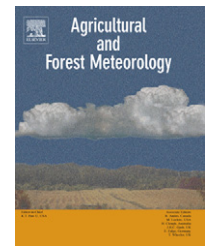


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Short communication

Application of an alternative method to derive reliable estimates of nighttime respiration from eddy covariance measurements in moderately complex topography

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ABSTRACT

Even moderately complex topography can lead to significant horizontal and vertical advection and a consequent underestimation of nocturnal CO₂ effluxes derived from eddy covariance measurements on a single tower. The standard approach to select nighttime eddy flux data uses a threshold in friction velocity to exclude periods when advection is important but this is problematic in situations where turbulence is intermittent. van Gorsel et al. [van Gorsel, E., Leuning, R., Cleugh, H.A., Keith, H., Suni, T., 2007. Nocturnal carbon efflux: reconciliation of eddy covariance and chamber measurements using an alternative to the u^* -threshold filtering technique. *Tellus* 59B, 397–403] have developed an alternative method that estimates the CO₂ flux from the maximum of the eddy flux plus change in storage term in the period after sunset when stable stratification develops. During this time the advection terms do not contribute significantly to the mass balance of the air layer below the eddy flux instruments at the Tumbarumba flux station (SE Australia). Advection dominates only later in the night, following the development of large horizontal and vertical gradients of CO₂. As net nighttime and daytime fluxes are often of similar magnitude but opposite in sign, underestimation of respiration can lead to large errors in annual ecosystem carbon budgets.

Nocturnal respiration rates obtained using the new approach are systematically higher compared to previously published results that used a u^* -threshold filter, and are in excellent agreement with independent chamber measurements. Revised net ecosystem exchange (NEE) calculations are therefore substantially reduced compared to those previously published (differing by 5.6 ± 0.5 t C ha⁻¹ year⁻¹ based on a 34-month period) and compare well with results from an ecosystem model (differing by -0.2 ± 0.7 t C ha⁻¹ year⁻¹ based on the same time period).

Due to a drought period in 2003 and a subsequent insect attack NEE at Tumbarumba has been highly variable. Within 5 years the forest changed from being a carbon sink of

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–7.5 t C ha⁻¹ year⁻¹ to a source of +2.3 t C ha⁻¹ year⁻¹. This high variability demonstrates the importance of long-term, high-resolution time series when interpreting ecosystem data. The study further confirms the importance of using multiple measurement techniques and modelling to improve confidence in the mutually constrained NEE values.

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1. Introduction

A global network of eddy covariance towers (>450) has been established across the world to monitor net ecosystem exchange (NEE) from a variety of ecosystems. The increasing popularity of the method is due to its ability to provide high-resolution, long-term time series, and because large source areas can be monitored. However, there is concern that the micrometeorological community may be underestimating the nocturnal respiration rates of forests, and thus overestimating their sink capacity, due to a lack of advection measurements. Horizontal and vertical advection of CO₂ often occur during nocturnal, stable atmospheric conditions (Aubinet et al., 2003, 2005; Baldocchi et al., 2000; Feigenwinter et al., 2004; Gouliden et al., 1996; Marcolla et al., 2005; Staebler and Fitzjarrald, 2004). The net exchange of CO₂ between the underlying vegetation and the atmosphere is generally assumed to equal the sum of the turbulent flux and the rate of change in storage of CO₂ in the layer of air below the flux measurement height. Given a horizontally homogeneous surface, this assumption is typically satisfied during daytime when the atmosphere is well mixed and unstably stratified.

During stable conditions within canopy flow is often decoupled from that above (Froelich and Schmid, 2006) and drainage flows can develop close to the ground even on shallow slopes (Finnigan, 2007; Mahrt et al., 2001). Once drainage flows commence, the down flowing air has to be replaced with air from above that is characterized by lower CO₂ concentration. As it is entrained into the canopy layer horizontal CO₂ gradients develop, even if the vegetation cover is homogeneous. Theoretical arguments, numerical modelling and experimental evidence have shown that unmeasured vertical and horizontal advection lead to errors in the estimation of nighttime CO₂ efflux (Aubinet et al., 2000, 2005; Finnigan and Belcher, 2004; Katul et al., 2006; Miller et al., 2004; Sogachev et al., 2004; Staebler and Fitzjarrald, 2004). As net daytime and nighttime fluxes are often of similar magnitude but opposite in sign, this can lead to large errors in annual net ecosystem carbon budgets (Gouliden et al., 1996; Moncrieff et al., 1996).

This systematic error can be avoided by either measuring the advection terms in the mass balance of the air layer below the instruments or by excluding data during periods when advection is significant and subsequently filling the data gaps. Accurate assessment of vertical advection is still an unresolved problem and the elaborate and expensive experimental setup required to evaluate the full mass balance is beyond the scope of most research groups and particularly difficult to maintain over extended periods (Feigenwinter et al., 2008).

Filtering data based on the friction velocity, u^* , is the most commonly used approach to exclude periods when advection

is likely to occur since high u^* is associated with strong turbulence and advective effects are therefore likely to be small (Gouliden et al., 1996). There are several drawbacks to this approach. Above-canopy measurements are used to represent within-canopy processes which is not justified when turbulence is intermittent or the flow decoupled (Froelich and Schmid, 2006; Gouliden et al., 2006; van Gorsel et al., 2007). No unique threshold can be expected for canopies with spatial inhomogeneities such as patches of vegetation with different density properties (Sogachev et al., 2005). The u^* -threshold is often determined subjectively (Papale et al., 2006), although Gu et al. (2005) did propose an objective method for its selection. Selection of the u^* -threshold can be crucial, as shown by Miller et al. (2004) who found that relatively slight variations in the threshold led to a change in sign of the net ecosystem exchange of CO₂ of a tropical forest. There may also be sites where it is not possible to identify a unique u^* -threshold (Wilson et al., 2002; van Gorsel et al., 2007). To overcome this latter problem, van Gorsel et al. (2007) developed an alternative method that estimates the CO₂ flux from the maximum of the eddy flux plus change in storage term in the few hours after sunset when stable stratification develops. During this time the advection terms do not contribute significantly to the mass balance of the air layer below the eddy flux instruments at Tumbarumba (SE Australia). Advection dominates only later, following the development of large horizontal and vertical gradients of CO₂ (Leuning, personal communication).

This new approach is described in more detail in Section 2 which further describes chamber based respiration measurements and simulations with CenW, a comprehensive forest-growth model (Kirschbaum et al., 2007) against which we compare the micrometeorological measurements. In Section 3 we discuss the implications of using the new approach for parameterising respiration to calculate NEE. We show that complementary techniques to assess NEE offer a unique opportunity to assess the uncertainty in the CO₂ flux measurements. Furthermore, we discuss the dynamics of several years of NEE measurements in an Australian temperate eucalypt forest.

2. Methods

2.1. Site

Micrometeorological flux and respiration chamber measurements were made at the Tumbarumba flux station located in southeastern New South Wales, Australia (35°39'20.7"S, 148°09'07.5"E, elevation 1200 m). The native, wet sclerophyll forest is 40 m tall and dominated by *Eucalyptus delegatensis* R.T.

Baker and *Eucalyptus dalrympleana* Maiden. The species composition is reasonably homogeneous within a radius of >5 km around the flux tower. The site is situated in relatively complex topography that leads to deviations of the mean wind vector from the horizontal of -6° to $+2^\circ$ (Finnigan et al., 2003).

2.2. Micrometeorological approach

Extensive descriptions of the micrometeorological instrumentation and subsequent data processing have been given by Leuning et al. (2005). Therefore we present only the most important measurements and revisions to the earlier data processing.

NEE (E_{NE}) can be determined by considering the mass balance for a scalar quantity c in a control volume with sides L and height h_r :

$$E_{NE} = \underbrace{\overline{c_d w' \chi_c'}}_I + \underbrace{\int_0^{h_r} \overline{c_d} \frac{\partial \overline{\chi_c}}{\partial t} dz}_II + \underbrace{\frac{1}{L^2} \int_0^L \int_0^L \int_0^{h_r} \left[u c_d \frac{\partial \overline{\chi_c}}{\partial x} + v c_d \frac{\partial \overline{\chi_c}}{\partial y} + w c_d \frac{\partial \overline{\chi_c}}{\partial z} \right] dz dx dy}_III \quad (1)$$

where x, y, z define the Cartesian coordinates and t is time. The scalar quantity under consideration is carbon dioxide. χ_c is the mixing ratio of the molar density of CO_2 (c) to dry air (c_d) (Leuning, 2004). u, v, w are the longitudinal, lateral and vertical components of wind velocity, respectively. Overbars denote time averages and primes stand for departures from the mean. We have assumed that the canopy is sufficiently homogeneous to neglect the horizontal turbulent flux divergence terms in Eq. (1).

NEE is the time- and space-averaged flux density of CO_2 at the lower boundary of the control volume plus the fluxes originating from the vegetation within the control volume. Term I on the right-hand side of Eq. (1) is the vertical eddy flux of CO_2 . This term was measured at the reference height (h_r) of 70 m using an ultrasonic anemometer thermometer (Type HS, Gill Instruments Ltd., Lymington, UK), and an open-path infrared gas analyzer (IRGA) for CO_2 and water vapour (Li7500, Li-Cor Inc., Lincoln, NE, USA). To calculate Term II, the rate of change in storage of CO_2 in the layer below h_r , CO_2 concentrations were measured at nine heights (0.5, 4.6, 10.2, 18.1, 26.3, 34.4, 42.6, 54.4 and 70.1 m) using a closed path IRGA (Li6262, Li-Cor Inc.) and gas switching valves. Note that we implicitly assume that the rate of change of CO_2 in the control volume can be represented by a single profile where ideally it would be calculated from instantaneous profiles of space-averaged concentrations (Finnigan, 2006). The advection term (term III) is not routinely measured at our site, but an intensive field campaign in March 2005 showed that advection is significant below the canopy during light winds and stable stratification (Leuning, personal communication).

During daytime when the atmosphere is unstably stratified and well mixed, advection at Tumberumba is small and NEE reduces to good approximation to terms I and II of Eq. (1). Daytime data were first filtered for physically reasonable values and the resultant gaps in the data time series were filled

using a neural network analysis (Leuning et al., 2005), a multi-layered canopy model (Leuning, 1995; Leuning et al., 1995; Wang and Leuning, 1998; Haverd et al., 2007), and a simple big-leaf approach, where we fitted a light-response curve to the data using a Michaelis–Menten equation (Falge et al., 2001). Although no one gap-filling method was superior according to criteria developed by Sun (1994), we used the big-leaf approach because it yielded the least bias in modelled NEE and hence in calculated gross primary production (GPP).

After sunset, when the boundary layer becomes sufficiently stably stratified through radiative cooling of the canopy, we expect the sum of terms I and II to underestimate NEE because the advection term (III) will then be significant as a result of the following postulated sequence of events. Much of the respired CO_2 is stored in the canopy, and CO_2 concentrations close to the ground start to increase (Fig. 1a). The cool layer within the canopy modifies buoyancy and hence the hydrostatic pressure gradient. Gravity flows commence once the air close to the surface has cooled to the extent that the hydrostatic pressure gradient exceeds the sum of hydrodynamic pressure gradient and foliage drag (Finnigan, 2007). Entrainment of air with a lower CO_2 concentration at the hill crests leads to the development of horizontal CO_2 gradients (Fig. 1b), and advection then starts to drain CO_2 out of the control volume. van Gorsel et al. (2007) found that there is a time period of a few hours after sunset when term III is still small at Tumberumba. This allows use of the maximum in the sum of terms I and II (defined as R_{\max}) in the early evening (Fig. 1c) to derive a temperature response function to parameterize respiration for the remaining hours of the night.

van Gorsel et al. (2007) have demonstrated that their approach of estimating nighttime respiration leads to excellent agreement with independent chamber measurements at their site (Fig. 1c). However, the time window where term III is small enough to allow the use of respiration data will depend on factors such as slope length, position of the site with respect to ridge and floor as well as density of the forest. Testing the limitations of this approach is ongoing and will be presented elsewhere.

2.3. Chamber measurements

Chambers were used to measure respiration rates of soil, wood and leaves at thirty permanent 0.1 ha plots located within a 1000 m radius around the flux tower (Keith, personal communication). According to the flux footprint model of Schuepp et al. (1990), >70% of the eddy flux measured at 70 m comes from within this 314 ha area. The footprint model predicts the relative contribution to the flux as a function of distance from the tower and this distribution function was used to select the radial distribution of the permanent plots, while position at any radius was chosen at random.

Static chambers containing soda lime to absorb CO_2 (Keith and Wong, 2006) were used to measure soil respiration for consecutive daytime and nighttime hours in 10 plots during weeklong periods in each season. Individual chamber measurements were related to *in situ* soil temperature and moisture measurements and weighted averages were then used to calculate the soil respiration of the site. Averages were taken for each of four vegetation strata, and summed to the

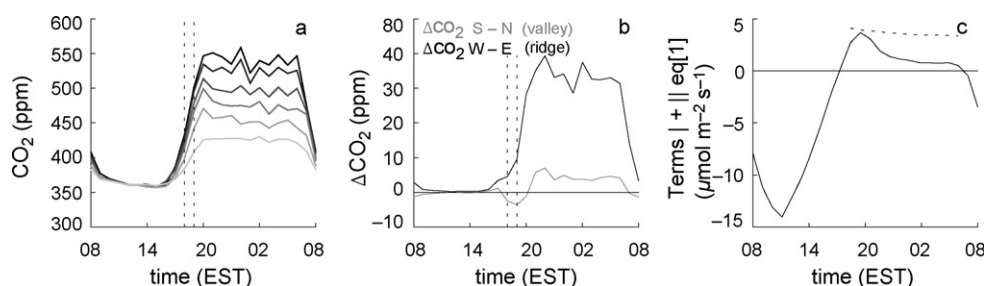


Fig. 1 – Mean daily course of (a) CO₂ concentrations [6–21 March 2005]. Darker colours denote measurements closer to the ground. Vertical lines indicate time period of strongest CO₂ increase; (b) horizontal gradients of CO₂ (time period and vertical lines as in (a)); (c) of the sum of eddy flux and change in storage term (black line) and nighttime respiration derived from chamber measurements (dotted line) [years 2001–2005].

whole site based on areal proportion of each stratum. Temperature response functions for respiration rates per unit sapwood volume of stems, branches and woody roots were obtained using closed, dynamic chambers (Li6200, Li-Cor Inc.). The results were scaled to the site using tree inventory and air temperature data. Leaf respiration was also measured with closed dynamic chambers (Li6400, Li-Cor Inc.) and scaled to the site using leaf area index and air temperature data.

2.4. Ecosystem model CenW

The forest-growth model CenW is described in detail in Kirschbaum (1999, 2004) and Kirschbaum et al. (2007). CenW runs on a daily time step to simulate the fluxes and storage components of carbon, water and nitrogen in stand and soil. The model was parameterized by simultaneously comparing model outputs against a wide variety of observations obtained at the site. They included daytime micrometeorological measurements of CO₂ and water vapour exchange, estimates of the various above- and below-ground biomass pools, growth rates measured through stem-diameter increments and measurement of specific ecosystem processes, such as litter fall and soil-respiration rates (see Kirschbaum et al., 2007, for more details). The comparison between the revised method of analyzing eddy covariance data and CenW simulation runs is therefore not totally independent because both methods were to some extent constrained by common data.

3. Results

3.1. Comparison with chamber measurements

Fig. 2 shows hourly nighttime ecosystem respiration rates from October 2001 to September 2002 at Tumberumba, computed using both the temperature response function derived from R_{\max} and that from the u^* -threshold of 0.25 m s^{-1} used by Leuning et al. (2005). Also shown are results of chamber measurements of respiration taken during four intensive field campaigns. The excellent agreement between the independent chamber measurements and the revised respiration rates from R_{\max} provides confidence in the validity

of this approach (Table 1). In contrast, use of the u^* -threshold approach leads to a systematic underestimation of the nocturnal carbon efflux (NCE). In the time period shown in Fig. 2 the relative error in NCE (E_{NC}), calculated as $|E_{\text{NC},u^*} - E_{\text{NC},\text{cham}}|/|E_{\text{NC},\text{cham}}|$, varies from 0.56 to 0.77, where biggest differences occur in winter when stability conditions are favourable for the development of drainage flows.

3.2. Comparison with CenW model results

Confidence in the use of R_{\max} to derive nighttime respiration is further strengthened by the good agreement between GPP (P_{GP}) and NEE (E_{NE}) estimated from the micrometeorological measurements and simulations of the ecosystem model CenW (Fig. 3). Linear regression analysis between model and observations yields $E_{\text{NE,obs}} = 0.91E_{\text{NE,model}} + 0.08 \text{ t Cha}^{-1} \text{ month}^{-1}$, $R^2 = 0.69$ (Kirschbaum et al., 2007). Furthermore, both the measurements and the model show that the forest switched from a carbon sink to a carbon source after the summer of 2002–2003 (Fig. 3). Even better agreement is obtained between GPP predicted by CenW and that estimated from the micrometeorological measurements. GPP is calculated as the difference between NEE and daytime ecosystem respiration which is calculated using the temperature

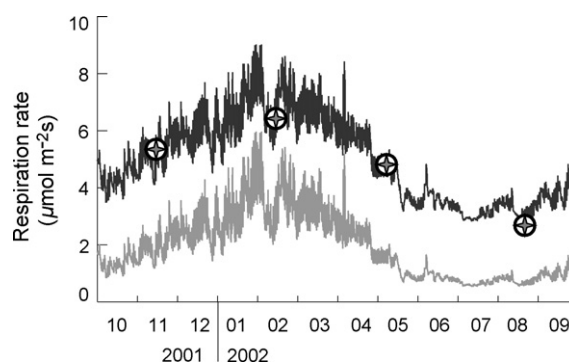


Fig. 2 – Gapfilled time series of nocturnal carbon efflux derived from chamber measurements (symbols), from micrometeorological measurements using a u^* -threshold of 0.25 m s^{-1} (light grey line) and from R_{\max} (dark grey line).

Table 1 – Mean and standard deviations of nocturnal carbon efflux derived from chamber measurements (NCE_{cham}), from a temperature response function using R_{max} in the early evening (NCE_{max}) and from micrometeorological measurements using a u^* -threshold of 0.25 m s^{-1} (NCE_{u^*}) during four intensive measurement campaigns

	NCE_{cham}	NCE_{max}	NCE_{u^*}	N
C11	5.34 ± 0.76	4.69 ± 0.51	1.57 ± 0.36	41
C02	6.42 ± 0.65	6.28 ± 0.48	2.84 ± 0.45	41
C05	4.81 ± 0.29	4.61 ± 0.27	1.50 ± 0.18	55
C08	2.68 ± 0.14	3.00 ± 0.12	0.62 ± 0.05	49

N stands for the number of data points used in each campaign. Values are given in $\mu\text{mol m}^{-2} \text{ s}^{-1}$.

response function derived from R_{max} and soil temperatures. Good agreement is expected because the daytime micrometeorological measurements were used to constrain CenW, although the two approaches use independent estimates of the nighttime respiration. Here linear regression between model and observations yields $P_{\text{GP,obs}} = 1.007P_{\text{GP,model}} - 0.05 \text{ t C ha}^{-1} \text{ month}^{-1}$, $R^2 = 0.94$ (Kirschbaum et al., 2007).

3.3. Variability in NEE and GPP

Fig. 3 shows a pronounced annual cycle in the estimates of GPP and to a somewhat lesser extent in NEE. Maximum GPP occurred in summer when solar radiation was at a maximum and temperatures were favourable for carbon uptake. NEE values were lowest in winter when the forest was a weak sink for carbon in some years and, on some occasions, a weak source, such as in 2003 and 2004.

Annual rainfall measured at Tumbarumba was similar in each of the years 2001–2003 (1156, 1225 and 1342 mm), but there were long dry periods from October 2002 to May 2003 and in autumn (February–May) 2004 and a significant decrease after mid-2006 through to the end of available measurements (Fig. 4(a)). The 2002–2003 drought was associated with an insect attack and damage to the canopy that turned the forest

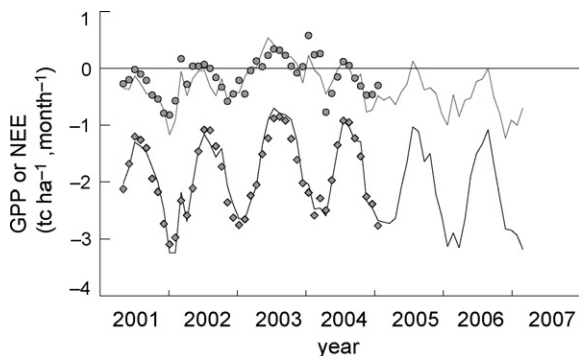


Fig. 3 – Monthly averages of NEE and GPP calculated using daytime eddy flux measurements and temperature response functions for respiration derived using R_{max} (light grey and dark grey lines, respectively), and modelled with the forest-growth model GenW (dots and square symbols, respectively).

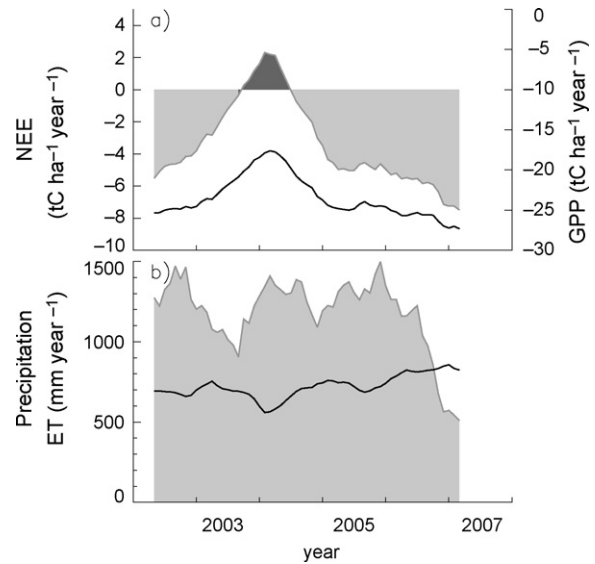


Fig. 4 – 12-Month running means of (a) NEE (grey area) and GPP (line). The period where the forest was a source of carbon is shaded in darker grey. The time axis is set to the end of the running mean window, and (b) precipitation (light grey area) and evapotranspiration (line).

into a temporary carbon source of up to $2.3 \text{ t C ha}^{-1} \text{ year}^{-1}$ (Fig. 4(a)). The reduced leaf area index further led to minimum evapotranspiration during the observation period (Fig. 4(b)). Fig. 4 suggests that the forest has fully recovered from the 2003 drought and insect attack and GPP and NEE reached the highest values over the carbon flux measurement period at Tumbarumba (-27.3 and $-7.5 \text{ t C ha}^{-1} \text{ year}^{-1}$, respectively) in early 2007 despite the recent strong decline in precipitation.

The high variability in measured NEE and GPP demonstrates the importance of long-term high-resolution time series when interpreting ecosystem data.

4. Conclusions

Gravity flows in even moderately complex topography can lead to significant horizontal and vertical advection and a consequent underestimation of nocturnal CO_2 effluxes derived from eddy covariance measurements on a single tower. We have used the approach of van Gorsel et al. (2007) to parameterize respiration and derive a revised estimate of NEE for the Tumbarumba flux station in southeast Australia. We have good confidence in this approach as respiration rates compare very well with independent chamber measurements. Comparison of NEE and GPP with the forest-growth model CenW also leads to extraordinarily good agreement.

The difference between revised annual-average and model-derived NEE values amounts to $-0.2 \pm 0.7 \text{ t C ha}^{-1} \text{ year}^{-1}$ for a period of 34 months. Previously published results using a u^* -threshold filter of 0.25 m s^{-1} systematically overestimates the sink capacity of the forest. The difference between NEE estimates of the two micrometeorological methods for the same period amounts to $5.6 \pm 0.5 \text{ t C ha}^{-1} \text{ year}^{-1}$.

Previously published NEE values suggested that the temperate *Eucalyptus* forest was a CO₂ sink during the whole measurement period. Revised NEE estimates however show that while the forest at Tumberumba can be a large sink, reaching net carbon uptake rates of up to 7.5 t C ha⁻¹ year⁻¹, a drought period in 2003 accompanied by an insect attack turned the forest into a source with maximum strength of 2.3 t C ha⁻¹ year⁻¹.

The high variability in NEE demonstrates the importance of long-term high-resolution time series when interpreting ecosystem data. It further confirms the importance of using multiple measurement techniques and modelling to improve confidence in the mutually constrained NEE values.

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