Physiologically Based Method for Partitioning Flux-Tower NEE Measurements in Grassland and Agricultural Ecosystems into Photosynthesis and Respiration

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Abstract: The work was supported in part by the USGS program of Geographic Analysis and Monitoring and Climate Effects Network and the South Dakota Corn Utilization Council. We express gratitude to Dr. T. Mayes, M. Heath, and J. Heilman, and to Mr. J. Schumacher for assistance with flux tower data from the Brookings, Lennox, and Freeman flux sites.

Introduction
Net CO₂ fluxes, F, provided by terrestrial flux-tower measurements represent the difference between two fundamental (and often close in magnitude) processes of gross photosynthesis (p) and ecosystem respiration (R):

\[ F = p - R_e \]  

In general, factors of photosynthesis and respiration are not the same (though overlap), and the patterns of their response to a given factor are not identical. Therefore, in order to understand the dynamics of CO₂ exchange and predict its response to climatic change or anthropogenic management, decomposition of the p, data into gross photosynthesis and respiration (1) is a necessary part of flux data processing, known as partitioning of p into F and R, components. While in the earlier period of flux data analysis partitioning was usually based on estimation of day-time respiration from night-time fluxes, derivation of day-time respiration from day-time measurements became a dominant approach (Gilmour et al. 2003, 2005, 2007, 2010; Reichstein et al. 2005; Lasslop et al. 2010). An essential feature of the daytime CO₂ exchange utilized in partitioning algorithms based on light-period measurements, is the decrease of p directly associated with the increase of respiration, which, in turn, is closely related to temperature. The problem is that the decrease of p may also be caused by decreasing photosynthesis, p, e.g., resulting from water stress. A number of methods to include water-stress into the partitioning, as proposed in the literature (e.g., Gilmour et al., 2003, Lasslop et al. 2010). In this presentation we describe a physiologically based approach incorporating combined effects of photosynthetic active radiation (Qa), soil temperature (T), and vapor pressure deficit (VPD).

Light-Soil temperature-VPD-responsiveness of the ecosystem CO₂ exchange
Analysis of the tower CO₂ exchange data in a wide range of grassland and crop sites is done on the partition equation:

\[ F = T_c \cdot VPD \cdot CO₂ = P + R_e \ (= R_e + T_c \cdot VPD) \]

(2)

where for the net flux F, radiation T, soil temperature, T, and vapor pressure deficit VPD only the 30-min data for single days are used. This assumption excludes the need to introduce factors which change slowly within a day (e.g., soil water content, soil nutrients concentrations, leaf area). A popular approach to describe photosynthetic response is to use the rectangular hyperbola:

\[ p = \frac{\alpha \cdot \text{Max} \cdot \text{CO}_2}{1 + \beta \cdot \text{VPD}} \]  

or the Mitscherlich-type

\[ p = \frac{\alpha \cdot \text{Max} \cdot \text{CO}_2}{1 + \beta \cdot \text{VPD}} \]  

where α is the initial slope (apparent quantum yield), and Max is the plateau photosynthetic capacity of the light-response. To incorporate VPD limitations these equations can not describe the same as observed at the present study. The model of the observations at these towers processed according to the standard protocol are as follows (1) available as the Level-1 data at the AMERIFLUX database (http://cdiac.esd.ornl.gov).

Study Sites
The light-soil temperature-VPD method of flux partitioning was applied to many grassland and agricultural sites worldwide from the AMERIFLUX, AGRIFLUX and other FLUXNET-member networks, as well as to the data from non-affiliated researchers (cf. references in Gilmour et al. 2007, 2008; Liu Zhang et al. 2011). With particular emphasis to the AMERIFLUX, sites in South Dakota: a C3 grassland (Brookings) dominated by C3 species (Fig. 2) and a C4 maize crop (Lennox/Sioux Falls) (Fig. 3).

Figure 1. Photosynthesis response function (VPD, Max) with canopy parameter α = 5.4 kcal

Because soil respiration is not closely linked to VPD, it was possible to describe ecosystem respiration by only temperature-dependent term Tc(T) in contrast to others using air temperature T as predictor for R, we found that soil temperature T as a more numerically robust driver for R and VPD, and Tc are closely correlated resulting in numerical difficulties in parameter estimation, Tc is less directly related to VPD, leading to more robust estimations. Following Tonley and Johnson(2000), we retained for Tc(T) the classical Vant-Hoff’s equation in its exponential form:

\[ T_c(T) = T_{\text{std}} \cdot e^{(\text{k} \cdot e^{-\frac{Q}{T}})} \]  

where k is the temperature sensitivity coefficient. Combining (5) and (6), we obtain the general equation for the net CO₂ exchange in the form:

\[ F = \frac{\alpha \cdot \text{Max} \cdot \text{CO}_2}{1 + \beta \cdot \text{VPD}} - \frac{\text{R}_e}{3} \cdot \text{e}^{\left(\frac{Q}{T}\right)} \]  

where R is the reference temperature, and k is the temperature sensitivity coefficient.

Estimation of the parameters
Parameters α, Max, θ, v, and k₁ of the function F(Tc, VPD) were numerically estimated for every day of the year with available T, VPD, and F data. Using the Global Optimization Package of the “Mathematica” system, for every day’s (T, VPD), F-data, i.e., a data set of 3348 values with 30-min time steps we identified best-fit parameter values (α, Max, θ, v, k₁). For example, Figure 4 shows the 3-D projection of the 4-D hyperspace corresponding to the average over 182 days of the year 2009 at the Brookings grassland site.

Numerical values and statistics of the equation (7) parameters that best fit the DOY 182-2009 Brookings data (Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Std. error</th>
<th>h</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>1.000293</td>
<td>0.000114</td>
<td>0.9975</td>
<td>0.0009</td>
</tr>
<tr>
<td>Max</td>
<td>1.000135</td>
<td>0.000075</td>
<td>0.9999</td>
<td>0.0000</td>
</tr>
<tr>
<td>θ</td>
<td>1.000135</td>
<td>0.000075</td>
<td>0.9999</td>
<td>0.0000</td>
</tr>
<tr>
<td>v</td>
<td>1.000135</td>
<td>0.000075</td>
<td>0.9999</td>
<td>0.0000</td>
</tr>
<tr>
<td>k₁</td>
<td>1.000135</td>
<td>0.000075</td>
<td>0.9999</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table 1. Numerical values and goodness-of-fit characteristics of the parameters of equation (7) for day 182-2009 at the Lennox maize site.

<table>
<thead>
<tr>
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<th>Value</th>
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<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>1.000054</td>
<td>0.000014</td>
<td>0.9964</td>
<td>0.0000</td>
</tr>
<tr>
<td>Max</td>
<td>1.000054</td>
<td>0.000014</td>
<td>0.9964</td>
<td>0.0000</td>
</tr>
<tr>
<td>θ</td>
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<td>0.000014</td>
<td>0.9964</td>
<td>0.0000</td>
</tr>
<tr>
<td>v</td>
<td>1.000054</td>
<td>0.000014</td>
<td>0.9964</td>
<td>0.0000</td>
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<td>0.9964</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Comparison of parameter estimates for various days and sites shows that while the numerical optimization routine practically always finds physiologically reasonable sets of parameters, there are differences in the uncertainties of these estimates. As exemplified by the z- and p-values in the above tables, parameter values are considerably lower uncertainties than parameters of light-response variability and temperature-response parameters α and k₁. Because of that, for comparative purpose we have also calculated average daytime respiration rate rₑ = rₑ(Exp) (kₑ) which has much lower uncertainty.

Significance of the VPD control of the net CO₂ exchange
Significance of the VPD as a factor controlling the net CO₂ flux may be characterized by the histogram of the estimated curvature parameters α₀, Max, and θ, of VPD-response curvature α₀, Max, and θ have considerably lower uncertainties than parameters of light-response variability and temperature-response parameters α and k₁. Because of that, for comparative purpose we have also calculated average daytime respiration rate rₑ = rₑ(Exp) (kₑ) which has much lower uncertainty.

Conclusions

Net flux partitioning using light, soil temperature and VPD factors provides robust estimates of photosynthesis, respiration, and ecophysiological parameters applicable to a wide range of grassland and crop ecosystems.

On a significant number of days photosynthesis is limited by drought, making introduction of the PFD factors necessary to prevent overestimation of respiration during light-response analysis.

References