spring rainfall up to a  
589 limit. Years with excessive rainfall, meet the water demand of the open woodlands and end up limiting  
590 G through cloudiness and limited light. Carbon uptake is limited by physiological soil water deficits  
591 during the dry hot summers, so small absolute changes in rainfall may have large relative.

592 *Wetlands/Peatlands/Tundra*

593 Two long term flux studies over wetlands were conducted on the British Isles, Scotland and Ireland  
594 (Helfter et al., 2015; McVeigh et al., 2014). Both studies reported very small annual fluxes ( $-64 \text{ gC m}^{-2} \text{ y}^{-1}$   
595 <sup>1</sup> in Scotland and  $-55 \text{ gC m}^{-2} \text{ y}^{-1}$  in Ireland). Moreover, the clement, maritime climate of these locales  
596 produced time series that ranked among the least variable (the standard deviations in  $N_E$  were less than  
597  $38 \text{ gC m}^{-2} \text{ y}^{-1}$ ).

598 Despite the small range, interannual variability in  $N_E$  depended upon the length of growing season and  
599 depth of the water table. These ecosystems experienced an anti-correlation between  $R_e$  and G, when  
600 drought increased  $R_e$ , by decreasing the water table, and decreased G (Helfter et al., 2015). Conversely,  
601 warmer winter temperatures lead to an earlier spring, longer growing season and greater G. Based on  
602 these studies, anticipated trends in declining water tables with global warming are anticipated to cause  
603 these ecosystems to become smaller carbon sinks and potentially carbon sources.

604 The first set of long term carbon flux data were published recently from two representative Arctic  
605 ecosystems in Alaska, a wet sedge and heath tundra (Euskirchen et al., 2016). These ecosystems are

606 shifting from being a small carbon sink to losing carbon, as increasing air and thawing soil temperatures  
607 are triggering the decomposition of stored organic matter that had been inactive in frozen layer. Later  
608 dates of autumnal freezing are also extending the period of net carbon loss.

### 609 *Crops*

610 Management has an overwhelming impact on interannual variability of crops, depending upon the  
611 choice of crop (corn or soybeans) and whether it is rainfed or irrigated (Knox et al., 2016; Suyker and  
612 Verma, 2012). With maize/soybean rotation, both irrigated and rainfed maize are a moderate carbon  
613 sink, compared to soybean, which ranges from being carbon neutral to a small carbon source (Suyker  
614 and Verma, 2012). Yet, given a specific crop, exogenous factors, like the wetness of the spring on the  
615 timing of planting, can modulated photosynthesis, and the temperature of the soil can affect ecosystem  
616 respiration (Knox et al., 2016).

### 617 **Discussion and Synthesis**

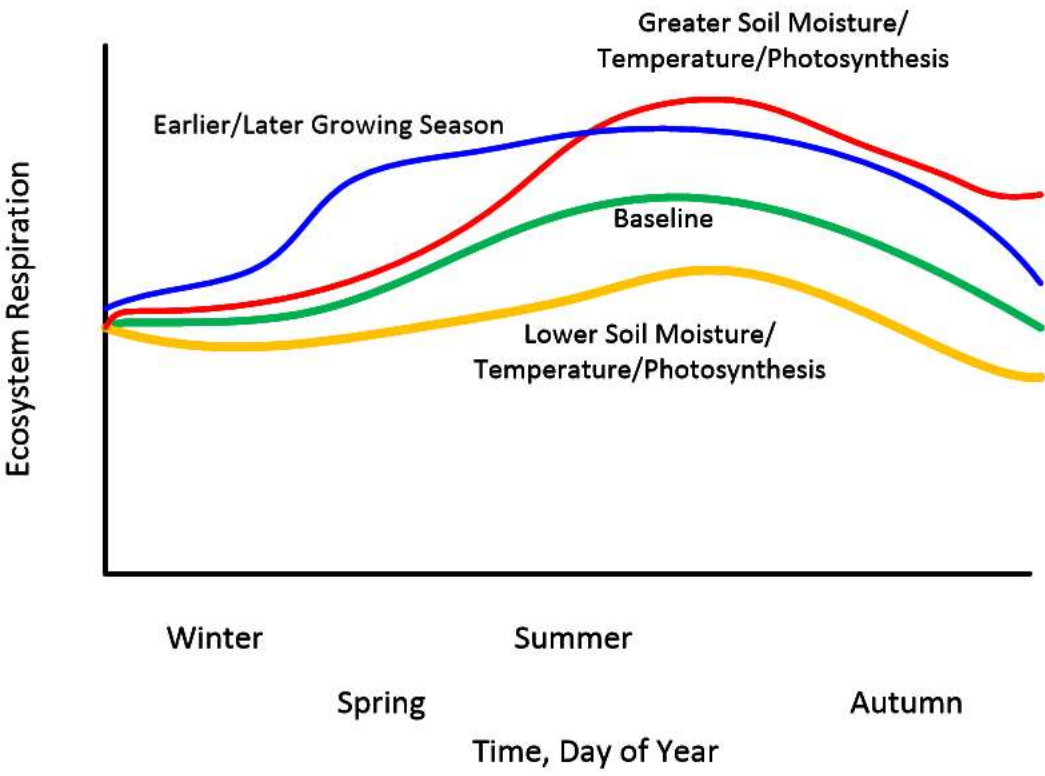
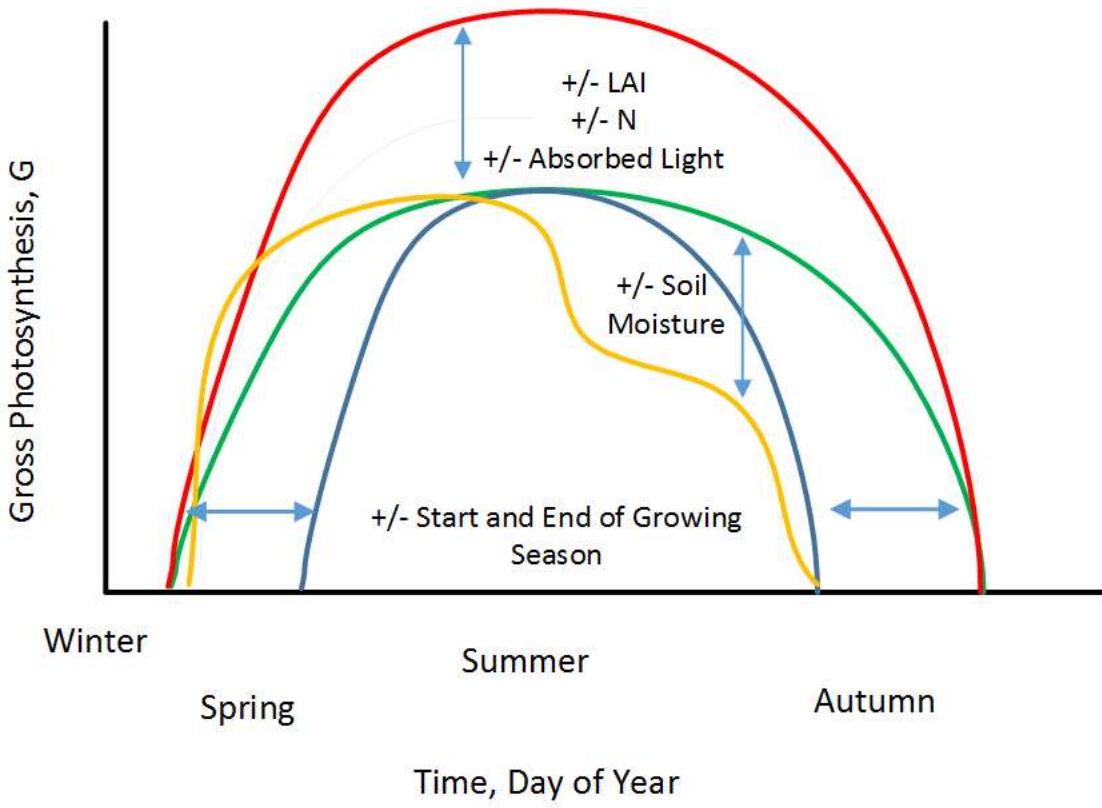
618 As we accumulate more and longer time series on net and gross carbon fluxes inquiries about the  
619 relative contribution of climatic vs biotic drivers are being produced (Richardson et al., 2007; Shao et al.,  
620 2015). The most exhaustive meta-analysis to date, using flux data from 65 sites, showed that biotic  
621 factors contributed to 57% of the variability in net ecosystem exchange and climatic factors were  
622 associated with the residual (43%) (Shao et al., 2015).

623 This literature review, performed on a larger body of data, reveals that a complex combination of  
624 climate, ecological and disturbance variables can explain year to year variability in net and gross carbon  
625 fluxes to different degrees in different parts of the world. Inspecting results from individual papers, we  
626 have learned that variability in ecosystem photosynthesis is the more dominant factor causing  
627 interannual variation in net ecosystem carbon exchange,  $N_E$ , for a complex combination of climatic and  
628 ecological reasons.

629 In principle, there **are** a variety of factors that can modulate annual gross primary productivity from one  
630 year to the next. Consider the conceptual figure where the green line is the baseline (Figure 9a).  
631 Changes in the area under the curve can occur if the season starts earlier and/or ends later (blue line).  
632 A growing number of studies are finding that that an earlier spring may positively modulate carbon  
633 fluxes in a deciduous forest more, while later autumn has a greater impact on accumulated  
634 photosynthesis of a boreal forest. Figure 9 also shows that there can be a bump in the midseason rate  
635 of carbon uptake if more light is absorbed via more leaf area index, fewer clouds or higher  
636 photosynthetic capacity and leaf nitrogen (red line). There can be a decrease in light absorption if there  
637 is any legacy effect of dead biomass competing for photons the following year. The experience of a  
638 summer drought will reduce carbon uptake later in the growing season, relative the baseline (yellow  
639 line) (Reichstein et al., 2007; Wolf et al., 2016); this can occur by direct physiological stress and/or by a  
640 co-occurring reduction in leaf area index.

641 The lower panel (figure 9b) shows related changes in ecosystem respiration, where the green line is the  
642 baseline. Drought and reductions in photosynthesis (yellow line) reduce the time course in respiration.  
643 Higher photosynthesis or photosynthetic capacity (red line) will have a compensatory increase in  
644 ecosystem respiration. An earlier or later growing season (blue line) will promote respiration compared  
645 to the base case.



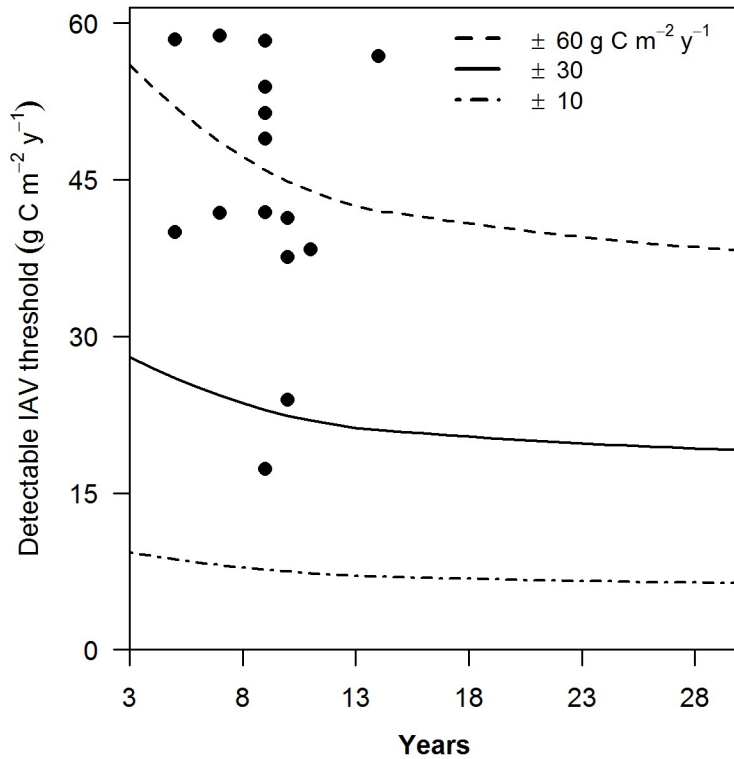


648 Figure 9 Conceptual figure on how ecosystem photosynthesis, or gross primary production and  
649 ecosystem respiration may vary year to year by a set of biophysical forcings. The green line is the  
650 baseline. Yellow line is for a season with less soil moisture in late growing season. The blue line is for  
651 earlier start and later end of the growing season. The red line is for conditions that increase  
652 photosynthesis through more leaf area, more light absorption or greater photosynthetic potential  
653 though greater leaf nitrogen. The lower panel shows how ecosystem respiration may respond to these  
654 changes in photosynthesis and environmental conditions.

655 The standard deviations and trends of interannual variability, reported here, have uncertainties  
656 associated the intrinsic sampling and measurement error associated with the eddy covariance method  
657 and with the length of the time series. Using statistical sampling of random synthetic time series, we  
658 estimated the uncertainty of interannual carbon fluxes that one must exceed given the duration of the  
659 time series and the error of the measurements. We ran Monte Carlo simulations (N=5,000) to derive  
660 the detectable thresholds for trends and inter-annual variability of the annual carbon fluxes. The  
661 simulations begin with three levels of random uncertainties (i.e., +/-10, +/-30, to +/-60 g C m<sup>-1</sup> y<sup>-1</sup>, 95%  
662 CI) in the annual carbon fluxes. A series of artificial time series are then drawn from the proposed  
663 uncertainty distributions, and are used to calculate the trends (i.e., linear regression slope) and  
664 interannual variability (i.e., standard deviation). The 95% quantiles of the simulated trends and  
665 interannual variability are interpreted as the detectable thresholds. The simulations are carried out  
666 subsequently for time series ranging from 5 to 30 years.

667 Figure 10 shows that the threshold for detecting interannual variability in net carbon flux decreases as  
668 the duration of the time series increases and the sampling/measurement error decreases. For a  
669 conservative case, the interannual variability must exceed 50 gC m<sup>-2</sup> y<sup>-1</sup> to be attributed to non-random  
670 causes if the random sampling error was +/- 60 gC m<sup>-2</sup> y<sup>-1</sup> and the time series was 5 years long. This  
671 threshold drops to about 40 gC m<sup>-2</sup> y<sup>-1</sup> as the time series exceeds 20 years.

672



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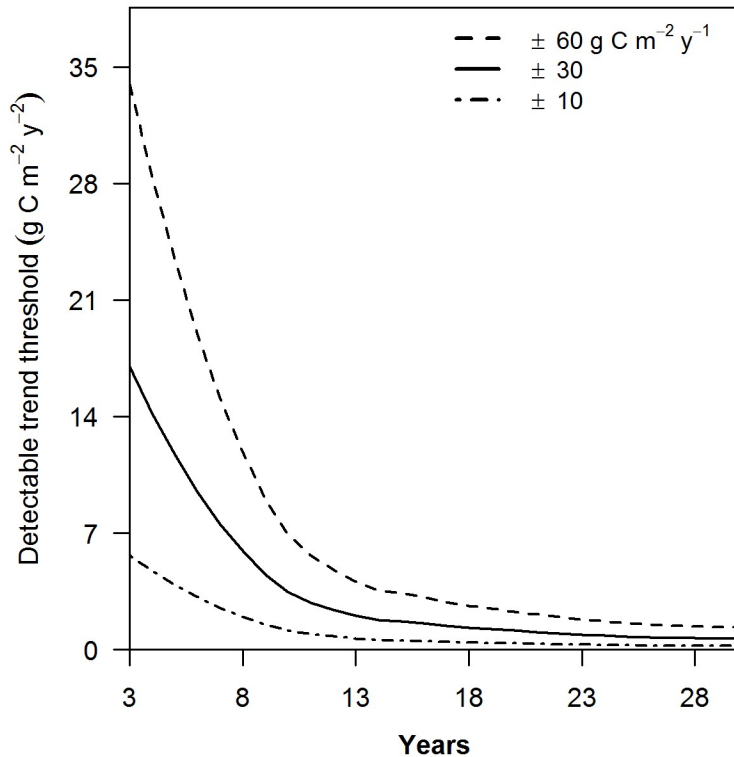
674 Figure 10 Confidence interval of standard deviation as a function of sample size and sampling error.  
 675 Superimposed on this figure are reported values (closed circles) from literature review. For better  
 676 presentation, only reported values lower than  $60 \text{ g C m}^{-2} \text{ y}^{-1}$  were showed here.

677 The length of the time series has a marked impact on how well we can detect temporal trends, or not,  
 678 too (Shao et al., 2015). Figure 11 shows that that the 95% confidence interval of detectable trends  
 679 reduces markedly as the duration of the time series extends from 3 to 30 years. We find that  
 680 measured trends of interannual  $N_E$  must exceed  $8 \text{ g C m}^{-2} \text{ y}^{-2}$  if the measurement error is  $30 \text{ g C m}^{-2} \text{ y}^{-1}$  and  
 681 the time series is 5 years long for one to conclude that the noted variation is natural and not due to  
 682 randomness. If we have longer records, exceeding 20 years, we should be able to detect trends as small  
 683 as  $3 \text{ g C m}^{-2} \text{ y}^{-2}$ .

684 Figure 11 gives us context with regards to interpreting reported trends if there is no systematic bias. For  
 685 example, Pilegaard et al (2011) reported a trend in their 13 year record equal to a slope of  $25 \text{ g C m}^{-2} \text{ y}^{-2}$   
 686 and Froelich et al. (2015) reported a trend of  $15 \text{ g C m}^{-2} \text{ y}^{-2}$  from an 18 year record. Assuming a  $30 \text{ g C m}^{-2}$   
 687  $\text{y}^{-1}$  measurement/sampling error, these trends exceed the detectable limit due to random causes.

688





689

690 Figure 11 95% confidence intervals of trends in random time series of varying length and varying  
 691 measurement uncertainty.

692 *Closing comments*

693 We need long term carbon flux measurements for many reasons. Most importantly is to study  
 694 ecosystems on ecosystem time scales, which exceed decades. For example, long time series give us a  
 695 better and direct understanding how landscapes recover from disturbance, slow and steady process  
 696 (Odum, 1969). So far we have relied on chrono-sequences, time for space, to understand how net and  
 697 gross carbon exchange changes with time since disturbance (Amiro et al., 2010; Goulden et al., 2006).  
 698 But, this approach does not control for soil type and is often applied across large geographical areas.  
 699 Extending the time series of many disturbed forest sites beyond a decade and into multiple decades  
 700 remains an important goal for future long term research.

701 Secondly, long term flux studies are needed to provide information on whether or not, and if so, how  
 702 fast, ecosystem metabolism may be responding to a changing world that is warmer, bathed in more CO<sub>2</sub>,  
 703 experiencing variation in rainfall and different degrees of nitrogen deposition, air pollution and  
 704 disturbance from humans, diseases and pests. This behavior, with co-occurring global warming, a  
 705 changing hydrological cycle and rising CO<sub>2</sub> will make even longer time series measurements crucial.  
 706 These datasets are invaluable and cannot be recreated if they are shut.

707 We also show clearly that longer time series are needed to distinguish trends from random noise and  
 708 that future evaluations of year to year variability should consider this possibility. Leaving on a positive  
 709 note, the uncertainty will decrease in a diminishing returns manner as the length of the time series  
 710 increase from 5 to about 20 years. Ideally, it will be a goal to produce a diverse number of carbon flux

711 time series reaching and exceeding 30 years. This will require long term investment by the funding  
712 agencies and an inter-generational transition in leadership of long term flux sites.

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1040 Table 1 Table of literature surveyed

			NEE	NEE	GPP	GPP	Reco	Reco		
			gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>		
Country	Site	Functional Type	mean	std dev	mean	std dev	mean	std dev	n	author
Australia	Tumbarumba	Temperate, broadleaved evergreen forest	-584	333	NaN	NaN	NaN	NaN	11	(van Gorsel et al., 2013)
Austria	Stubai Valley	alpine meadow	-1	72	NaN	NaN	NaN	NaN	6	(Haslwanter et al., 2009)
Belgium	Brasschaat	Temperate, mixed deciduous broadleaved/conifer forest	-112	221	NaN	NaN	NaN	NaN	13	(Carrara et al., 2003; Gielen et al., 2013)
Brazil	Jaru	Tropical broadleaved, evergreen forest	-450	388	3413	333	2963	235	7	(Zeri et al., 2014)
Canada-British Columbia	Campbell River	Temperate, evergreen conifer forest	-356	51	2124	125	1768	146	9	(Chen et al., 2009a; Krishnan et al., 2009)
Canada-Manitoba	Thompson	Boreal, evergreen conifer forest	23	42	654	98	631	113	15	(Dunn et al., 2007; Soloway et al., 2017)
Canada-Ontario	Borden	Temperate, deciduous broadleaved forest	-177	116	1373	164	1196	188	18	(Froelich et al., 2015)
Canada-Quebec	Chibougamau	Boreal, evergreen conifer forest	95	54	405	115	500	69	9	(Coursolle et al., 2012)
Canada-Saskatchewan	Prince Albert	Boreal, deciduous broadleaved forest	-168	96	1252	136	1084	103	9	(Barr et al., 2007)
China	Dinghushan	subtropical evergreen broadleaved forest	-393	104	1383	54	990	53	6	(Yan et al., 2013)
Denmark	Soroe	Temperate, deciduous broadleaved forest	-156	103	1727	136	1570	97	13	(Pilegaard et al., 2011)
Finland	Hyytiälä	Boreal, evergreen conifer forest	-206	38	1031	54	826	39	11	(Ilvesniemi et al., 2009)
Finland	Mekrijärvi	Boreal, evergreen conifer forest	-190	24	NaN	NaN	NaN	NaN	10	(Ge et al., 2011)
France	Hesse	Temperate, deciduous broadleaved forest	-386	171	1397	192	1011	137	10	(Granier et al., 2008)
France	Puechabon	evergreen oak woodland	-278	117	1317	151	1018	68	6	(Allard et al., 2008)
Germany	Hainich	Temperate, deciduous broadleaved forest	-483	70	1498	83	1015	51	7	(Herbst et al., 2015)
Germany	Tharandt	Temperate, evergreen conifer forest	-550	91	1845	162	1295	100	10	(Grunwald and Bernhofer, 2007)
Hungary	Hegihatsal	Temperate, grassland	-35	59	1096	180	1061	125	7	(Haszpra et al., 2005)

Ireland	Cork County, Ireland	Temperate, grassland	-164	150	1486	376	1343	247	8	(Jaksic et al., 2006)
Ireland	Glencar, County Kerry	Temperate, wetland	-56	17	288	18	232	8	9	(McVeigh et al., 2014)
Israel	Yatir	semi-arid evergreen conifer forest	-211	83	830	138	620	83	6	(Maseyk et al., 2008)
Japan	Fujiyoshida	Temperate, evergreen conifer forest	-388	58	1802	113	1413	97	9	(Mizoguchi et al., 2012)
Japan	Kiryu Watershed	Temperate, evergreen conifer forest	10	42	686	106	696	130	9	(Saigusa et al., 2005a)
Japan	Takayama Teshio	Temperate, deciduous broadleaved forest	-237	98	1110	409	829	264	9	(Kosugi et al., 2012)
Japan	Experimental Forest	Temperate, evergreen conifer forest	153	227	1013	315	1166	113	9	(Aguilos et al., 2014)
Mexico	LaPaz	desert scrub	92	113	NaN	NaN	NaN	NaN	7	(Bell et al., 2012)
Netherlands	Loobos	Temperate, evergreen conifer forest	-432	127	NaN	NaN	NaN	NaN	14	(Elbers et al., 2011)
Portugal	Espirra	Mediterranean, broadleaved evergreen forest	-472	319	1571	448	1099	148	8	(Rodrigues et al., 2011)
United Kingdom	Auchencorth Moss	Temperate, wetland	-64	38	737	168	674	165	10	(Helfter et al., 2011)
United Kingdom	Straights Inclosure	Temperature, deciduous broadleaved forest	-486	115	1993	275	1548	192	12	(Wilkinson et al., 2012)
US-Alaska	Alaska	Boreal, evergreen conifer forest	10	42	686	106	696	130	9	(Ueyama et al., 2014)
US-Alaska	Imnavait Creek Watershed	Wet sedge tundra	83	66	225	55	308	85	8	(Euskirchen et al., 2016)
US-Alaska	Imnavait Creek Watershed	Heath tundra	20	23	187	46	206	41	8	(Euskirchen et al., 2016)
US-Arizona	Flagstaff	Temperate, evergreen conifer forest	-104	99	952	97	866	44	5	(Scott et al., 2014)
US-Arizona	Flagstaff	Temperate, evergreen conifer forest	-113	70	935	94	844	79	5	(Dore et al., 2012)
US-Arizona	San Pedro	semi-arid woodland	-309	110	979	185	670	135	15	(Dore et al., 2012)
US-California	lone Twitchell	Mediterranean, savanna/grassland	-110	57	1056	145	946	141	14	(Ma et al., 2016)
US-California	Island	rice	-34	237	1437	140	1414	223	6	(Ma et al., 2016)
US-California	lone Gainsville, Donaldson	Mediterranean, grassland	7	113	682	169	689	126	15	(Knox et al., 2016)
US-Florida	Tract	Sub-tropical, evergreen conifer forest	-669	99	2490	144	1821	156	10	(Bracho et al., 2012)

US-Florida	Gainsville, Mize Tract	Sub-tropical, evergreen conifer forest	112	683	2200	794	2312	245	11	Bracho et al. 2012)
US-Indiana	Morgan-Monroe	Temperature, deciduous broadleaved forest	-351	81	1452	118	1098	82	13	(Sulman et al., 2016)
US-Iowa	Ames	Prairie	-105	80	919	99	813	79	9	(Dold et al., 2017)
US-Iowa	Ames	Corn	-128	211	1016	383	888	194	10	(Dold et al., 2017)
US-Iowa	Ames	Corn	-137	241	927	358	789	130	10	(Dold et al., 2017)
US-Maine	Howland	boreal, evergreen conifer forest	-188	49	1343	95	1168	80	9	(Hollinger et al., 2004)
US-Massachusetts	Harvard Forest, Petersham	temperate, deciduous broadleaved forest	-245	100	1400	164	1153	105	13	(Urbanski et al., 2007)
US-Michigan	Douglas Lake	mixed deciduous forest	-151	40	NaN	NaN	NaN	NaN	5	(Curtis et al., 2005)
US-Missouri	Ozarks	temperate, deciduous broadleaved forest	-479	65	1125	164	646	121	5	(Shao et al., 2014)
US-Nebraska	Mead	irrigated crops	-253	334	1384	447	1131	125	8	(Suyker and Verma, 2012)
US-Nebraska	Mead	rainfed crops	-225	268	1201	347	976	102	8	(Suyker and Verma, 2012)
US-New Mexico	Sevilleta LTER	desert grassland	28	63	155	72	183	39	5	(Petrie et al., 2015)
US-North Carolina	Duke Forest, Durham	grassland	218	58	1648	371	1868	422	5	(Novick et al., 2015)
US-North Carolina	Duke Forest, Durham	temperate, deciduous broadleaved forest	-402	96	1982	300	1580	237	8	(Novick et al., 2015)
US-North Carolina	Duke Forest, Durham	temperate, evergreen conifer forest	-503	176	2343	319	1848	179	8	(Stoy et al., 2008)
US-Oregon	Metolius	temperate, evergreen conifer forest	-465	116	1583	173	1118	89	7	(Thomas et al., 2013)
US-Tennessee	Oak Ridge	temperate, deciduous broadleaved forest	-577	63	NaN	NaN	NaN	NaN	5	(Wilson and Baldocchi, 2001)
US-Washington	Wind River	temperate, evergreen conifer forest	-32	85	1382	92	1350	145	16	(Wharton and Falk, 2016)
US-Wisconsin	Park Falls	mixed deciduous forest	123	42	NaN	NaN	NaN	NaN	7	(Ricciuto et al., 2008)

Table

			NEE	NEE	GPP	GPP	Reco	Reco		
			gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>	gC m <sup>-2</sup> y <sup>-1</sup>		
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Belgium	Brasschaat	Temperate, mixed deciduous broadleaved/conifer forest	-112	221	NaN	NaN	NaN	NaN	13	(Carrara et al. 2003; Gielen et al. 2013)
Brazil	Jaru	Tropical broadleaved, evergreen forest	-450	388	3413	333	2963	235	7	(Zeri et al. 2014)
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Canada-Manitoba	Thompson	Boreal, evergreen conifer forest	2	41	706	57	713	79	10	(Dunn et al. 2007)
Canada-Ontario	Borden	Temperate, deciduous broadleaved forest	-177	116	1373	164	1196	188	18	(Froelich et al. 2015)
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Japan	Takayama	Temperate, deciduous broadleaved forest	-237	98	1110	409	829	264	9	(Kosugi et al. 2012)
Japan	Teshio Experimental Forest	Temperate, evergreen conifer forest	153	227	1013	315	1166	113	9	(Aguilos et al. 2014)
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Netherlands	Loobos	Temperate, evergreen conifer forest	-432	127	NaN	NaN	NaN	NaN	14	(Elbers et al. 2011)
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US-Alaska	Imnavait Creek Watershed	Heath tundra	20	23	187	46	206	41	8	Euskirchen et al
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US-Arizona	Flagstaff	Temperate, evergreen conifer forest	-113	70	935	94	844	79	5	(Dore et al. 2012)
US-Arizona	San Pedro	semi-arid woodland	-309	110	979	185	670	135	15	(Dore et al. 2012)
US-California	Ione	Mediterranean, savanna/grassland	-110	57	1056	145	946	141	14	(Ma et al. 2016)
US-California	Twitcheil Island	rice	-34	237	1437	140	1414	223	6	(Ma et al. 2016)
US-California	Ione	Mediterranean, grassland	7	113	682	169	689	126	15	(Knox et al. 2016)
US-Florida	Gainsville, Donaldson Tract	Sub-tropical, evergreen conifer forest	-669	99	2490	144	1821	156	10	(Bracho et al. 2012)
US-Florida	Gainsville, Mize Tract	Sub-tropical, evergreen conifer forest	112	683	2200	794	2312	245	11	Bracho et al. 2012)
US-Indiana	Morgan-Monroe	Temperature, deciduous broadleaved forest	-351	81	1452	118	1098	82	13	(Sulman et al. 2016)

US-Iowa	Ames	Prairie	-105	80	919	99	813	79	9	(Dold et al. 2017)
US-Iowa	Ames	Corn	-128	211	1016	383	888	194	10	(Dold et al. 2017)
US-Iowa	Ames	Corn	-137	241	927	358	789	130	10	(Dold et al. 2017)
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US-Maine	Harvard Forest,	temperate, deciduous broadleaved forest	-245	100	1400	164	1153	105	13	(Urbanski et al. 2007)
US-Massachusetts	Petersham									
US-Michigan	Douglas Lake	mixed deciduous forest	-151	40	NaN	NaN	NaN	NaN	5	(Curtis et al. 2005)
US-Missouri	Ozarks	temperate, deciduous broadleaved forest	-479	65	1125	164	646	121	5	(Shao et al. 2014)
US-Nebraska	Mead	irrigated crops	-253	334	1384	447	1131	125	8	(Suyker; Verma 2012)
US-Nebraska	Mead	rainfed crops	-225	268	1201	347	976	102	8	(Suyker and Verma, 2012)
US-New Mexico	Sevilleta LTER	desert grassland	28	63	155	72	183	39	5	(Petrie et al. 2015)
US-North Carolina	Duke Forest, Durham	grassland	218	58	1648	371	1868	422	5	(Novick et al. 2015)
US-North Carolina	Duke Forest, Durham	temperate, deciduous broadleaved forest	-402	96	1982	300	1580	237	8	(Novick et al. 2015)
US-North Carolina	Duke Forest, Durham	temperate, evergreen conifer forest	-503	176	2343	319	1848	179	8	(Stoy et al. 2008)
US-Oregon	Metolius	temperate, evergreen conifer forest	-465	116	1583	173	1118	89	7	(Thomas et al. 2013)
US-Tennessee	Oak Ridge	temperate, deciduous broadleaved forest	-577	63	NaN	NaN	NaN	NaN	5	(Wilson; Baldocchi 2001)
US-Washington	Wind River	temperate, evergreen conifer forest	-32	85	1382	92	1350	145	16	(Wharton; Falk 2016)
US-Wisconsin	Park Falls	mixed deciduous forest	123	42	NaN	NaN	NaN	NaN	7	(Ricciuto et al. 2008)

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## List of Figures

### Figure 1.

Histogram of published values of net ecosystem carbon exchange,  $N_E$ , derived from annual long studies using the eddy covariance method. The histogram is based on 1781 site years of data. The y axis represents the probability density function, pdf.

### Figure 2.

a) Histograms of published values of ecosystem photosynthesis ( $G$ ) at annual time scales, reported in the literature; b) histogram of published values of ecosystem respiration ( $R_e$ ) at annual time scales, reported in the literature. These gross carbon fluxes were derived from eddy covariance measurements of net ecosystem carbon exchange. The y axes represent the probability density function, pdf.

### Figure 3.

Histogram of yearly anomalies in net ecosystem carbon exchange from the literature data pool of 544 site years of data. Anomalies were computed with regards to the annual mean of each time series in the database.

### Figure 4.

Histogram of yearly anomalies in a) gross primary production, or photosynthesis ( $G$ ) and b) ecosystem respiration,  $R_e$ . These data are derived literature data pool of 454 site years of data. Anomalies were computed with regards to the mean of each time series in the database.

### Figure 5.

The regression between the variance in net ecosystem exchange ( $N_E$ ) and gross photosynthesis ( $G$ ) and ecosystem respiration ( $R_e$ ). Regression coefficients are for the log transform of  $\log(y) = b(0) + b(1) \log(x)$

### Figure 6.

Examination of the covariance between ecosystem photosynthesis ( $G$ ) and respiration ( $R_e$ ). Plotted here are the yearly anomalies with the long term means of the data.

### Figure 7.

Relation between year to year changes in gross ecosystem photosynthesis ( $dG/dt$ ) vs ecosystem respiration ( $dR_e/dt$ ). The slope of the population is 0.494, the intercept is -1.137 and  $r^2$  equals 0.552,  $N = 398$ . Color codes indicate data points from each study.

### Figure 8.

Lagged auto-correlation function for net ecosystem exchange at the 59 sites listed in Table 1. Each line denotes results from time series of one site study. To detect if the lag correlation values were significantly different from zero we performed a set of auto-correlation computations on a set of random numbers of progressive lengths (5 to 18). From these computations, we computed the 95% confidence intervals of lag correlations from an repeated ensemble (5000) of calculations, as shown with the red lines.

Figure 9.

Conceptual figure on how ecosystem photosynthesis, or gross primary production and ecosystem respiration may vary year to year by different biophysical forcings. The green line is the baseline. Yellow line is for a season with less soil moisture in late growing season. The blue line is for earlier start and later end of the growing season. The red line is for conditions that increase photosynthesis through more leaf area, more light absorption or greater photosynthetic potential through greater leaf nitrogen. The lower panel shows how ecosystem respiration may respond to these changes in photosynthesis and environmental conditions.

Figure 10.

Confidence interval of standard deviation as a function of sample size and sampling error. Superimposed on this figure are reported values (closed circles) from literature review. For better presentation, only reported values lower than  $60 \text{ gC m}^{-2} \text{ y}^{-1}$  were showed here.

Figure 11.

95% confidence intervals of trends in random time series of varying length and varying measurement uncertainty.

Figure 1

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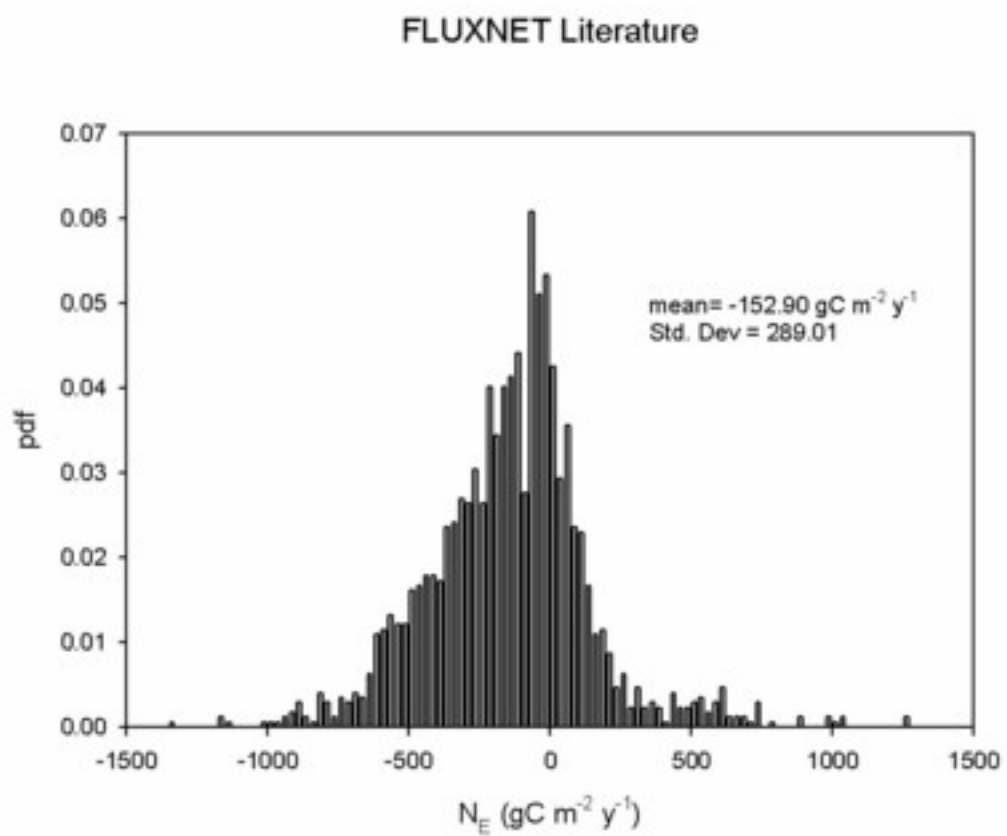
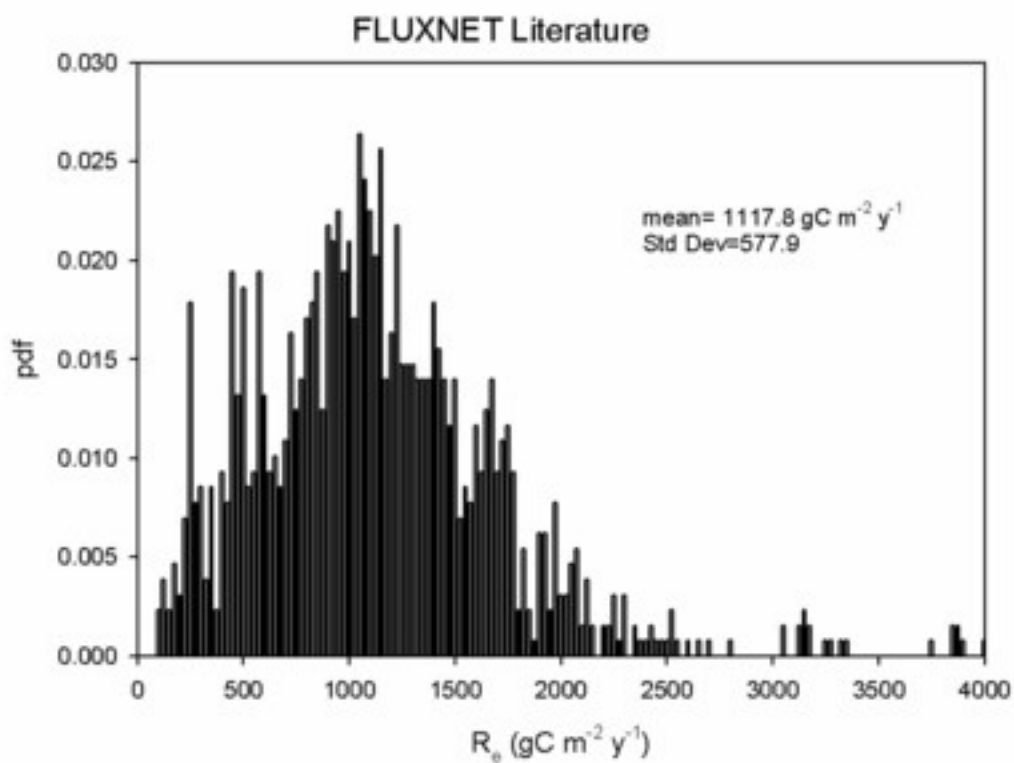
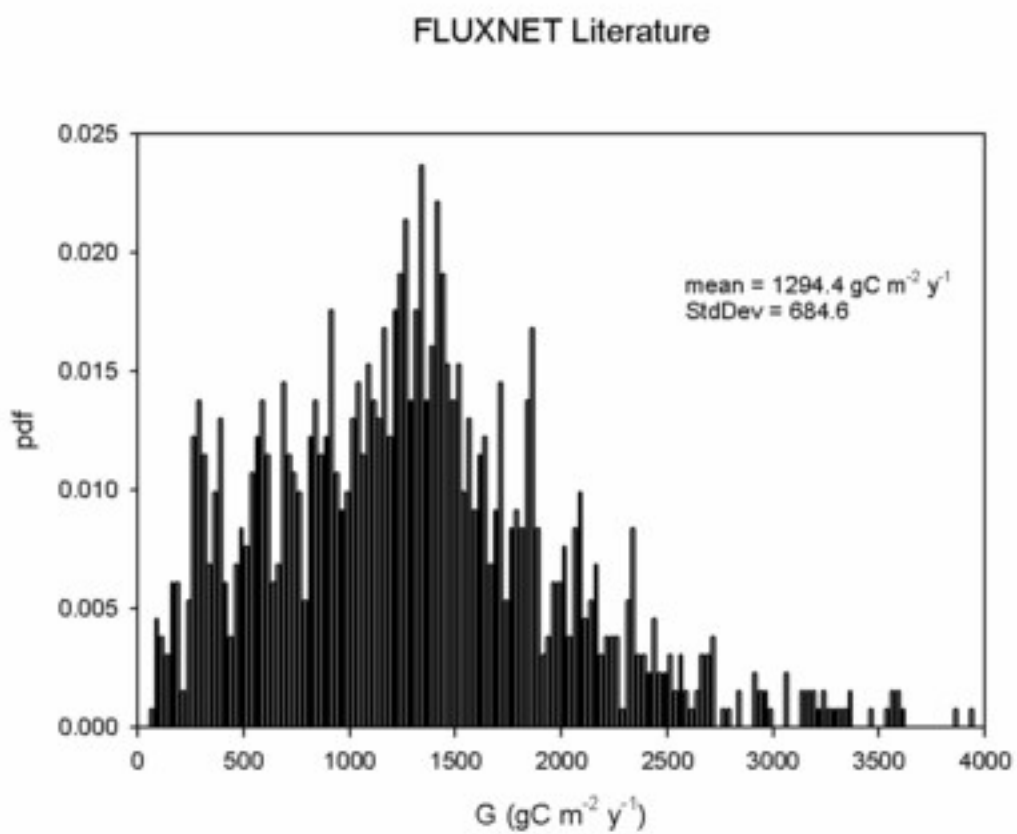


Figure 2

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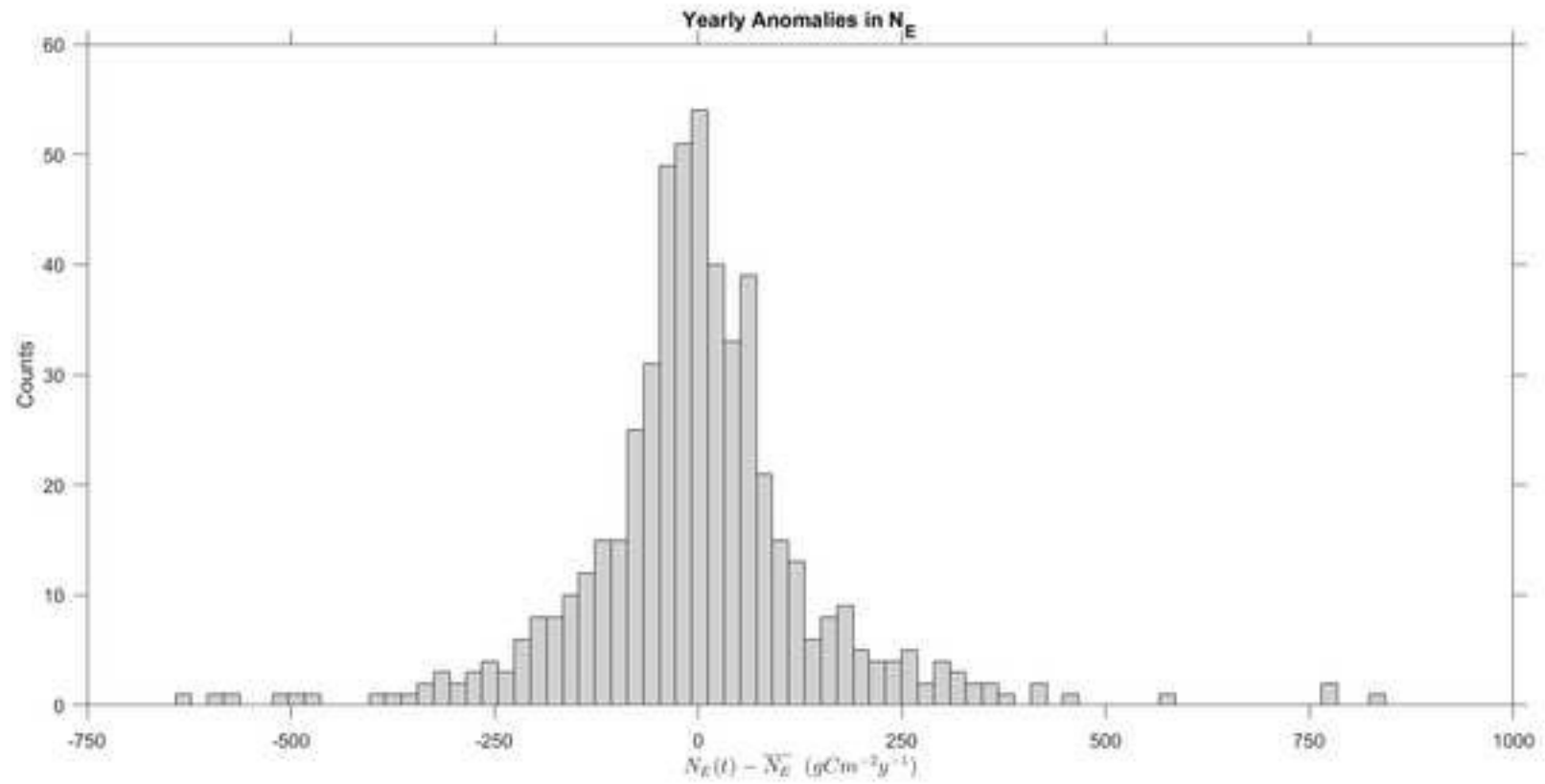




Figure 4ab

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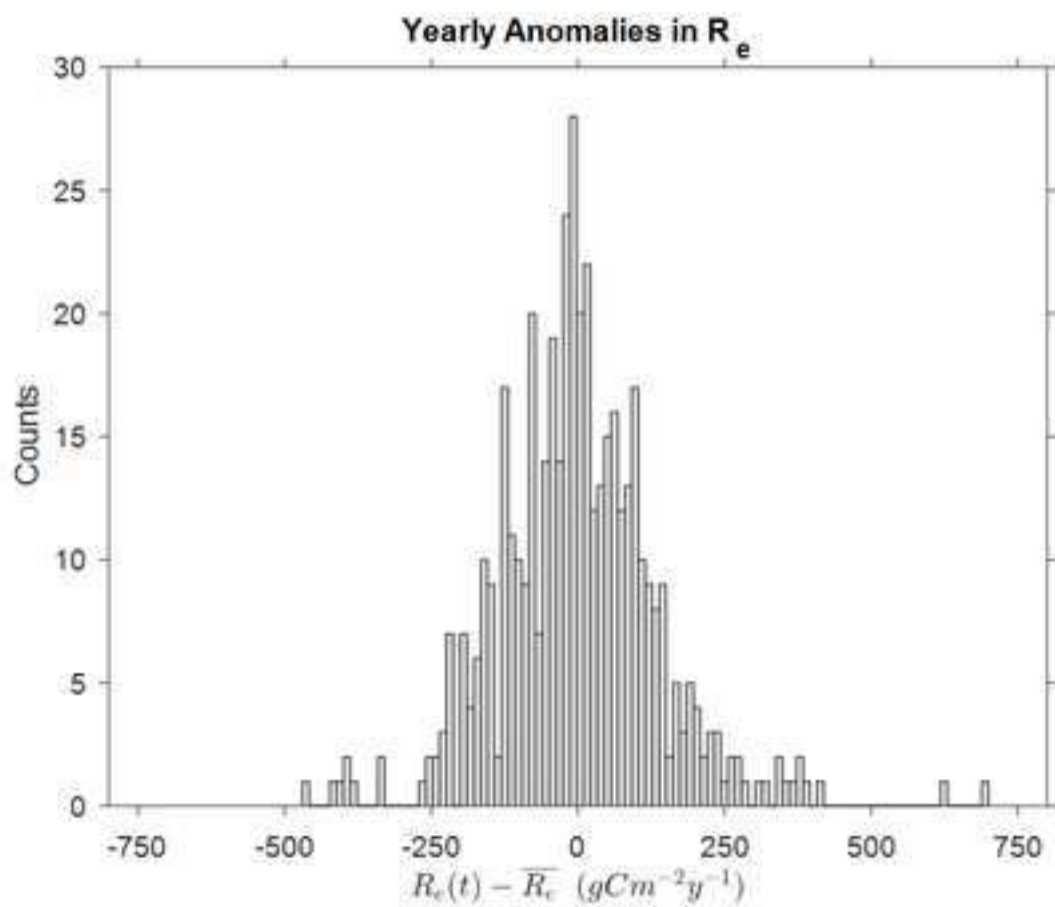
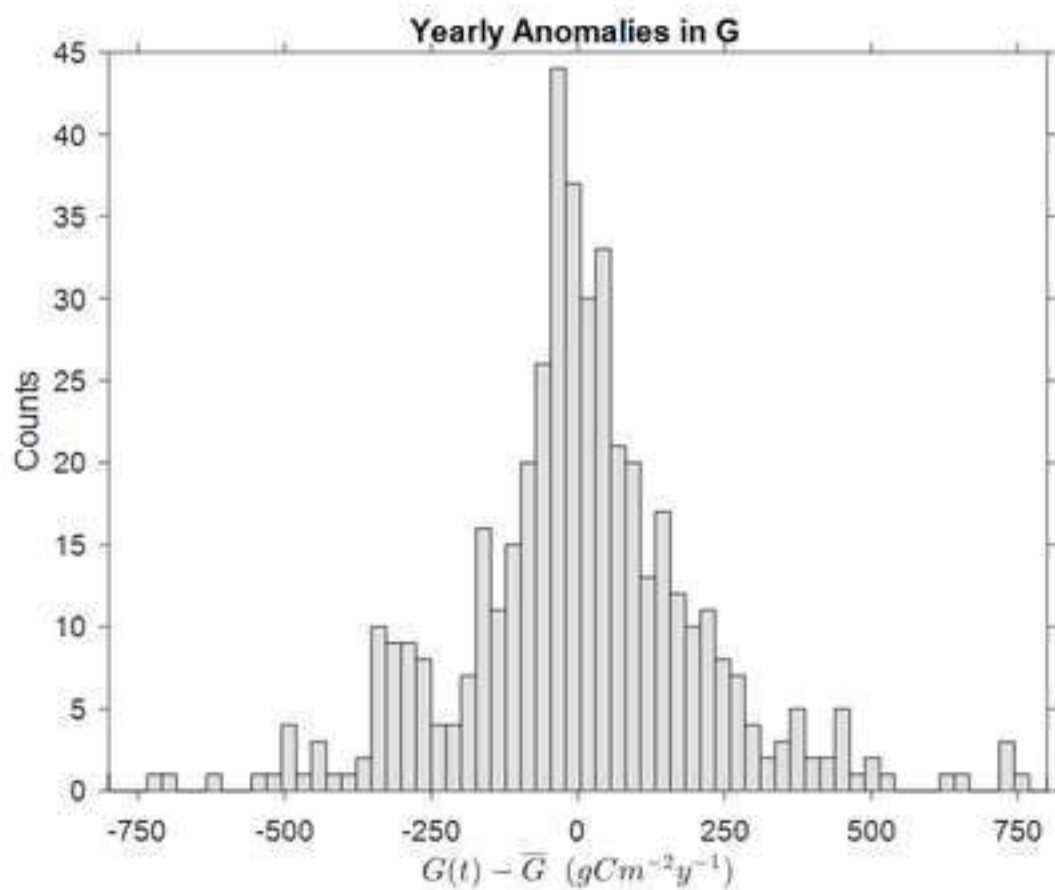


Figure 5

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