A robust method of net CO_2 flux partitioning into photosynthesis and respiration using light, soil temperature, *VPD*, and *LAI* or *NDVI* data

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Introduction

Partitioning of the net CO_2 exchange data from flux-towers (*F*) into gross photosynthesis (*P*) and ecosystem respiration (*R*) components is an essential stage in the analysis and utilization of ecosystem-scale CO_2 flux measurements. Most of traditionally used partitioning algorithms for non-forest ecosystems are based on simple light-response (Blackman 1905; Mitscherlich 1909; Baly 1935, Smith 1936) and temperature-response (Van't Hoff 1884, Arrhenius 1896, or their modifications) models, which can't describe convexity of the light response and rarely include the effects of vapor pressure deficit (*VPD*) and leaf area index (*L*). We propose a numerically robust method of *F* = *P*–*R* partitioning taking into account light (*Q*), top-soil temperature (T_s), and *VPD* data in their diurnal dynamics, which for dense enough canopies (leaf area index *L*~ 3 m^2 m^{-2} or higher) may be combined with leaf area data estimated directly or from remote sensing.

Study area

Our light-soil temperature-*VPD*-response method was applied to data sets of flux tower measurements at a number of cropland sites of midcontinent North America (Fig. 1)

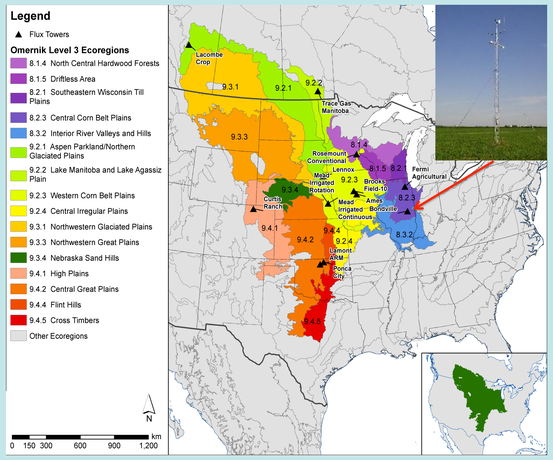

Figure 1. Location of the crop sites and Omernik Level 3 Ecoregions (Gilmanov et al. 2013)

Objectives

- Partitioning of the tower-based *F* data into gross photosynthesis *P* and ecosystem respiration *R*.
- Incorporate leaf area index *L* into flux-partitioning algorithm.
- Determine magnitudes and dynamic patterns of the light-response parameters of ecosystem-scale CO_2 exchange.
- Establish relationships of *L to* remotely sensed 7-day eMODIS normalized difference vegetation index (*NDVI*) to account for canopy effects for sites without *L* data.

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Methods

Diurnal dynamics of the leaf-level (per 1 m^2 of leaf area) gross photosynthesis, P_L, was described by a modified nonrectangular hyperbolic model:

$$P_L(q, VPD) = \frac{\varphi(VPD)}{2\theta}\left(\alpha_L q + A_{\max,L} - \sqrt{(\alpha_L q + A_{\max,L})^2 - 4\alpha_L A_{\max,L}\theta q}\right)$$

where $q = q(l)$ is light intensity at the *LAI* level *l* within the canopy ($q(0) = Q$ – incident solar radiation), α_L is leaf-level apparent quantum yield, $A_{max,L}$ – leaf-level photosynthetic capacity, θ – convexity of the light-response, and $\varphi(VPD)$ is the normalized *VPD*-response function depending on two parameters: critical VPD_{cr}, below which water deficit doesn't affect photosynthesis, and the curvature parameter, σ_{VPD} ($1 \le \sigma_{VPD} \le 30$), with lower values describing a strong water-stress effect, and higher values describing a weak effect (Fig. 2):

$$\varphi(VPD) = \begin{cases} 1, & VPD \le VPD_{cr} \\ Exp\left(-\left(\dfrac{VPD - VPD_{cr}}{\sigma_{VPD}}\right)^2\right), & VPD > VPD_{cr} \end{cases}$$

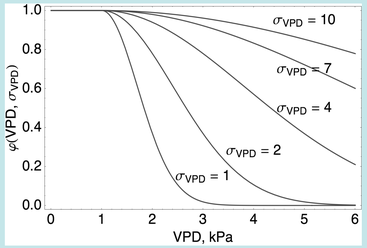

Figure 2. *VPD*-response functions of gross photosynthesis with VPD_{cr} = 1 kPa and various values of the curvature parameter σ_{VPD} = 1, 2, 4, 7 and 10 kPa (Gilmanov et al. 2013).

Total canopy (per 1 m^2 of ground) gross photosynthesis, P_G, was calculated as a canopy integral of P_L:

$$P_G(Q,VPD,L) = \int_0^L P_L\left(q(l),VPD\right)dl,$$

where $q(l)$ is the light intensity at the *LAI* level *l* within the canopy ($0 < l < L$, $q(0) = Q$).

Total ecosystem respiration *R* was calculated diurnally as a function of top-soil temperature, $R = f(T_s)$, where, depending on conditions, either exponential, or bell-shaped form of the function $f(T_s)$ was used. Finally, total ecosystem-scale CO_2 exchange was estimated for every 30-min time increment as:

$$F(Q,T_s,VPD,L) = P_G(Q,VPD,L) - R(T_s).$$

Light, temperature, and VPD-response parameters of the model were numerically estimated using 30-min data for every individual day with available flux and meteorological data using numerically robust tools from the "Global Optimization" package of the *Mathematica*® (Wolfram Research, Inc.) software system.

Gap filling was accomplished using multivariate nonlinear regression of the flux rate to meteorological drivers on diurnal or daily scales.

Results

Ability of the model to describe *VPD* limitation of the canopy CO_2 exchange is illustrated in Fig. 3 describing diurnal CO_2 flux patterns at the Bondville, IL, maize site on a day with strong *VPD* limitation (*DOY* = 168, left) and no *VPD* limitation (*DOY* = 201, right).

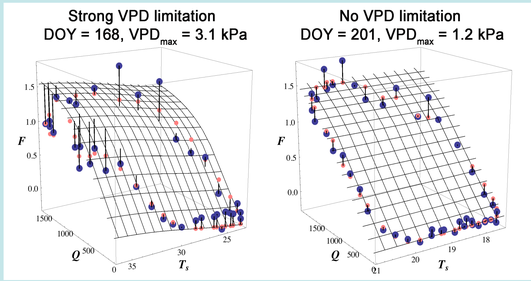

Figure 3. CO_2 exchange *F* (mg CO_2 m^{-2} s^{-1}) at the Bondville maize site, 2007, on a day with strong *VPD* limitation (left) and no *VPD* limitation (right). Blue dots – tower flux data (Ameriflux); red dots – model predictions; surface describes flux values calculated for the mean daily *VPD*.

On a day with high *VPD* (left), red dots representing predicted fluxes deviate from the response surface corresponding to mean daily *VPD*, but are close to the measure values (blue dots). On day with low *VPD*, red dots, blue dots, and the response surface are close to each other.

Annual curves of cumulative distribution of the curvature parameter of photosynthesis *VPD* response, , σ_{VPD} , may be used for inter-site comparison of drought conditions (Fig. 4)

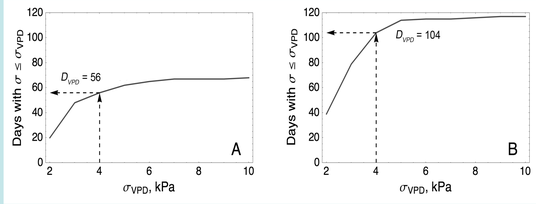

Figure 4. Cumulative distribution of the *VPD*-response parameter, σ_{VPD} of maize crops: (A) – Lennox, SD, 2009, and (B) – ARM main site, OK, 2005 (Gilmanov et al. 2013).

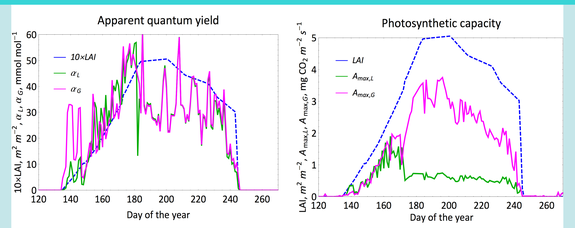

Figure 5. Eco-physiological parameters of the Bondville maize site, 2007: α_L – leaf base quantum yield; α_G – ground base quantum yield; $A_{max,L}$ – leaf base photosynthetic capacity; $A_{max,G}$ – ground base photosynthetic capacity.

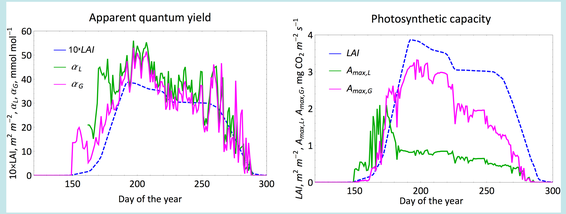

Figure 6. Eco-physiological parameters of the Mead rainfed maize site, 2001: α_L – leaf base quantum yield; α_G – ground base quantum yield; $A_{max,L}$ – leaf base photosynthetic capacity; $A_{max,G}$ – ground base photosynthetic capacity.

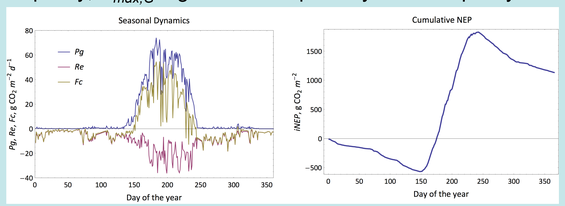

Figure 7. Seasonal dynamics of gross photosynthesis (*Pg*), ecosystem respiration (*Re*), net CO_2 exchange (*F*), and cumulative net ecosystem production (*iNEP*) at the Bondville maize site, 2007.

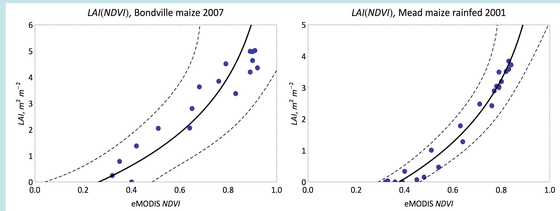

Figure 8. For sites without on-site leaf area measurements seasonal dynamics of *LAI* may be approximated by the site/crop specific function of the normalized difference vegetation index, *NDVI*.

Conclusions

- Described method generates parameter estimates at both the leaf-, and the stand-level (Fig. 5–6) allowing reconstruction of the full carbon budget (Fig. 7).
- Leaf-level estimates of parameters derived from ecosystem-scale measurements (Fig. 5–6) are in agreement with physiological leaf-level data.
- *VPD*-limitation of CO_2 uptake (Fig. 3–4) is observed in all crops of midcontinent North America (23 to 133 days) and should be taken into account in flux partitioning studies. Number of days when σ_{VPD} < 4 kPa may be used as a measure of drought stress complementary to precipitation (Fig. 4).
- For sites lacking direct *LAI* measurements, the method may be applied using pilot *LAI* estimates derived from remotely sensed eMODIS *NDVI* data (Fig. 8).

Acknowledgments

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