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Vegetation indices, CO_2 flux, and biomass for Northern Plains Grasslands

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Abstract

Native grasslands are a sink for atmospheric CO_2 sequestration, but ways for extending site-specific CO_2 flux measurements to a regional scale are lacking. Objectives of this study were to determine the utility of using canopy radiometric reflectance for estimating CO_2 fluxes for semiarid grasslands. The relationship between the normalized difference vegetation index (NDVI) calculated from spectral reflectance data obtained with hand-held radiometers was compared to CO_2 flux calculated from Bowen ratio/energy balance measurements. Carbon dioxide flux was measured during the plant growing season over a nongrazed prairie, grazed prairie, and a shrub dominated prairie site near Mandan, N.D. Measurements were also made of evapotranspiration (ET), green biomass, and green leaf area index (LAI). Correlation coefficients of NDVI with vegetation parameters of biomass and LAI for each site and year exceeded 0.84 in 1999, 0.74 in 2000, and 0.91 in 2001; with CO_2 flux correlations exceeded 0.63 in 1999, 0.68 in 2000, and 0.69 in 2001; with ET correlations exceeded 0.91 in 1999, 0.92 in 2000, and 0.90 in 2001. Regression analysis over all years and sites produced a nonlinear relation between NDVI and both biomass (R^2 = 0.83) and LAI (R^2 = 0.77) and a linear relationship between NDVI and both CO2 flux (R^2 = 0.51) and ET (R^2 = 0.81). The relationships between NDVI and biomass, LAI, CO_2 flux, and ET for the 3 grassland sites, which differed in management and vegetation, were generally quite similar suggesting that NDVI has potential for use in predicting canopy CO_2 flux rates for semiarid grasslands in the Northern Great Plains.

Key Words: global carbon cycle, rangelands, Bowen ratio, remote sensing, sequestration

Resumen

Los pastizales nativos son un depósito de fijación de CO_2 atmosférico, pero faltan maneras de extender los mediciones del flujo de CO_2 realizadas en un sitio especifico a una escala regional. Los objetivos de este estudio fueron determinar la utilidad de usar la reflección radiométrica de la copa para estimar los flujos de CO_2 de pastizales semiáridos. La relación entre el Índice de la Diferencia Normalizada de Vegetación (NDVI) calculada a partir de los datos de reflección espectral obtenidos con radiometros manuales se comparó con los flujos de CO_2 calculado a partir de mediciones de la relación Bowen/balance de energía. El flujo de dióxido de carbono se midió durante la estación de crecimiento de las plantas en una pradera no apacentada, en una apacentada y en una pradera dominada por arbustos, situadas cerca de Mandan, N.D. También se hicieron mediciones de evapotranspiración (ET), biomasa verde índice de área foliar verde (LAI). Los coeficientes de correlación del NDVI con los parámetros de vegetación y LAI para cada sitio excedieron 0.84 en 1999, 0.74 en 2,000 y 0.91 en 2001, con coeficientes de correlación del flujo de CO_2 mayores a 0.63 en 1999, 0.68 en 2000, y 0.69 en 2001; y correlaciones con ET superiores a 0.91 en 1999, 0.92 en 2000 y 0.90 en 2001. El análisis de regresión a través de todos los años y sitios produjo una relación no lineal entre NDVI y biomasa (R^2 = 0.83) y LAI (R^2 = 0.77) y una relación lineal entre NDVI y el flujo de CO_2 (R^2 = 0.51) y la ET (R^2 = 0.81). Las relaciones entre NDVI y la biomasa, el LAI, el flujo de CO_2 y la ET en los 3 sitios de pastizal, los cuales difirieron en el manejo y vegetación, fueron generalmente muy similares, sugiriendo que el NDVI tiene el potencial para ser usado en predecir las tasas de flujo de CO_2 de la copa de la vegetación de los pastizales semiáridos de las Grandes Planicies del Norte.

Carbon dioxide flux measurements have shown that grasslands function as a net sink for sequestration of atmospheric CO_2 (Kim et al.1992, Dugas et al. 1999, Frank et al. 2000, Frank and Dugas 2001, Sims and Bradford 2001). Tropical forests are the largest terrestrial biomass sink for C, containing about 40% of the total C stored in terrestrial ecosystems (Dixon et al. 1994). Grassland ecosystems comprise about one-fifth of the earth's land surface and contain more than 10% of the global C stocks (Eswaran et al. 1993). Temperate-region grassland ecosystems have extensive fibrous root systems for storing C compounds and may be important C sinks for balancing the global C budget (Rastetter et al. 1992, Sundquist 1993, Gifford 1994, Schimel 1995, Keeling et al. 1996, Batjes 1998, Fan et al. 1998).

Native grasslands are a diverse mixture of species that generally occupy landscape sites that have less productive soils than cropland and are often located in regions that receive less precipitation. Although considerable heterogeneity is present in grasslands, the use of remotely sensed data to predict biomass production (Tucker 1977, Aase et al. 1987, Burke et al. 1991, Anderson et al.1993, Wylie et al. 2002a) and C flux (Wylie et al. 2002b) has been encouraging. A positive relationship between NDVI and biomass or above ground net primary production has been shown for several grassland ecosystems (Pearson et al. 1976, Paruelo et

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al. 1997, Tucker 1977, Aase et al. 1987). Wylie et al. (2002a) showed a strong relationship, an R^2 of 0.85, for the relationship between biomass vs. NDVI for diverse grasslands ranging from about 36° to 52° N latitude in the Great Plains. Others have shown a strong relationship between canopy absorbed photosynthetically active radiation and canopy indices based on reflectance in the red and infrared bands (Anderson et al.1993, Paruelo et al. 1997), which provides support for the use of vegetative indices, such as NDVI, as an indicator of CO_2 fluxes.

Although prediction of biomass from vegetative indices has shown considerable promise, information on estimating CO_2 fluxes from vegetative indices is limited. Some have used the relation between NDVI and absorbed photosynthetically active radiation (Monteith et al. 1964) as estimates of canopy photosynthesis (Paruelo et al. 1976, Wylie et al. 2002a). Wylie et al. (2002b) found that the time-integrated normalized vegetative index was a strong predictor of day time CO_2 fluxes in a sagebrush-steppe ecosystem, suggesting that this index could be used to scale ecosystem CO_2 fluxes to the regional level. Scaling-up of vegetation responses from the site specific to the regional-global level was identified by Schimel (1995) as a critical area for future research.

Ecosystem CO_2 flux measurements are being made by researchers in coordinated efforts over diverse landscapes; the USDA-Agricultural Research Service Rangeland CO_2 flux Project (Svejcar et al. 1997), Ameriflux Network (Wofsy et al. 1993, Hollinger et al. 1999), and Euroflux Network (Aubinet et al. 2000). There is a need to extend these data from site of measurement to the regional and global scale. The objectives of this study were to evaluate the relationship between NDVI and CO_2 flux, above ground biomass, and leaf area index from 3 semiarid grasslands for purposes of extending CO_2 flux data to a regional scale.

Materials and Methods

Three grassland sites located at the Northern Great Plains Research Laboratory, Mandan, N.D. (latitude 46°46'N, longitude 100°55'W, elevation 518 m) were used in this study. The sites are typical Northern Great Plains mixed-grass prairie dominated by western wheatgrass [*Pascopyrum smithii* (Rybd) Löve], needle-and-thread (*Stipa comata* Trin. and Rupr.), *Carex* (Carex spp.), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], side-oats grama [*Bouteloua curtipendula* (Michx.) Torr.], Kentucky bluegrass (*Poa pratensis* L.) and blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Griffiths]. The sites included a long-term (86 yr) continuously grazed historical site (grazed prairie), a site that was grazed prior to 1992 and again after 1999 (prairie), and a grazed site with about 20% of the land area occupied by dense shrub thickets of mainly buffalo berry (*Sheperdia argentea* Nutt.),western snowberry (*Symphoricarpos occidentalis* Hook), and several other tree and shrub species with the remainder of the area being typical grassland (shrub prairie). The grazing intensity for all sites was moderate or about 2.6 ha per steer. Soil at the sites belong to the Werner-Sen-Chama complex (loamy, mixed, superactive, frigid shallow Entic Haplustoll; fine-silty, mixed, superactive, frigid Typic Haplustoll; fine-silty, mixed, superactive, frigid Typic Calciustoll). The sites never had fertilizer or herbicides applied.

Canopy reflectance measurements were obtained with an Exotech 100-BX 4 band radiometer (Exotech Inc., Gaithersburg, Md) with a 15° field of view. The unit was mounted on a portable mast at 2 m above the soil surface. Reflectance in bands 1 (450–520nm) and 2 (520–600nm) were not used in calculations. Reflected radiation in bands 3 or the RED band (630–690nm) and 4 or the NIR band (760–900nm) were measured looking vertically downward from the mast height. Ten readings were taken near the location of each biomass sampling within each site and averaged. Measurements were made on clear days between 1300–1500 hours CDT at 15–21 day intervals from spring greenup in April to fall dormancy in late October in 1999, 2000, and 2001. The radiometer was calibrated prior to taking readings at each site using measurements of a barium sulfate standard panel. The normalized difference vegetative index (NDVI=(NIR-RED)/(NIR+RED)) was calculated as described by Jackson (1983).

Green biomass and leaf area were measured at each site by clipping 4 representative 0.25 m^2 quadrats within 40 m of the Bowen ratio/energy balance towers on the same day, or if biomass sampling days were cloudy, within several days of making the radiometric measurements. The taller and dense shrub thickets constituted about 20% of the area in the shrub prairie site and were sampled for leaf area index (LAI) during mid-June each year. Leaves were manually separated from stems, and LAI was measured using a belt-driven photoelectric area meter. Leaves and stems were oven dried (70° C) and weighed to obtain total above-ground biomass.

Concentrations of CO_2 and water vapor were measured every 20 minutes during the growing period from spring greenup in April to late October in 1999, 2000, and 2001 using Bowen ratio/energy balance instrumentation towers (Model 023/CO_2 Bowen ratio system, Campbell Scientific, Inc., Logan, Ut.) located centrally at each site to provided at least 200 m of fetch in all directions from the towers. Evapotranspiration (ET) was measured simultaneously with CO_2 flux. Fluxes were calculated using methods described by Dugas (1993) and Dugas et al. (1999). Bowen ratios were calculated from temperature and humidity gradients measured every second at 1 and 2 m above the canopy. Sensible heat flux was calculated from the Bowen ratio, average net radiation was measured using a model Q*7.0 and 7.1 net radiometer (REBS, Seattle, Wash.), and soil heat flux was calculated from 2 soil heat flux plates (Model HFT, REBS) with soil temperature measured by thermocouples above the plates. Net radiometers were calibrated against a laboratory standard (Model 7.1, REBS) over grass each year before use. Plant height was measured at least 3 times each growing season and was occasionally used in calculation of turbulent diffusivity (Dugas et al. 1999). The turbulent diffusivity, assumed equal for heat, water vapor, and CO_2, was calculated using the 20-minute sensible heat flux and temperature gradient measurements. Twenty-minute averages of CO_2 and water vapor flux, corrected for vapor density differences at the 2 heights (Webb et al., 1980), were calculated as a product of turbulent diffusivity and the 20-minute average CO_2 and water vapor gradient measured every second at 1 and 2 m above the canopy. When the Bowen Ratio/Energy Balance (BREB) method for calculating turbulent diffusivity was not valid because of differences in the sign of the flux and the gradient, diffusivity was calculated using wind speed, atmospheric stability, and canopy height (Dugas et al. 1999). This alternate method of calculation of diffusivity was used very infrequently to calculate the daytime flux measurements. Carbon dioxide and water vapor concentration gradients between the 2 heights were measured with infrared gas analyzers (Model 6262, Li-Cor Inc., Lincoln, Nebr.) that were calibrated weekly. Fluxes were not corrected for temperature differences in the 2 air streams because in a separate test, fine-wire thermocouples indicated air temperatures from the 2 heights did not differ when entering the gas analyzer (unpublished observations). Soil water content was measured at 3.8 cm depth with time-domain reflectometry methods (Model CS615 Water Content Reflectometer, Campbell Scientific Inc.) every 20 minutes and averaged daily. All data generated from the Bowen ratio/energy balance system were stored in a model 21X data logger (Campbell Scientific Inc.).

The Bowen ratio/energy balance method is an indirect method compared to the direct eddy covariance method of measuring CO_2 fluxes. Bowen ratio calculations use measurements of air temperature and humidity gradients, net radiation, and soil heat flux for estimating surface latent heat flux. The Bowen ratio may become highly variable especially during instances of stable atmospheric conditions when diffusivities for heat and water vapor become very small. Such conditions generally occur near dusk and dawn and would be excluded from our data set since we removed fluxes at radiation levels less that 25 W m-2. Reports using the Bowen ratio/energy balance method for measuring CO_2 fluxes over grasslands have been made by Dugas et al. (1997), Dugas et al. (1999), Frank et al. (2000), Frank and Dugas (2000), Sims and Bradford (2001), and Frank (2002). Angell et al. (2001) showed CO_2 fluxes from the Bowen ratio/energy balance method were very similar to those for closed chamber measurements for both daytime and nighttime flux measurements on a sagebrush steppe site.

Daily CO_2 flux and ET was calculated for the daylight period or when net radiation exceeded 25 W m^{-2}, which approximates the period between sunrise and sunset. Daily flux were then averaged for the time interval between reflectance readings. Regression and correlation analysis were used to evaluate the relationship between CO_2 flux, ET, biomass, and LAI with NDVI using SAS (SAS Institute 1989).

Results and Discussion

Precipitation received during the flux measurement period was 520 mm in 1999, 337 mm in 2000, and 392 mm in 2001 compared to the long-term average of 320 (Figs 1–3). The long-term (85 yr) annual precipitation total at Mandan is 404 mm. Historically, the greatest average monthly

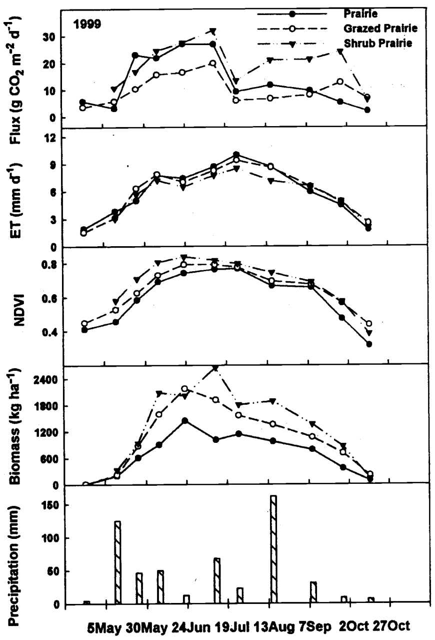

Fig. 1. Seasonal trends of CO_2 flux, ET, NDVI, biomass, and precipitation for a prairie, grazed prairie, and shrub prairie site in 1999.

precipitation occurs in June, when 21% of the annual precipitation is received. Unusually high amounts of precipitation were received in single-day, high-intensity events during May and August 1999.

The temporal dynamics of the biophysical parameters measured at each site were characteristic of cool-season grassland ecosystems in that activities of CO_2 flux, ET, and biomass accumulation increased rapidly in the spring, peaked in early summer, and decreased in late summer through early autumn (Figs. 1, 2, 3). The season-long data for CO_2 flux, ET, and biomass exhibited a similar response pattern across sites and years. This relationship is typical for Northern Great Plains grasslands where air temperature and soil water are the primary driving factors controlling cool-season grass phenology and biomass accumulation (Frank and Bauer 1995). Periods of peak biomass differed slightly among years, but generally occurred during the late-June to late-July period. Peak biomass across all years and sites ranged from 1,804 kg^{-1} ha for 2000 to 2,088 kg^{-1} ha in 1999 with an average of 1,936 kg^{-1} ha, which along with an LAI of < 1 (as shown in Fig. 4), indicated that the canopy of these grasslands was generally sparse when viewed from the nadir position.

Flux of CO_2 showed greater variation among sampling periods throughout the 3 years compared to the other measured biophysical parameters (Figs. 1–3). This was especially apparent during a drought period from 12 July to 26 July 1999 or between the sixth and seventh sampling when fluxes decreased sharply for all 3 sites (Fig. 1). The difference in CO_2 flux among sites for periods following the 1999 drought period were greater between the shrub prairie site compared to the prairie and grazed prairie sites than during similar periods in 2000 and 2001. This response may have been due to less leaf senescence following the drought period for the shrubs in the shrub prairie site compared to mainly grass species in the prairie and grazed prairie sites. Differences in CO_2 fluxes for the grazed prairie vs. the prairie (grazed only in 2000) varied only slightly over all periods (Fig. 2).

Period of maximum CO_2 flux varied across years and sites and occurred prior to mid-July each year except for the grazed prairie site in 2000. Peak CO_2 flux per period across years ranged from 28.8 g CO_2 m^{-2} day^{-1} for the prairie in 2001 (Fig. 3) to 32 g CO_2 m^{-2} day^{-1} for the shrub prairie in 1999 (Fig. 1). The greater CO2 uptake for the shrub prairie site compared to the prairie and grazed prairie in 1999 was probably due to the greater shrub

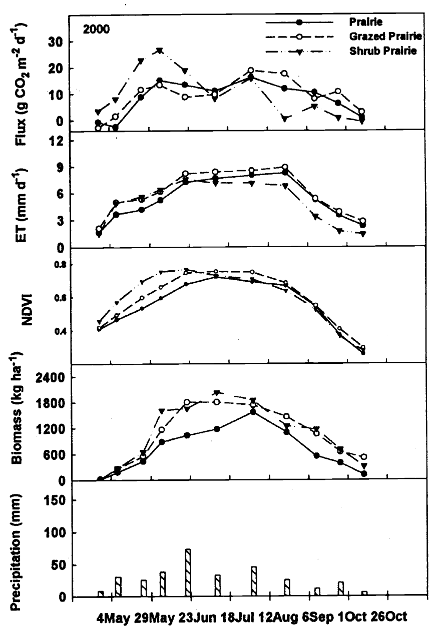

Fig. 2. Seasonal trends of CO_2 flux, ET, NDVI, biomass, and precipitation for a prairie, grazed prairie, and shrub prairie site in 2000.

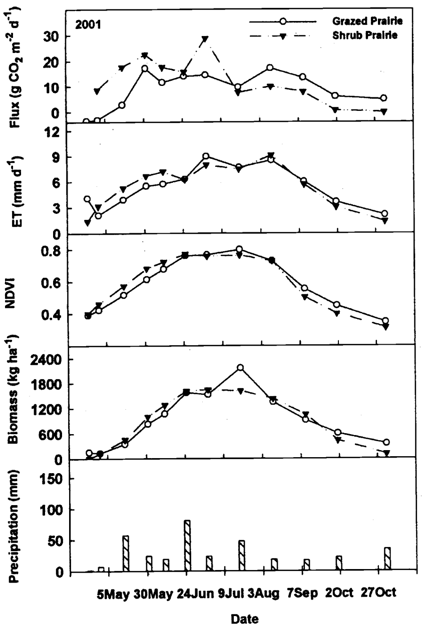

Fig. 3. Seasonal trends of CO_2 flux, ET, NDVI, biomass, and precipitation for a grazed prairie and shrub prairie site in 2001.

green leaf area available for fixing CO_2. Peak LAI of the shrub thicket alone for the shrub prairie site averaged 4.6 compared to 0.7 for the grazed prairie and prairie sites.

Rates of ET showed a similar seasonal pattern as that observed for biomass and CO_2 flux, except that peak ET rates occurred later than those for biomass and CO_2 flux. Peak ET rates ranged from a low of 7.6 mm day^{-1} for the shrub prairie site in 2000 to 10.0 mm day^{-1} for the prairie site in 1999. These Northern Great Plains grasslands are typically exposed to high atmospheric evaporative demand and relatively low annual precipitation (404 mm), which results in pan evaporation often exceeding precipitation. Also, cool-season grasslands characteristically have high rates of transpiration as grassland vegetation typically extract all available soil water to about 120 cm depth by end of the growing season. The slight increase in ET during the drought period in 1999 was probably due to a greater reduction in photosynthesis than plant transpiration in response to water stress causing stomatal conductance to decrease (Cowan 1982) which is similar to that reported by Frank and Berdahl (2001) for Russian wildrye [*Psathyrostachys juncea* (Fisch.) Nevski].

Values of NDVI for each period showed a very similar seasonal responses for the 3 sites. The NDVI was low in the spring, then increased until about 1 June, changed little during June, July and August, and then decreased as plants senescenced in autumn. There were only slight differences in NDVI across years within sites and between sites, which was expected because the difference in biomass among sites across years averaged only 284 kg ha^{-1}. Correlation coefficients between NDVI and the vegetation parameters of biomass and LAI for each site and year exceeded 0.84 in 1999, 0.74 in 2000, and 0.91 in 2001 (Table 1). Regression analysis showed a nonlinear relationship with the general shape of the regression line being similar for both biomass and LAI vs. NDVI (Fig. 4). Values of R^2 with NDVI were relatively high as evidenced by values of 0.83 for biomass and 0.77 for LAI (Fig. 4). The uniformly high correlation coefficients (r) and regression coefficient of determination (R^2) suggested that a single regression equation based on data from all years and sites should reliably predict biomass and LAI from NDVI. Aase et al. (1987) showed a similar relationship between LAI and NDVI for 2 managed native prairie sites, but a unique relationship existed for crested wheatgrass [*Agropyron desertorum* (Fisch. Ex Link) J. A. Schultes]. Wylie et al. (1996) showed a linear relationship between NDVI and biomass for hand-held radiometer spectral data and a nonlinear relationship for satellite derived spectral data (Wylie et al. 2002a). Values of NDVI have been shown to provide a good estimate of biomass for a shortgrass prairie (Anderson et al. 1993) and across a range of precipitation amounts ranging from 280 to 1,150 mm year^{-1} (Paruelo et al. 1997).

The range in correlation coefficients for NDVI and CO_2 flux were greater among years than sites within years (Table 1). Within years the greatest range in correlation coefficients was from 0.68 for the grazed prairie in 2000 to 0.79 for the prairie in 2000, whereas, over years correlation coefficients ranged from 0.63 for the grazed prairie in 1999 to 0.79 for the prairie in 2000. Correlation coefficients were lowest in 1999 compared to 2000 and 2001, but the range in correlation coefficients were similar over years. Correlation coefficients within years for NDVI vs. CO_2 flux exceeded 0.63 in 1999, 0.68 in 2000, and 0.69 in 2001. The reason for the lower correlations in 1999 was probably due to the drought period in mid July (Fig. 1) causing greater variation among factors affecting plant CO_2 uptake. For example, precipitation in 1999 exceeded 100 mm twice during the data

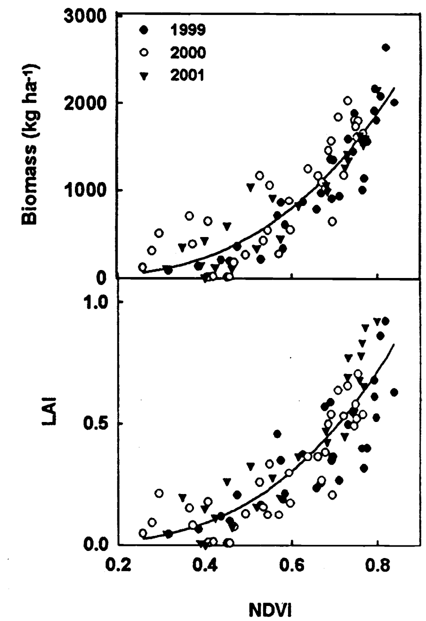

Fig. 4. Relationship between biomass and NDVI (top) and LAI and NDVI (bottom) for data combined across prairie, grazed prairie, and shrub prairie sites for 1999, 2000, and 2001. For biomass the equation for the fitted line is: biomass = 2.698 + (3709.449 x NDVI^3); R^2 = 0.83 ($P \leq 0.05$); standard error of regression is 266, and for LAI the fitted line is: LAI= -0.093 + (–0.192/lnNDVI); R^2 = 0.77 ($P \leq 0.05$); standard error of regression is 0.13.

Table 1. Correlation coefficients between NDVI and biomass, LAI, CO_2 flux and ET for a prairie, grazed prairie, and shrub prairie site in 1999, 2000, and 2001. All correlation coefficients are significant at $P \leq 0.05$.

	1999			2000			2001	
	Prairie	Grazed prairie	Shrub prairie	Prairie	Grazed prairie	Shrub prairie	Grazed prairie	Shrub prairie
Biomass	0.95	0.97	0.90	0.88	0.86	0.74	0.93	0.92
LAI	0.88	0.87	0.84	0.87	0.83	0.79	0.93	0.91
CO_2 flux	0.73	0.63	0.70	0.79	0.68	0.77	0.76	0.69
ET	0.95	0.93	0.91	0.92	0.93	0.94	0.90	0.93

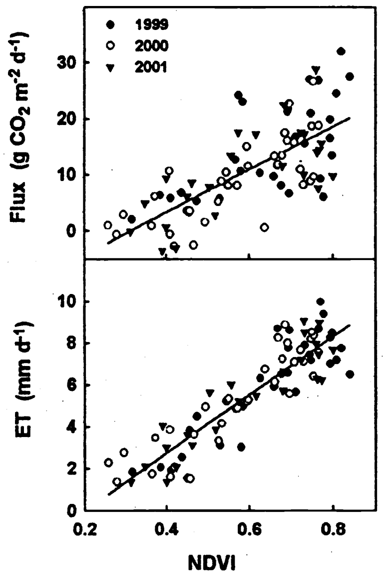

Fig. 5. Relationship between CO_2 flux and NDVI (top) and ET and NDVI (bottom) for data combined across prairie, grazed prairie, and shrub prairie sites for 1999, 2000, and 2001. For CO_2 flux the equation for the fitted line is: flux = –11.49 + (37.99 x NDVI); R^2 = 0.51 ($P \leq 0.05$); standard error of regression is 5.74, and for ET the fitted line is: ET = -2.81 + (13.92 x NDVI); R^2 = 0.81 ($P \leq 0.05$); standard error of regression is 1.04.

collection period, but never during 2000 and 2001. Law et al. (2000) reported that water stress in conifer tree significantly reduced the association between CO_2 flux and NDVI. The regression analysis of NDVI vs. CO_2 flux across years and sites (8 site years) was linear with an R^2 of 0.51 (Fig. 5). The greater variability at the higher NDVI and CO_2 flux values in 1999 contributed mostly to the lower R^2 across all sites and years. Because the greatest difference in the NDVI vs. CO_2 flux relationship occurred over years and not among sites within years suggested that the seasonality of biomass accumulation and environmental factors affecting CO_2 uptake may have a significant effect on the NDVI vs. CO_2 flux relationship.

A major difference in the biomass response curves for 1999 and 2000 that may have affected the CO_2 flux and NDVI relationship was that peak biomass occurred on the 23 June 1999 sampling, whereas in 2000 peak biomass occurred on the 11 July sampling or 18 days later. Another factor that may have contributed to the greater variability between NDVI and CO_2 flux occurred between 12 July and 26 July 1999 when drought conditions caused a large decrease in CO_2 flux, but not NDVI or biomass.

Wylie et al. (2002b) reported a strong relationship between satellite derived time-integrated normalized vegetative index and CO_2 flux measurements for a sagebrush-steppe ecosystem (*Artemisia* spp.) which suggested that the time-integrated normalized vegetative index could be used for mapping regional CO_2 fluxes for semiarid grasslands. Our point measurements of canopy radiometric reflectance when matched with CO_2 flux data provides further evidence for using NDVI for scaling data to a regional level. Correlation coefficients between NDVI and the daily 24 hour day and night CO_2 flux were lower for all sites and years than for only daylight CO_2 flux measurements; however the same general trend existed (data not presented).

The relationship between NDVI and ET was less variable than NDVI vs. CO_2 flux as evident by the greater R^2 of 0.81 (Fig. 5). The range in correlation coefficient across years and sites for NDVI vs. ET were similar, ranging from 0.90 to 0.95 (Table 1), which supports the higher R^2 obtained for the regression analysis that used data across all years and sites.

Conclusions

The relationships between NDVI and biomass, LAI, CO_2 flux, and ET for 3 grassland sites that differed in management and plant composition were generally quite similar, suggesting that NDVI has good potential for use in predicting canopy CO_2 flux rates for grasslands in the Northern Great Plains. The relatively high correlation coefficient and regression R^2 values for NDVI with CO_2 flux, ET, biomass, and LAI were similar among sites within years, but greater variation was observed for 1999 when drought conditions occurred.

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