Introduction
Partitioning of the net CO₂ 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 CO₂ flux measurements. Most of traditionally used partitioning algorithms for non-forest ecosystems are based on simple light-response (Blackman 1905; Mitscherlich 1909; Bald 1935) and temperature-response (Van’t Hoff 1884, Arrhenius 1896, or their modifications) models, which can’t describe convoluted 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 a single function, which for dense enough canopies (leaf area index L ≥ 3 m² 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).

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 CO₂ 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.

Methods
Dielurnal dynamics of the leaf-level (per 1 m² of leaf area) gross photosynthesis, P_L, was described by a modified nonrectangular hyperbolic model:

\[
P_L(q, VPD) = \frac{P_{L_{max}}}{\alpha VPD_{2}} \left( \frac{q - \alpha_{L_{max}}}{\alpha_{L_{max}} - q} \right)^{1/2} + \frac{q}{\alpha_{L_{max}} VPD_{2}}
\]

where \( q = q(0) \) is light intensity at the LAI level \( L \) within the canopy (\( q(0) = Q \) = incident solar radiation), \( \alpha_{L_{max}} \) is leaf-level apparent quantum yield, \( A_{L_{max}} \) - leaf-level photosynthetic capacity, \( \theta \) – convexity of the light-response, and \( q(VPD) \) is the normalized VPD-response function depending on two parameters: critical VPD, \( VPD_{crit} < VPD_{s} \) below which water deficit doesn’t affect photosynthesis, and the curvature parameter, \( \alpha_{VPD} \) (1 ≤ \( \alpha_{VPD} \) ≤ 30), with lower values describing a strong water-stress effect, and higher values describing a weak effect (Fig. 2).

Total canopy (per 1 m² of ground) gross photosynthesis, P, was calculated as a canopy integral of \( P_L \):

\[
P(q, VPD) = \int_{0}^{L} P_L(q(VPD)) dL
\]

where \( q(0) \) 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, \( R = f(T_s) \), depending on conditions, either exponential, or bell-shaped form of the function \( f(T_s) \) was used. Finally, total ecosystem-scale CO₂ exchange was estimated for every 30-min time increment as:

\[
F(T_s, VPD) = P(q(VPD), VPD) - R(T_s)
\]

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 CO₂ exchange is illustrated in Fig. 3 describing diurnal CO₂ 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. CO₂ exchange F (mg CO₂ 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 calculations 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 VPD-response parameter, \( \alpha_{VPD} \), may be used for inter-site comparison of drought conditions (Fig. 4).

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

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).

Figure 5. E-physiological parameters of the Bondville maize site, 2007. \( \alpha_{L} \) – leaf base quantum yield; \( \alpha_{L} \)– ground base quantum yield; \( A_{L_{max}} \) – leaf base photosynthetic capacity; \( A_{L_{max}} \) – ground base photosynthetic capacity.

• Leaf-level estimates of parameters derived from ecosystem-scale measurements (Fig. 5–6) are in agreement with physiological leaf-level data.

• VPD-limitation of CO₂ 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 \( \alpha_{VPD} < 4 \) 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 LAI estimates derived from remotely sensed eMODIS NDVI data (Fig. 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.

Key references


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