REMOTE SENSING OF VEGETATION RECOVERY IN GRASSLANDS AFTER THE 1988 FIRES IN YELLOWSTONE NATIONAL PARK

EVELYN MERRILL
DEPARTMENT OF ZOOLOGY AND PHYSIOLOGY

RONALD MARRS ✦ DEPARTMENT OF GEOLOGY
UNIVERSITY OF WYOMING ✦LARAMIE

✦ INTRODUCTION

Traditional methods for measurement of vegetative characteristics can be time-consuming and labor-intensive, especially across large areas. Yet such estimates are necessary to investigate the effects of large scale disturbances on ecosystem components and processes. Because foliage of plants differentially absorbs and reflects energy within the electromagnetic spectrum, one alternative for monitoring vegetation is to use remotely sensed spectral data (Tueller 1989). Spectral indices developed from field radiometric and Landsat data have been used successfully to quantify green leaf area, biomass, and total yields in relatively homogeneous fields for agronomic uses (Shibayama and Akiyama 1989), but have met with variable success in wildland situations (Pearson et al. 1976). Interference from soils (Hardinsky et al. 1984, Huete et al. 1985), weathered litter (Huete and Jackson 1987), and senesced vegetation (Sellers 1985) have diminished the relationship between green vegetation characteristics and various vegetation indices.

In 1987, we found that a linear combination of Landsat Multi-spectral Scanner (MSS) band 7 and the ratio of MSS bands 6 to 4 explained 63% of the variation in green herbaceous phytomass (GHP) in sagebrush-grasslands on ungulate summer range in the northeastern portion of Yellowstone National Park (Merrill et al. 1993). The extensive fires that occurred in the Park in the summer of 1988 provided an opportunity to determine whether remote sensing could be used to estimate green phytomass in burned areas and to monitor grassland vegetation recovery in the Park after the fires. Remote sensing has previously been used to follow succession of seral stages in pine forests (Jakubauskas et al. 1990) after burning and to monitor plant cover in tundra (Hall et al. 1980) after wildfires.

The objectives of our study were to: (1) develop a model for predicting GHP in sagebrush-grassland communities using Landsat TM spectral information and field data on GHP for 2 years, (2) validate the model by comparing predictions made from the model to actual field data collected in a third year, and if successful (3) compare initial vegetation recovery in burned areas relative to unburned sagebrush-grassland.

✦ STUDY AREA

The study was conducted in the northeast portion of Yellowstone National Park with major focus on the upper Lamar, Cache and Calfee River drainages and the Mirror Plateau (Fig. 1). General descriptions of physiogamy and soils are given by Despain (1990). Elevations range from 1,500 to 3,300 m. Climate of the Park is characterized by long, cold winters and short dry summers, but climatic patterns within the Park vary considerably Fig 1 (Houston 1982). Mean annual precipitation in Cooke City, located to the northeast of the Park is 67.0 cm (26.8 in) and mean daily temperature in January and July is -10.3^{o} C (13.5^{o} F) and 13.9^{o} C (57.1^{o} F), respectively.

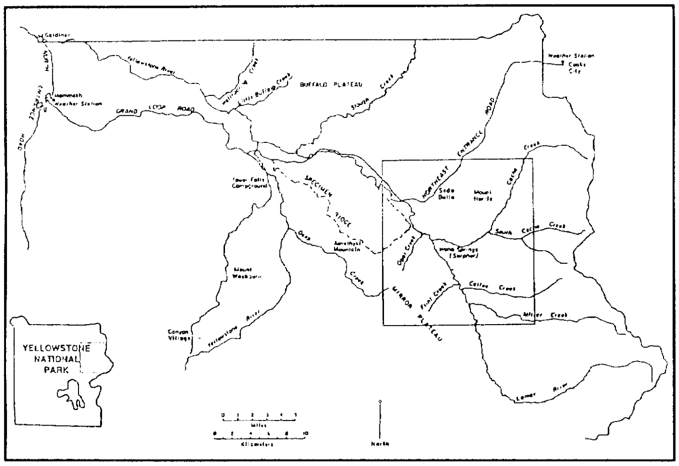

Figure 1. Location of study area in the northeastern portion of Yellowstone National Park.

Descriptions of vegetation communities in the park have been given by Despain (1990). Our work focused on the non-forested plant communities within the study area. These included sagebrush *Artemisia tridentata* communities which have an understory of bluebunch wheatgrass *Agropyron spicatum* in dry areas, and Idaho fescue *Festuca idahoensis* on the more mesic sites. Silver sagebrush *Artemisia cana* with an Idaho fescue co-dominant is found on areas associated with high water table such as stream banks and seeps. High elevation grasslands are dominated by Idaho fescue/tufted hairgrass *Deschampsia cespitosa* and tufted hairgrass/sedge *Carex* spp. At intermediate elevations, Idaho fescue/wheatgrass *Agropyron spicatum* and *A. caninum* communities are encountered with the latter dominating in the more mesic sites.

Elk *Cervus elaphus*, mule deer *Odocoileus hemionus* bison *Bison bison*, moose *Alces alces*, bighorn sheep *Ovis canadensis*, and pronghorn *Antilocapra americana* are the major ungulates in this area (Houston 1982).

✦ METHODS

VEGETATION SAMPLING

Vegetative data were collected in the field from 25 July - 10 August 1989, 30 July - 11 August 1990, 30 July - 11 August across Norris-Cache/Calfee ridge complex and Mirror Plateau in the northeastern portion of Yellowstone National Park. Each site encompassed at least 0.81 hectares (9 TM pixels) of relatively homogeneous vegetation. At each site, elevation, aspect (degrees), and average slope (%) of the plot were recorded using 1:24,000 topographic maps and the site mapped. Grassland habitat types assigned to sites followed Yellowstone National Park habitat mapping (Despain 1990).

We qualitatively assessed the intensity of burning in the field at each site according to the following categories: (1) severely burned: $\geq$ 80 % of the ground cover and litter consumed, presence of shrubs noted only by trunk stubs, usually heavy ash layer, (2) moderate burn: < 80 % but usually > 35 % of the ground cover and litter consumed, few live shrubs but standing dead shrubs present, (3) lightly burned: < 35% ground cover and litter consumed; many live shrubs remaining, (4) no burn.

A double sampling approach was used to estimate biomass of green forbs, green grasses, and standing dead herbaceous vegetation at each site (Eberhardt and Simmons 1987). Percent cover of graminoids, forbs, bareground, rock, moss and lichens, and dead wood were visually estimated and average heights of plant types (forbs, graminoids, standing herbaceous phytomass) were measured in 30 microplots (0.01 m^2) at each site. Ten of the microplots at each site were clipped to ground level. Vegetation was separated into green graminoids, green forbs, and standing dead herbaceous material. A criterion of $\geq$ 25 % "green" was used to differentiate green from senescent (standing dead) plants. Biomass samples were dried at 70^{o} C for 48 hours and weighed to the nearest 0.1 g. An index of plant volume was calculated (canopy cover x plant height) for each of the 30 microplots. The ratio of dry plant biomass to plant volume in clipped microplots at a site was used to estimate dry plant biomass in the 20 microplots which were not clipped (Eberhardt and Simmons 1987).

Differences in mean standing dead, green forb, green graminoid, total (green plus standing dead) biomass at sites that were sampled in all 3 years were tested using a Wilcoxon matched-pairs signed-ranks test. Differences in plant biomass between 3 burn categories (unburned, lightly burned, moderately to severely burned) were tested within years using Kruskal-Wallis one-way analysis of variance, and between two burn categories (unburned to lightly burned, moderately to severely burned) using a Mann-Whitney U test.

LANDSAT DATA ACQUISITION AND PREPROCESING

We used thematic mapper (TM) data from Landsat-5 satellite to quantify spectral characteristics of our study area. TM imagery for 2 August 1989, 13 August 1990, 31 July 1991 of the study area were acquired from EOSAT by the National Park Service. Due to mechanical problems with the receiving station in Golden, California, EOSAT was unable to provide us with data from our projected 6 August 1990 satellite overpass. The closest date to our field sampling (July 30 - August 11) for which imagery was available was 13 August 1990. Data from this overpass was less than ideal because the date of the overpass was outside our sampling window and there were considerable clouds in the scene. Because of the cloud cover, we were unable to obtain spectral values for 6 field plots sampled in 1990.

Digital data were transferred from 9-track computer tape to the Micro-computer Image Processing System (MIPS) for data processing. Data from each scene were georeferenced to 1:24,000 USGS topographic using 8 control points.

Environmental conditions that differed among years at the time of the satellites overpasses, such as sun angle and atmospheric conditions, were standardized to 1989 conditions in the following manner. First, we located 6 control sites of 9 TM pixels each in the 3 images, including bright landscape elements (Wahb hot springs and Lamar trail thermal area) and dark landscape elements (Trout and Soda Butte Lakes, rock faces of Abiathar and Thunderer peaks). Second, we recorded the spectral values of the 9 pixels for each spectral band at each site and calculated the average for the site. Third, we estimated the parameters of a linear relationship between average spectral values of each band in 1989 to the other 2 years (Appendix 1). Finally, we used the relationships derived from the control points for each band to adjust reflectance values of all pixels in 1990 and 1991 to 1989.

RELATIONSHIP BETWEEN GREEN PHYTOMASS AND SPECTRAL VALUES

Values for each of the 6 TM bands were recorded for 9 pixels (0.81 ha) encompassing each field site and averaged to represent the spectral value of the site. Linear combinations of the TM values, as well as published vegetation indices (Jackson 1983), were related to field estimates of biomass at field sites using least squares linear regression. Three indices were based on ratios of the red and near infrared (NIR) TM bands: the ratio vegetation index (RVI = NIR/red), the normalized difference index (NDVI = (NIR-red)/(NIR+red) and the transformed vegetation index (TVI= SQRT(ND + 0.05) (Huete and Jackson 1987). The soil brightness index (SBI), the perpendicular vegetation index (PVI), and the green vegetation index (GVI) were derived using the Graham-Schmidt orthogonalization process (Jackson 1983) in the MIPS software. Jackson (1983) showed that these indices minimize soil background variations while improving green vegetation signals.

We evaluated the relationship between the Landsat spectral values and the field estimates of biomass in two steps. First, the regressions between vegetative and spectral characteristics were evaluated based on their F value ($\underline{P} \leq 0.05$), the amount of variation in the dependant variable explained by the independent variables (r^2), and the standard error of the estimate. Second, 21 field sites were sampled in more than one year. We used data from only one year to develop relationships between spectral characteristics and green herbaceous biomass. The remaining data were used to "validate" estimates of phytomass predicted from spectral values and actual field data.

GIS ANALYSES

Standarized spectral values in TM bands 3 and 4 were used to calculate NDVI using data from the 1989, 1990, and 1991 TM Landsat imagery at a 28-m resolution. TM bands 3 and 4 for each year were imported into the GRID program of ARC/INFO and co-registered with the vegetative cover, burn intensity, and elevation GIS coverages obtained from Yellowstone National Park in GRASS format and imported into ARC/INFO. The cell resolution of all GIS layers were standarized to a 30-m resolution.

Average green and total biomass was estimated from NDVI in burned and unburned sagebrush-grasslands across the study area in 1989 to 1991 in a 4-step process. First, the study area was stratified in ARC/INFO into high (>2620 m) and low ($\leq$2621 m) elevation coverage. Second, equations 1 - 4 were used to calculate total and green herbaceous biomass and a predicted biomass coverage was created for each elevational stratum. Because cloud cover constituted > 10 percent of the 1990 Landsat image, locations of clouds were identified using Landsat spectral band 4 and removed from the analyses in 1990. Finally, areas that were forested were removed from the analysis using the vegetative cover map. Average estimates of total and green herbaceous biomass in burned and unburned sagebrush-grasslands in our study from 1989-1991 and their variances, corrected for autocorrelation, were to be determined following procedures described by Isaaks and Srivastava (1989).

✦ RESULTS AND DISCUSSION

FIELD ESTIMATES OF PHYTOMASS

Vegetation was sampled at 61 individual field sites, with 21 sites resampled in all 3 years (Table 1). Plots were distributed about equally among Lamar Flat-Norris Mount, Cache-Calfee Ridge, and the Mirror Plateau in the northeastern portion of Yellowstone National Park. Total herbaceous standing crop (Table 2) was within the range of variation documented by Merrill et al. (1993) in the same area in 1987 for the same vegetative types. Graminoids consistently averaged about 50% of the total green herbaceous phytomass (GHP) in the 3 years of the study. Biomass of green forbs, green graminoids, and total herbaceous biomass (green biomass plus standing dead) on the 21 sites sampled each year was higher in 1990 than in 1989 and 1991 ($\underline{P}$ < 0.05) (Fig. 2). The proportion of total herbaceous vegetation that was standing dead was lower in 1989 (0.04 ± 0.06, x ± s.d.) than in 1990 (0.12 ± 0.11) and lower in 1990 than in 1991 (0.24 ± 0.17) ($\underline{P} \leq 0.01$). Weather data were incomplete (Fig. 3), but did not indicate that either high growing season precipitation or early snow melt was responsible for an increase in herbaceous standing crops in 1990.

There were no significant differences in biomass of green graminoids and forbs between unburned, lightly burned, and moderately to severely burned in any year, but sample sizes within each burn category were low (5 - 8 sites). When sites were combined into lightly to unburned (n = 13) and severely to moderately burned (n = 8), graminoid biomass was lower, but not significantly lower, on severely to moderately burned sites in all years and forb biomass was higher in burned areas (Fig. 2) with a significant difference occurring in only 1990 ($\underline{P}$ < 0.05). Since our study was not directed at looking at small scale differences in burned and unburned sites, our sample sizes are small and the power of these tests is low. Nevertheless, increases in forb biomass and decreased grass biomass is not an uncommon response in the initial years after burning in sagebrush, Fig. 2 and Fig. 3, grasslands (Wright and Bailey 1982).

SPECTRAL INDICES AND VEGETATION CHARACTERISTICS

TVI and TM band 7 were most highly correlated with standing dead phytomass (Table 3). The normalized difference index (NDVI) was the spectral index most highly correlated with total and green vegetative characteristics (Table 3). NDVI has consistently been found to be related to green leaf biomass or photosynthetically active radiation absorbed by plants (Tucker 1979). There was considerable scatter, however, in the relationship between total (THP) and green herbaceous vegetation (GHP) and NDVI when examined across years and no simple or multiple regression model could be found that explained more than 40 % of the variation in NDVI in all years. In particular, data from 1990 had higher biomass for the same NDVI values as in other years. This was not unexpected since the satellite overpass in 1990 occurred several days after the vegetation sampling at field sites was completed rather than during the middle of the sampling period. Thus, we did not use field data collected in 1990 to develop the relationship between spectral NDVI and field estimates of phytomass.

THP and GHP alone explained 45 and 46% ($\underline{P}$ = 0.001) of the variation, respectively, in NDVI at field sites sampled in either 1989 or 1991 (Fig. 4). Elevation explained an additional 6% of the variation in NDVI (Table 4). Neither burn intensity nor standing dead herbaceous phytomass (SDHP) or the proportion of standing dead of THP explained additional variation in these data once the effects of elevation were accounted for. The effect of standing

Table 1. Location and characteristics of field sites sampled during August of 1989, 1990 and 1991 in Yellowstone National Park.

Plot #	Year Sampled	Latitude/Longitude		Location	Burn[1]	Elev (m)	Asp (°)	Slp (°)	Habitat Type[2]
101	1989, 1991	44 50 38.6	110 08 32.7	Lower Norris	T3	7520	180	15	TFG
102	1989, 1990, 1991	44 50 51.7	110 09 03.5	Lower Norris	No	7740	179	17	TFG
103	1989, 1990, 1991	44 50 28.3	110 07 49.7	Middle Norris	T1	7800	252	15	TFG
104	1989, 1990, 1991	44 50 13.6	110 08 07.1	Middle Norris	T2	7520	302	9	TFG
105	1989, 1990, 1991	44 49 16.0	110 08 35.0	Lower Cache	T2	7460	250	14	TFG
106	1989, 1990, 1991	44 49 20.2	110 08 25.2	Lower Cache	No	7700	253	6	FN
107	1989, 1990	44 48 21.0	110 05 49.2	Upper Cache	No	8140	0	0	FN
108	1989	44 48 11.1	110 06 40.0	Upper Cache	No	7940	230	1	TFG
109	1989, 1990, 1991	44 48 47.3	110 05 58.6	Upper Cache	T3	8025	2	3	TFG
110	1989, 1990, 1991	44 48 19.1	110 06 24.4	Upper Cache	No	7960	200	18	TFG
111	1989, 1990, 1991	44 48 06.9	110 06 40.0	Upper Cache	No	7850	0	0	TFG
112	1989	44 48 18.2	110 07 19.2	Upper Cache	No	7760	295	4	TFG
113	1989, 1990, 1991	44.48 45.9	110 07 40.9	Upper Cache	T3	7680	211	11	TFG
114	1989, 1990, 1991	44 51 05.0	110 11 03.1	Lamar Flat	T2	6640	0	0	TF
115	1989, 1990, 1991	44 50 59.7	110 11 12.3	Lamar Flat	No	6640	0	0	TFG
116	1989	44 51 05.0	110 11 03.1	Upper Lamar Flat	T2	6710	0	1	TF
121	1989, 1990, 1991	44 48 30.3	110 11 59.7	Opal Creek	T2	8800	127	8	FNG
122	1989, 1990, 1991	44 48 44.3	110 11 51.5	Opal Creek	T2	8740	95	15	FNG
123	1989, 1990	44 48 26.1	110 11 53.5	Opal Creek	T3	8760	101	6	FNG
124	1989, 1990, 1991	44 47 56.8	110 11 00.3	Above Opal Camp	No	8960	90	6	FNG
125	1989, 1990, 1991	44 47 28.0	110 11 22.0	Above Opal Camp	No	8800	170	15	FNG
126	1989, 1990, 1991	44 47 16.1	110 10 55.4	Above Opal Camp	T3	8760	353	4	FNG
127	1989, 1990, 1991	44 48 10.6	110 12 13.6	Opal Creek	T3	8800	15	1	FNG
128	1989, 1990, 1991	44 48 26.7	110 11 44.5	Opal Creek	No	8680	287	8	FNG
129	1989, 1990	44 50 12.7	110 12 10.2	Specimen Ridge Trail	T2	7950	80	7	TFG
130	1989	44 48 25.3	110 13 35.8	Mirror Plateau	No	9120	192	20	FNG
131	1989	44 48 51.5	110 14 11.8	Mirror Plateau	No	9170	0	2	FNG
132	1989	44 49 09.8	110 13 45.2	Top Specimen Ridge Tr	No	8840	150	20	FNG
133	1989, 1990, 1991	44 50 27.7	110 09 46.2	Above Norris Hot Sp	T2	7000	239	7	TFG
134	1989, 1990, 1991	44 50 18.9	110 09 19.5	Lower Norris	T1	7250	213	14	TFG
136	1989	44 50 57.8	110 09 51.4	West Of Norris Cliff	T2	7440	180	15	FA
137	1989	44 51 05.8	110 06 48.6	Upper Norris	No	8130	121	5	TFG
138	1989, 1991	44 51 07.2	110 08 03.5	Pk Midway To Norris	No	8250	171	10	FNG
139	1989, 1990, 1991	44 50 54.2	110 09 06.2	Top/Draw Mid-Norris	No	7860	276	6	TFG
140	1989, 1990	44 50 57.8	110 09 30.7	Norris/Next To Cliff	No	7800	294	7	TFG
141	1990, 1991	44 50 54.3	110 09 57.0	Lower Norris	T2	7440	220	18	FA
142	1990, 1991	44 50 50.2	110 06 55.8	Upper Norris	No	8000	187	14	TFG
143	1990, 1991	44 50 46.6	110 07 56.7	Midway to Norris	No	7700	186	14	FNG
144	1990, 1991	44 50 33.6	110 10 15.0	Lower Norris	T3	6760	261	6	FNG
145	1990	44 48 46.1	110 06 57.0	Upper Cache	No	8140	211	7	FNG
146	1990	44 48 41.6	110 06 48.0	Upper Cache	No	8030	148	12	FNG
147	1990	44 48 35.7	110 07 20.3	Upper Cache	No	7720	296	1	DW
148	1990	44 48 56.1	110 07 37.3	Upper Cache	No	7800	55	2	FN
149	1990	44 48 38.3	110 06 57.5	Upper Cache	No	7920	240	82	TFG
151	1990	44 99 10.1	110 05 57.4	Upper Cache	No	7900	310	18	TFG
153	1990	44 48 15.0	110 06 02.2	Upper Cache	No	7920	0	0	TFG
155	1990	44 48 13.9	110 13 15.4	Above Opal Creek	No	9280	136	5	FN
156	1990	44.48 28.6	110 13 59.2	Mirror Plateau	No	9040	208	28	FNG
157	1990	44 48 53.1	110 14 11.3	Mirror Plateau	No	9200	12	10	FN
200	1991	44 47 51.4	110 11 51.4	Opal Creek	No	8840	200	12	FNG
201	1991	44 48 07.3	110 11 36.7	Mirror Plateau	No	8920	260	3	FNG
202	1991	44 47 23.8	110 11 36.2	Mirror Plateau	No	8820	130	5	FNG
203	1991	44 48 31.3	110 13 24.0	Opal Creek	No	9080	200	8	FNG
204	1991	44 48 08.4	110 13 21.0	Speciman Ridge Trail	No	9360	82	8	FN
205	1991	44 49 08.7	110 14 09.1	Opal Creek	No	9160	210	5	FNG
206	1991	44 49 23.2	110 13 19.0	Speciman Ridge Trail	No	8680	160	18	FNG
210	1991	44 51 43.1	110 10 09.7	Lamar Flat	No	6640	0	0	TF
211	1991	44 50 50.6	110 11 02.0	Lamar Flat	T3	6720	0	0	TF
212	1991	44 51 25.7	110 10 33.7	Lamar Flat	T2	6720	0	0	TF
213	1991	44 48 40.1	110 07 34.1	Cache Calfee Ridge	No	7720	0	0	FNG
214	1991	44 49 08.5	110 07 49.7	Cache Calfee Ridge	No	7960	0	0	FA

---

[1] Burn rankings: No - unburned; T1 - severe burn; T2 - severe-moderate burn; T3 - moderate burn; T4 - light burn. See text for complete description.

[2] Despain (1990)

Table 2. Plot characteristics, percent cover of bareground (Bg), rock, litter (Lit), dead wood, moss, dry weight (g/0.01 m^2) of graminoids, forbs, standing dead herbaceous vegetation (SDHP), values of thematic mapper spectral bands, and spectral indices for field plots sampled in Yellowstone National Park in August 1989-1991.

	Plot	Plot Characteristics					Percent Cover					Phytomass (g/0.01 m^2)					Landsat Spectral Data						Spectral Vegetation Indices					
Year	#	Burn	Elev	Asp	Slp	CT	Bg	Rock	Lit	Wood	Moss	Grass	Forbs	SDHP	GHP	THP	TM1	TM2	TM3	TM4	TM5	TM7	NDVI	RVI	TVI	GVI	SBI	PVI
1989	8901	T3	7520	180	15	TFG	30.1	1.3	9.1	3.5	3.7	2.30	5.70	0.00	8.00	8.00	69	29	32	75	101	49	0.40	2.34	1.59	35.0	145.4	3.7
1989	8902	NO	7720	196	25	TFG	7.6	0.1	11.8	5.9	1.4	3.62	4.00	0.55	7.62	8.17	68	30	32	41	100	41	0.12	1.28	2.86	6.6	129.9	1.8
1989	8903	T1	7800	254	20	TFG	49.0	4.3	6.3	0.3	0.0	4.09	2.65	0.00	6.74	6.74	64	25	25	50	84	50	0.33	2.00	1.75	15.3	121.4	3.4
1989	8904	T2	7520	328	10	TFG	53.2	5.4	7.5	0.4	0.0	1.35	2.10	0.00	3.45	3.45	65	26	29	52	88	52	0.28	1.79	1.89	15.7	127.0	2.8
1989	8905	T2	7460	250	10	TFG	40.5	2.6	9.5	5.3	0.0	4.71	5.70	0.00	10.41	10.41	65	26	28	69	88	42	0.42	2.46	1.55	32.0	130.9	4.1
1989	8906	NO	7680	235	5	FN	2.4	14.7	72.3	0.0	4.5	0.34	0.20	0.18	0.54	0.72	83	35	45	57	121	65	0.12	1.27	2.92	10.5	166.2	1.7
1989	8907	NO	8100	230	20	FN	8.6	9.8	69.0	0.0	4.0	0.18	0.52	0.13	0.70	0.83	74	32	43	58	100	55	0.15	1.35	2.60	14.1	148.4	1.8
1989	8908	NO	7940	230	1	TFG	0.5	0.0	26.3	0.0	0.7	15.17	3.45	0.21	18.62	18.83	63	27	29	90	93	37	0.51	3.10	1.41	51.8	139.8	5.3
1989	8909	T3	8025	283	5	TFG	40.9	2.3	16.9	2.4	2.4	4.87	3.42	0.02	8.29	8.31	70	29	36	70	96	52	0.32	1.94	1.78	28.2	144.3	2.9
1989	8910	NO	7960	195	20	TFG	16.0	0.1	43.1	6.4	6.0	1.50	2.42	0.25	3.92	4.17	74	32	43	58	100	55	0.15	1.35	2.60	14.1	148.4	1.8
1989	8911	NO	7850	184	3	TFG	8.4	0.3	49.9	0.0	0.0	8.34	5.44	0.11	13.78	13.89	67	30	31	95	101	40	0.51	3.06	1.42	54.4	149.9	5.0
1989	8912	NO	7760	295	4	TFG	2.9	0.0	30.0	0.0	0.0	10.65	5.04	0.47	15.69	16.16	60	29	30	94	99	40	0.52	3.13	1.41	56.1	143.9	5.2
1989	8913	T3	7750	230	10	TFG	23.8	1.3	40.6	2.1	0.0	4.91	5.58	0.10	10.49	10.59	67	30	30	96	93	38	0.52	3.20	1.40	54.9	145.9	5.4
1989	8914	T1	6630	0	0	TF	54.2	1.0	8.9	1.7	0.0	7.10	4.32	0.36	11.42	11.78	69	28	31	64	99	51	0.35	2.06	1.71	25.4	139.9	3.2
1989	8915	NO	7160	206	25	TFG	3.2	0.8	70.2	12.4	1.7	2.57	4.90	0.16	7.47	7.63	76	31	38	62	107	51	0.24	1.63	2.05	19.9	150.7	2.3
1989	8916	T2	6710	0	1	TF	33.5	0.0	26.8	0.0	0.0	5.53	14.92	0.11	20.45	20.56	74	31	35	88	99	42	0.43	2.51	1.54	44.2	152.8	3.9
1989	8921	T2	8800	145	5	FNG	10.1	0.5	32.3	0.0	0.2	6.29	3.45	0.37	9.74	10.11	70	30	35	83	104	51	0.41	2.37	1.58	40.8	152.4	3.6
1989	8922	T2	8740	95	15	FNG	18.4	15.0	31.2	0.0	5.1	2.04	2.57	0.60	4.61	5.21	70	29	35	67	96	51	0.31	1.91	1.80	26.0	142.5	2.8
1989	8923	T4	8800	95	7	FNG	9.9	0.5	27.7	0.0	2.0	4.70	4.79	0.14	9.49	9.63	63	27	29	69	83	42	0.41	2.38	1.58	31.7	128.4	3.9
1989	8924	NO	8960	90	7	FNG	17.4	0.1	39.4	0.0	0.0	4.29	3.59	0.25	7.88	8.13	67	30	31	103	101	40	0.54	3.32	1.38	61.4	152.9	5.5
1989	8925	NO	8880	190	15	FNG	47.5	1.1	18.7	0.0	0.0	4.23	5.25	0.21	9.48	9.69	66	29	30	116	102	39	0.59	3.87	1.32	73.7	156.8	6.6
1989	8926	T3	8760	356	3	FNG	1.8	0.0	51.5	0.0	0.0	5.80	1.79	0.06	7.59	7.65	64	29	31	93	98	40	0.50	3.00	1.43	53.4	145.8	4.9
1989	8927	T4	8800	15	1	FNG	0.0	0.1	22.0	0.0	0.0	11.20	1.80	0.15	13.00	13.15	63	29	27	107	89	33	0.60	3.96	1.31	66.9	143.4	7.2
1989	8928	NO	8660	305	6	FNG	0.6	0.1	26.1	0.0	0.5	10.80	2.30	0.09	13.10	13.19	63	29	27	111	86	31	0.61	4.11	1.30	70.3	143.2	7.5
1989	8929	T2	8770	90	5	TFG	6.9	0.1	16.1	0.0	0.0	10.40	11.10	0.36	21.50	21.86	69	30	37	84	106	46	0.39	2.27	1.62	42.3	153.0	3.4
1989	8930	NO	9120	192	20	FNG	13.2	0.3	54.9	0.0	0.0	5.20	4.30	0.25	9.50	9.75	74	33	40	88	111	51	0.38	2.20	1.65	42.8	162.8	3.2
1989	8931	NO	9170	0	2	FNG	5.7	0.0	38.9	0.0	3.3	9.10	4.60	1.35	13.70	15.05	71	32	38	89	107	50	0.40	2.34	1.59	45.0	158.4	3.5
1989	8932	NO	8840	150	20	FNG	33.5	3.7	25.4	0.0	0.0	6.90	4.00	0.41	10.90	11.31	82	38	49	83	120	64	0.26	1.69	1.98	31.9	177.7	2.3
1989	8933	T2	6980	233	5	TFG	20.1	3.0	17.8	0.0	0.0	6.70	16.50	0.93	23.20	24.13	68	28	30	64	81	44	0.36	2.13	1.68	24.7	129.6	3.4
1989	8934	T1	7250	230	12	TFG	55.3	6.1	7.6	0.3	0.0	1.80	13.00	0.00	14.80	14.80	69	28	32	57	83	48	0.28	1.78	1.90	17.5	130.1	2.7
1989	8936	T2	7440	180	15	FA	33.5	23.4	14.1	0.0	0.0	5.20	5.80	0.27	11.00	11.27	76	32	42	56	89	50	0.14	1.33	2.66	11.3	142.5	1.8
1989	8937	NO	8130	121	5	TFG	2.3	0.0	21.9	0.0	0.1	14.70	8.30	0.35	23.00	23.35	68	31	33	104	99	41	0.52	3.15	1.41	60.8	154.4	5.1
1989	8938	NO	8250	171	10	FNG	17.6	29.0	38.4	0.0	0.2	2.20	1.60	0.00	3.80	3.80	76	32	41	66	103	53	0.23	1.61	2.08	21.6	152.6	2.2
1989	8939	NO	7880	338	10	TFG	6.9	2.1	47.7	4.0	4.0	3.40	8.90	0.23	12.30	12.53	72	30	33	78	91	40	0.41	2.36	1.59	36.2	142.7	3.7
1989	8940	NO	7760	302	5	TFG	7.8	0.2	20.1	0.0	0.0	15.10	9.60	0.35	24.70	25.05	67	28	28	94	78	30	0.54	3.36	1.38	53.2	135.4	5.9
1990	9002	NO	7740	179	17	TFG	8.0	2.0	13.0	37.0	0.0	2.20	1.50	0.60	3.70	4.30	74	30	44	65	105	49	0.19	1.48	2.29	32.4	145.2	2.0
1990	9003	T1	7800	252	15	TFG	45.0	4.0	3.0	1.0	0.0	1.90	10.70	1.20	12.60	13.80	67	27	39	55	77	37	0.17	1.41	2.43	22.3	121.2	1.9
1990	9004	T2	7520	302	9	TFG	10.0	1.0	9.0	4.0	5.0	13.30	5.10	1.30	18.40	19.70	68	29	39	56	86	44	0.18	1.44	2.37	24.4	127.6	2.0
1990	9005	T2	7460	250	14	TFG	45.0	1.0	16.0	1.0	0.0	4.50	11.50	1.40	16.00	17.40	64	26	34	64	75	31	0.31	1.88	1.82	32.3	118.5	2.8
1990	9006	NO	7700	253	6	FN	4.0	1.0	46.0	0.0	10.0	0.40	1.60	2.00	2.00	4.00	82	34	51	63	119	61	0.11	1.24	3.09	28.1	161.1	1.6
1990	9007	NO	8140	0	0	FN	19.0	36.0	34.0	0.0	5.0	0.20	1.60	0.60	1.80	2.40	74	33	47	59	94	52	0.11	1.26	2.98	22.9	142.1	1.6
1990	9009	T3	8025	2	3	TFG	31.0	1.0	17.0	1.0	0.0	13.40	6.50	4.90	19.90	24.80	70	31	44	76	96	47	0.27	1.73	1.95	40.1	144.6	2.4
1990	9010	NO	7960	200	18	TFG	10.0	0.0	26.0	15.0	0.0	2.50	5.30	1.00	7.80	8.80	67	29	36	82	83	34	0.39	2.28	1.62	46.4	133.2	3.4
1990	9011	NO	7850	0	0	FN	2.0	0.0	8.0	0.0	0.0	18.60	7.70	1.60	26.30	27.90	65	29	36	99	87	31	0.47	2.75	1.48	61.9	140.1	4.2
1990	9013	T3	7680	211	11	TFG	23.0	3.0	14.0	1.0	0.0	4.70	7.00	0.40	11.70	12.10	68	28	33	85	76	31	0.44	2.58	1.52	48.3	129.7	4.0
1990	9014	T2	6640	0	0	TFG	39.0	1.0	7.0	1.0	0.0	15.40	8.20	0.00	23.60	23.60	74	31	47	58	105	53	0.10	1.23	3.10	25.3	145.2	1.6
1990	9015	NO	6640	0	0	TFG	0.0	0.0	23.0	11.0	7.0	11.20	2.80	0.04	14.00	14.04	73	32	45	70	100	44	0.22	1.56	2.16	34.8	145.3	2.1
1990	9021	T2	8800	127	8	FD	15.0	6.0	18.0	0.0	3.0	7.30	3.70	2.50	11.00	13.50	.	.	.	.	.	.	.	.	.	.	.	.
1990	9022	T2	8740	95	15	FNG	21.0	5.0	7.0	2.0	0.0	8.90	6.20	0.70	15.10	15.80	.	.	.	.	.	.	.	.	.	.	.	.
1990	9023	T4	8760	101	6	FN	13.0	1.0	15.0	0.0	0.0	15.70	5.80	2.70	21.50	24.20	.	.	.	.	.	.	.	.	.	.	.	.
1990	9024	NO	8960	90	6	FNG	20.0	1.0	25.0	0.0	0.0	6.10	5.50	1.80	11.60	13.40	.	.	.	.	.	.	.	.	.	.	.	.
1990	9025	NO	8800	170	15	FNG	25.0	1.0	18.0	0.0	0.0	6.60	6.40	2.60	13.00	15.60	65	29	36	130	97	34	0.57	3.61	1.35	89.4	157.3	5.7
1990	9026	T3	8760	353	4	FNG	4.0	0.0	24.0	0.0	0.0	14.40	2.60	2.00	17.00	19.00	59	22	27	57	50	17	0.36	2.11	1.69	25.8	95.8	3.5
1990	9027	T4	8800	15	1	FNG	3.0	0.0	13.0	0.0	1.0	18.30	2.80	1.60	21.10	22.70	63	29	34	114	92	33	0.54	3.35	1.38	76.5	146.6	5.3
1990	9028	NO	8680	287	8	FNG	6.0	0.0	10.0	0.0	0.0	23.70	3.80	1.10	27.50	28.60	.	.	.	.	.	.	.	.	.	.	.	.
1990	9029	T2	7950	80	7	TFG	20.0	2.0	12.0	1.0	12.0	4.40	3.50	3.30	7.90	11.20	70	30	44	66	92	45	0.20	1.50	2.25	31.3	138.2	2.0
1990	9033	T2	7000	239	7	TFG	29.0	2.0	12.0	1.0	0.0	2.70	15.30	4.30	18.00	22.30	68	29	33	64	85	39	0.32	1.94	1.78	33.0	126.4	2.9
1990	9034	T1	7250	213	14	TFG	39.0	4.0	6.0	0.0	0.0	3.50	11.60	2.80	15.10	17.90	75	31	44	59	86	45	0.15	1.34	2.63	22.4	135.7	1.8
1990	9039	NO	7860	276	6	TFG	8.0	1.0	13.0	40.0	1.0	2.70	6.00	0.80	8.70	9.50	71	30	43	66	96	45	0.21	1.53	2.19	32.4	139.6	2.1
1990	9040	NO	7800	294	7	TFG	11.0	1.0	27.0	0.0	1.0	5.00	8.50	1.00	13.50	14.50	67	29	41	68	66	34	0.25	1.66	2.02	29.0	123.7	2.3
1990	9041	T2	7440	220	18	FA	43.0	4.0	5.0	7.0	0.0	3.50	5.00	3.40	8.50	11.90	71	30	44	61	78	39	0.16	1.39	2.50	23.6	130.1	1.8
1990	9043	NO	7700	186	14	FNG	10.0	2.0	14.0	6.0	0.0	5.80	8.40	1.30	14.20	15.50	67	30	39	87	90	38	0.38	2.23	1.64	50.8	140.6	3.3
1990	9044	T3	6760	261	6	FNG	6.0	1.0	23.0	0.0	0.0	12.70	4.80	3.10	17.50	20.60	66	29	36	83	75	28	0.39	2.31	1.61	45.7	128.9	3.5
1990	9045	NO	8140	211	7	FNG	6.0	1.0	37.0	3.0	5.0	1.20	1.10	0.80	2.30	3.10	76	33	48	65	100	52	0.15	1.35	2.59	28.3	148.2	1.8
1990	9046	NO	8030	148	12	FNG	6.0	1.0	19.0	30.0	0.0	1.40	3.30	0.50	4.70	5.20	74	32	46	70	113	58	0.21	1.52	2.21	37.0	154.0	2.0
1990	9047	NO	7720	296	1	DW	2.0	0.0	10.0	0.0	3.0	13.10	4.30	1.70	17.40	19.10	66	28	35	87	80	47	0.43	2.49	1.55	50.2	135.4	3.8
1990	9048	NO	7800	55	2	FN	5.0	6.0	34.0	0.0	19.0	0.50	0.90	1.70	1.40	3.10	77	33	34	66	102	51	0.32	1.94	1.78	34.6	142.3	2.9
1990	9049	NO	7920	240	0	TFG	6.0	0.0	24.0	1.0	0.0	9.90	6.40	1.30	16.30	17.60	70	30	40	79	99	45	0.33	1.98	1.76	45.1	144.0	2.8
1990	9051	NO	7900	310	18	TFG	32.0	39.0	3.0	0.0	0.0	3.50	1.70	3.10	5.20	8.30	66	27	36	59	75	36	0.24	1.64	2.04	26.5	119.8	2.3
1990	9053	NO	7920	0	0	TFG	4.0	0.0	8.0	0.0	0.0	11.80	6.50	6.00	18.30	24.30	67	29	39	90	93	39	0.40	2.31	1.61	54.1	142.8	3.4
1990	9055	NO	9280	136	5	FN	14.0	5.0	23.0	0.0	8.0	5.00	2.70	1.40	7.70	9.10	72	32	44	86	104	47	0.32	1.95	1.77	49.4	153.0	2.7
1990	9056	NO	9040	208	28	FNG	5.0	0.0	14.0	0.0	0.0	17.00	7.20	1.90	24.20	26.10	67	29	33	83	76	30	0.43	2.52	1.54	46.7	128.6	3.9
1990	9057	NO	9200	12	10	FN	14.0	21.0	39.0	0.0	8.0	4.50	11.50	0.60	16.00	16.60	74	33	44	83	105	46	0.31	1.89	1.82	46.4	153.2	2.6
1991	9101	T3	7520	141	12	TFG	14.6	7.0	22.8	4.7	0.0	1.40	4.50	1.50	5.90	7.40	70	30	43	67	102	49	0.22	1.56	2.15	42.7	133.0	2.1
1991	9102	NO	7740	180	23	TFG	13.4	2.9	11.8	29.2	0.4	1.60	5.20	0.60	6.80	7.40	70	29	40	68	89	42	0.26	1.70	1.98	40.2	127.3	2.4
1991	9103	T1	7800	210	21	TFG	17.0	5.8	17.5	0.9	0.0	1.30	1.70	0.30	3.00	3.30	69	29	42	61	88	46	0.18	1.45	2.34	34.0	125.0	2.0
1991	9104	T2	7520	190	25	TFG	31.9	2.6	20.9	4.8	0.0	0.30	0.90	0.30	1.20	1.50	33	30	44	59	102	58	0.15	1.34	2.63	47.6	112.3	1.8
1991	9105	T2	7460	290	15	TFG	35.7	2.3	26.4	2.3	0.0	2.40	5.20	2.60	7.60	10.20	67	27	37	64	93	46	0.27	1.73	1.95	41.0	123.1	2.5
1991	9106	NO	7460	230	2	FN	169.4	12.2	17.3	0.0	41.7	0.00	0.30	1.10	0.30	1.40	83	35	53	59	113	60	0.05	1.11	4.33	31.5	147.5	1.4
1991	9109	T3	8025	0	0	TFG	32.5	1.2	35.2	4.2	0.0	4.20	2.70	1.90	6.90	8.80	73	31	45	72	100	52	0.23	1.60	2.09	43.8	138.3	2.2
1991	9110	NO	7960	230	12	TFG	16.7	0.6	31.6	10.8	3.2	2.10	4.20	1.10	6.30	7.40	67	29	38	77	92	42	0.34	2.03	1.73	49.8	129.6	3.0
1991	9111	NO	7850	160	7	FN	12.3	0.1	42.9	0.0	0.0	4.80	3.10	0.90	7.90	8.80	68	30	39	89	104	47	0.39	2.28	1.62	62.3	140.2	3.3
1991	9113	T3	7680	211	9	TFG	27.0	3.4	27.9	4.6	0.0	3.10	3.80	3.70	6.90	10.60	70	30	40	69	96	46	0.27	1.73	1.95	43.2	130.4	2.4
1991	9114	T2	6640	0	0	TFG	21.1	0.4	40.6	2.4	0.0	1.60	3.00	5.10	4.60	9.70	79	33	50	60	119	65	0.09	1.20	3.32	37.1	145.7	1.5
1991	9115	NO	6640	0	0	TFG	5.7	0.3	39.8	18.2	8.6	2.60	1.80	3.80	4.40	8.20	75	31	44	58	107	53	0.14	1.32	2.71	35.4	134.1	1.7
1991	9121	T2	8800	15	1	FNG	7.2	0.0	41.6	0.0	0.0	10.70	2.90	3.10	13.60	16.70	68	29	38	93	99	45	0.42	2.45	1.56	64.2	139.6	3.6
1991	9122	T2	8740	95	15	FNG	25.8	5.8	33.7	0.0	0.6	2.90	6.40	0.80	9.30	10.10	69	30	41	75	94	49	0.29	1.83	1.86	46.9	133.2	2.6
1991	9124	NO	8960	83	10	FNG	17.1	0.5	25.0	0.0	0.0	4.90	4.80	4.10	9.70	13.80	71	31	42	88	99	45	0.35	2.10	1.70	57.5	141.8	3.0
1991	9125	NO	8800	170	10	FNG	21.5	0.9	15.2	0.0	0.0	5.70	3.60	2.40	9.30	11.70	62	28	32	114	90	35	0.56	3.56	1.35	81.4	139.1	5.9
1991	9126	T3	8760	4	5	FNG	3.2	0.0	25.7	0.0	0.0	9.20	3.20	1.70	12.40	14.10	62	27	31	111	86	32	0.56	3.58	1.35	78.4	135.3	6.0
1991	9127	T4	8800	15	1	FNG	8.7	0.0	25.7	0.0	0.0	11.10	2.60	2.00	13.70	15.70	62	28	32	113	86	31	0.56	3.53	1.36	79.3	137.1	5.8
1991	9128	NO	8680	195	8	FNG	10.5	0.1	23.2	0.0	0.0	9.80	2.30	5.80	12.10	17.90	63	28	31	113	80	29	0.57	3.65	1.34	77.2	135.3	6.1
1991	9133	T2	7000	239	7	TFG	20.1	9.4	24.7	0.6	0.0	1.60	8.10	1.20	9.70	10.90	68	27	38	61	90	47	0.23	1.61	2.09	36.9	122.2	2.3
1991	9134	T1	7250	246	36	TFG	18.1	17.1	24.9	7.1	0.0	1.20	1.90	0.20	3.10	3.30	69	29	40	60	83	45	0.20	1.50	2.25	32.1	122.1	2.1
1991	9138	NO	8240	144	15	FNG	11.0	13.6	16.1	0.0	4.2	2.00	0.50	1.60	2.50	4.10	70	30	41	69	39	45	0.25	1.68	1.99	21.8	117.4	2.3
1991	9139	NO	7860	276	6	TFG	5.0	1.0	13.6	25.7	0.0	2.60	3.00	1.80	5.60	7.40	58	21	28	37	53	27	0.14	1.32	2.70	13.8	86.5	1.9
1991	9140	NO	7840	28	10	TFG	8.0	0.4	28.1	0.0	0.0	3.20	1.00	2.20	4.20	6.40	92	41	59	63	92	56	0.03	1.07	5.53	20.6	154.0	1.3
1991	9141	T2	7040	220	18	FA	29.9	8.0	21.1	6.7	0.0	4.30	1.90	2.30	6.20	8.50	61	24	28	98	69	25	0.56	3.50	1.36	64.5	121.0	6.1
1991	9143	NO	7640	186	14	FNG	9.1	3.1	20.0	7.9	0.0	2.20	6.60	1.90	8.80	10.70	64	29	37	88	100	39	0.41	2.38	1.58	62.6	134.1	3.6
1991	9144	T3	6760	261	6	FNG	10.2	1.3	23.7	0.8	0.0	6.30	5.90	0.70	12.20	12.90	67	28	33	80	84	37	0.42	2.42	1.57	51.4	125.3	3.8
1991	91200	NO	8840	200	12	FNG	8.6	0.6	44.3	0.0	0.0	4.50	4.40	1.00	8.90	9.90	65	30	37	103	85	37	0.47	2.78	1.47	68.0	138.1	4.2
1991	91201	NO	8920	260	3	FNG	6.3	0.0	20.2	0.0	0.0	13.70	2.60	1.00	16.30	17.30	64	29	34	90	90	36	0.45	2.65	1.50	61.6	130.6	4.1
1991	91202	NO	8820	130	5	FNG	2.7	0.0	22.0	0.0	0.0	13.10	3.20	1.10	16.30	17.40	65	30	35	113	98	41	0.53	3.23	1.40	81.0	145.3	5.1
1991	91203	NO	9080	200	8	FNG	21.3	0.0	22.7	0.0	0.0	5.60	9.10	2.10	14.70	16.80	69	31	41	90	101	43	0.37	2.20	1.65	60.9	141.3	3.2
1991	91204	NO	9360	82	8	FN	37.6	2.6	23.1	0.0	0.0	3.10	1.40	1.30	4.50	5.80	80	37	53	87	115	59	0.24	1.64	2.04	54.1	160.0	2.2
1991	91205	NO	9160	210	5	FNG	26.7	0.3	23.7	0.0	0.0	3.20	4.80	1.30	8.00	9.30	69	30	40	70	87	43	0.27	1.75	1.93	41.1	127.8	2.5
1991	91206	.	8680	160	18	FNG	16.1	0.1	12.3	0.0	0.0	7.40	5.10	4.40	12.50	16.90	62	27	30	124	89	33	0.61	4.13	1.30	89.7	141.7	7.1
1991	91210	NO	6640	0	0	TF	1.6	1.2	47.4	9.5	3.7	2.90	0.90	2.30	3.80	6.10	76	31	44	60	101	54	0.15	1.36	2.56	34.4	134.2	1.8
1991	91211	T2	6720	0	0	TF	19.9	0.0	49.0	0.0	0.0	3.30	2.30	1.40	5.60	7.00	78	32	48	54	115	65	0.06	1.13	4.13	32.3	139.9	1.4
1991	91212	T2	6720	0	0	TF	12.4	0.0	39.7	6.3	0.0	3.90	2.20	3.70	6.10	9.80	74	31	44	67	103	50	0.21	1.52	2.21	41.2	136.3	2.1
1991	91213	NO	7720	0	0	FNG	1.0	0.0	14.0	0.0	0.0	21.90	4.20	2.50	26.10	28.60	64	28	32	103	85	33	0.53	3.22	1.40	70.7	133.5	5.2
1991	91214	NO	7960	0	0	FA	12.0	7.0	13.0	0.0	47.0	0.30	0.60	1.40	0.90	2.30	72	30	43	62	62	49	0.18	1.44	2.36	23.5	122.2	1.9

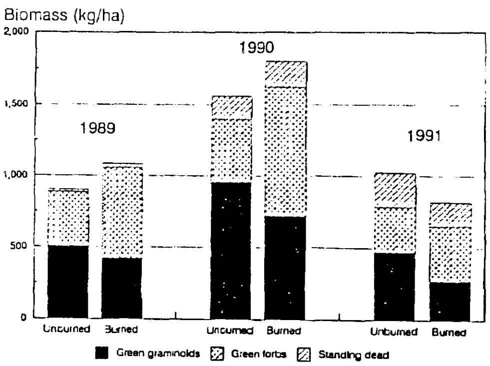

Figure 2. Average herbaceous phytomass in unburned to lightly burned field plots (n = 13 and moderately to severely burned field plots (n = 8) sampled in all 3 years of the study, Yellowstone National Park.

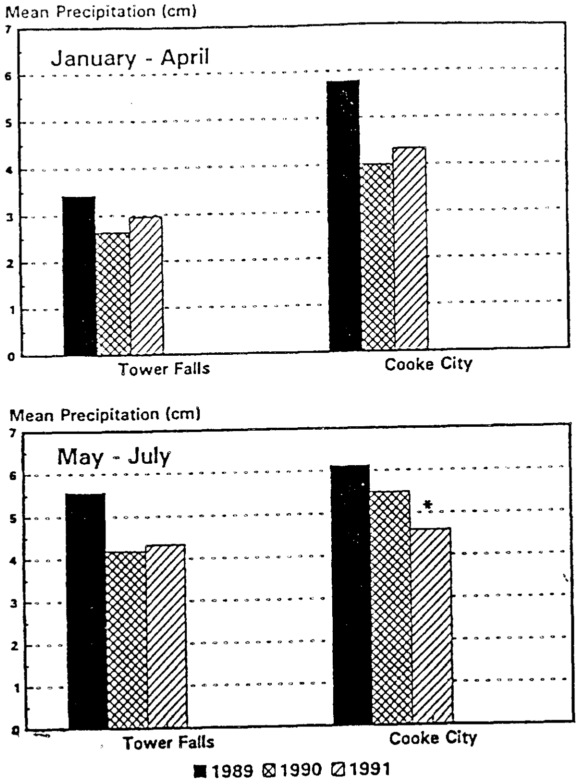

Figure 3. Mean winter and growing season precipitation at the Cooke City, Montana during the 3 years of the study.

dead vegetation on spectral signatures has been well established (Boutton and Tieszen 1983, Sellers 1985, Tueller 1989). For example, Pearson et al. (1976) found that relationships were not reliable when green vegetation comprised less than 30% of the standing crop. Heute and Jackson (1987) also reported that yellow senesced vegetation also increased the greenness response of plots with low green vegetation (Table 4).

Table 3. Significant ($\underline{P} \leq 0.05$) correlation coefficients between TM spectral bands and spectral indices and vegetation characteristics measured during late summer 1989-1991 in Yellowstone National Park. NS indicates not significant.

Vegetative Characteristic	Year	Spectral Index	r
Total standing biomass	1989	NDVI[1]	0.53
	1990	NDVI	0.45
	1991	NDVI	0.72
Green herbaceous phytomass	1989	NDVI	0.53
	1990	NDVI	0.46
	1991	NDVI	0.74
Green graminoids	1989	NDVI	0.66
	1990	NDVI	0.48
	1991	NDVI	0.74
Green forbs	1989		NS
	1990		NS
	1991		NS
Standing dead herbaceous phytomass	1989		NS
	1990		NS
	1991		NS
Percent standing dead of total standing phytomass	1989	TVI[2],TM7[3]	0.61, 0.52
	1990	TM7	0.35
	1991	TVI,TM7	0.52, 0.42

[1] NDVI = normalized difference vegetation index: (TM Band 4 - TM Band 3)/(TM Band 4 + TM Band 3).

[2] TVI = transformed vegetation index: SQRT(NDVI+0.05)

[3] TM7 = thematic mapper spectral band 7

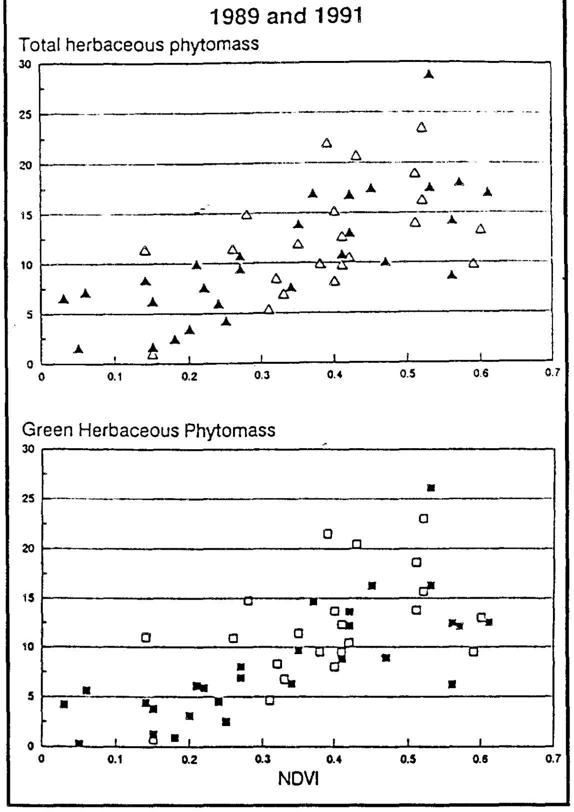

Figure 4. The relationship between total and green herbaceous phytomass (g/0.01 m^2) in field plots in late summer 1989 and 1991 and the mormalized difference ratio (NDVI) calculated for the field plots using Landsat TM data, Yellowstone National Park.

Table 4. Significant)$\underline{P}$ <0.001) linear regression models that predict $\geq$ 50% of the variation in NDVI at 50 field sites sampled in 1989 and 1991 Yellowstone National Park.

Independent variables	Coefficients	T	P	r^2
Constant	0.272	5.79	0.00	0.56
Total biomass	0.013	4.40	0.00	
Proportion standing dead	-0.301	-3.07	0.00	
Burn intensity	-0.071	-2.10	0.04	
Constant	0.321	8.41	0.00	0.55
Green grass	0.016	4.31	0.00	
Proportion standing dead	-0.329	-3.32	0.00	
Burn intensity	-0.057	-1.62	0.11	
Constant	-0.113	-0.65	0.518	0.53
Green herbaceous phytomass	0.016	6.14	0.000	
Elevation	0.0005	1.78	0.082	
Burn intensity	-0.029	-0.78	0.438	
Constant	-0.216	-1.37	0.18	0.51
Total phytomass	0.016	6.02	0.00	
Elevation	0.0005	2.41	0.02	
Constant	-0.202	-1.29	0.20	0.52
Green herbaceous phytomass	0.017	6.07	0.00	
Elevation	0.0005	2.46	0.02	

from Landsat TM spectral data in Yellowstone

Since the proportion of THP that was dead did not explain a significant amount of additional variation in NDVI when elevation was included in the model, the amount of standing dead in the plots apparently followed an elevational gradient. Burn intensity explained a significant amount of the variation in NDVI when combined with THP but not when combined with green grass GG or GHP (Table 4) which may also reflect the effects of standing dead on spectral characteristics. Average percent canopy cover of other site characteristics that we measured, such as litter or bareground, did not contribute significantly to explaining additional variation in NDVI.

When NDVI was used to predict biomass, less than 50% of the variation in THP and GHP was explained by NDVI. The relationship appeared weak because a number of high-elevation fields sites with high NDVI values had low GHP (Fig. 4). As a result, we stratified sites by elevation and found that following linear models (Fig. 5) explained 55% of the variation in TGP and GHP at low elevational ($\leq$ 2620 m) sites:

$$\text{THP (g/0.1 m}^2) = 29.25 \times \text{NDVI} - 1.191 \quad (\underline{P} < 0.001, \text{s.e.} = 4.61) \quad \text{Eq. 1}$$

$$\text{GHP (g/0.1 m}^2) = 31.2 \times \text{NDVI} - 0.501 \quad (\underline{P} < 0.001, \text{s.e.} = 4.54) \quad \text{Eq. 2}$$

Using an exponential model, NDVI explained only an additional 1% of the variation in either THP or GHP.

The relationships between NDVI and THP and GHP at high elevation sites (Fig. 6) was asymptotic and the following curves were used to describe the relationships:

$$\text{THP (g/0.1 m}^2) = \frac{19 \times (\text{NDVI} - 0.18)}{0.110 + (\text{NDVI} - 0.18)} \quad \text{Eq. 3}$$

$$\text{GHP (g/0.1 m}^2) = \frac{17 \times (\text{NDVI} - 0.18)}{0.102 + (\text{NDVI} - 0.18)} \quad \text{Eq. 4}$$

The asymptotic value of phytomass in high elevation grasslands in Yellowstone National Park was considerably lower than that found by Ripple (1985) who studied reflectances of vegetation in tall fescue *Festuca aruninacea* grasslands in Oregon.

The effect of elevation on spectral characteristics is likely due to earlier stages of plant growth at high elevations ($\geq$ 2620 m) than low elevation sites in early August in our study area. Seasonal changes in NDVI due to plant growth have been documented (Tueller 1989). Mahey et al. (1991) reported that red wave lengths (0.63 to 0.69 um: TM band 3) is highly sensitive to chlorphyll absorption and decreases a result of leaf senescence; the reflected energy in the NIR wave lengths (0.79-0.90: TM band 4) decreases due to cell degeneration and a decrease in leaf area. Kleman and Fagerlund (1987) noted in agricultural areas that the seasonal NDVI differed between irrigated and non irrigated fields.

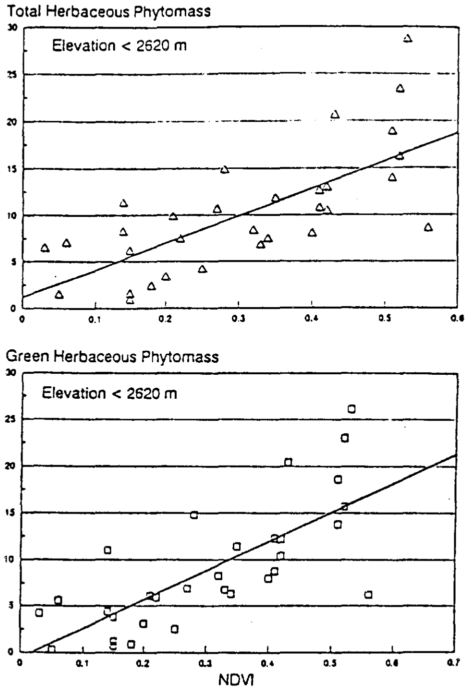

Figure 5. The relationship between total and green herbaceous phytomass (g/0.01 m^2) in field plots > 2620 m in late summer 1989 and 1991 and the normalized difference ratio (NDVI) calculated for the field plots using Landsat TM data, Yellowstone National Park.

The above equations were used to predict the THP and GHP of 16 low elevation sites and 7 high elevation sites that were not used to develop the above predictive equations. On average, GHP was underestimated at low elevations by 0.93 g/0.01 m^2 (93 kg/ha) and THP overestimated by 1.01 g/0.01 m^2 (101 kg/ha). At high elevations, GHP was overestimated by 2.34 g/0.01 m^2 (234 kg/ha) and THP by 2.73 g/0.01 m^2 (273 kg/ha). Mean percent error in estimates of GHP (37%) at low elevations was greater than at high elevations (24%) because phytomass was generally lower at low elevation sites than at high elevations sites. The magnitude of these errors are similar to those found by Merrill et al.(1993) who used MSS data to predict green phytomass and suggested that remotely sensed data provided estimates too imprecise to be used to estimate green biomass at specific sites.

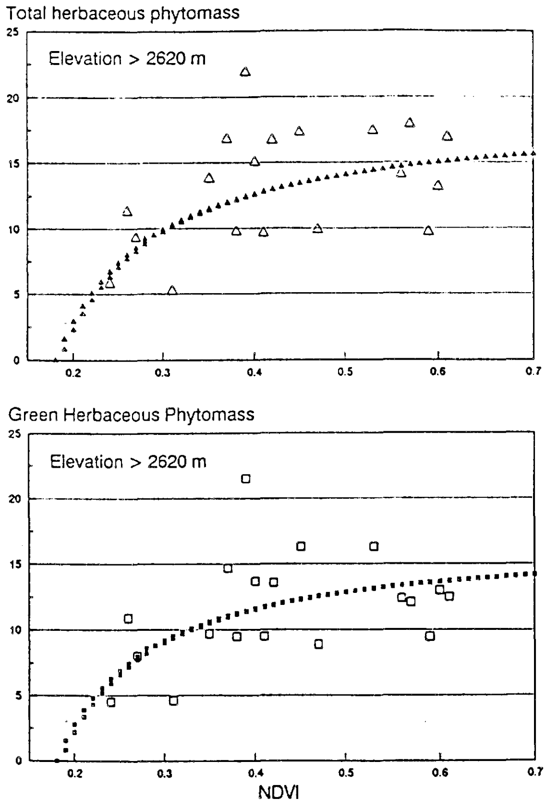

Figure 6. The relationship between total and green herbaceous phytomass (g/0.01 m^2) in field plots $\leq$ 2620 m in late summer 1989 and 1991 and the normalized difference ration (NDVI) calculated for the field plots using Landsat TM data, Yellowstone National Park.

VEGETATION RECOVERY ACROSS THE STUDY AREA

Average THP and GHP predicted across the study area in 1989 to 1991 were unreasonably low (< 400 kg/ha), even in the unburned areas, and the data are believed to be faulty. Three reasons have been identified as possible sources of error, but examination of the data to date have not provided any insight into explaining the poor results. First, differences in pixel sizes of the various GIS layers and their standardization may have caused sufficient smoothing errors to influence the results; however, this seems unlikely. Second, machine rounding errors within the GIS may have been sufficiently large to affect our results. Third, co-registration errors among GIS layers (spectral data, elevation, burn map, forest mask) may be sufficiently large to influence our analyses.

Earlier work suggested that remote sensing could be used to monitor biomass of grasslands in Yellowstone National Park, although the approach was probably not amendable to providing accurate estimates for small sites (Merrill et al. 1993). Merrill et al. (1993) found that low estimates of GHP (> 600 kg/ha) were obtained during years when average December through March precipitation at Cooke City was either high or low and attributed this to either late or early phenological development (the green-wave effect) at the time of satellite overpass as a result of early and late snow melt. During the years of this study, December through March precipitation was not sufficiently low to account for the low estimates of GHP that we observed, nor was growing season precipitation sufficiently low.

In this study, we used Landsat TM data to make predictions of total green biomass across the study area rather than MSS data (Merrill et al. 1993). We chose to use TM data rather than MSS data to increase the band options for developing a predictive model. Gallo (1987) found that differences in vegetation indices based on MSS and TM data were greatest during mid-season when the maximum amounts of green vegetation was present. Differences in pixel size (MSS: 57 x 57 m vs TM: 28 x 28 m) of the two sets of remotely sensed spectral data may also contribute to these differences. It is also possible that there is considerably higher variation in the TM data across the landscape than in MSS data due to the small pixel size. The high variability would not necessarily explain the unreasonably low average GHP values we obtained, even in the unburned areas. However, there may be inherent problems using a small number of field plots (n = 61) to reflect the variation across the large landscape.

Further comparisons of GHP estimates predicted from MSS and TM imagery is merited but beyond the budget of this project. Without further technological and biological understanding of our results, we can not advocate the use of our models to predict vegetation recovery in grassland in Yellowstone National Park. Other investigators have indicated poor results when working with a heterogenous vegetation-soil complex and suggest that stratifying by relatively uniform-soil complexes may be necessary. While our overall approach is promising for homogeneous areas such as crop lands, the complexity of natural communities in heterogeneous environments will require substantially more field effort to create useful and interpretable results for monitoring fine-grain vegetation change from remotely sensed data in Yellowstone National Park.

✦ ACKNOWLEDGEMENTS

I would like to thank Cathy Wilson for her assistance in field work and initial data analysis. John Baldwin, Jon Hak, Robin Reid, Verda and Mike Shingleton, Greg McDaniel, and Bob Brennen provided assistance in collecting field data and processing samples. We also thank Rich Kluckus, Don Despain, Francis Singer, John Varley, Jennifer Whipple, George McKay, and Jack Norland of Yellowstone National Park for their administrative and field support. Drs. Kenneth Gerow and Jeff Pontius of the University of Wyoming provided statistical advice.

✦ LITERATURE CITED

Boutton, T. W. And L. L. Tieszen. 1983. Estimation of plant biomass by spectral reflectance in an East African grassland. J. Range Manage. 36:213-126.

Despain, D. G. 1990. Yellowstone Vegetation: consequences of environment and history in a natural setting. Roberts Rinehart. 239 pp.

Eberhardt, L. L. and M. A. Simmons. 1987. Calibrating population indices by double sampling. J. Wildl. Manage. 51:665-675.

Gallo, K. P. And C. S. T. Dauchtry. 1987. Differences in vegetation indices for simulated Landsat-5 MSS and TM, NOAA-9, SPOT-1 sensor systems. Remote Sens. of Environ. 23:339-352.

Hall, D. K. J. P. Ormsby, L. Johnson, and J. Borwn. 1980. Landsat digital analysis at Kokolik River, Alaska. Remote sensing of the Environment 10:263-272.

Hardinsky, M.A., F. C. Daiber, C.T. Roman, and V. Klemas. 1984. Remote sensing of biomass and annual net aerial primary productivity of a salt marsh. Remote Sens. of Environ. 16:91-106.

Heute, A. R., R. D. Jackson, D.F. Post. 1985. Spectral response of a plant canopy with different soil backgrounds. Remote Sens. Environ. 17:37-53.

Heute, A. R. and R.D. Jackson. 1987. Suitability of spectral indices for evaluating vegetation characteristics on arid rangelands. Remote Sens. Environ. 23:213-232.

Houston, D. B. 1982. The Northern Yellowstone elk: ecology and management. Macmillian Publishing, New York. 474 pp.

Isaaks, E. H. And R. M. Srivastava. 1989. An introduction to applied geostatistics. Oxford Univertsity Press, New York. 561 pp.

Jackson, R. D. 1983. Spectral indices in n-Space. Remote Sens. Environ 13: 409-421.

Jakubauskas, M. K., P. Lulla and P. W. Mausel. 1990. Assessment of vegetation change in a fire-altered forest landscape. Photogr. Eng. Remote Sens. 56:371-377.

Kleman, J. And E. Fagerlund. 1987. Influence of different nitrogen and irrigation treatments on the spectral reflectance of barley. Remote Sens. of Environ. 21:1-14.

Mahey, R. K., R. Singh, S.S. Sidhu and R.S. Narang. 1991. The use of remote sensing to assess the effects of water stress on wheat. Expl. Agric. 27:423-429.

Merrill, E. H., M. K, Bramble-Brodahl, R. W. Mares, M. S. Boyce. 1993. Estimation of green herbaceous phytomass from Landsat MSS data in Yellowstone National Park. J. Range Manage. 46:151-157.

Pearson, R.L., C. J. Tucker, and L.D. Miller. 1976. Spectral mapping of short grass prairie biomass. Photogramm. Eng. Remote Sens. 42:317-3245.

Ripple, W.J. 1095. Asymptotic reflectance characteristics of grass vegetation. Photogr. Eng. Remote Sens. 51:1915-1921.

Shibayama, M. and T. Akiyama. 1989. Seasonal visible, near-infra-red and mid-infrared spectra of rice canopies in relation to LAI and above-ground dry phytomass. Remote Sens. Environ. 27:119-127.

Sellers, P.J. 1985. Canopy reflectance, photosynthesis and transpiration. Int. J. Remote Sens. 6:1335-1372.

Tucker, C. J. 1979. Red and photographic infrred linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127-150.

Tueller, P. T. 1989. Remote sensing technology for rangeland management applications. J. Range Manage. 42: 442-453, Remote Sens. Environ. 8:127-150.

APPENDIX 1

Equations used to calibrate spectral values from Landsat imagery for Yellowstone National Park on 13 August 1990 and 31 July 1991 to August 2, 1989 for 6 thematic mapper (TM) spectral bands.

Year	TM Band	a	b	s.e.	r^2
1990 to 1989	1	-10.90	1.174	3.05	0.99
	2	- 4.14	1.097	1.25	0.99
	3	0.31	1.081	16.94	0.86
	4	- 6.81	1.162	3.89	0.99
	5	- 0.27	1.018	4.51	0.99
	7	- 1.54	1.146	3.54	0.98
1991 to 1989	1	2.53	0.962	1.39	0.99
	2	- 0.87	0.955	0.82	0.99
	3	4.96	0.906	17.14	0.88
	4	- 2.47	1.043	3.42	0.99
	5	3.32	0.901	1.19	0.99
	7	2.64	0.935	5.85	0.96