Agricultural and Grassland Ecosystems of the North American Great Plains as Sinks for Atmospheric CO_2: Scaling-Up Long-Term Flux Tower Measurements

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Introduction

Since the classics of agronomy of the 19th century, later supported by direct measurements at the famous Rothamsted unmanured wheat culture experiment (since 1839), it is known that certain agricultural practices may result in negative carbon balance of agroecosystems. Generalization of these views have led to qualification of agroecosystems as mostly source (or a least carbon-neutral) components of the regional carbon cycling systems (cf. Conant et al. 2007). These views, mostly based on inventory data, have recently come to contradiction with results of the three independent study areas: (i) long-term continuous CO_2 exchange measurements at flux-tower networks, (ii) remote sensing measurements, and (iii) inverse atmospheric CO_2 modeling. These studies demonstrated that many (though not all) agroecosystems take up from the atmosphere considerably more CO_2 with photosynthetic assimilation than return with respiration and abiotic oxidation, thus acting as strong (often, the strongest), though temporary, sinks for atmospheric CO_2 (Fig. 1).

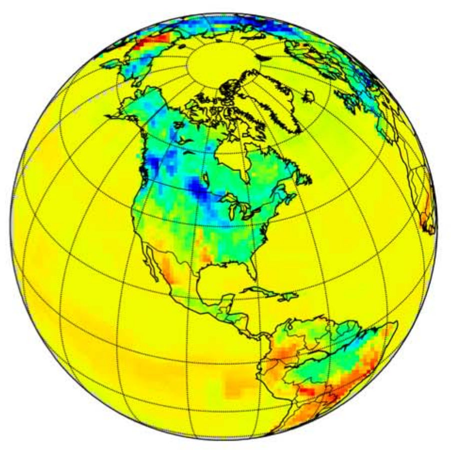

Figure 1. Strong CO_2 sinks in the agroecosystem region of the Midwest (blue colors) identified by the CarbonTracker (http://www.noaanews.noaa.gov/stories2007/s2823.htm).

In this publication we present examples from long-term CO_2 exchange observations illustrating high CO_2 uptake performance of grassland and agricultural ecosystems in the Great Plains region and analyze their relationships to remote sensing indices.

Analyzing CO_2 Exchange Data Sets

As the data sets of long-term CO_2 exchange measurements at the flux towers became available, the need for their post-processing was recognized, in particular, the need to partition net fluxes (F_c) into gross photosynthesis (P_g) and ecosystem respiration (R_e). While the simplified method based on estimating daytime respiration from nighttime measurements is still in use, an approach when daytime respiration is derived from daytime measurements is gaining popularity, especially when the effect of light is combined with other key ecophysiological factors such as soil temperature and vapor pressure deficit (Gilmanov 2011). A broad set of CO_2 exchange measurements in grassland and agroecosystems partitioned into P_g and R_e components using light-response methods was organized into the WORLDGRASSAGRIFLUX database (Gilmanov et al. 2010). In this study we have focused on the North American component of this data set containing towers across the Great Plains and surrounding territories from the AMERIFLUX and AGRIFLUX networks as well as data sets from unaffiliated researchers (Fig. 2).

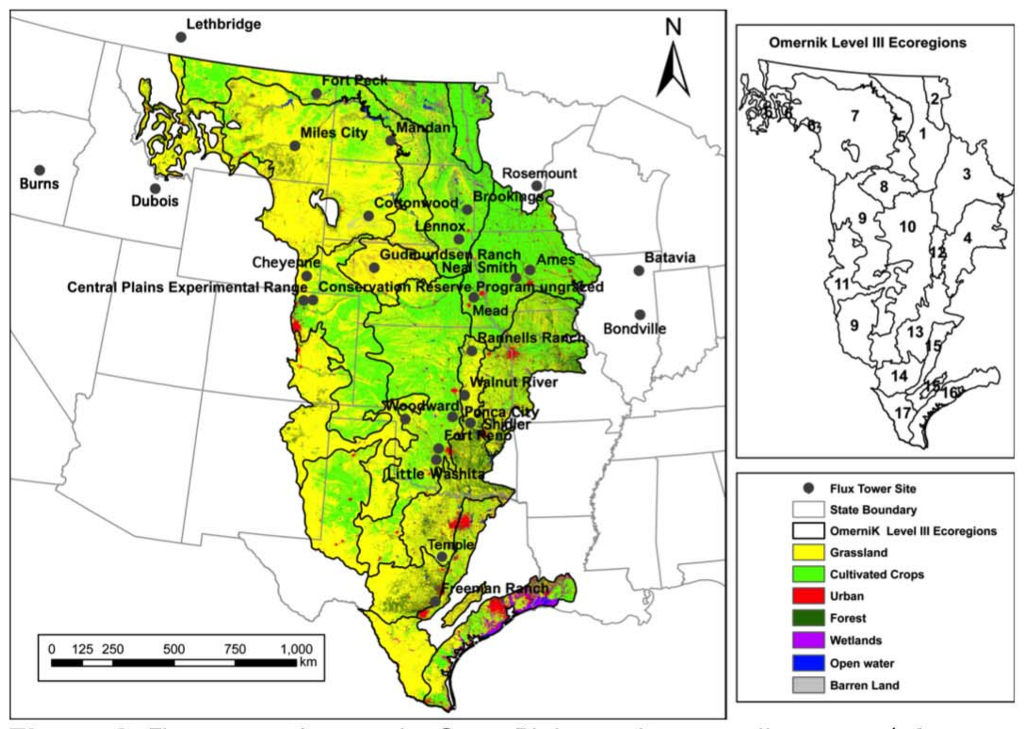

Figure 2. Flux tower sites on the Great Plains and surrounding areas (after Zhang et al. 2011), Omernik Level III Ecoregions: 1) Northern Glaciated Plains, 2) Lake Agassiz Plain, 3) Western Corn Belt Plains, 4) Central Irregular Plains, 5) Northwestern Glaciated Plains, 6) Montana Valley and Foothill, 7) Northwestern Great Plains, 8) Nebraska Sandhills, 9) Western High Plains, 10) Central Great Plains, 11) Southwestern Tablelands, 12) Flint Hills, 13) Central Oklahoma/Texas Plains, 14) Edwards Plateau, 15) Texas Blackland Prairies, 16) Western Gulf Coastal Plain, and 17) Southern Texas Plains.

Major Ecosystem-scale Characteristics

The light-response functions method is one of the few approaches to post-processing flux tower data which generates physiologically based and numerically robust quantitative estimates of ecosystem-scale characteristics. These include gross primary productivity P_g and its annual integral GPP, total ecosystem respiration R_e and its annual integral RE, and the key parameters apparent quantum yield α (initial slope of the light response), photosynthetic capacity A_{max} (plateau of the light response), daytime ecosystem respiration rate r_{day}, and ecological light-use efficiency $\varepsilon_g = P_g/Q_{day}$.

Statistical data for the Great Plains and surrounding areas show that agroecosystems have considerably higher ecophysiological parameters of the carbon cycling than grasslands (Table 1), reflecting their high physiological potential to take up atmospheric CO_2.

Table 1. Major ecophysiological parameters of grasslands and crops (average of annual maximum weekly values, n = 67 for grasslands and n = 17 for crops) derived from flux tower data.

	$A_{max,wk}$ mg CO_2 m^{-2} s^{-1}	$r_{day,wk}$ mg CO_2 m^{-2} s^{-1}	α_{wk} mmol/mol	$\varepsilon_{g,wk}$ mmol/mol
Grasslands	0.98±0.55	0.22 ±0.10	27.7 ±8.48	15.01 ±7.30
Crops	2.02 ±0.89	0.33 ±0.12	35.12 ±9.29	27.59 ±10.99

Strong CO_2 Sinks without Terminal Sequestration

Reflecting their physiological potential, long-term year-round CO_2 exchange measurements in grasslands and agroecosystems of the Great Plains revealed that on an annual basis many agroecosystems take up from the atmosphere considerably more CO_2 with photosynthesis than return with total respiration (Figs. 2–4).

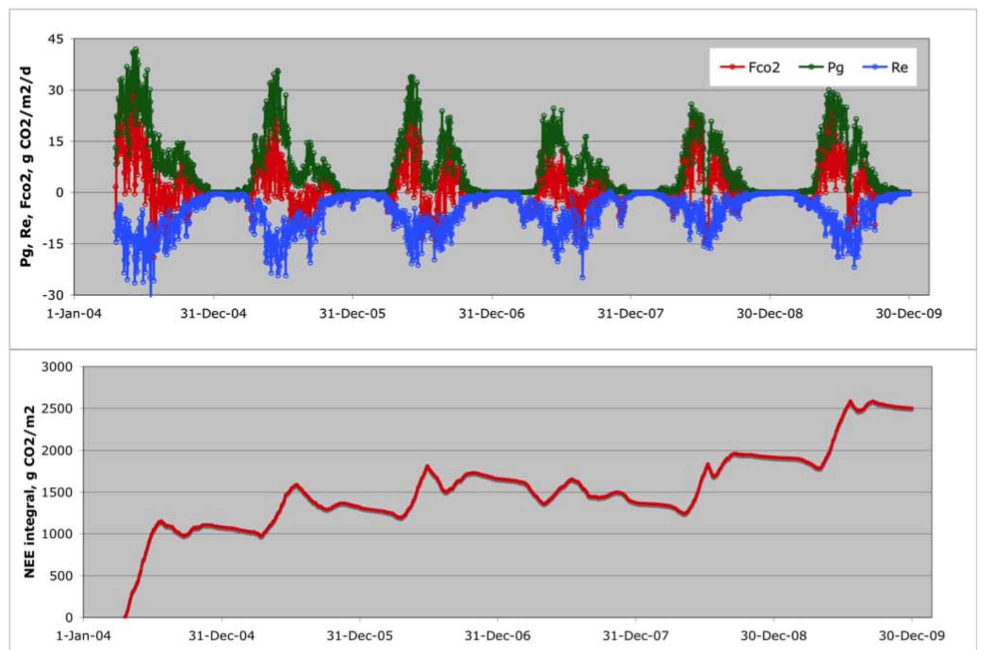

Figure 3. Gross photosynthesis, ecosystem respiration, and net CO_2 exchange (top panel), and cumulative net CO_2 exchange (lower panel) of the Brookings, SD, grassland during the 2004–2009 measurement period.

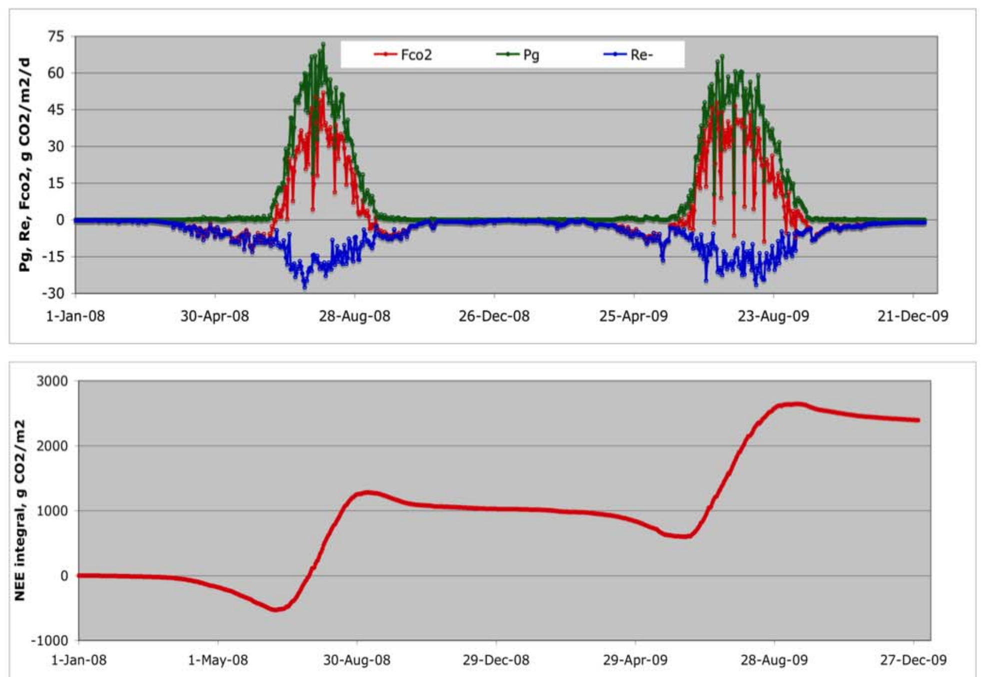

Figure 4. Gross photosynthesis, ecosystem respiration, and net CO_2 exchange (top panel), and cumulative net CO_2 exchange (lower panel) of the Lennox/Sioux Falls, SD, maize field during the 2008–2009 measurement period.

Flux tower data from the North American grasslands and crops confirm and further strengthen observations made earlier on data from other continents (Gilmanov et al. 2010) that GPP in these systems is significantly higher than RE, so that on H. Odum's RE vs. GPP plots (Fig. 5) many more points lie below the major diagonal than above, indicating positive net annual production (NEP > 0). Cases with GPP < RE correspond to years with drought stress or to crops with agronomically brief leaf area duration periods like soybeans.

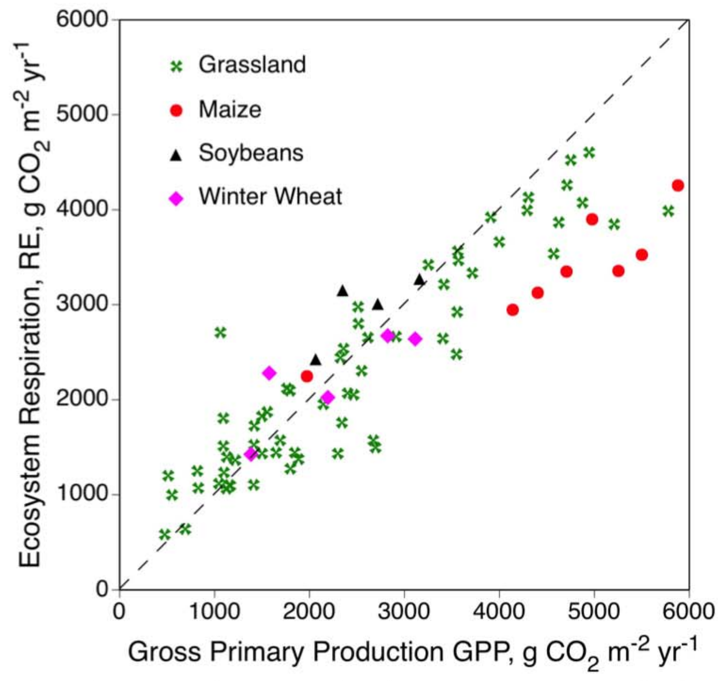

Figure 5. Annual gross primary production–ecosystem respiration diagram for 84 site-years of CO_2 exchange measurements on the Great Plains.

Flux partitioning as a basis for scaling-up CO_2 exchange using remote sensing

Scaling-up tower measurements to describe CO_2 exchange at larger geographic scale is a formidable task. Fig. 6 shows relationships between NDVI and photosynthesis and daytime net flux at the Brookings grassland for the 2009 spring-summer period. NDVI explains 98% of the variance of photosynthesis and only 91% of the variance of the daytime CO_2 flux. Comparison of correlation coefficients of P_g and P_{day} with NDVI on the broad statistical material of n = 73 site-years of measurements on the Great Plains (Fig. 7) demonstrated that the histogram of the *ATANH*-transformed r-values for P_{day} are skewed to the left compared to the r-values for the P_g, indicating lower P_{day}-NDVI correlations than P_g-NDVI correlations. Therefore, from the viewpoint of predictive modeling with remotely sensed data, using P_g values is preferable to using original tower data.

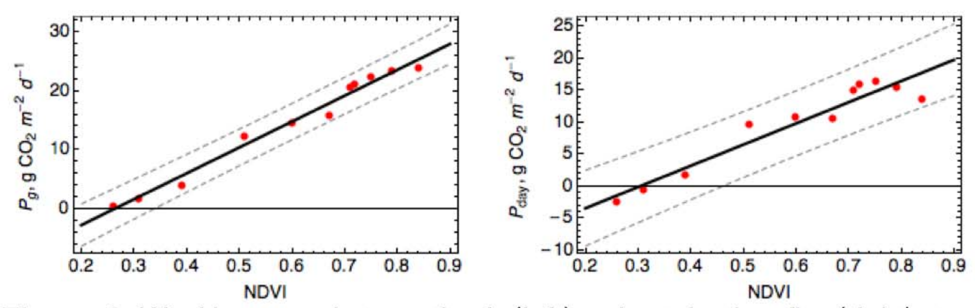

Figure 6. Weekly gross photosynthesis (left) and net daytime flux (right) at the Brookings grassland during spring-mid summer 2009 (DOY 110–187) in relation to the normalized difference vegetation index (eMODIS NDVI).

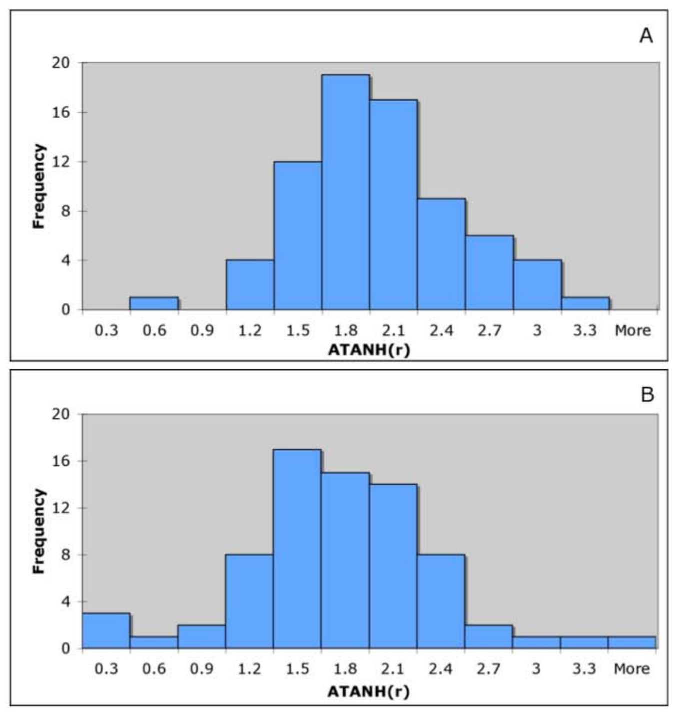

Figure 7. Distributions of ATANH-transformed correlation coefficients of gross photosynthesis P_g (A) and the net daytime flux P_{day} (B) with eMODIS NDVI for 73 site-years of flux tower measurements on the Great Plains.

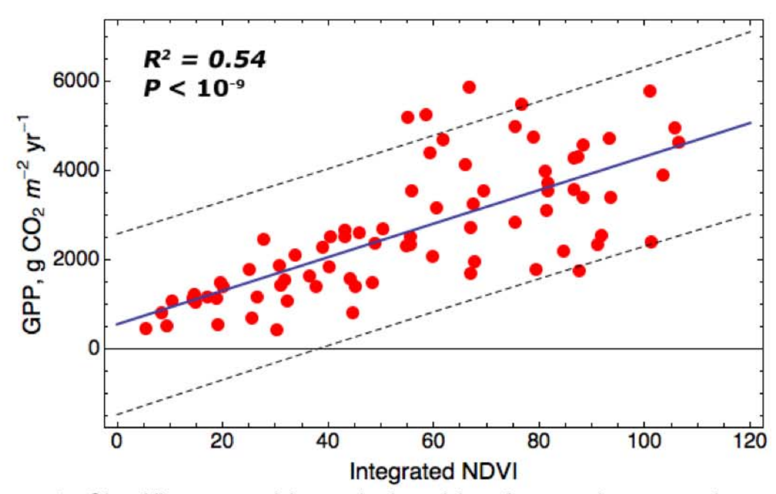

Figure 8. Significant positive relationship of annual gross primary production of the Great Plains ecosystems with seasonally integrated NDVI:

$$IntegrNDVI = \int_{t_1}^{t_2} Max(0, NDVI(t) - NDVI_{gr})dt$$

where t_1 and t_2 denote start and end of the growing season, and $NDVI_{gr}$ describes the background level.

Significant positive correlation between annual GPP and the seasonally integrated NDVI corrected for background (Fig. 8) serves as an additional justification for including spectral vegetation indices as predictors for CO_2 exchange models.

Nonlinear Multivariate Functions for Scaling-Up CO_2 Fluxes

Post-processing of flux tower data combined with remote sensing and on-site information in the form of appropriate GIS layers (e.g., State Soil Geographic Database) allows identification of sets of factors-predictors $x_1, x_2, \ldots, x_n$ to serve as arguments to nonlinear time-dependent multivariate models $y_i = F_i(t, x_1, x_2, \ldots, x_n)$ for geographically distributed CO_2 flux components (Zhang et al. 2011). Application of this methodology to the Great Plains tower data sets produced first estimates of the region-scale CO_2 budgets. These results demonstrated high spatial and temporal variability of CO_2 fluxes across the Great Plains during the 2000–2008 period (Fig. 9, 10), while overall the region served as a sink for atmospheric CO_2 with a total magnitude of 336 Tg C yr^{-1} (Zhang et al. 2011).

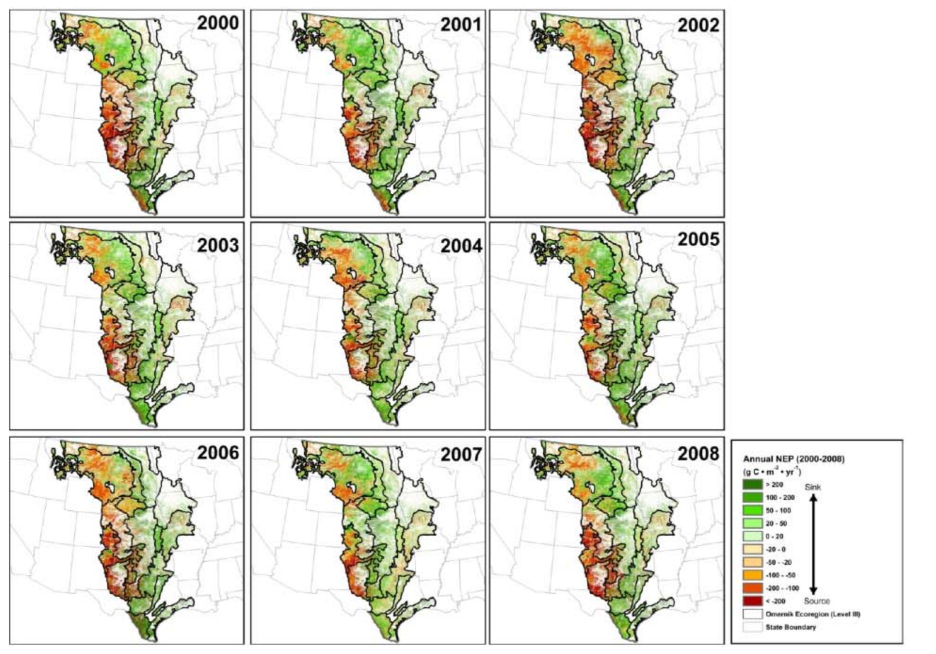

Figure 9. Spatial and temporal heterogeneity of the net ecosystem production of the Great Plains grasslands, 2000–2008 (model results by Zhang et al. 2011).

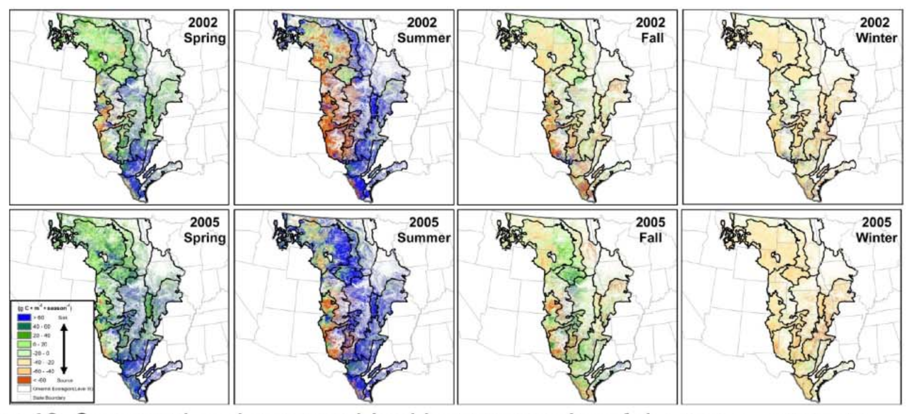

Figure 10. Seasonal and geographical heterogeneity of the net ecosystem production on the Great Plains during the dry year 2002 and the wet year 2005 (Zhang et al. 2011).

Conclusions

- The light-response functions method confirmed higher photosynthetic and efficiency parameters of agroecosystems of the Great Plains compared to grasslands.
- Photosynthesis derived through flux partitioning is more closely related to remote sensing factors (NDVI) than original (NEE) flux data.
- Long-term tower measurements showed that grasslands and crops take more CO_2 from the atmosphere with photosynthesis than return with respiration. Lateral transport with harvest and erosion does not change the fact that these ecosystems act as temporary sinks (often, strong sinks) for atmospheric CO_2.
- Computer-intensive nonlinear multivariate models combined with GIS and remote sensing techniques help to identify complex relationships of ecosystem CO_2 exchange components to constellations of ecological factors providing tools to scale-up tower data to produce regional estimates of CO_2 exchange.

Acknowledgements

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