Scaling-up of CO_2 Fluxes to Assess Carbon Sequestration in Rangelands of Central Asia

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Abstract—*Flux towers provide temporal quantification of local carbon dynamics at specific sites. The number and distribution of flux towers, however, are generally inadequate to quantify carbon fluxes across a landscape or ecoregion. Thus, scaling up of flux tower measurements through use of algorithms developed from remote sensing and GIS data is needed for spatial extrapolation of carbon fluxes and to identify regional sinks and sources of carbon. Spatial and temporal quantification of carbon dynamics are useful in understanding the biophysical factors that cause regions to be sinks or sources of carbon. We analyzed data sets from the Northern Great Plains and the Kazakh Steppe and found similarities in latitude, precipitation, and carbon fluxes between the two regions. These similarities allowed us to pool carbon flux data, remotely sensed data, and GIS data from these two regions to map gross primary productivity (Pg), total ecosystem respiration (Re), and net ecosystem exchange (NEE) for Kazakh Steppe for 2001 using regression tree techniques. We estimated 10-day Pg and Re with mean absolute errors of 3.2 and 2.7 g* CO_2/m^2*/day, respectively. The NEE for grasslands in the Kazakh Steppe during the growing season (April through October 2001) was 0.79 t C/ha. Localized carbon sinks and sources were positively correlated with growing season precipitation and Pg. The regression tree technique provided an effective method for the regional mapping of carbon dynamics as seasonally quantified by flux towers in the Northern Great Plains of North America and the Kazakh Steppe of Central Asia.*

Keywords: *Kazakhstan, carbon sinks, carbon sources, carbon dynamics, Northern Great Plains.*

Introduction

Increasing levels of atmospheric carbon dioxide (CO_2), one of several "greenhouse gases" that impact global climate, have been well documented. Vegetation absorbs atmospheric carbon through photosynthesis to form biomass and ultimately soil organic matter. Increased plant primary productivity can, therefore, partially offset fossil fuel emissions of CO_2 into the atmosphere.

Although rangelands have relatively small magnitudes of net carbon fluxes compared to forests, they cover a vast area that

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represents about 30 to 40 percent of the earth's land surface area (Brown 1989, World Resources Institute 2000). As a result, rangelands could have a substantial effect on global carbon budgets. Grasslands store 90% of their carbon below ground and through time can accumulate significant soil carbon. For example, it has been estimated that grasslands contain 10 to 30% of the world's soil organic carbon (Schuman and others 2002) with temperate grasslands containing about 18% of global carbon reserves (Burke et al. 1997).

Isotopic analysis of atmospheric CO_2 suggests a significant carbon sink (removal of atmospheric carbon) in Central Asia (Miller and others 2003). This appears to be related to the abandonment of collective wheat farms in the 1990s, which were expansively established during the Kruschev era (De Beurs and Henebry 2004), although the effects of this land use change may be confounded by the impacts of global warming. Quantification of rangeland carbon fluxes may be important for possible trading of carbon credits, wherein industries with excessive point sources of carbon emissions must pay for carbon sequestration through improved vegetation production elsewhere. The USAID GL-CRSP project "Livestock Development and Rangeland Conservation Tools for Central Asia (LDRCT)" has provided a crucial database for quantifying carbon fluxes in Central Asia.

Flux towers, micrometeorological instruments that use Bowen ratio-energy balance or eddy covariance techniques, provide detailed quantification of fluxes of carbon into and out of the atmosphere at the land surface. The quantification of soil carbon stocks that include biomass and soil organic matter have large sampling errors so sampling can detect only relatively large changes in carbon pools across 5- to 10-year time-frames for most systems. Flux towers, on the other hand, are capable of quantifying daily, seasonal and annual carbon dynamics. Flux tower equipment and operation, however, can be both expensive and complex, and may result in an under-sampling of carbon fluxes across many ecosystems and land uses. Therefore, the ability to scale up localized flux tower observations is important for quantifying carbon budgets, identifying and mapping carbon sinks and sources, and understanding the dynamics and causal factors for areas being carbon sinks and sources. The scaling of flux measurements is particularly important for expansive rangeland ecosystems that have heterogeneous soils and variable precipitation.

Our study sought to quantify rangeland carbon dynamics across growing seasons for the Kazakh Steppe ecoregion in Central Asia, as defined by Olson and others (2001; fig. 1). This ecoregion is representative of vast Eurasian rangelands extending from the Ural Mountains in the west to the Altai Mountains in the east.

Based on the similar vegetation structures in the Kazakh Steppe and Northern Great Plains (fig. 1), we hypothesize that these ecoregions also have functionally similar carbon fluxes. If this is true, then rangeland flux towers from these two ecoregions can be used to develop algorithms to scale up carbon fluxes. This synergistic use of rangeland flux data from rangelands in Central Asia and North America should strengthen flux predictions in both regions and would maximize the use of flux tower data, which are currently under-sampling these extensive ecosystems and their various management scenarios.

Study Area

A Bowen ratio-energy balance (BREB) flux tower was established in 1998 on a virgin prairie site (51° 40' N, 71° 00', 367 m above sea level) near the town of Shortandy, Kazakhstan on the Baraev Research and Production Center for Grain Farming. This area is classified as a true grass and forb steppe dominated by *Stipa capillata* L., *Stipa lessingiana* S. Zalesskii, *Agropyron cristatum* L., *Kochia prostrata* L., *Medicago falcata* L., *Festuca valesiaca* Hackel, *Salvia stepposa* Schost., *Artemisia marshalliana* Spreng., and *Artemisia glauca* Pall. The long-term (1936-2001) average annual precipitation at the study site is 324 mm with a mean annual temperature of 1.6 °C. Precipitation is variable, and drought is common during June and July.

Partitioning of Carbon Fluxes

Flux towers measure net exchanges of CO_2 above the land surface (Dugas and others 1997). These carbon fluxes can be summed seasonally or annually to quantify net ecosystem exchange (NEE). However, NEE is determined by two basic ecosystem processes, gross primary productivity (Pg) and total ecosystem respiration (Re), which have opposite effects on carbon fluxes. Partitioning carbon fluxes into Pg and Re components improves the regional predictions by allowing them to be more process-based and also contributes to understanding the driving factors for carbon sinks and sources. We use detailed light curve analysis to separate daytime respiration and daytime Pg (Gilmanov and others 2003). Night-time fluxes represent only respiration fluxes so Re is the sum of daytime respiration and night-time respiration and includes both autotrophic and heterotrophic respiration.

Two light curve equations are used, one without soil temperature (*Ts*):

$$P(Q;\alpha,\beta,\gamma,\theta)=\frac{1}{2\theta}\left(\alpha Q+\beta-\sqrt{(\alpha Q+\beta)^2-4\alpha\beta\theta Q}\right)-\gamma,$$

and one with soil temperature:

$$P(Q,T_s;\beta,\gamma_0,\theta,k)=\frac{1}{2\theta}\left(\alpha Q+\beta-\sqrt{(\alpha Q+\beta)^2-4\alpha\beta\theta Q}\right)-\gamma_0 e^{kT_s},$$

where P is the theoretical magnitude of daytime CO_2 flux, Q is the incoming photosynthetically active radiation (PAR), α is an initial slope of the light response curve, β is a plateau parameter (equal to the maximum rate of gross photosynthesis), γ is the respiration term, θ is the curvature parameter that modifies the shape of the light-response curve, and k describes the strength of the hysteresis of the light-response curve (Gilmanov and others 2003).

This detailed nonlinear analysis was conducted using flux tower 20- or 30-minute time step data and allowed independent determination of night-time and daytime respiration components. Lastly, Pg and Re were summarized to match

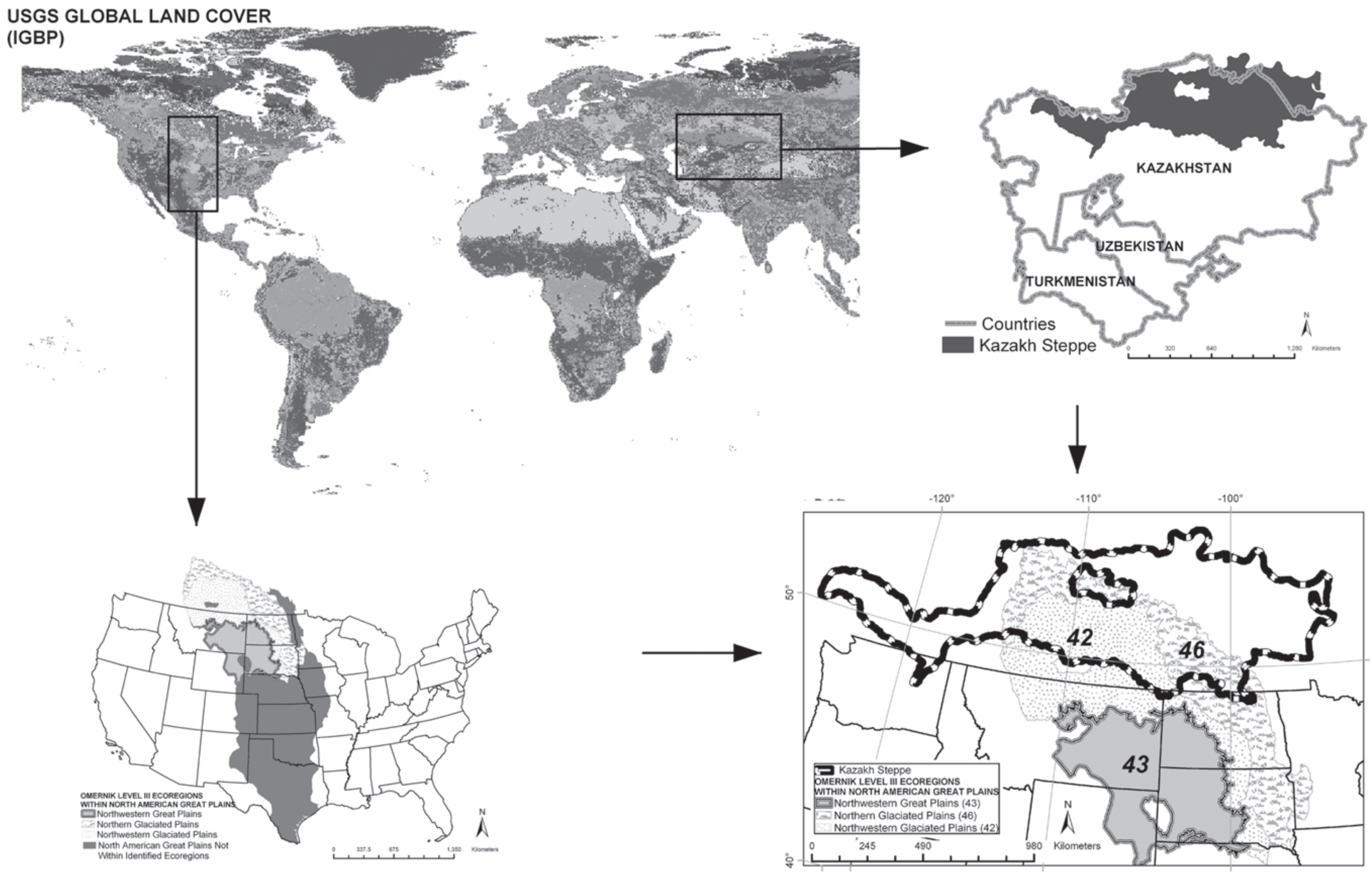

Figure 1—Latitudinal comparison of the Kazakh Steppe ecoregion (Olson and others 2001) and the Northern Great Plains ecoregions (Omernik 1987).

the 10-day time steps of SPOT VEGETATION Normalized Difference Vegetation Index (NDVI) composite periods.

Regression Tree Analysis

Biogeochemical models have been the typical approach for producing regional or global carbon fluxes. Some of these models primarily use precipitation and temperature to simulate plant growth for a theoretical ecosystem and estimate land use-specific net primary production (Liu and others 2003), while other models use the light-use-efficiency approach (Running and others 1999). However, input demands and model parameterization can be problematic for both of these approaches because they require "spin up" model runs to establish initial conditions and parameterization (Running and others 1999). For our study, we utilized a bottom up, robust, empirical approach that seeks to minimize input variables and yet maintain prediction accuracy. We used regression tree analysis to develop predictive relationships between GIS and remotely sensed data as independent variables, and flux tower observations from multiple sites and multiple years as the dependent variable. Prince and Steininger (1999) proposed the use of a regression tree technique to scale up ecosystem and meteorological parameters. De'ath and Farbricius (2000) demonstrated the robustness of the regression tree approach and its insensitivities to high-order interactions, ability to fit nonlinear trends, and ability to reveal new relationships not evident in classical regression analysis. Regression tree analysis has been used successfully to scale up flux tower data in the western United States and Central Asia (Wylie and others 2003; Wylie and others 2004). For this study, we used the regression tree software Cubists (www.rulequest.com) to identify GIS and remotely sensed variables and respective thresholds, which stratifies the data set into near-optimal linear subsets. Multiple linear regression equations were then established for each linear subset. This resulted in a series of "rules" or stratified regression equations that were used to map the predicted variable (10-day Pg or Re).

The data used to train the regression trees and develop the predictive rules consisted of flux tower, GIS, and remotely sensed data sets with a 10-day time step (table 1). Data values from each of these spatial and temporal variables were extracted at each tower location. These values were combined with the 10-day Pg and Re data from flux tower observations and then used to develop regression tree algorithms. The relative frequency of use of variables utilized to stratify the training data combined with a relevance weight (a surrogate for partial R^2 values associated with respective independent variables used in each regression model) was used to identify heavily and slightly used variables (Wylie and others 2003). The effects of ignoring slightly used variables on the accuracy of regression tree prediction were quantified by cross validation. This approach allowed selection of a minimum number of input variables required to retain model prediction accuracy.

To ensure the robustness of the regression tree algorithms, multiple flux tower sites and multi-year data sets were used to develop the regression tree algorithms. Flux tower locations used in this study were from both the Kazakh Steppe and similar ecoregions in the Northern Great Plains of North America (table 2).

Is the Kazakh Steppe Functionally Similar to the Northern Great Plains?

To establish the functional similarity between the Northern Great Plains and the Kazakh Steppe, we made regional comparisons based on latitude, precipitation, and seasonal NDVI patterns. Latitudes for the Omernik ecoregions (Omernik 1987) of the Northwestern Glaciated Plains and the Northwestern Great Plains were quite similar to those for the Kazakh Steppe (fig. 1). Because incident solar radiation is primarily determined by day of year and latitude (Charles-Edwards 1982), this suggests that PAR levels should be similar in the two ecoregions.

To compare precipitation between the two regions, 0.25 degree daily estimates of precipitation for 1998 through 2001

Table 1—GIS and remotely sensed variables used to predict and map 10-day gross primary productivity (Pg) and total ecosystem respiration (Re).

Variable	Description	Time step	Surrogate for:
NDVI	SPOT VEGETATION, 10-day composites	10 day	photosynthetic potential
Precipitation	NOAA Climate Prediction Center	10 day	
Temperature	NOAA Climate Prediction Center	10 day	
Start of season date (SOSt)	NDVI metrics algorithm	annual	DOY of beginning of growth
Solar radiance (RAD)	derived from latitude and DOY[1]	10 day	day length
Day of year (DOY)		10 day	photoperiodisum
Days since SOSt	NDVI metrics algorithm	10 day	vegetation age or phenology
Time integrated NDVI	NDVI metrics algorithm	annual	annual biomass production
Start of season NDVI	NDVI metrics algorithm	annual	soil and litter background

[1] from Charles-Edwards (1982)

Table 2—Flux tower data sets used to develop regression tree algorithms for the scaling up of carbon fluxes.

Location	Year(s)
Cheyenne, WY	1998
Fort Peck, MT	2000
Leithbridge, Canada	2000, 2001
Mandan, ND	1999, 2000, 2001
Miles City, MT	2000, 2001
Shortandy, Kazakhstan	1998, 1999, 2000

were obtained from the NOAA Climate Prediction Center. These were mapped with a one km^2 cell size and masked to remove all areas that were not comprised primarily of shrub or grass cover. For the U.S.A., this was done by using one km^2 areas that had less than 70% area of shrub and grass as determined by the USGS NLCD 1992 (Vogelmann and others 2001), and for the Kazakh Steppe by areas classified as grass in the MODIS land cover (MODIS/Terra Land Cover Type 96-day L3). Precipitation across the rangeland pixels in both the Kazakh Steppe and Northern Great Plains was summarized both for the growing season (April thru October) and annually (table 3). Mean annual precipitation was similar between the two ecoregions; however, mean precipitation for the growing season was less for the Kazakh Steppe with growing season precipitation representing a lower percentage of annual precipitation. For example, growing season precipitation for a dry year in the Northern Great Plains (2000) was similar to a wet year in the Kazakh Steppe (2001). In addition, precipitation was more variable for the Kazakh Steppe than the Northern Great Plains. Although annual precipitation amounts were similar for the two regions, seasonal proportions appeared to differ.

The temporal patterns of NDVI at the flux tower locations in the Northern Great Plains and Kazakh Steppe were used to evaluate similarity to other pixel locations using Euclidian distance criteria. Data for 10-day SPOT VEGETATION NDVI (http://free.vgt.vito.be) were temporally smoothed to remove residual clouds (Swets and others 1999). Then, pixels with NDVI patterns and magnitudes (or NDVI – time signatures) similar to various flux tower locations were mapped. Time profiles for flux tower NDVI in this analysis corresponded to the flux tower locations and years where flux data were processed to obtain Pg and Re (table 2). Results from the Euclidian distance comparisons allowed identification of pixels similar and dissimilar to the flux tower sites and year, which were used to develop the algorithms for the regression tree scaling up. Spatial estimates made in areas with similar NDVI patterns and magnitudes as the flux towers would likely be more accurate than those made in areas with dissimilar NDVI patterns. By comparing similarities in NDVI patterns for the flux towers in the Northern Great Plains and northern Kazakhstan, the utility of merging the flux data sets can be better evaluated. The flux tower located in northern Kazakhstan best represented the northern rangelands in the Kazakh Steppe; however, the drier rangelands of southern Kazakh Steppe were more similar to the flux tower located at Miles City, Montana (fig. 2). This suggests that combining the flux tower data sets from Central Asia and Northern Great Plains would yield a regression tree algorithm that would be more robust in scaling up carbon fluxes to a wider range of environmental conditions and would minimize over-extrapolation from the single flux tower in the Kazakh Steppe, thereby, improving the accuracy of regional mapping of Pg and Re.

Table 3—Comparison of regional average rangeland precipitation (mm) in the Northern Great Plains and the Kazakh Steppe.

	Year	April-Oct.	Annual	Percent of Annual
Northern	1998	311.97	383.21	0.81
Great	1999	312.83	353.49	0.88
Plains	2000	255.88	315.60	0.81
	2001	277.32	304.93	0.91
Mean		289.50	339.31	0.85
Std. Dev.		27.86	35.93	0.05
CV		0.10	0.11	0.06
Kazakh	1998	117.85	187.40	0.63
Steppe	1999	172.82	264.28	0.65
	2000	224.41	328.39	0.68
	2001	248.15	349.56	0.71
Mean		190.81	282.41	0.67
Std. Dev.		57.92	72.98	0.04
CV		0.30	0.26	0.05

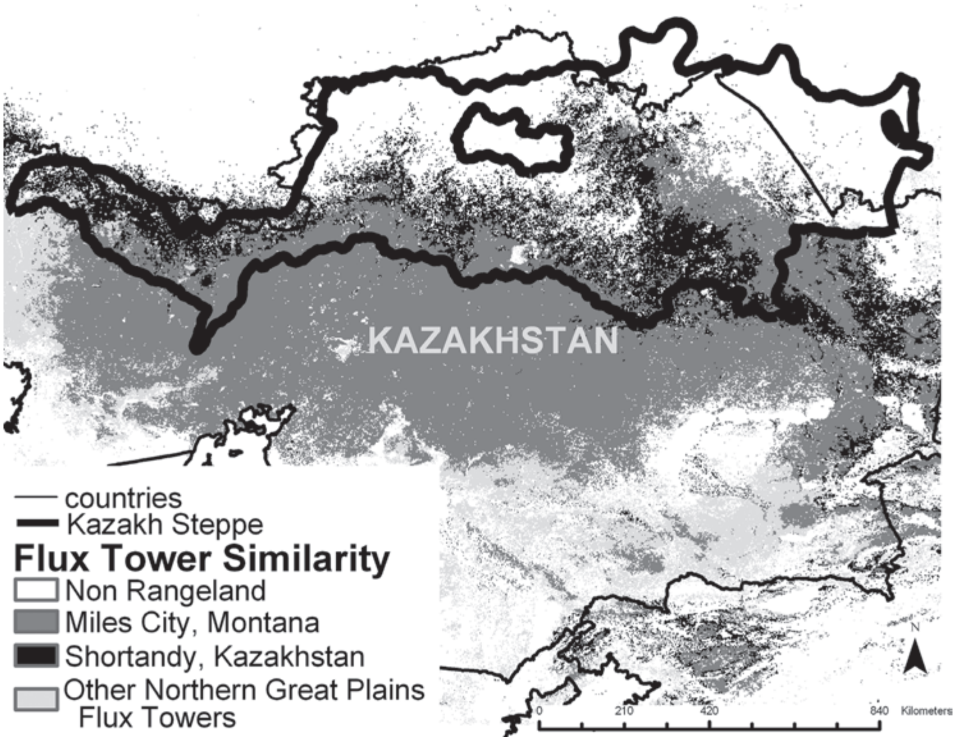

Figure 2—Flux tower similarity for Central Asia based on NDVI patterns and magnitudes from Northern Great Plains and Kazakh Steppe flux tower locations.

To assess similarities in ecosystem carbon functionality, a regression tree was developed from data from the Northern Great Plains and compared to flux measurements from the flux tower on the Kazakh Steppe. Regression for Pg from the Northern Great Plains used the following input variables to map 10-day Pg: day of year (DOY), DOY of start of growing season (SOSt, derived from NDVI seasonal patterns), NDVI, time-integrated NDVI (TiNDVI), precipitation, temperature, and radiant flux (RAD). This regression resulted in an average absolute error of 1.5 g CO_2/m^2/day and an R^2 of 0.85. We applied this regression tree model to the flux tower data from Shortandy, Kazakhstan for the 1998 to 2000 growing seasons and found that it performed remarkably well (fig. 3), accounting for 79 percent of the variation in 10-day Pg. This general agreement occurred despite a severe midsummer drought in 1998. These results suggest substantial similarity in the functionality of carbon fluxes in the Northern Great Plains and the Kazakh Steppe and considerable robustness in the regression tree algorithm. They also provided justification for pooling the flux data sets from these two distant regions.

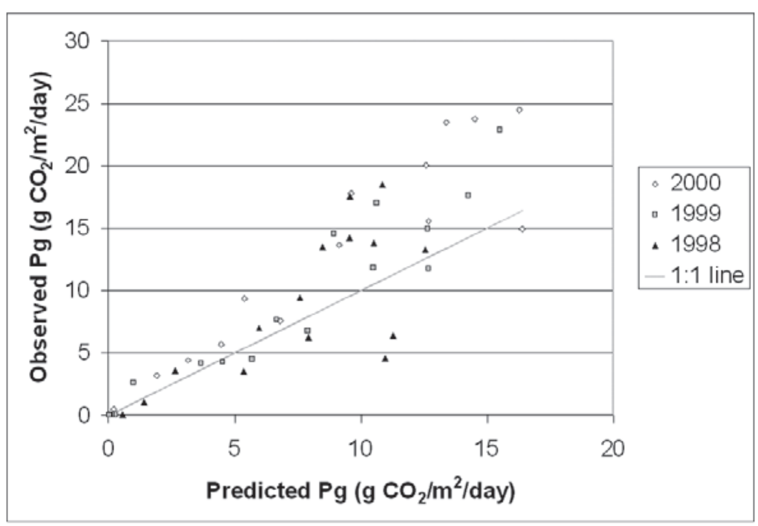

Figure 3—Application of a Northern Great Plains 10-day gross primary productivity (Pg) regression tree (predicted) to a flux tower (observed) in Northern Kazakhstan (1998-2000).

Pooled Northern Great Plains Kazakh Steppe Scaling Up

Based on the above comparative analysis, the training data sets of carbon fluxes, GIS, and remote sensing for the tower locations in the Northern Great Plains and the Kazakh Steppe were pooled, and predictive regression trees were developed for 10-day Pg and Re. After elimination of slightly-used or under-used variables, the resulting regression tree model for predicted 10-day Pg included the input variables of NDVI, SOSt, TiNDVI, days since SOSt, RAD, and precipitation. The accuracy of this regression tree was evaluated by jack-knifing each year of data at Shortandy sequentially as test data. The pooled regression of observed and predicted carbon fluxes for all three jack-knifed years yielded an R^2 of 0.81 and a standard error of 3.24 g CO_2/m^2/day. Using the same jack-knifing approach, a similar regression tree used to predict 10-day Re had an R^2 value of 0.63 and a standard error of 2.7 g CO_2/m^2/day. The regression tree for predicting Re used the input variables of precipitation, NDVI, temperature, TiNDVI, and SOSt.

We applied these regression trees to map Pg and Re every 10 days from April through October. Ten-day maps were then summed to construct maps of growing season fluxes, with non-grass and non-shrub areas removed (fig. 4). This approach identified regional carbon sinks and sources through the calculation of regional net ecosystem exchange (NEE), where NEE = Pg – Re. Localized sink and source areas for growing season NEE are evident in this map. A preliminary paired-plot analysis was conducted to assess the environmental drivers of these localized variations in carbon fluxes. Arbitrary pixel locations with high and low values of growing season NEE were selected from areas in the eastern, western, and northern areas in the Kazakh Steppe. These three pixel pairs of high and low NEE were then compared to growing season environmental variables (fig. 5). The selected paired points that represented sink and source trends in NEE were relatively consistent across the eastern, western, and northern areas. Similar and consistent trends also were observed for Pg and precipitation.

Valentini and others (2000) used a comprehensive data set from European forests and suggested that Re was the primary determinant of carbon sinks and sources, but we did not observe this based on our limited data set. The significance of Re in determining carbon sinks and sources may be important if annual fluxes are considered rather than growing season fluxes. Alternatively, the proportion of Re with respect to NEE and Pg in grasslands may be smaller than that in forests. Although small differences in growing season temperatures were observed between the carbon sink and source areas, the differences were consistent with what we would expect with more productive areas being cooler and less productive areas warmer. This analysis indicates that precipitation was apparently the primary driver of carbon sinks and sources for the Kazakh Steppe. Mapping of multi-year carbon fluxes for the Kazakh Steppe would allow an assessment of consistency of carbon sink and source locations. We expect that precipitation-related carbon dynamics would vary locally from year to year, and that carbon sources would be associated with shallow, poor, or degraded soils.

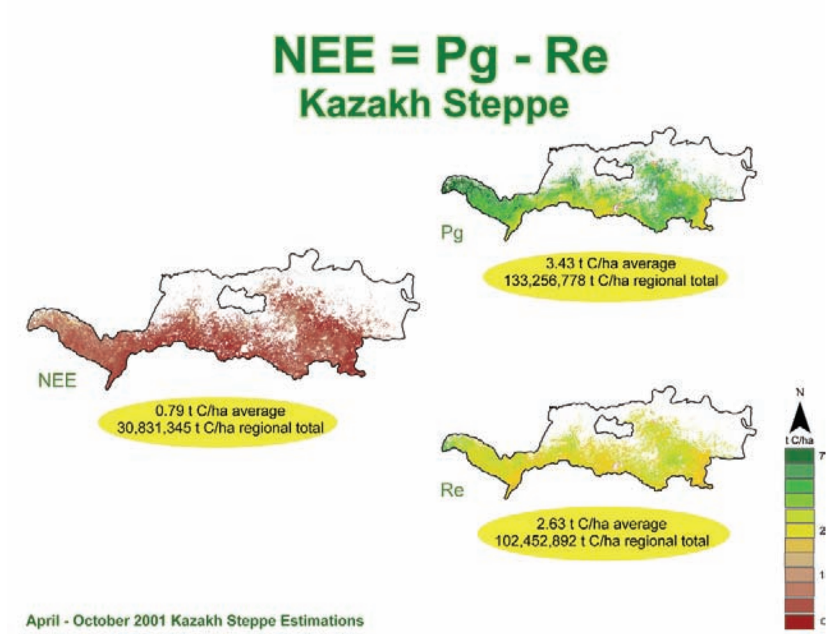

Figure 4—Growing season (April – October) 2001 regional carbon flux maps of gross primary productivity (Pg), total ecosystem respiration (Re), and resultant net ecosystem exchange (NEE = Pg – Re) for grasslands within the Kazakh Steppe.

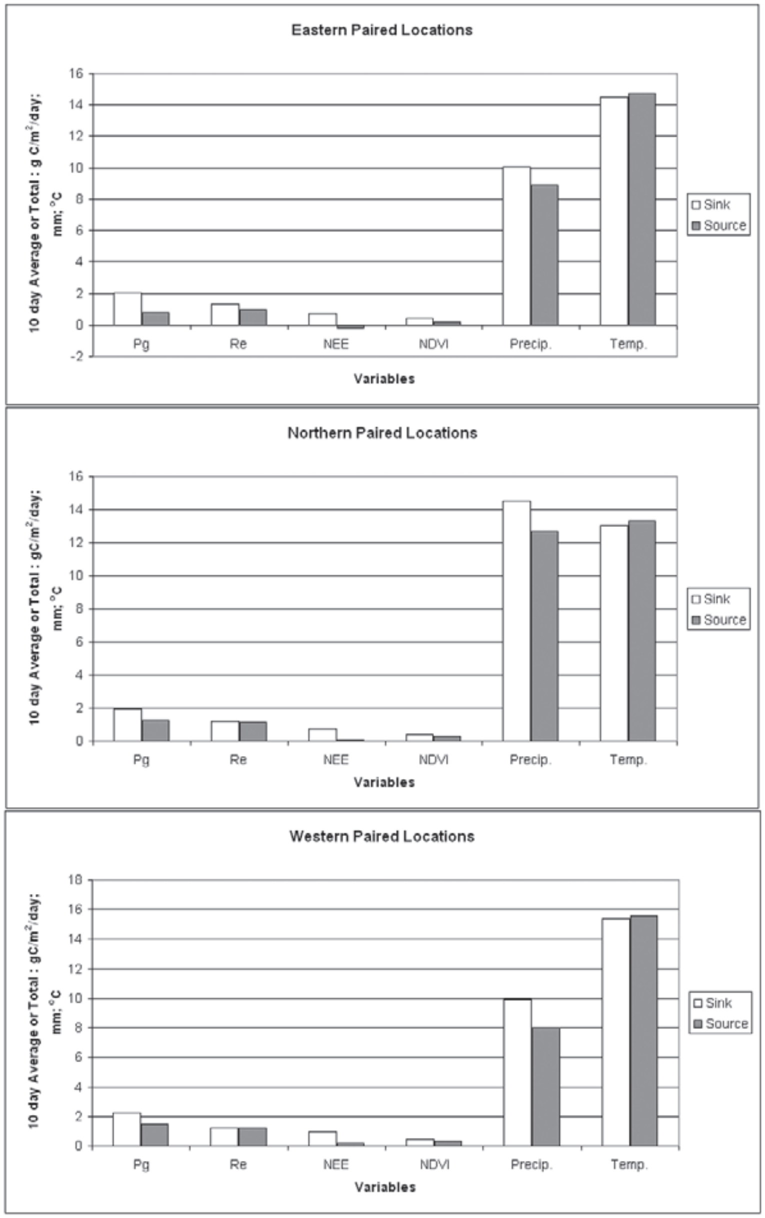

Figure 5—Comparison of selected growing season (April through October) carbon sink and source paired locations in the northern, eastern, and western Kazakh Steppe.

Although the magnitudes and dynamics of carbon fluxes during the growing season are larger and more variable than winter fluxes, quantification of annual fluxes is essential. Efforts to quantify winter fluxes in the Kazakh Steppe have been complicated by extreme winter conditions resulting in a limited number of days with reliable winter flux data. A modeling and gap-filling approach based on temperature, wind speed, and snow depth allowed preliminary quantification of annual fluxes in northern Kazakhstan. Results indicated the flux tower site in northern Kazakhstan was a weak annual carbon sink during 2001-2002 (Gilmanov 2002).

Summary

Similarities in vegetation structure, latitude, precipitation, seasonal patterns of NDVI and carbon flux responses from flux tower sites in the Northern Great Plains in western North America and the Kazakh Steppe in Central Asia indicated that data sets for carbon flux, GIS and remote sensing could be pooled from these two regions. These data were used to map 10-day and seasonal Pg, Re, and NEE for quantifying seasonal regional carbon dynamics. Pooling of data optimized the application of data sets from the Northern Great Plains and improved the robustness of regional flux mapping in the Kazakh Steppe. Carbon sink and source relationships in the Kazakh Steppe were strongly influenced by precipitation and Pg. Regression tree analysis was an effective method for scaling up localized carbon flux data to a regional scale.

This bottom-up regional scaling of flux tower information provides one km quantification of carbon dynamics at the 10-day time step that can be used for carbon monitoring, quantification of environmental drivers to carbon fluxes, and validation or training data for biogeochemical models. Future studies will assess geographic consistency of growing season carbon sinks and sources.

Acknowledgments

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