Scaling-up tower CO_2 fluxes in semiarid grasslands of the Great Plains using spectral vegetation indices and phenomenological modeling

Tagir G. Gilmanov[1], Bruce K. Wylie[2,] and Larry L. Tieszen[2]

[1]South Dakota State University, Brookings, SD, 57007 (tagir_gilmanov@sdstate.edu); [2]USGS/EROS Data Center, Sioux Falls, SD, 57198 (http://edcintl.cr.usgs.gov/carboninfosheetca.html)

Introduction

Semiarid grasslands occupy approximately 10% of the world terrestrial area and remain one of the few large ecosystem classes for which no measurement-based estimates of CO_2 flux are available. Since the mid-1990s, long-term continuous measurements of the CO_2 exchange have been initiated in a number of semiarid grassland ecosystems of the Great Plains under the auspices of the USDA-ARS RangeFlux (AgriFlux) and AmeriFlux (USGCRP) networks (Fig. 1). Results of these measurements may be used to obtain ecoregion-scale estimates of the CO_2 exchange at these grasslands.

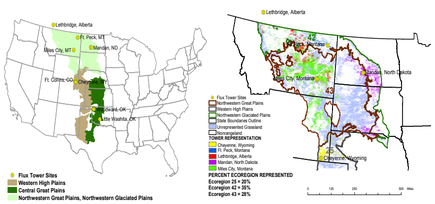

Fig. 1. Distribution of the CO_2 flux towers in the semiarid grassland ecoregions of the Great Plains (a) and estimates of flux tower representation for the Northwestern Great Plains and North Western Glaciated Plains ecoregions (b). Ecoregions are defined according to Omiernik (Level III). Representation is defined with respect to similarity of NDVI dynamics in spectral space.

Objectives

Calculate ecoregion-scale fluxes CO_2 and components (gross primary production, *GPP*) and total ecosystem respiration (R_e)) using flux tower observations, remote sensing, and modeling. We will identify the important environmental controls of ecosystem CO_2 exchange.

How are Flux Towers Representative of Ecoregions?

The flux towers of the AgriFlux network use the Bowen ratio-energy balance methodology (Dugas et al.1997), while measurements of the AmeriFlux network are conducted using the eddy covariance principle (Meyers, 2001; Flanagan et al., 2002). Representation for respective ecoregions is evaluated to scale-up measurements at flux tower sites. The Euclidian distance in spectral space was used to identify grasslands having similar Normalized Difference Vegetation Index (NDVI) trends and magnitudes as those observed at the flux tower. The NDVI Euclidian distance was summed across all 10-day periods from April 1 to October 31. Using the resulting spectral distance image, a consistent threshold of ≤ 3 in NDVI units was established for all towers. This threshold was determined by comparing the NDVI temporal curve at the flux towers with temporal curves at varying spectral distances. The 1992 USGS National Land Cover Data Set was used to remove representative 1-km pixels which were less than 70% grassland.

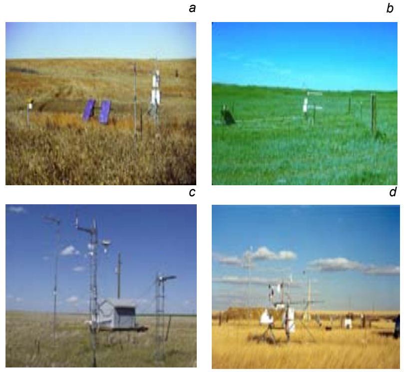

Fig. 2. CO_2 flux towers in semiarid grasslands of the Great Plains: (a) mixed prairie, Mandan, ND (BREB system, photo courtesy Al Frank, USDA-ARS); (b) mixed prairie, Cheyenne, WY (BREB system, photo courtesy Jack Morgan, USDA-ARS); (c) mixed prairie. Lethbridge, Alberta (EC system, Ameriflux photo); (d) mixed prairie, Fort Peck, MT (EC system, Ameriflux photo).

Ecosystem-Scale Light Response Functions and Evaluation of CO_2 Fluxes

Grassland CO_2 flux data from the USDA-ARS AgriFlux database (Blackland Research Center, Temple, TX: Miles City (M. Haferkamp), Mandan (A. Frank), and Cheyenne (J. Morgan)) and from the Ameriflux database (ORNL/CDIAC, Oak Ridge, TN: Lethbridge (P. Flanagan), Ft. Peck (T. Meyers)) were used to identify site specific ecosystem-scale light-response functions (Fig. 3) and to estimate day-time ecosystem respiration (R_d), gross primary productivity (P_g), and total ecosystem respiration (R_e). In contrast to widely adopted practice to estimate R_d from night-time respiration measurements, following Marshall and Biscoe (1980) and Causton and Dale (1990), we estimated R_d from day-time measurements using the light-response function analysis (Gilmanov, 2001). We modified their approach by using the non-rectangular hyperbolic curves (Fig. 3, a, b) or, for days with hysteresis of the flux-PAR relationship, non-rectangular hyperbolic surfaces (Fig. 3, c, d), which allowed more precise estimates of the light response parameters, compared to traditionally used hyperbolic model (Gilmanov et al., 2003; Gilmanov et al., in press, a, b).

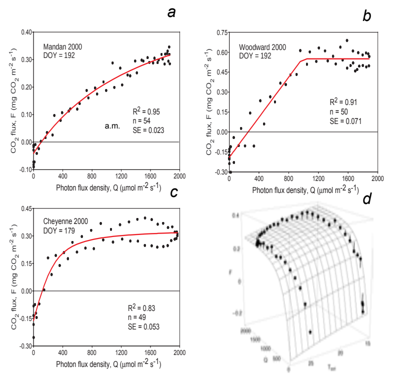

Fig. 3. Ecosystem-scale light-response functions for semiarid grasslands: (a) Mandan, DOY 145, 2000; (b) Woodward, OK, DOY 192, 2000; (c) Cheyenne, WY, DOY 179, 1998; (d) same, light-temperature response surface: Q - photon flux density, µmol m^{-2} s^{-1}; T_{soil} - soil temperature (5 cm), ºC; F - CO_2 flux, mg CO_2 m^{-2} s^{-1}.

Site-specific light-response functions identified for every tower site allowed estimation of daytime respiration R_d, calculation of daily gross primary productivity P_g as the sum of R_d and daytime flux P_d (obtained directly from measurements, $P_g = P_d + R_d$), and gap-filling daytime fluxes. We filled missing nighttime measurements using either temperature-dependent regressions for night-time fluxes or temperature corrected relationships between day-time and night-time respiration rates. This resulted estimated daily values of gross primary productivity (P_g), daytime flux (P_d), ecosystem respiration (R_e) and net ecosystem CO_2 exchange (F) for every day of the growing season at every grassland tower site.

Which Flux Component Is Most Closely Related To NDVI?

For each grassland site, we calculated for a 10-day time step: 1) SPOT VEGETATION NDVI, 2) average values of P_g, P_d, R_e, F (net flux), and 3) relevant environmental factors (Q, T_{air}, T_{soil}, W_{soil}, RH, etc.). Our analysis demonstrates that gross primary productivity (P_g) is most closely correlated with NDVI: the R^2 values of the relationships between P_g and *NDVI* are substantially higher than those between daytime flux P_d and *NDVI* (Fig. 4 and Table 1).

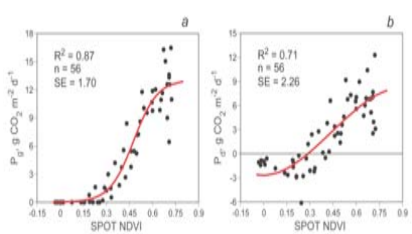

Fig. 4. Relationships of gross primary productivity (P_g) (a) and daytime production (P_d)(b) to NDVI for the Mandan 2000-2001 data set.

Table 1. Comparison of relationships of ten-day average gross primary productivity (P_g) and ten-day average daytime CO_2 flux (P_d) R^2 to ten-day composite NDVI in semiarid grasslands of the Northern Great Plains region.

Site, ecosystem	Year	R^2	
		P_g(NDVI)	P_d(NDVI)
Lethbridge, northern mixed prairie	2000	0.77	0.52
Fort Peck, northern mixed prairie	2000	0.90	0.63
Miles City, northern mixed prairie	2000-2001	0.71	0.18
Mandan, northern mixed prairie	2000-2001	0.87	0.71
Cheyenne, mixed prairie	1998	0.63	0.36
Fort Collins, shortgrass steppe	2000	0.68	0.33
Fort Collins, shortgrass steppe	2001	0.85	0.77
Little Washita, pasture in mixed/tallgrass prairie	1997	0.85	0.78
Woodward, southern mixed prairie	1997	0.75	0.45
Woodward, southern mixed prairie	2000	0.91	0.78
Woodward, southern mixed prairie	2001	0.89	0.54
Mean		0.80	0.55

Phenomenological Models for Ecosystem-Scale CO_2 Exchange in Relation to NDVI and Environmental Drivers

Multivariate analysis demonstrated statistically significant relationships between major CO_2 exchange components (such as P_g, R_e), and various combinations of *NDVI* and other factors-predictors: $P_g = f(NDVI, X_1, …, X_n)$ and $R_e = g(NDVI, X_1, …, X_k)$. Characteristically for phenomenological (semi-empiric, non-mechanistic) models, the functions $f(…)$ and $g(…)$ obtained in our analysis are site-specific (especially with respect to numerical parameters), though often quite similar to one another in functional form (Fig. 5). **It should be noted, that in terms of systems analysis, the functions $P_g = f(NDVI, X_1, …, X_n)$, and $R_e = g(NDVI, X_1, …, X_k)$ might be characterized not as pure "black box"-type models, but rather as "gray box"-type models, because they have as inputs not only external drivers such as solar radiation, air temperature, precipitation, etc., but also the state variables such as *NDVI* and other remotely sensed ecosystem state variables.** This allows resultant models to achieve a high agreement with data (R^2 in the range 0.7 to 0.9) and makes it possible to use them to calculate fluxes in other pixels that were similar to the towers within the ecoregions. Some functional characteristics of the established $P_g(NDVI, X_1, …, X_n)$ relationships for various grassland sites are summarized in Table 2.

Table 2. Functional characteristics of phenomenological models $P_g(NDVI, X_1, …, X_n)$ of the relations of average ten-day gross primary productivity (g CO_2 m^{-2} d^{-1}) to NDVI and other ecological factors for semiarid grasslands of the Northern Great Plains region.

Site	Years	Factors-predictors	Maximum P_g	n	R^2	SE
Lethbridge, Alberta	1999-2000	*NDVI, PAR, Tair*	15	71	0.79	1.58
Fort Peck, MT	2000	*NDVI, Wsoil*	16	21	0.87	1.32
Miles City, MT	2000-2001	*NDVI, PAR, TempSum*	12	44	0.81	1.37
Mandan, ND	2000-2001	*NDVI, PAR, Wsoil*	17	56	0.86	1.55
Cheyenne, WY	1998	*NDVI, Tair*	28	21	0.82	3.35

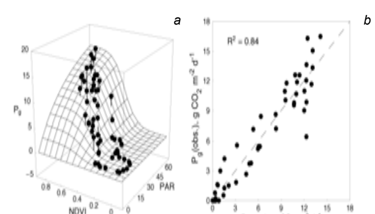

Fig.5. Partial response function $P_g(NDVI, PAR)$ showing dependence of gross primary productivity on *NDVI* and *PAR* for Mandan 2000-2001: response surface (a); scatter diagram of observed *vs* predicted values(b).

Calculation of Ecoregion-Scale Fluxes

We calculate and map spatial and temporal dynamics of CO_2 flux by superpositioning the tower-specific functions $f_i(NDVI, X_1, …, X_n)$ on the GIS layers of *NDVI* and other factors $\{X_j\}$ for all the pixels belonging to the areas represented by each tower. Figure 6 is an example of monthly gross primary production (GPP) dynamics in semiarid grasslands of the Northern Great Plains region derived from NDVI.

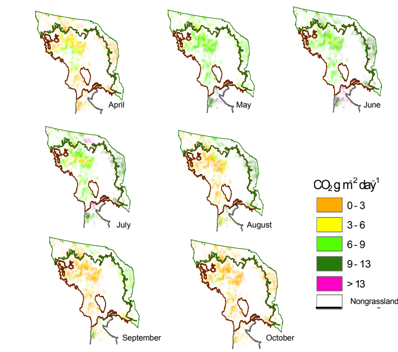

Fig. 6. Maps of seasonal dynamics of gross primary production in semiarid grasslands of the Northern Great Plains region.

Growing season average GPP by ecoregions

Ecoregion	C t/ha
25	4.3
42	3.5
43	2.9

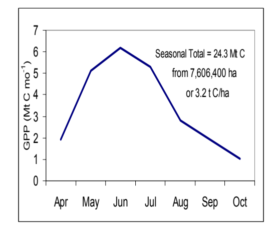

Fig. 7. Dynamics of gross primary production of the semiarid grasslands of the Northern Great Plains region during the 2000 growing season.

Summary

- Gross Primary Productivity was most strongly related to NDVI at the 10-day time step.
- Spectral distance derived form the NDIV temporal curve allows identification of areas of the ecoregion which have NDVI patterns similar to the flux towers.
- Statistically significant relationship to NDVI and other environmental factors were established for gross primary productivity and other CO_2 flux components (R_e, P_d).
- These algorithms allow scaling up of flux tower observations and mapping CO_2 fluxes at the ecoregion scale.

Acknowledgements

This study was supported in part by the United States Geological Survey, South Dakota State University, USAID-CRSP, and the USDA Agricultural Research Service

References

Gilmanov, T. G. 2001. A method to estimate gross primary production from the Bowen ratio - energy balance CO_2 flux measurements and construction of predictive relationships between NDVI and CO_2 flux. A report to Raytheon Company, EROS Data Center, Sioux Falls, SD, August 15, 2001.

Gilmanov, T. G., D. A. Johnson, Saliendra, N.Z. 2003. Growing season CO_2 fluxes in a sagebrush-steppe ecosystem in Idaho: Bowen ratio.energy balance measurements and modeling. Basic and Applied Ecology, 4: 167-183.

Gilmanov, T.G., D.A. Johnson, N.Z. Saliendra, K. Akshalov, B.K. Wylie. 2003. Gross Primary Productivity of the True Steppe in Central Asia in Relation to NDVI: Scaling up CO_2 Flux Measurements. Environmental Management, submitted.

Gilmanov, T.G., S.B. Verma, P.L. Sims, T.P. Meyers, J.A. Bradford, G.G. Burba, and A.E. Suyker. 2003. Gross primary production and light response parameters of four Southern Plains ecosystems estimated using long-term CO_2-flux tower measurements. Global Biogeochemical Cycles. In press.

Wylie, B.K., T.G. Gilmanov, D.A. Johnson, N.Z. Saliendra, K. Akahalov, L.L. Tieszen, B.C. Reed, and E. Laca. 2003. Remote sensing and GIS in rangelands of northern Kazakhstan: quantification and mapping of seasonal CO_2 fluxes from Bowen ratio-energy balance measurements. Environmental Management, submitted.

Wylie, B.K., D.A. Johnson, E. Laca, N.Z. Saliendra, T.G. Gilmanov, B.C. Reed, L.L. Tieszen, and B.B. Worstell. 2003. Calibration of remotely sensed, coarse resolution NDVI to CO_2 fluxes in a sagebrush-steppe ecosystem. Remote Sensing of Environment, 85:243-255.