USING TIME-SERIES AIRBORNE MULTISPECTRAL IMAGERY TO CHARACTERIZE GRASSLAND COVER AND LAND MANAGEMENT PRACTICES INFLUENCING SOIL CARBON STOCKS

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ABSTRACT

Land use practices greatly influence soil carbon stocks, which in turn influences the potential for soils to store carbon. With a growing interest in the use of a carbon credit system to decrease atmospheric carbon dioxide, there is increasing interest in development of cost effective methods for identifying land cover types and land use practices that maximize carbon storage potential. This study focuses on the use of remotely sensed data for characterizing Central Great Plains grassland land types and their management practices.

During this study, near-biweekly multispectral submeter resolution imagery was collected throughout two growing seasons over 30 grassland study sites. These measurements were related to field data collected within five grassland management types including cool-season (C3) hayed, C3 grazed, warm-season (C4) hayed, C4 grazed, and USDA Conservation Reserve Program (CRP) lands. Field variables measured included: green Leaf Area Index and Fraction of Intercepted PAR, live and senescent plant cover, and topsoil carbon.

Our findings show significant differences in topsoil carbon and bulk density levels among management categories, with grazed fields exhibiting generally higher levels of both carbon and bulk density compared to hayed fields. The airborne multitemporal datasets showed optimal data collection periods, which varied considerably from conventional wisdom on this matter. Our findings show remotely sensed measurements useful for discriminating among management practices influencing grassland soil carbon stocks. We also examined the relationship between our high-resolution airborne imagery and Landsat Thematic Mapper data and found them to be highly correlated, suggesting that our finding can be scaled up to the regional scale.

INTRODUCTION

The global atmospheric concentration of carbon dioxide (CO_2) has increased markedly since the onset of the industrial revolution, as shown by data collected from long-term monitoring stations and by glacial ice cores. Indications are that this change in atmospheric chemistry may be leading to significant increases in average global temperature (e.g., Mann *et al*., 1999), with as-yet unknown, but potentially devastating consequences for global food production capacity, biodiversity, sea level changes, and other areas of social and ecological concern. One way to approach this daunting global problem is to more closely examine the potential for carbon storage in the terrestrial biosphere, an idea that has garnered much attention recently in the scientific discourse (see, e.g., Burke *et al*., 1997; Mermut *et al*., 2001). It can be argued that terrestrial sequestration of atmospheric C has the potential to temporarily mitigate anthropogenic CO_2 increases in the atmosphere, giving the scientific community additional time to find more long-term solutions to this environmental issue. Soil carbon sequestration also has the potential of increasing organic matter in soils that have been depleted by past land management practices (Lal *et al*., 1998).

Grassland systems have been identified as a tremendous storehouse of terrestrial carbon (Seastedt, 1995; Burke *et al*., 1997; Johnson and Matchett, 2001), in part because of the large component of biomass that is found below the ground in these systems. Much of the grassland soil carbon stock worldwide has been compromised by the disturbances associated with land use conversion, primarily to agriculture. The conversion of natural grassland systems to cultivated agriculture has led to a significant loss of the soil carbon resource through processes of volatilization, increased rates of microbial respiration, and complex problems associated with soil erosion (Lal *et al*., 1998; Ellert *et al*., 2001); each of these problems can also be precipitated by excessive grazing (Follett, 2001; Lal, 2001).

BACKGROUND

In general, the importance of land use and management on soil C stocks has been noted in many studies (e.g. Sperow *et al*., 2001; Lal *et al*., 1998). Evidence in the literature with respect to the impacts of grassland management on the soil carbon resource, however, is largely incomplete and in many cases inconsistent (Milchunas and Lauenroth, 1993). Many studies have suggested some potential for sequestration of C in soils of re-established grasslands (e.g., Gebhart *et al*., 1994; Potter *et al*., 1999) although the time period required for recovery to pre-cultivation conditions is not yet known and may be very long compared to the time period required for depletion (Burke *et al*., 1995). Any systematic study of how grassland management might impact the soil carbon resource could potentially make a significant contribution to this debate. Any such study, however, should not focus solely on manipulation of management practices to sequester additional soil C on lands that have been depleted, but also on the protection of lands that still have much of their soil C resource intact, such as native prairies.

Part of the inconsistency associated with studies of the impacts of management on grassland soils stems from the shortage of workable direct methods for measuring the relevant biophysical parameters of the carbon-fixing plant/soil interface, especially when the goal is to objectively monitor geographically extensive study areas. Thus it becomes necessary to identify more readily measured parameters for examining the carbon–fixing properties of grasslands and their relationship to soils. Previous work by many scientists has demonstrated great promise for the measurement and characterization of the above-ground component of the plant/soil system in grasslands using visible/near infrared (VNIR) remote sensing methods (e.g., Weiser *et al*., 1986; Bartlett *et al*., 1990; Lauver and Whistler, 1993; Price *et al*., 1993; Friedl *et al*., 1994; Guo *et al*., 2000b; Pickup *et al*., 2000; Davidson and Csillag, 2001; Peterson *et al*., 2002; Guo *et al*., 2003; many others), although parameterization through empirical studies using ground data is generally necessary for each area studied. Although some research has indicated the potential utility of VNIR remote sensing for the direct measurement of C in bare soil conditions (Frazier and Cheng, 1989; Wilcox *et al*., 1994; Chen *et al*., 2000), this approach is of limited utility in mesic grassland systems where there is little or no bare soil apparent at the surface. In these systems, inferences about grassland soil carbon resources using remote sensing must be made based on what can be detected with the sensor: grassland type, management practices, and productivity. By supplementing remotely sensed indices with field sampling sufficient to characterize the appropriate relationships, spatially complete information can be derived to characterize the aboveground conditions, and then related to the belowground soil and root system characteristics.

OBJECTIVES

The objectives of this research are as follows:

1) Determine whether there are biophysical and soil carbon differences among the grassland treatments.
2) Evaluate the potential of multi-date airborne remotely sensed imagery for characterizing differences among Central Great Plains grasslands under varying management practices that influence processes of soil carbon sequestration.
3) Assess the potential of scaling up high spatial resolution airborne remotely sensed measurements to more moderate resolution (e.g., 30 m Landsat) remotely sensed measurements for extrapolating our modeling results over larger geographic regions.

STUDY AREA

This research was conducted within an area directly north of the Kansas River floodplain and the city of Lawrence, KS. Five categories of managed grassland were identified as common in the region: 1) cool-season (dominated by C3 grasses) hayfields; 2) C3 grazed fields; 3) warm-season (dominated by C4 grasses) hayfields; 4) C4 grazed fields; and 5) USDA Conservation Reserve Program (CRP) fields, subject to minimal management or harvest. The C3 fields are dominated by non-native grasses and are characterized by soils in recovery from past cultivation. These fields are typically managed using annual inputs of fertilizer; the grasses in the hayfields are typically harvested in June. By contrast, the C4 fields are relict prairie sites, having never been plowed. These fields are typically not managed with fertilizer, although early-season prescribed burning is occasionally applied as a tool to stimulate production and eliminate undesired plant species. The C4 grazed fields are characterized by varying levels of non-native plant invasion, depending on the intensity and duration of cattle grazing as well as the proximity of seed sources for exotic species. The C4 hayfields are generally characterized by native, warm-season grasses and by native forb species. Hay in these fields is typically harvested in late July or early August. The CRP fields used in this study were similar to the C3 fields in terms of land use history, but more similar to the C4 fields in terms of vegetation community composition (these are fields in recovery from cultivation that have been reseeded back to warm-season native grasses). For a more detailed floristic description of these grassland classes, see Guo *et al*. (2000a) and Peterson *et al*. (2002). Of each type, six accessible privately managed fields were identified (total of 30 fields). Fields were selected based on observed vegetation characteristics, knowledge about past land use and management (when available), landowner cooperation, and conformity to the criteria of an upland setting and a clay loam or silt loam soil association (USDA Soil Conservation Service, 1977).

METHODS

Field Data Collection

Field data were collected in the test fields in June and then again in November of 2002. In order to standardize the areal unit of analysis within each of the study fields (which varied widely in total area), three 50 m transects were established in a random direction, oriented parallel to one another at a distance of 50 m, thus forming a box measuring 50 x 100 meters. With a few local modifications and exceptions for eroded drainages, trees, and other obstructions, this pattern was generally followed in each of the field sites. The endpoints of each transect were mapped using a Garmin 76 handheld GPS unit, with Wide Area Augmentation System (WAAS) differential correction.

Within each transect, six one m^2 quadrats were observed, spaced 10 m apart. Ocular estimates of vegetative cover were made at each quadrat using five categories: live grass, live forbs, standing dead, ground litter, and bare ground. These categories were recorded by the observer in unit sum proportions, in the form of percentages adding up to 100.

Measurements were also made in each quadrat using an Accupar Linear Ceptometer (Decagon Devices, Pullman, WA), positioned as close to the ground as possible, with the operator taking care not to position the light bar below any ground litter material. Four measurements were taken and averaged at each quadrat, in order to remove any biases associated with the directional orientation of the light bar. The Ceptometer measures the incident photosynthetically active radiation (PAR) above and below the canopy, and then uses a series of transformations to estimate Leaf Area Index or LAI (Lang, 1987). The PAR data can also be used to calculate the fraction of PAR intercepted by the canopy (FIPAR) by simplification of the FIPAR formula to eliminate the canopy reflectance term, which is typically trivial (Weiser *et al*., 1986; Bartlett *et al*., 1990). In all cases, the LAI and FIPAR measures were also corrected using the fraction of green canopy material, recovered from the ocular cover estimates. During the June collection interval, biomass samples were taken by clipping of a 8x100 cm strip along the edge of each quadrat. These samples were separated into live grass, live forb, and litter categories before weighing. The sample weights were then rescaled to grams per square meter. The number of grass and forb species in each biomass sample were counted and used as an index of species richness.

During the November, 2002 field visit, soil samples were taken at three locations along each transect. Two samples were obtained at each location, one for measuring the soil chemistry and one for estimation of bulk density. Soil cores were drawn using a simple tube-style coring device of diameter 2.54 cm, to a depth of 15 cm. Bulk density samples were oven dried to constant mass. Chemistry samples were air dried, ground, and packaged for laboratory analysis at Kansas State University. Soil results were converted to an area basis (top 15 cm) using the bulk density measurements.

Image Data Collection

A time series of aerial imagery was collected using a high spatial resolution multispectral imaging system developed by the Kansas Applied Remote Sensing (KARS) Program. The major components of the system include a Duncan Tech MS3100 digital camera, a PC computer for data storage, a frame grabber, and a GPS receiver.

The camera collects data in three spectral bands: blue (450-520 nm), red (630-690 nm) and near infrared (760-900 nm). The imagery acquired for this study was flown at approximately 3200 m AGL for a nominal pixel resolution of 1.0 meter. The camera data were radiometrically calibrated using a procedure developed by Schiebe *et al*. (2001). The resultant imagery is in units of absolute radiance. By applying a ratio index (in this case the Normalized Difference Vegetation Index or NDVI), direct comparison of imagery from one date to another is made possible. This calibration procedure allows time series and phenology analysis throughout the growing season.

All image data used in this study were geocorrected using an orthorectified basemap generated from frame camera imagery (acquired in April, 2002) supplied by Western Air Maps, Inc. of Overland Park, KS. The image data were resampled (nearest neighbor algorithm) to a UTM projection, Zone 15 North, North American Datum of 1983. RMS errors in the geocorrection process were generally kept to 1.5 meters or less, although due to localized anomalies in the planimetric basemaps, the actual positional error in the corrected imagery was believed to be somewhat higher in places. Following calibration, the radiance imagery was processed to NDVI by application of the standard formula (NIR-R)/(NIR+R), and then rescaled by multiplying by 200.

A time series of satellite imagery from the Landsat 5 TM and Landsat 7 ETM+ sensors was also assembled for 2002-2003. These data were georeferenced using a conventional ground control point method. Radiometric calibration of each image was performed using methods described by Chavez (1996) and Markam and Barker (1986). Rescaled NDVI values were obtained using the same formula as described above. Only those images with cloud-free coverage of the study area were selected. This temporal series of satellite imagery was more complete overall than the aerial time series, which lacked early season coverage in 2002. The aerial imagery, however, generally had a more frequent repeat interval during the growing season, and offered a more detailed temporal picture at the time of peak greenness in each year (June-July).

A GIS database was constructed in order to extract appropriate sets of pixels corresponding to the locations of the field sites. Using the transect-endpoint GPS data as a guide, a polygon was established around each set of transects. Due to the degree of positional error in the GPS measurements and the airborne image geocorrection process, the polygon size was made slightly larger than 50x100 m to ensure correspondence of field and spectral data. From each of these polygons was extracted the median NDVI value for each of the image acquisition events in the study period. This included 8 aerial images collected between June 7 and November 12, 2002, 9 aerial images collected between April 12 and October 25, 2003, and 14 Landsat TM images collected between April 3 2002 and November 24, 2003.

Statistical Analysis

Statistical analysis was carried out using SPSS version 12.0 (Statistical Product and Service Solutions). All data were aggregated to the field level prior to analysis, yielding an overall sample size of 30 fields, or 6 in each treatment. Due to incomplete image coverage of the study fields, two fields had to be dropped from any analysis involving airborne image data. These fields have been included in analyses involving only ground data. For the ground data, ANOVA tests were conducted on each variable, and homogeneous subsets were identified using Tukey's HSD test ($p \leq 0.05$). For the aerial and satellite time series data, an overall Repeated Measures ANOVA was run to establish significance of the time x treatment interaction in the multivariate data set, prior to testing for significant differences among grassland types for individual dates using the ANOVA and Tukey's HSD procedure ($p < 0.05$). Finally, the correlation was tested between satellite and aerial data for roughly co-incident time periods, and regression analysis was run to establish the slope and intercept of the relationship between satellite data and airborne data for these periods.

RESULTS AND DISCUSSION

Treatment Biophysical Factors

Results from the analyses of our plant biophysical data show significant differences in cover components between the cool and warm-season grasses and their various land management practices. The cover components also differ between the 2002 June and early November sampling periods (Figure 1 and 2). In June, the cool season grass treatments were found to have the most live grass cover, the warm season treatments the most live forb cover, and the CRP the least live cover. The CRP sites also had the greatest amount of standing dead plant material and exposed bare ground. During the early November field data collection period, the general cover patterns remain similar to June, but the treatments exhibited a much lower percentage of live grass and forbs cover overall, and more ground litter and standing dead plant material were found at each treatment. A noteworthy observation also being that most grasses and forbs for the CRP treatment had gone into dormancy by the later sampling period (Figure 2). Note also that during the June sampling period, the total live cover (grass and forbs combined) for four of the five treatments were very similar, with the CRP site being most advanced in plant dormancy. In Table 1 and 2 we present the numerical mean values and their standard deviations by treatment for the cover components collected in June and early November, complementing figures 1 and 2 above. These two tables also list the live plant (green) fraction of intercepted photosynthetically active radiation (FIPAR), green LAI, and canopy height. Besides mean and standard deviation, these tables report ANOVA probabilities, and Tukey's HSD tests for multiple comparisons ($p \leq 0.05$). The ANOVA tests on the June data show statistically significant differences among treatments for all biophysical factors except cover by ground litter, bare ground and LAI for the photosynthetically active (green) plant materials. The associated alpha characters below each mean value in the following tables indicate which

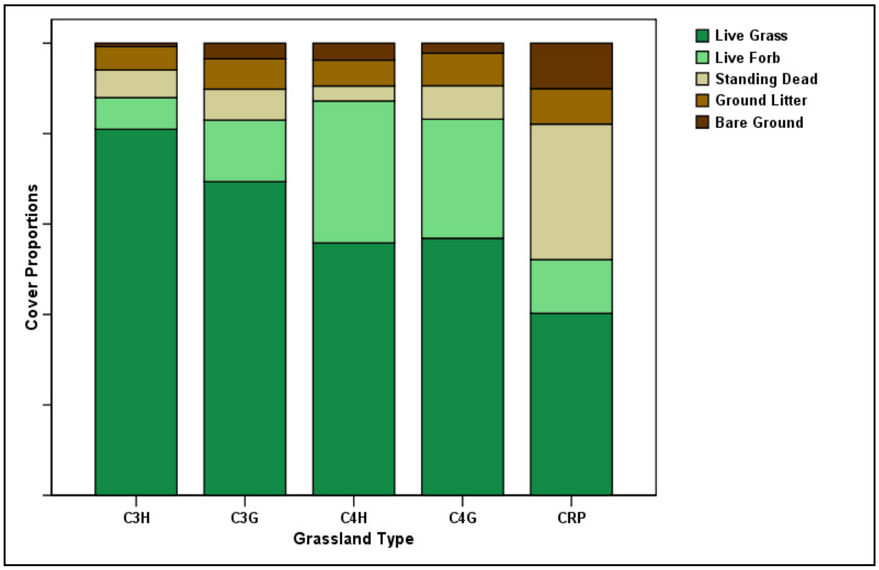


Figure 1. June 2002 proportional cover by treatment for biotic and abiotic factors**.**

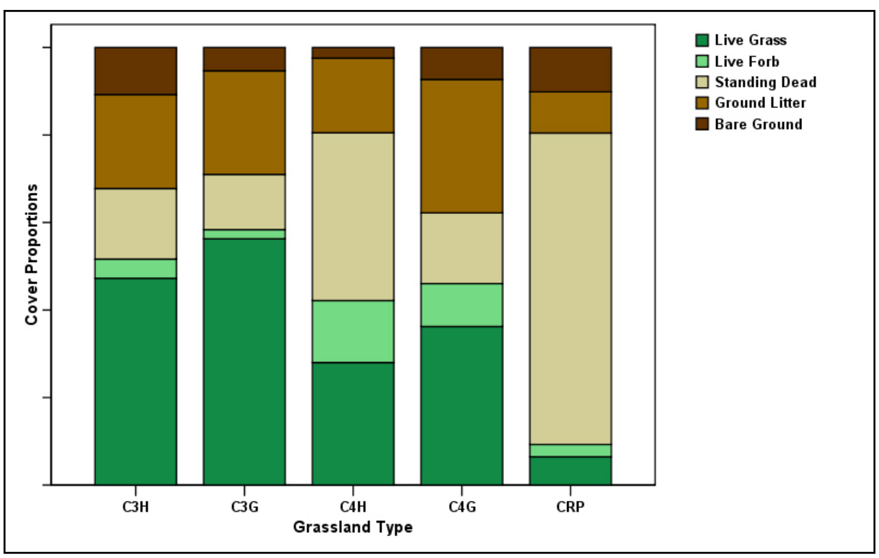


Figure 2. Early November 2002 proportional cover by treatment for biotic and abiotic factors**.**

treatments were found to be statistically similar according to the Tukey's HSD test. Treatments without the same alpha character in the table cell below the mean values are statistically different. From these results, we find biophysical differences among treatments varied considerably depending on the biophysical factor being considered. A general observation from these findings is that the two cool season treatments produced more live grass cover and the canopy height for the cool season hayed and CRP treatments were generally taller. The C3H also had a higher green FIPAR.

Table 1. Comparison of June 2002 mean and standard deviations (SD) for cover components, fraction of incident photosynthetically active radiation (FIPAR), and leaf area index (LAI) among treatments. The ANOVA results show biophysical factors are often dissimilar among treatments.

Variable	C3H		C3G		C4H		C4G		CRP		F	Prob.
	mean	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD		
Percent Cover: Live Grass	**81.0**	13.4	**69.4**	7.9	**55.8**	8.9	**56.9**	15.7	**40.2**	8.5	11.0	0.000
	c		***bc***		***ab***		***ab***		***a***			
Percent Cover: Live Forb	**7.0**	5.9	**13.6**	10.8	**31.4**	8.7	**26.3**	13.8	**11.9**	6.9	6.9	0.001
	a		***ab***		***c***		***bc***		***ab***			
Percent Cover: Standing Dead	**6.1**	8.6	**6.9**	8.1	**3.3**	2.0	**7.4**	4.3	**30.0**	18.0	7.3	0.000
	a		***a***		***a***		***a***		***b***			
Percent Cover: Ground Litter	**5.2**	4.4	**6.7**	4.5	**5.7**	3.0	**7.2**	3.6	**7.8**	5.6	0.4	0.824
	a		***a***		***a***		***a***		***a***			
Percent Cover: Bare Ground	**0.7**	0.7	**3.5**	3.1	**3.8**	5.6	**2.2**	2.1	**10.1**	14.2	1.5	0.219
	a		***a***		***a***		***a***		***a***			
Percent Cover: Live Green	**88.0**	9.3	**83.0**	5.8	**87.2**	5.7	**83.2**	3.9	**52.1**	8.5	28.1	0.000
	b		***b***		***b***		***b***		***a***			
Green FIPAR	**0.83**	0.12	**0.65**	0.15	**0.75**	0.08	**0.61**	0.17	**0.52**	0.10	5.6	0.002
	c		***ab***		***bc***		***ab***		***a***			
Green LAI	**3.77**	1.19	**2.29**	0.85	**2.54**	0.55	**1.84**	0.65	**1.86**	0.36	6.3	0.001
	b		***a***		***ab***		***a***		***a***			
Canopy Height (cm)	**99.9**	14.9	**62.9**	23.7	**65.4**	10.8	**60.6**	11.1	**93.3**	31.2	4.7	0.006
	b		***a***		***ab***		***a***		***ab***			

The ANOVA results for the biophysical factors collected in early November (Table 2) show cover by live grass live forb, and standing dead to be different among some of the treatments. The Tukey's HSD test confirms the differences among cover components as described above for figures 1 and 2. We found the CRP treatment to be different from the other treatments with respect to standing dead cover, live green cover, and canopy height.

Table 3 ANOVA results show significant differences among treatments for June biomass. The C3H treatment produced considerably greater amounts of grass biomass, while the warm season treatments produced more forb biomass generally speaking. Table 4 shows significant differences in plant species richness among treatments, with the cool season and CRP treatments having generally fewer grass and forb species than the warm season treatments.

Figure 3 shows soil carbon in g/ m^2 by treatment. Tukey's HSD test results indicate similar soil carbon amounts for C3H and CRP soils, and greater amounts of carbon for the soils of the C3G, C4H and C4G treatments.

Comparison of Spectral Factors

The Repeated Measures ANOVA test indicated a highly significant ($p<=.01$) overall effect of treatment for both the TM and aerial camera time series datasets. Individual ANOVA and Tukeys HSD test results indicated significant differences in NDVI among at least some of the treatments for all TM image dates except September 26, 2002 and July 3 2003. For the aerial camera data, these tests indicated significant differences among at least some treatments for all dates except September 6, 2002, September 20, 2002, and June 27, 2003. In general, the best times to discriminate grassland types appear to be in April-May during the spring green-up, and later in the autumn when the C4 and CRP types are senescing.

A separate greenness peak can be observed for the C3 and C4 types, with the peak C4 greenness occurring later in the summer. All the C3 and C4 types exhibited a drop in greenness during mid-summer due to harvesting and grazing, and also due to the hot and dry conditions during this period in both years. The late-season green-up

Table 2. Comparison of early November 2002 mean and standard deviations (SD) for cover components, fraction of incident photosynthetically active radiation (FIPAR), and leaf area index (LAI) among treatments. The ANOVA results show biophysical factors are often dissimilar among treatments.

Variable	C3H		C3G		C4H		C4G		CRP		F	Prob.
	mean	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD		
Percent Cover: Live Grass	**47.3**	12.2	**56.3**	21.1	**28.0**	18.4	**36.2**	11.3	**6.5**	7.5	9.9	0.000
	bc		***c***		***ab***		***bc***		***a***			
Percent Cover: Live Forb	**4.4**	5.2	**2.1**	3.5	**14.1**	8.5	**9.8**	11.9	**2.8**	3.0	3.1	0.035
	a		***a***		***a***		***a***		***a***			
Percent Cover: Standing Dead	**16.1**	10.6	**12.6**	8.5	**38.4**	32.4	**16.1**	11.2	**71.2**	16.4	11.3	0.000
	a		***a***		***a***		***a***		***b***			
Percent Cover: Ground Litter	**21.5**	11.1	**23.7**	16.6	**17.0**	15.8	**30.5**	8.5	**9.4**	6.0	2.5	0.072
	ab		***ab***		***ab***		***b***		***a***			
Percent Cover: Bare Ground	**10.8**	7.5	**5.3**	8.3	**2.5**	1.7	**7.3**	4.4	**10.1**	13.4	1.1	0.383
	a		***a***		***a***		***a***		***a***			
Percent Cover: Live Green	**51.6**	9.6	**58.4**	18.2	**42.2**	20.4	**46.1**	5.8	**9.3**	9.6	11.2	0.000
	b		***b***		***b***		***b***		***a***			
Green FIPAR	**0.41**	0.07	**0.41**	0.24	**0.33**	0.17	**0.29**	0.16	**0.10**	0.10	4.2	0.009
	b		***b***		***ab***		***ab***		***a***			
Green LAI	**0.76**	0.22	**1.03**	0.92	**0.63**	0.35	**0.54**	0.39	**0.30**	0.30	2.0	0.119
	a		***a***		***a***		***a***		***a***			
Canopy Height (cm)	**25.1**	9.4	**38.7**	14.4	**36.6**	22.3	**33.2**	9.4	**95.1**	27.8	14.3	0.000
	a		***a***		***a***		***a***		***b***			

Table 3. Comparison of June 2002 mean and standard deviations (SD) for biomass components. The ANOVA results show biomass factors are often dissimilar among treatments. All units are reported in g/m^2.

Variable	C3H		C3G		C4H		C4G		CRP		F	Prob.
	mean	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD		
Biomass: Live Grass	**590.7**	172.5	**183.9**	93.2	**206.1**	95.0	**189.2**	75.1	**164.8**	75.0	8.4	0.000
	b		***a***		***a***		***a***		***a***			
Biomass: Live Forb	**9.2**	14.0	**9.4**	7.4	**81.6**	36.9	**29.3**	22.0	**15.5**	9.5	5.2	0.003
	a		***a***		***b***		***ab***		***ab***			
Biomass: Litter	**129.5**	41.3	**136.2**	130.7	**101.8**	52.6	**297.7**	171.1	**749.0**	568.4	1.1	0.380
	a		***a***		***a***		***a***		***a***			
Biomass: Total Green	**599.9**	162.4	**193.2**	90.3	**287.7**	102.4	**218.5**	57.9	**180.3**	75.7	10.5	0.000
	b		***a***		***a***		***a***		***a***			
Biomass: Total	**729.3**	140.9	**329.5**	184.8	**387.7**	120.6	**516.2**	213.8	**929.4**	569.5	3.4	0.023
	ab		***a***		***ab***		***ab***		***b***			

Table 4. Comparison of plant species richness among treatments. The ANOVA results show significant differences in species richness among treatments, with the warm season hayed (C4H) treatment showing the greatest number of species and the cool season hayed (C3H) having the lowest numbers of species.

Variable	C3H		C3G		C4H		C4G		CRP		F	Prob.
	mean	SD	**mean**	SD	**mean**	SD	**mean**	SD	**mean**	SD		
Grass Species	**2.3**	1.2	**5.0**	1.2	**7.4**	2.0	**6.9**	1.2	**2.9**	1.2	16.4	0.000
	a		***bc***		***d***		***cd***		***ab***			
Forb Species	**2.1**	2.2	**2.4**	1.7	**8.9**	2.4	**4.2**	1.4	**2.2**	0.8	15.7	0.000
	a		***a***		***b***		***a***		***a***			
Total Species	**4.4**	2.8	**7.4**	2.3	**16.4**	3.4	**11.1**	1.8	**5.1**	0.8	25.6	0.000
	a		***ab***		***c***		***b***		***a***			

following mid-summer was more pronounced in the C3 than in the C4 treatments. The CRP type exhibited a more moderated drop in the NDVI curve in mid-summer, due to the lack of any substantial reduction in greenness due to harvesting or grazing. CRP had the lowest NDVI of all treatments in fall and winter, indicating a condition of greatest dormancy.

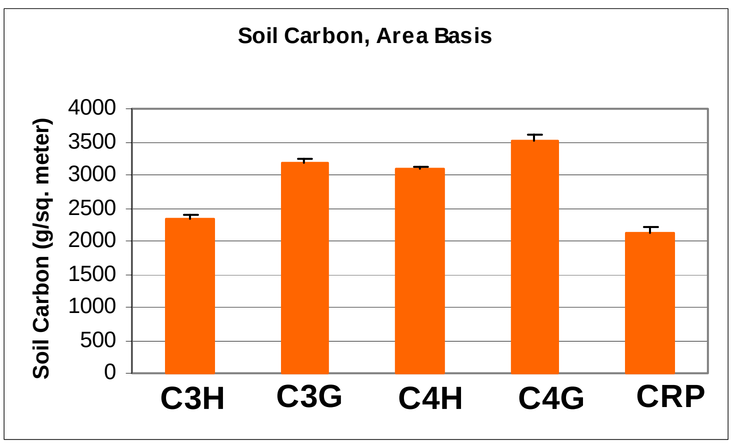


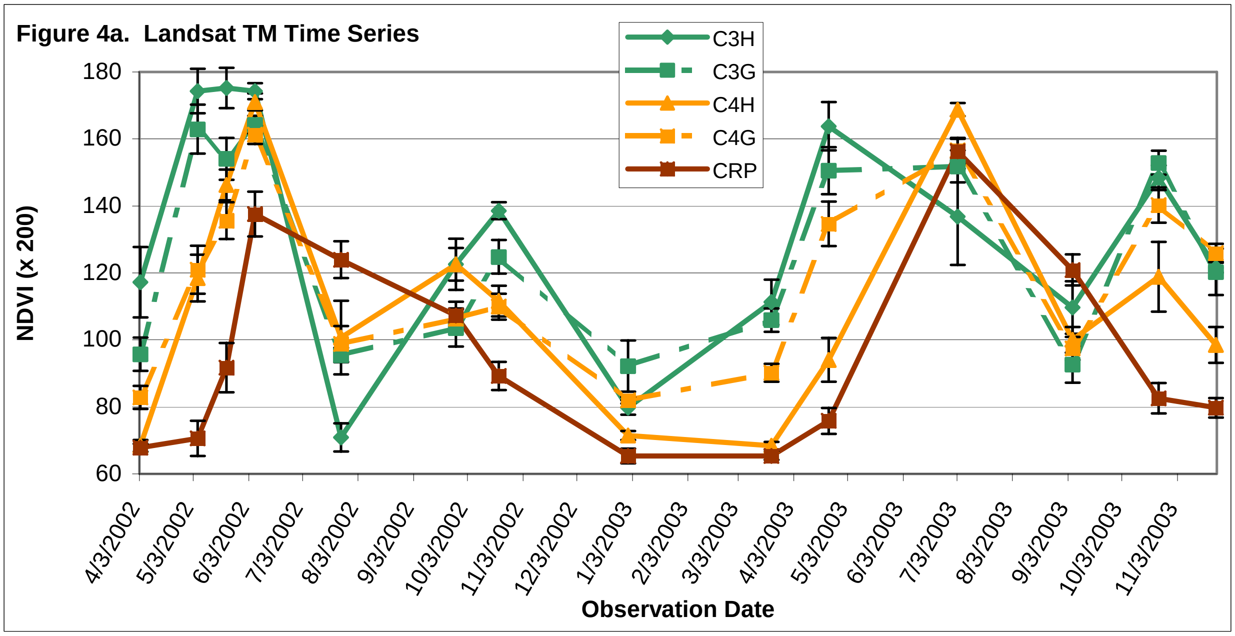
Figure 3. Soil carbon by treatment (area basis) for the top 15 cm.

The temporal coverage of the NDVI time series from the TM sensor (Fig. 4a) was more complete over the course of the two years than the aerial time series (Fig. 4b). During the spring green-up of 2002 and during the time period between the two growing seasons (mid-November 2002 to mid-April 2003), no imagery was available from the aerial camera. On the other hand, the aerial camera data exhibited a more frequent repeat interval during the growing season than the TM data (Figures 4a and 4b). In some cases, the lower temporal resolution TM imagery are likely to have missed significant important events during the phenology cycle. For example, the peak greenness of 2003 for both of the cool-season (C3H and C3G) treatments seems likely to have been underestimated in the TM data, compared to the aerial imagery result. Note that this was not a problem in 2002, because more complete TM coverage was available at the time of peak greenness. Another example is the late summer minimum in the C3 treatments, which was missed by the TM sensor in 2003, but picked up in the aerial camera imagery. Also note that the late season greenness peak in the C3 treatments in October 2002 was missed by lack of coverage in the aerial dataset, but was picked up by the TM image collected on October 20, 2002.

Scaling up from Airborne Imagery to Landsat TM

A common question when one works at the field level is whether the patterns and processes one observes at the field or local scales can be extrapolated across a larger area such as an ecosystem or ecoregion. A step that we took towards addressing this question was to investigate the correlation between our 1.0 m airborne imagery and the 30 m Landsat TM imagery. To test the relationships, we correlated the aggregated 1.0 m NDVI values from the airborne imagery with the 30 m Landsat TM pixels that fell within 50 x 100 m polygons positioned over the field data collection sites. From among the 14 Landsat TM images and 17 airborne datasets, we selected pairs of TM/airborne images that were acquired most closely to the same time of the year. Six pairs of images were found to have acquisition dates that were no more than 10 days apart. The correlation between these image pairs varied from r^2 =

0.60 – 0.98 with a mean value of 0.82. After looking more closely at these datasets, we determined that the one image pair that correlated most poorly was significantly influenced by a change in vegetation condition between the time that the TM and airborne imagery was acquired. Ranchers who hayed their cool season grass fields between image acquisition periods caused this change. When the cool season hayed sites were eliminated from the analysis, the correlation between these images increased from $r^2 = 0.60$ to 0.89, and the average correlation value increased from $r^2 = 0.82$ to 0.92. Figure 5a shows the regression analysis results for the image pair that had the strongest correlation, and Figure 5b shows the correlation results for the image data that was influenced by ranchers mowing their hay fields in between acquisition dates.



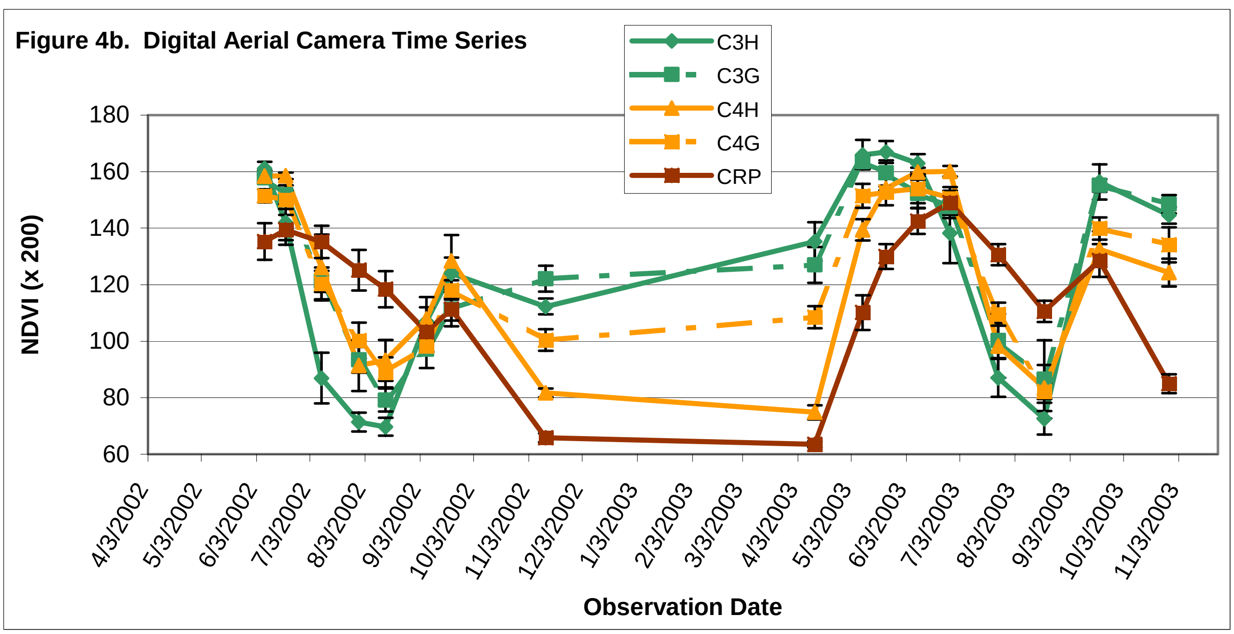


Figure 4a and 4b. These figures show the NDVI time series from the Landsat TM sensor (Fig. 4a) and from the digital aerial camera system (Fig. 4b). The mean NDVI values by treatment are depicted. Error bars show +/- 1.0 standard error.

Summary and Conclusions

We examined the biophysical properties and topsoil C stocks of five grassland management types typical of the Central Great Plains, identifying significant differences among treatments for most of the variables studied. Biophysical characteristics also varied between two different times of year. We compared two remote sensing time series data sets, Landsat TM imagery and airborne digital camera imagery, using them to examine the phenology of these grassland types. Each of the grassland types exhibited a strongly unique time-series NDVI signal. We identified the best time periods for spectral discrimination of these five types to be during the spring green-up and later in the fall as the warm-season grasses became dormant and the cool-season grasses exhibited a secondary green-up. The worst time for spectral discrimination was found to coincide with the time of peak greenness (June-July) and at the onset of autumn (September). The high temporal frequency of the aerial data set was found to be advantageous in characterizing critical features during the growing season such as the magnitude of peak greenness, which may be missed if only lower temporal frequency imagery are used. Results indicate a strong correlation between NDVI measurements with the two sensors, indicating a strong potential for scaling up airborne remotely sensed measurements to more moderate resolution remotely sensed measurements for extrapolating model results over larger geographic regions.

We would conclude from our findings that time-series remotely sensed spectral imagery could be used effectively to discriminate among Central Great Plains grasslands and their most common management practices. We also found different levels of soil carbon among these management practices and grassland life forms, which suggest that the remotely sensed methods used in this study could be used to identify grassland types that vary with respect to the soil carbon stocks.

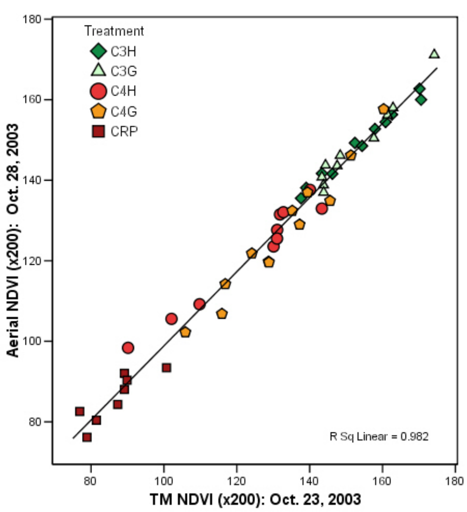


Figure 5a. Aerial imagery vs. Landsat TM correlation

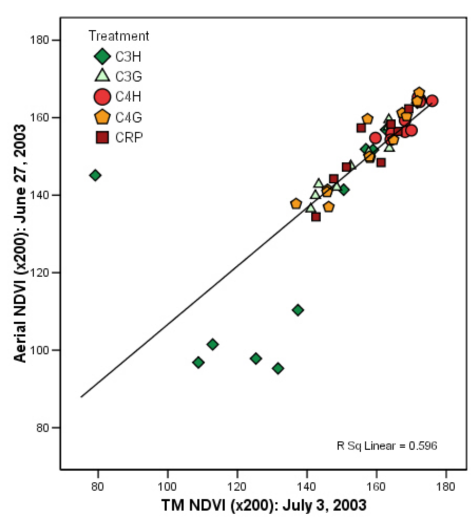


Figure 5b. Aerial imagery vs. Landsat TM correlation. Note the scatter in the C3H treatment due to haying of the fields in between image acquisition dates.

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