Technical Report No. 214

MAPPING STANDING CROP BIOMASS BY COMPUTER PROCESSING OF AERIAL MULTISPECTRAL IMAGERY

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GRASSLAND BIOME

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ABSTRACT

This technical report describes the processing of multispectral scanner data obtained over the Pawnee National Grassland in September 1968, for estimation of the amount of standing crop. Large area biomass determinations were tested on the scanner data using both a channel ratio technique and multispectral pattern recognition technique. The resulting biomass maps show correlations with several ground truth sites of 80% and 90% between the estimated biomass values from the multispectral data of an area and biomass values taken from clipped plots in the same area.

INTRODUCTION

One of the most important parameters of a shortgrass prairie which needs to be mapped on a spatial basis is the amount of the standing vegetative crop present on that prairie. Traditional estimates of the standing crop have been based on an estimation method which employs the destructive clipping and weighing of a known area of vegetation to determine this standing crop. There are two particular disadvantages to this clipping method. The first is that an area once clipped is not available for resampling at a later date. The second is that the method is tediously performed by hand and is a very inefficient method of biomass estimation.

A more efficient method of biomass determination is described which is based on the selective reflectance by varying amounts of vegetation of the incoming sunlight. This method can be implemented from ground-based or aerial platforms and is performed much more easily and rapidly than the hand-clipping method.

The basis of the biomass estimation method which was implemented for this report has been described earlier (Pearson and Miller, 1972*a*; Pearson and Miller, 1971*a*). The technique which exploits the relationship between the reflectance of light from a grass plot and the amount of green vegetation present on that plot was established on the ground using the U.S. IBP field spectrophotometer lab (Pearson and Miller, 1971*b*).

This technical report is a discussion of the results of the evaluation of two aircraft methods of multispectral biomass determination and mapping. The test data were collected on 17 September 1968 over the Pawnee Site of the U.S. International Biological Program (IBP) Grassland Biome, located 27 miles northeast of Fort Collins, Colorado (Fig. 1).

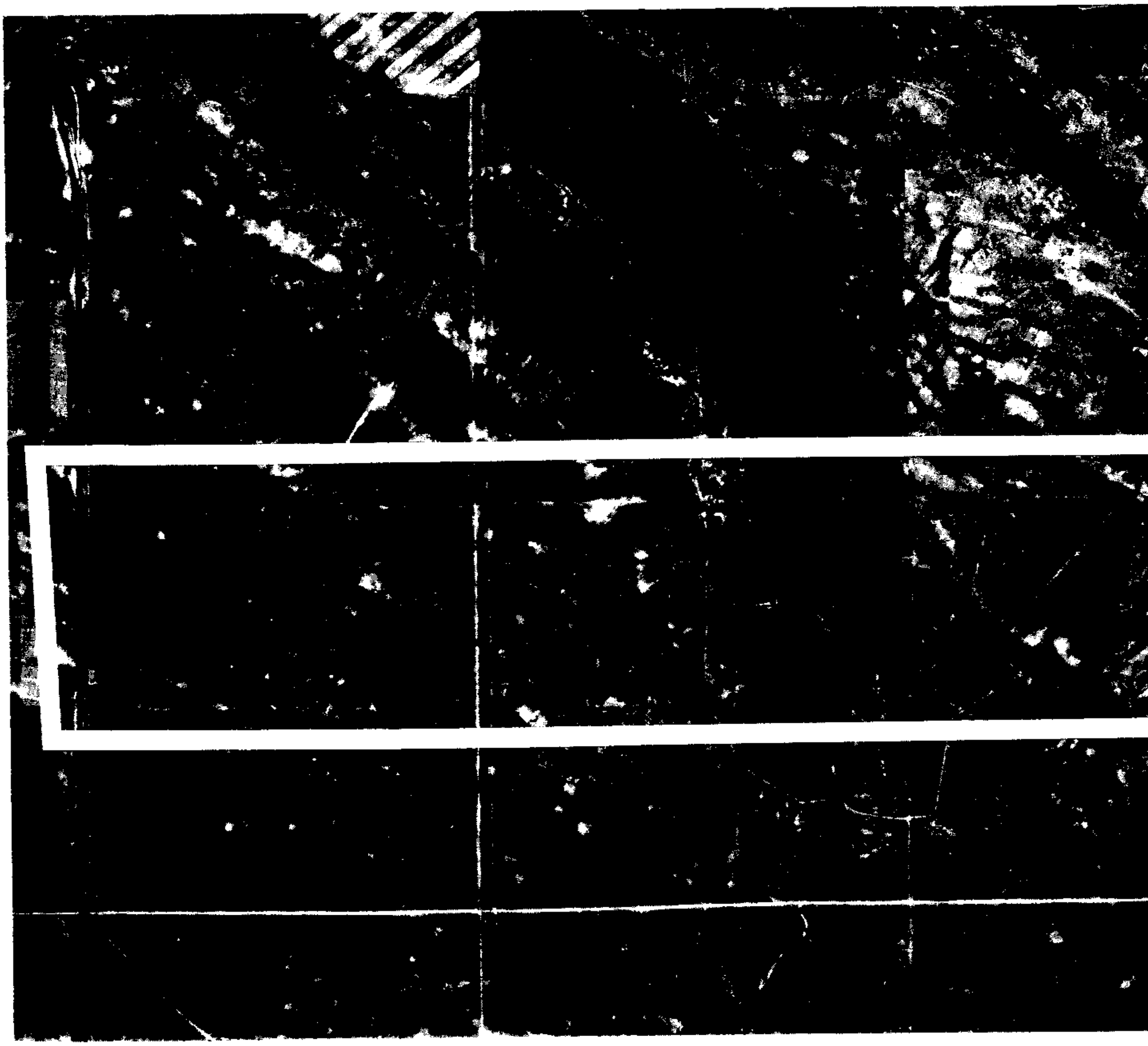
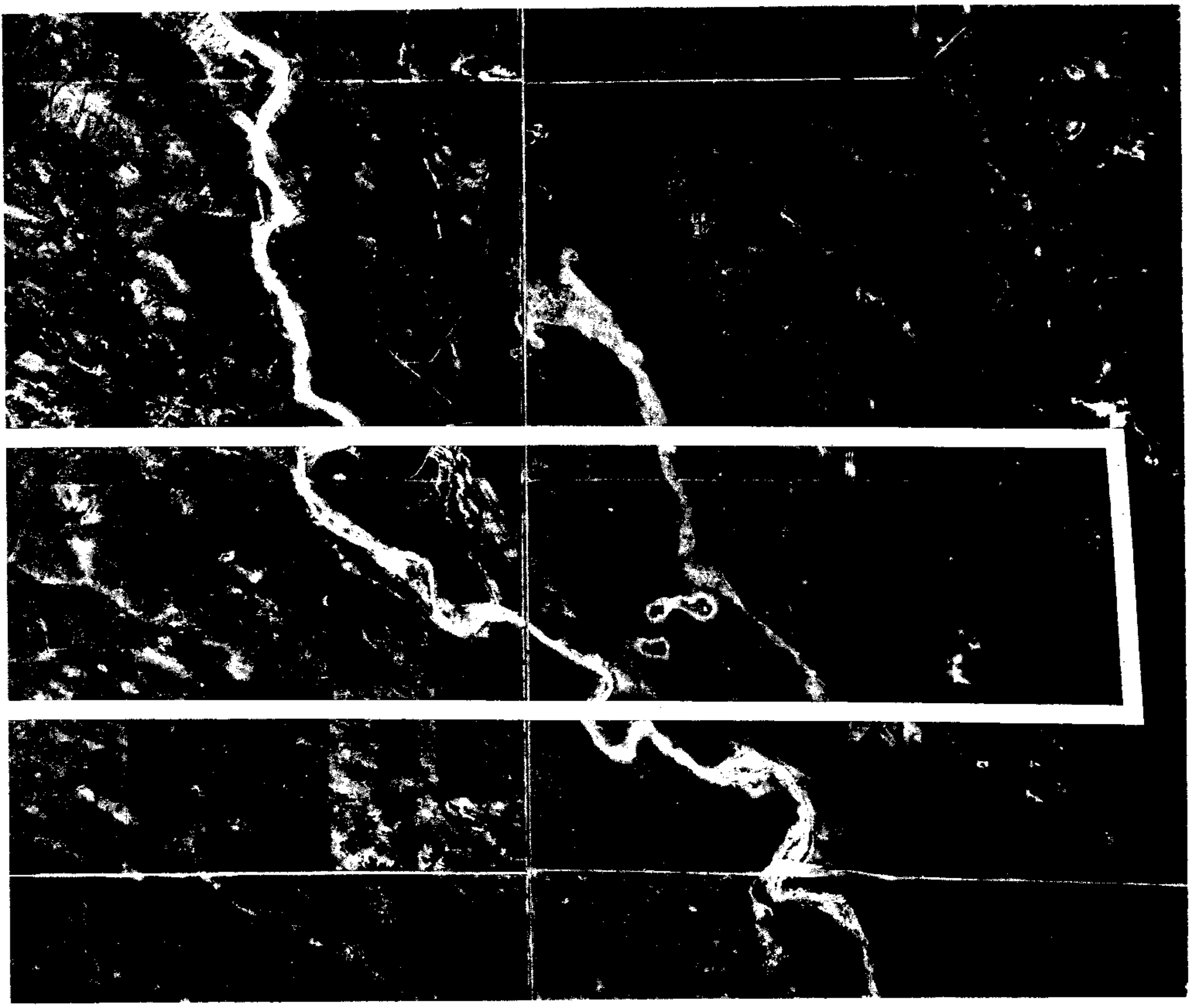


Fig. 1. The outline of the portion of the Pawnee Site of the U.S. IBP Grasslan
white was sampled by airborne multispectral scanner Run 24 on Septemb
scanner system. Aerial photography for this mosaic was flown on July



ome whose biomass was mapped from the air. The area outlined in
, 1968, by the University of Michigan's airborne multispectral
.963. Approximate scale is 1/25000 or 1 inch = 2100 ft.

MULTISPECTRAL DATA COLLECTION

The aerial data used in this study were collected by the University of Michigan under the sponsorship of North American Rockwell Corp., Space Division. A preliminary report was written by the University of Michigan (Wagner and Colwell, 1969) for the project sponsors, describing in detail the data gathering and data processing techniques employed. Summaries of the important points presented in this limited-distribution report have been included here for the benefit of the reader.

The Michigan data collection system was an optical mechanical multispectral scanner system mounted in a C-47 aircraft which sampled the radiance (brightness) from the ground in 10 narrow wavelengths or spectral bands[1/] of the visible and photo infrared region of the electromagnetic spectrum (Fig. 2).

The scanner is constructed so that the radiance levels in 10 spectral bands (Table 1) are sampled simultaneously from a single patch of ground. The size of the ground patch is controlled by the optics of the particular scanner system and is a circular area approximately 2.5 m (8 ft) in diameter directly below the aircraft at the mapping altitude of 731 m (2400 ft) above average terrain height. This ground patch resolved grows correspondingly larger at locations to either side of ground directly beneath the aircraft due to the corresponding increased distance to the ground. The average ground patch resolved for this flight was about 10 m on a side. The radiant energy from each ground patch in each of the 10 spectral bands measured by the scanner was recorded on an analog tape recorder aboard the aircraft and subsequently digitized onto another tape for processing on a digital computer.

1/ These wavelength bands could correspond to colors in the visible spectrum or some other wider or narrower interval of wavelength.

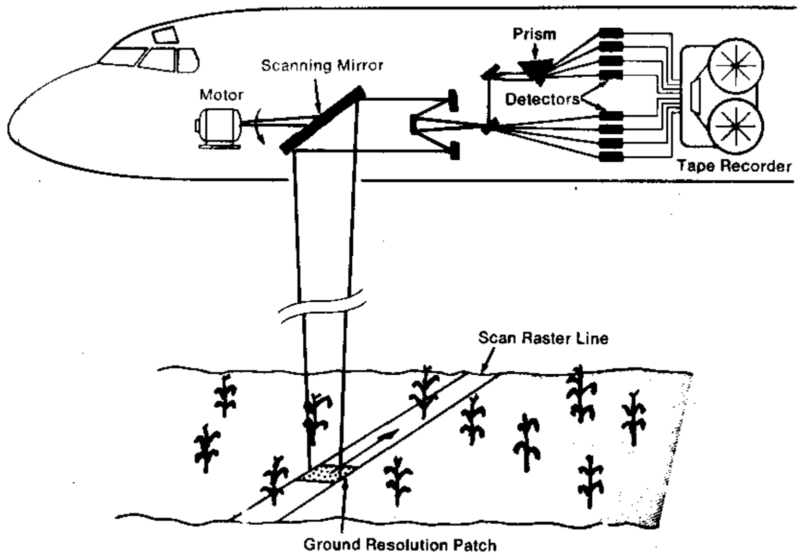


Fig. 2 Airborne multispectral scanner system. The scanner sweeps an optical path from one side to the other as the plane flies forward; thus viewing, in successively scanned strips, the ground passing beneath the aircraft. The radiation from each ground resolution patch is broken down into its constituent wavelength intervals, converted to electronic signals, and recorded on an analog tape recorder for later playback. (Figure courtesy of Laboratory for Applications of Remote Sensing, Purdue University).

Table 1. Spectral bands sampled by multispectral scanner.

Channel Identification Number	Color Seen by Human Eye	Wavelength (measured in micrometers[a/])
1	Violet	0.40 to 0.44 μm
2	Blue-Violet	0.46 to 0.48 μm
3	Blue-Green	0.50 to 0.52 μm
4	Green	0.52 to 0.55 μm
5	Yellow-Green	0.55 to 0.58 μm
6	Yellow	0.58 to 0.62 μm
7	Orange	0.62 to 0.66 μm
8	Red	0.66 to 0.72 μm
9	Deep Red	0.72 to 0.80 μm
10	The Photo Infrared (Not seen by eye)	0.80 to 1.0 μm

[a/] 0.40 micrometers is 4000 Å

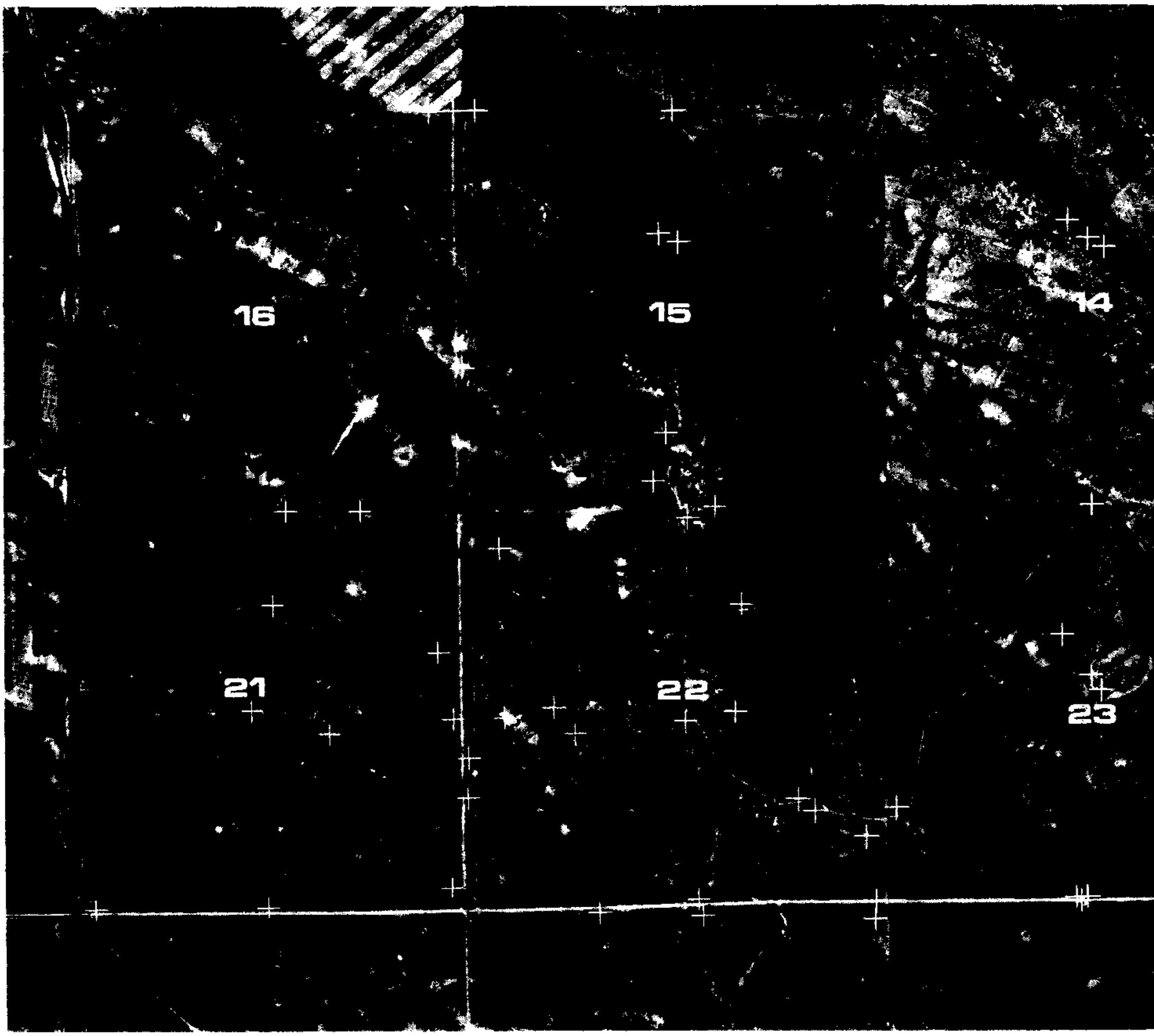
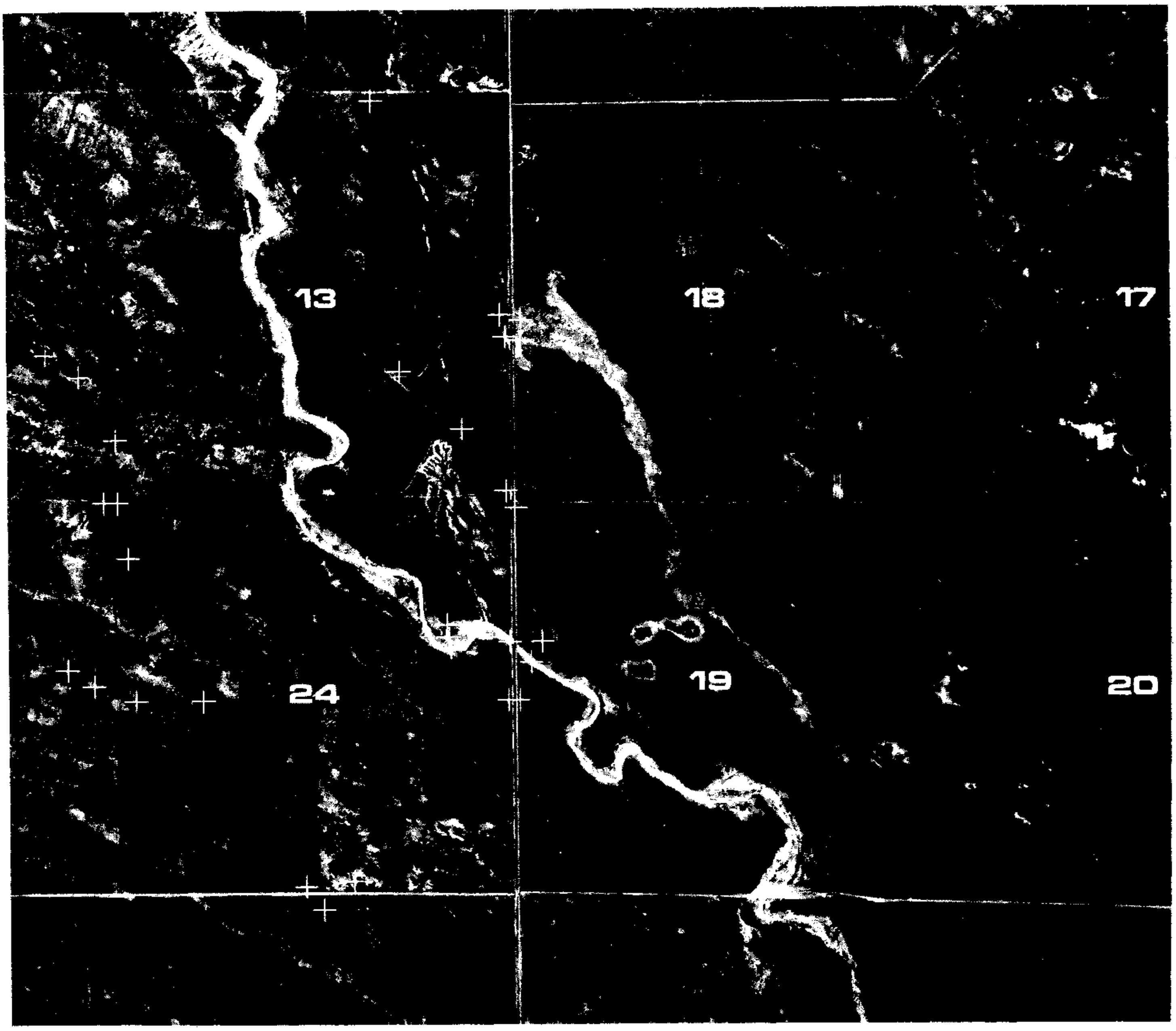


Fig. 3. Annotated photomap of the Pawnee Site and neighboring sections showing gro
for exact outline of Run 24. The numbered sections lie in Township 10 Nor
denote locations where the ground control sampling was conducted. The sca



control points sampled during the overflight. See Fig. 1
Range 65,66 West, 6th Principal Meridian. The white crosses
is approximately 1/25000.

Simultaneous with the aerial data collection, detailed "ground truth" data was collected at 87 separate locations on the Pawnee Site (Fig. 3). These ground data were collected by U.S. IBP, University of Michigan, and North American Rockwell personnel. At each location, values were obtained for target type (vegetation, soil, ridge top, etc.), dominant species, soil type, soil water, and wet and dry total forage biomasses for a one square meter area. At selected locations, measurements were also made of vegetation temperature and soil surface temperature.

The aerial data for the entire mission were collected between the hours of 9:00 A.M. and 12:00 Noon, Mountain Standard Time, on 17 September 1968. There was no cloud cover at the start of the data gathering mission, but by the end of the flight the cloud cover was approximately 50%. A total of 26 flight passes were made by the aircraft, 12 in a north-south orientation from an altitude of 1463 m (4800 ft) above mean terrain, 11 in an east-west orientation from an altitude of 731 m (2400 ft) above mean terrain, and three in a northwest-southeast orientation from 365 m (1200 ft) above mean terrain. Because of the large amount of total aerial data collected, and because of the cloudy conditions later in the flight, one representative line (Run 24) was chosen for further data processing and analysis (Fig. 1).

UNIVERSITY OF MICHIGAN PROCESSING OF THE DATA

The aerial data, after being recorded on the analog tape in the aircraft, were taken to Ann Arbor, Michigan, for digitizing and data processing. The first step was the electronic preprocessing of the raw analog data to remove a continuous, predictable variation in the signal levels of all 10 channels across the flight line. This variation was caused by the unequal reflection of light from the ground in directions away from the sun as compared to directions toward the sun (bidirectional reflectance). Several preprocessing techniques were tried, but the most successful was an angular function of the form $f(\theta) = a + b\theta + c\theta^2$ where θ is the angle measured at the aircraft from the edge of the flight strip to the ground location being adjusted. This preprocessing function did a fairly good job of adjusting the scanner imagery so that the bidirectional reflectance scan angle or bias was substantially removed. However, some minor errors were introduced into the data, specifically, in the northwest corner of section 23 where the radiance levels from a small cloud-shadowed area were raised to levels of heavy green vegetation, causing misclassification in later processing.

The next processing step was the display on film of the preprocessed image for each spectral channel (Fig. 4) so that the ground control areas of known composition on the ground could be located and identified in the scanner imagery.

The final processing step performed by the University of Michigan was the computer recognition processing (Lowe and Braithwaite, 1966) of the Run 24 scanner imagery using first an analog computer and then a digital computer. The classification methods used were similar to the methods used in the Colorado State University (CSU) recognition processing described later.

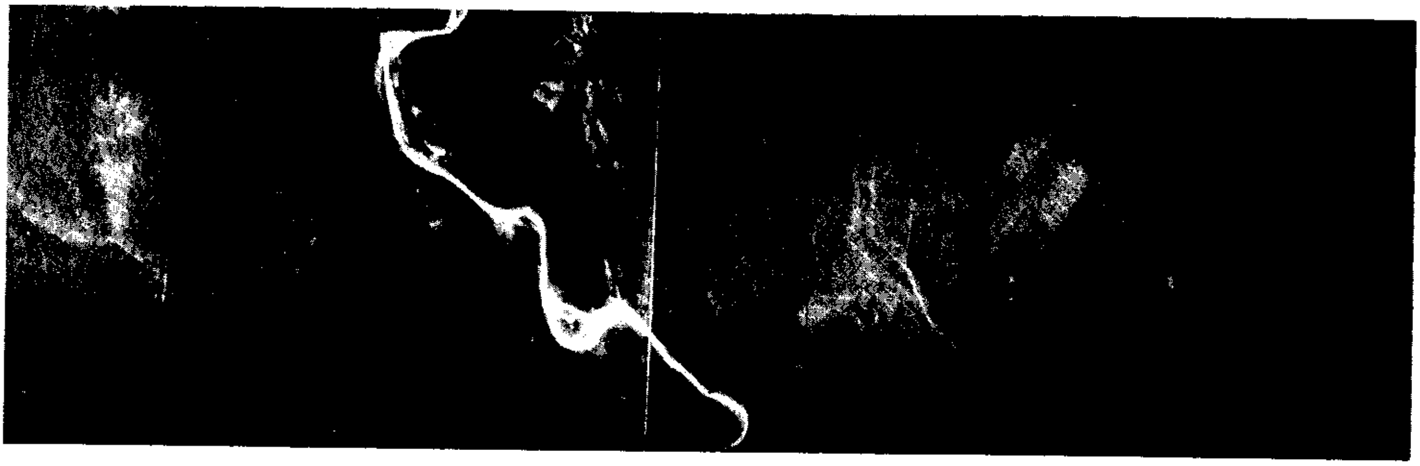
The general conclusions reached by the University of Michigan personnel for the Run 24 set of data collected in September was that individual species of the shortgrass vegetation could not be mapped with the available imagery, but that classes of vegetation representing different biomass ranges could be mapped with fair reliability. They recommended that a more optimum classification of biomass (and possibly individual species) could be made from multispectral data collected during the spring growing season in May or June rather than under the very dry fall conditions.

a) Channel 1

b) Channel 2,

c) Channel 3,

Fig. 4. Photoprints of analog scanner imagery of 3 of the 10 different simultane
Grasslands flown September 17, 1968, from west to east at an altitude of
of the specific ground area overflown. The scale is approximately 1/250



0 to .44 μm.

6 to .48 μm.

) to .52 μm.

ıly acquired wavelength bands for Run 24 of the Pawnee National
31 m (2400 ft) above mean terrain. See Fig. 1 for the outline

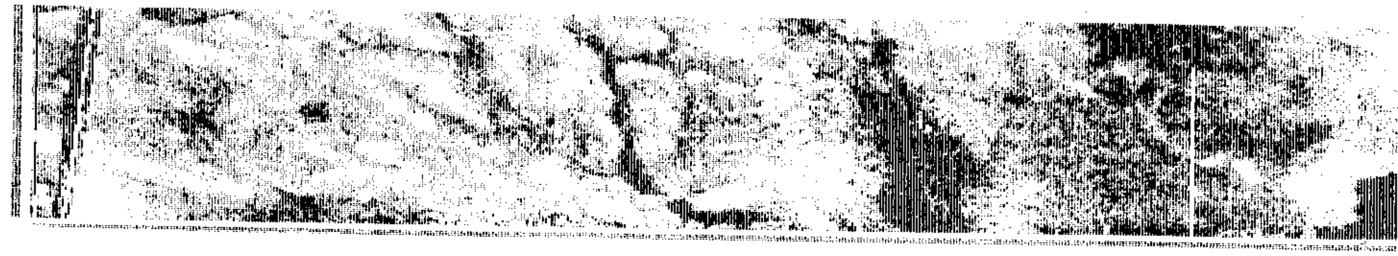
RECOGNITION (RECOG) PROCESSING AT CSU

After the multispectral data were processed at the University of Michigan and the final report written (Wagner and Colwell, 1969) and distributed, it was decided to reprocess the flight line of data through the Pattern RECOGnition Programs (RECOG) package on the CSU CDC 6400 computer. The RECOG package of routines is used to examine and display a tape of multispectral imagery and to classify the imagery into several surface classifications (Smith, Miller and Ells, 1972; Ells, Miller and Smith, 1972*a*; Ells, Miller and Smith, 1972*b*). This reprocessing was justified by the fact that a great deal was now known about the biomass distribution on the shortgrass prairie and its relationship to the spectral characteristics of the surfaces involved (Pearson and Miller, 1972*a*).

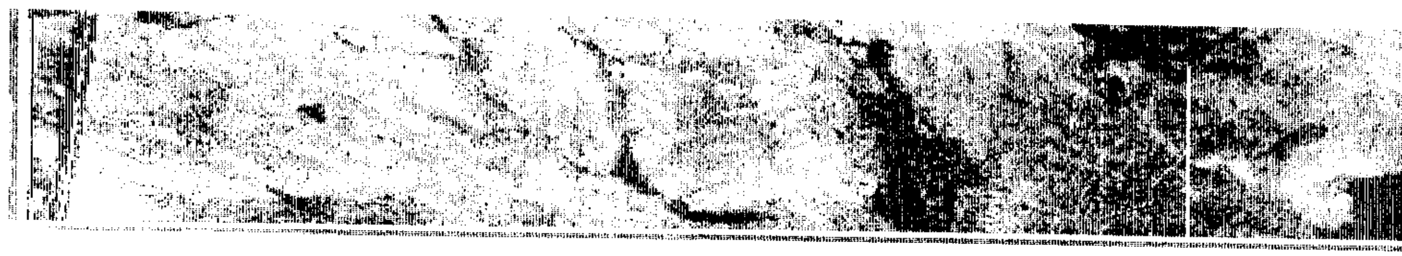
A digital tape of the Run 24 data which had been preprocessed as described above was obtained from the University of Michigan. The tape was reformatted for processing by the RECOG package; individual channel grey maps (Fig. 5) were printed out on a standard line printer by Phase 1 of RECOG[2/] so that training sets could be established. The amount of computer time used in all of the RECOG processing to be described was reduced 75% by processing only every other point within every other line.

The training sets were chosen within the imagery so that they corresponded to known areas on the ground which were representative of the final recognition classes of biomass desired from the RECOG processing. The sets were selected so that as many of the 87 known ground control points as possible from as many separate areas as possible were used in computing the statistical parameters of the reflectance of each biomass class in each

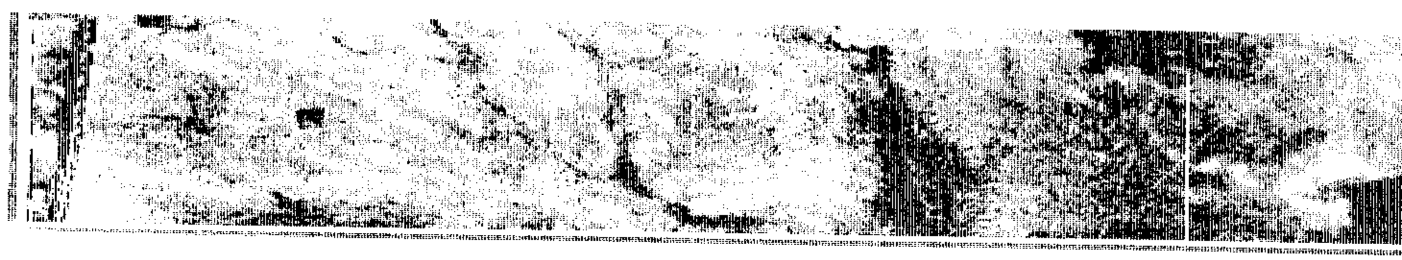
2/ RECOG is organized into six ordered phases for easy interaction and use.



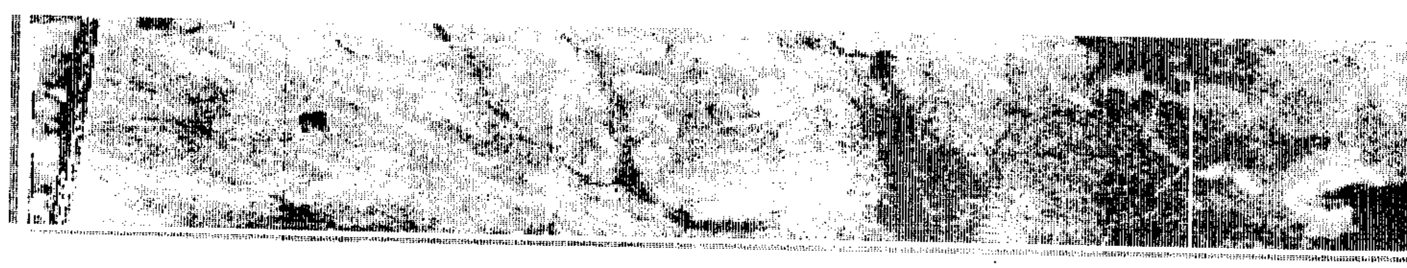
a) Channel 1, .40



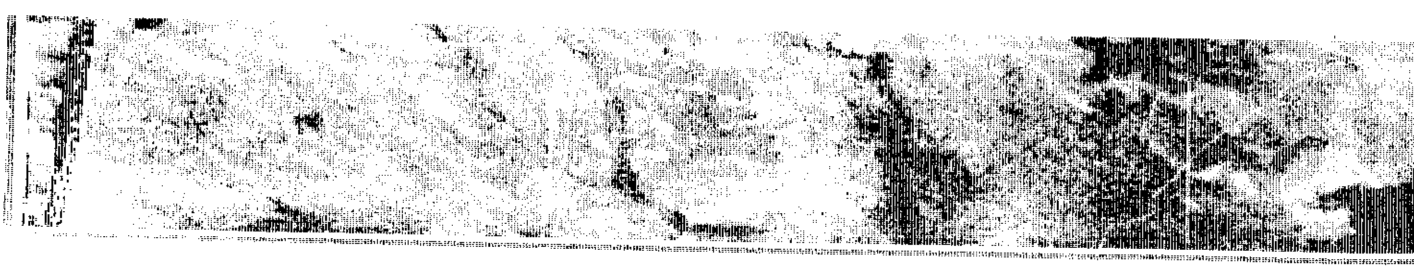
b) Channel 2, .46



c) Channel 3, .50 t



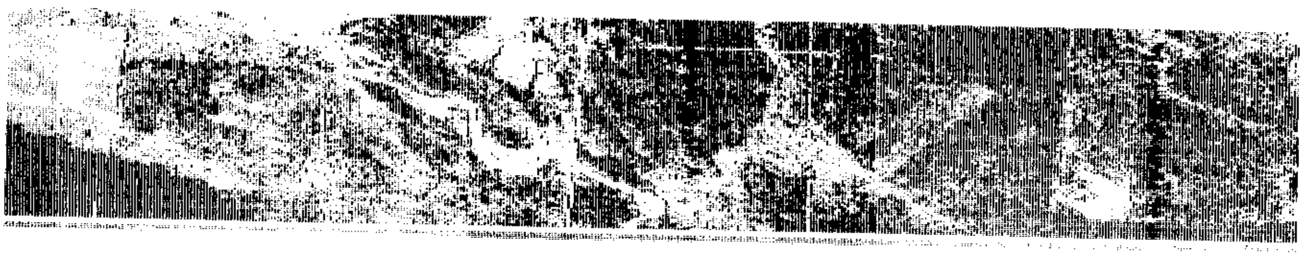
d) Channel 4, .52 t



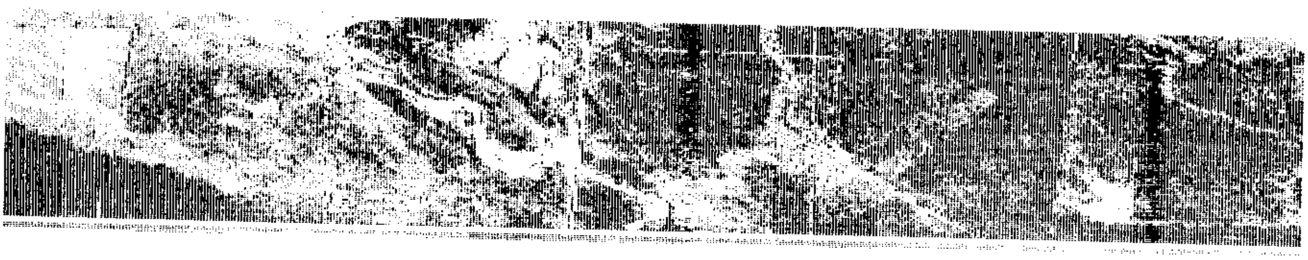
e) Channel 5, .55 to

Fig. 5. Digital grey maps of Run 24 scanner imagery of the Pawnee Site. Printed on
of low radiance in the spectral band, and a light or missing symbol represe
represents an average ground area of 10 m on a side. Fig. 1 shows the spec

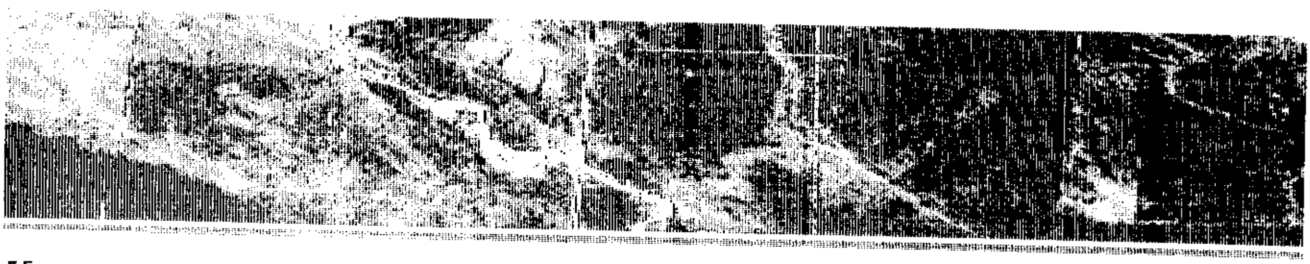
.44 μm.



.48 μm.



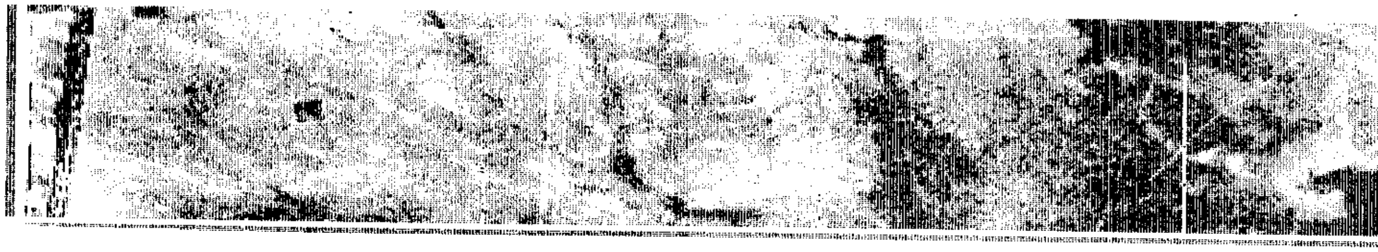
.52 μm.



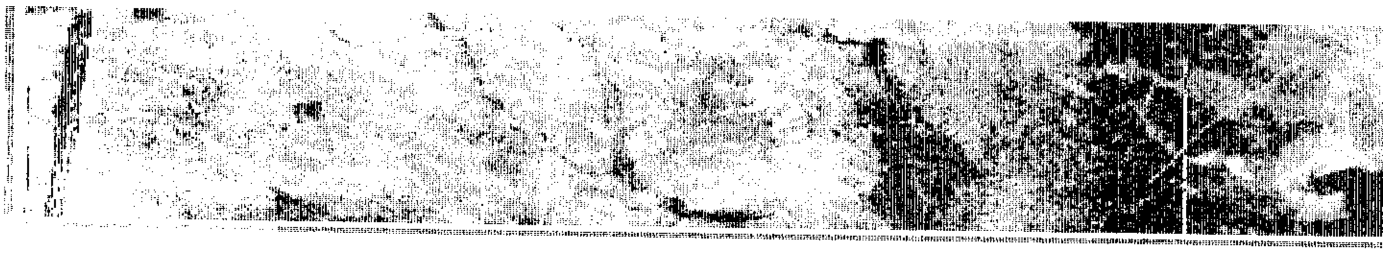
55 μm.

58 μm.

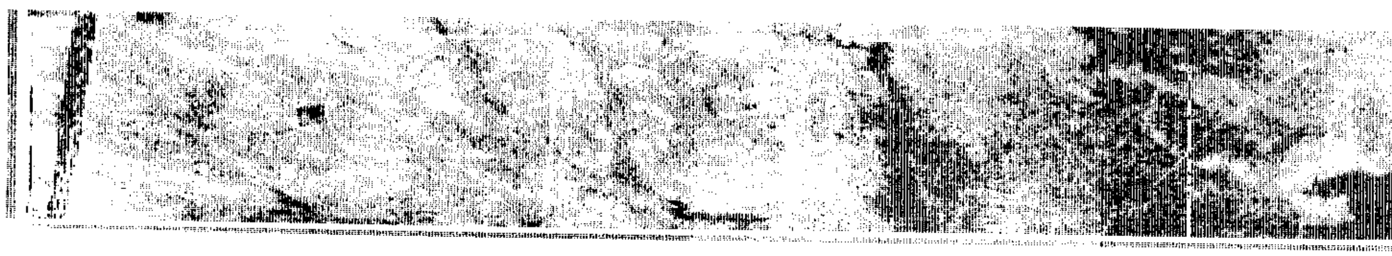
computer line printer where a heavy symbol represents an area
s an area of high radiance in the spectral band. Each symbol
ic ground area overflown. The scale is approximately 1/25000.



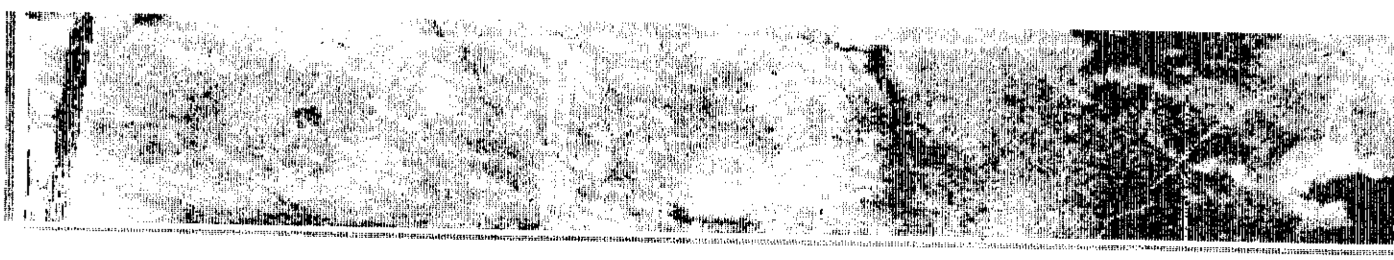
f) Channel 6, .58



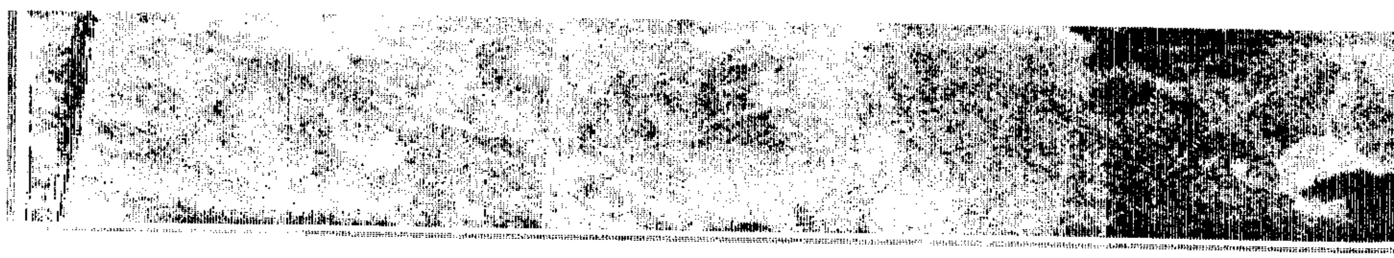
g) Channel 7, .62



h) Channel 8, .66



i) Channel 9, .72



j) Channel 10, .80

Fig. 5. Continued.

62 μm.

66 μm.

72 μm.

80 μm.

1.00 μm.

of the 10 spectral bands. These training sets were selected by inspection of aerial photography (Fig. 2) and the grey maps (Fig. 5). The training sets can be located by the computer within the total flight strip by the input of the two rows and two columns which define a rectangle bounding the selected area (Table 2).

Once the training sets representing the known biomass conditions had been chosen and input, Phase 2 of RECOG computed statistical parameters of each of the training sets. These parameters consisted of the mean and standard deviation of the radiance in each of the 10 channels for each individual training set and each total class. These results were presented in the form of tabular listings, channel histograms, and coincident class spectral plots (Fig. 6). These spectral plots are similar to spectro-radiance data which can be obtained from a ground based spectrometer system (Pearson and Miller, 1971*b*) and therefore could have been correlated to ground spectral measurements had they been taken at the time of over-flight.

RECOG Phase 3 was used to select the set of multispectral channels which would optimally distinguish between the six biomass mapping classes specified by the training sets. The criterion of optimality was based on the maximum statistical divergence of all of the classes for a minimum number of spectral channels. Divergence is a statistical parameter which measures the relative differences between the means of the classes for a particular combination of available multispectral channels. The higher the divergence for a set of recognition classes in a spectral band, the better the possibility of correctly classifying each recognition class in later RECOG processing (Smith et al., 1972). For the Run 24 data, RECOG Phase 3 was run to select the best 1, 2, 3, 4, and 5 out of 10 channels for

Table 2. Run 24 training sets.

Biomass Class	Number of Sample Points	Grey Map Rows From	Grey Map Rows To	Grey Map Columns From	Grey Map Columns To	Geographic Description
Cloud shadow	3354	899	976	191	233	Cloud shadow occurring in SE ¼ of section 23 and SW ¼ of section 24.
400 g/m²	836	552	570	122	165	Western wheatgrass lowland in eastern half of section 22.
400 g/m²	1159	556	574	166	226	Same.
250 g/m²	225	175	189	108	122	Grazing exclosure north central portion of section 21.
250 g/m²	1763	655	697	90	130	Lightly grazed western half of section 23.
250 g/m²	3402	998	1051	70	132	Moderately grazed portion of NW ¼ of section 24.
250 g/m²	630	1052	1093	70	84	Same.
100 g/m²	3655	584	626	36	120	Heavily grazed portion of eastern half of section 22.
100 g/m²	1517	916	952	60	100	Heavily grazed portion of eastern half of section 23.
50 g/m²	465	430	460	198	212	Heavily grazed portion of NW ¼ of section 22.
50 g/m²	1166	452	504	176	197	Same.
50 g/m²	494	484	502	150	175	Same.
50 g/m²	1029	580	628	8	28	Moderately grazed portion of SW ¼ of section 15.
50 g/m²	133	820	838	158	164	Bottom of dry lake, section 23.
50 g/m²	170	834	850	148	157	Same.
Bare soil	85	431	435	26	42	Bald ridge top northern portion of NW ¼ of section 22.
Bare soil	375	436	460	22	36	Same.
Bare soil	90	436	450	37	42	Same.
Bare soil	174	451	479	22	27	Same.
Bare soil	330	1124	1133	12	44	Bottom of Owl Creek NW of section 24.
Bare soil	132	1224	1226	106	149	Same.
Bare soil	95	1230	1234	144	162	Same.
Bare soil	207	1236	1258	164	172	Same.
Bare soil	190	1248	1266	154	163	Same.

LEGEND

A= 250 g/m^2

B= Cloud shadow

C= 100 g/m^2

D= 50 g/m^2

E= Bare soil

F= 400 g/m^2

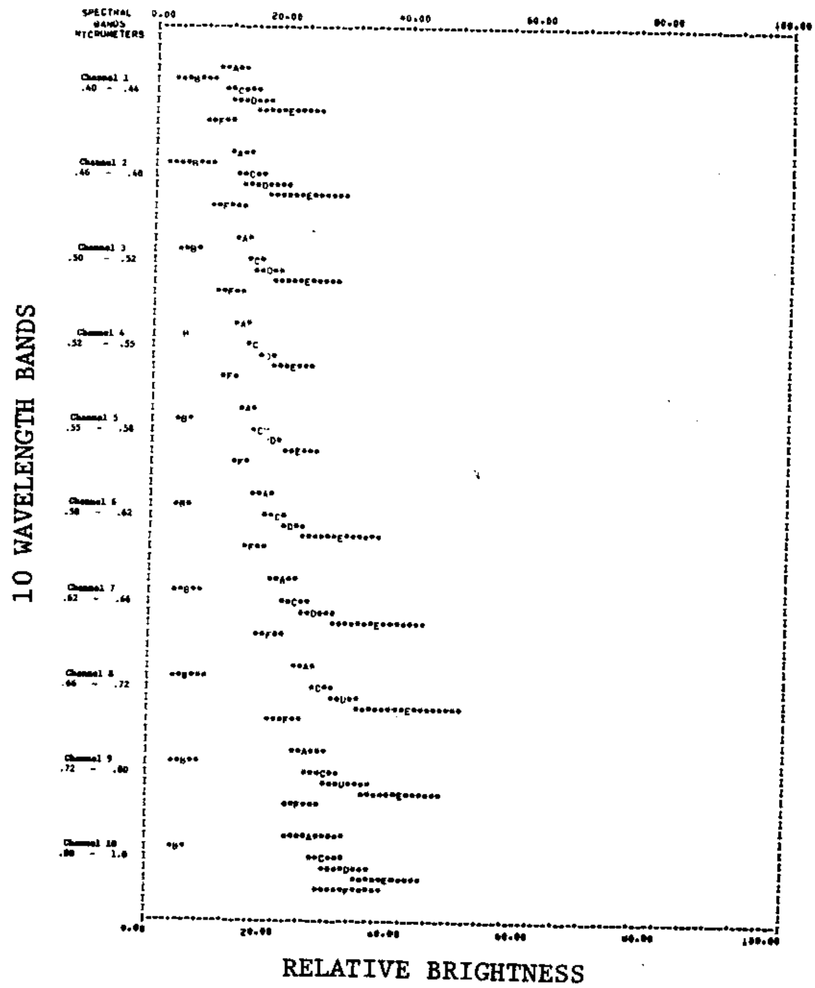


Fig. 6 Coincident class spectral plot. Abscissa is relative brightness from 0 to 100% and ordinate is channel number (color band) for all recognition classes. The plotted data is the mean ± one standard deviation of the brightness of each class in that channel.

distinguishing the six biomass classes to be mapped. The output determined that the combination of the wavelength bands, 0.52 to 0.55 μm, 0.55 to 0.58 μm, 0.66 to 0.72 μm, and 0.80 to 1.0 μm (channels 4, 5, 8, and 10) would give adequate distinction between the mapping classes with a minimum of computer effort.[3/]

Phase 4, the next RECOG processing step, was run to test classify using the best wavelength bands chosen in Phase 3 to process each of the known training sets chosen from Phase 1 above. The automatic classification method used for this and the next phase of RECOG processing was the maximum likelihood ratio based on the conditional multivariate Gaussian probability density functions of the classes for each of the multispectral bands. The results of the test field classification are given in Table 3. Computing the biomass of the data points in the ground areas used to train the processor gives the user a feel for the type of accuracy which can be expected from the approach. Decision rules other than the maximum likelihood ratio were also tested in this phase, but it was determined that the likelihood ratio method gave the best accuracy of classification.

The final step in the RECOG processing was the classification of the entire flight line using the maximum likelihood ratio in the same manner as Phase 4 noted above. This was done by classifying the entire flight line in RECOG Phase 5 and displaying the mapped results in Phase 6. The final recognition maps from Phase 6 were made with each class displayed separately, as a combined greytone display (Fig. 7, 8a, and 8b) from the line printer, and with the color composite of all classes and with each

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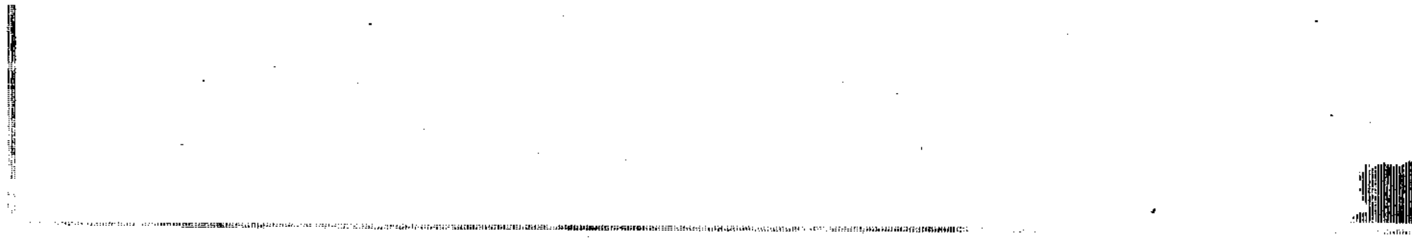
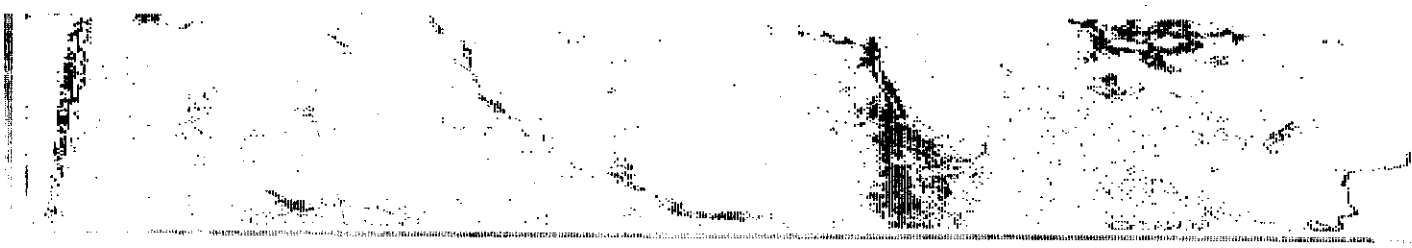
3/ Note that the last two wavelength bands are similar to the ones used in the ground based biomass estimation techniques referred to earler (Pearson and Miller, 1972).

Table 3. Results of Test Field Classification. Computing the biomass of the known ground areas used to train the processor indicates the accuracy which can be expected.

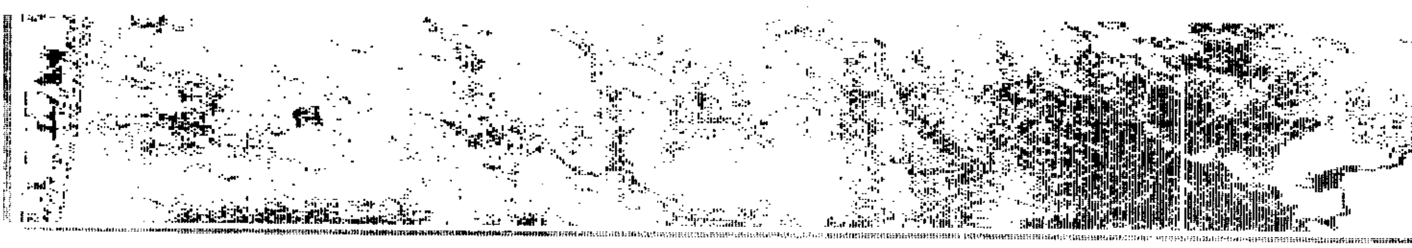
Biomass Class	Total Number of Sample Points in Training Sets	Percent Classified Correctly
Cloud shadow	3354	99.91
400 g/m^2	1995	86.61
250 g/m^2	6020	83.21
100 g/m^2	5172	83.06
50 g/m^2	3457	87.76
Bare soil	1678	84.92



a) Cloud shadow clas

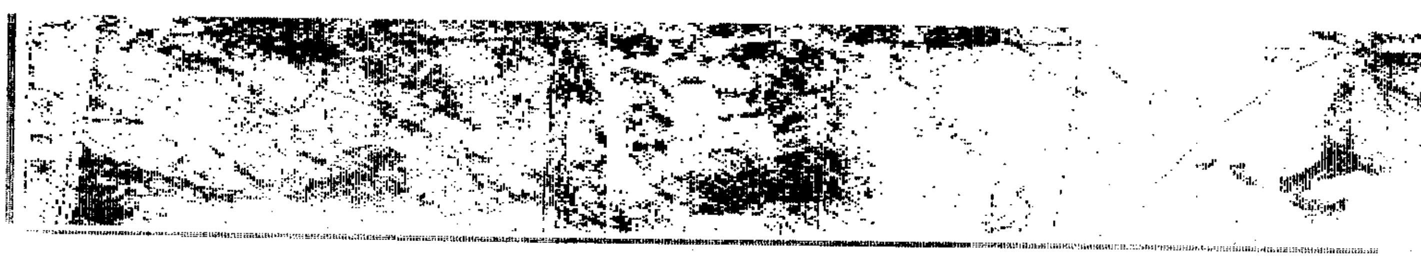


b) 400 g/m^2 average



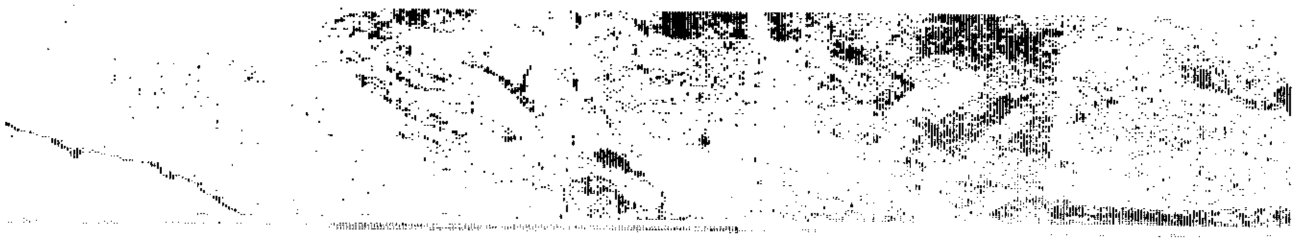
c) 250 g/m^2 average

d) 100 g/m^2 average

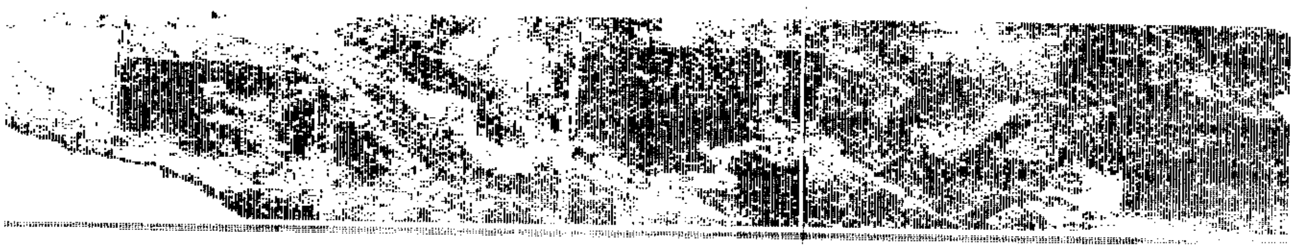


e) 50 g/m^2 average b

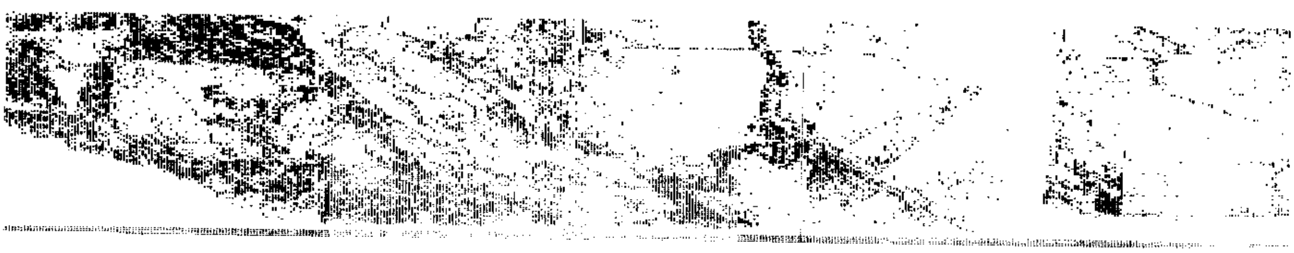
Fig. 7. Individual biomass class recognition maps. A symbol is printed only in ar
biomass class being mapped. Fig. 1 shows the specific ground area overflo



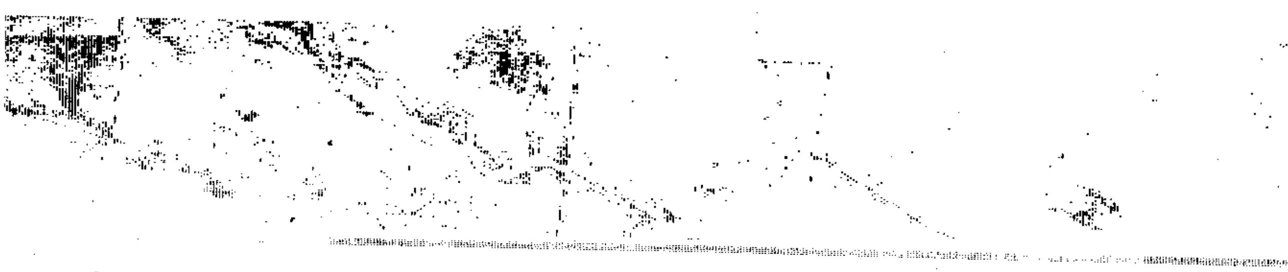
mass class.



mass class.

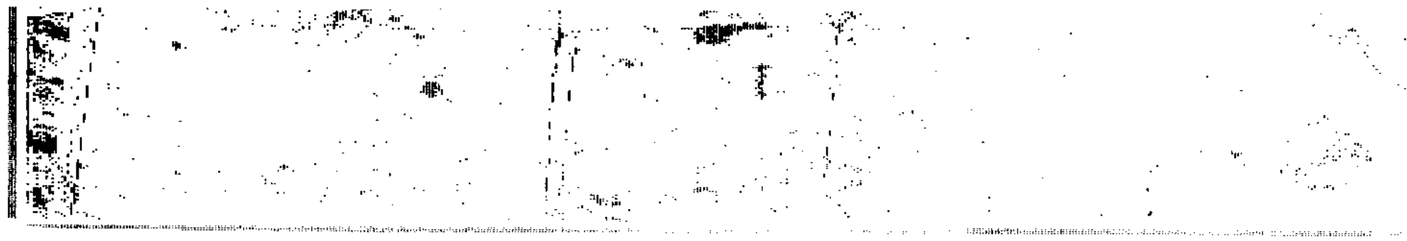


mass class.

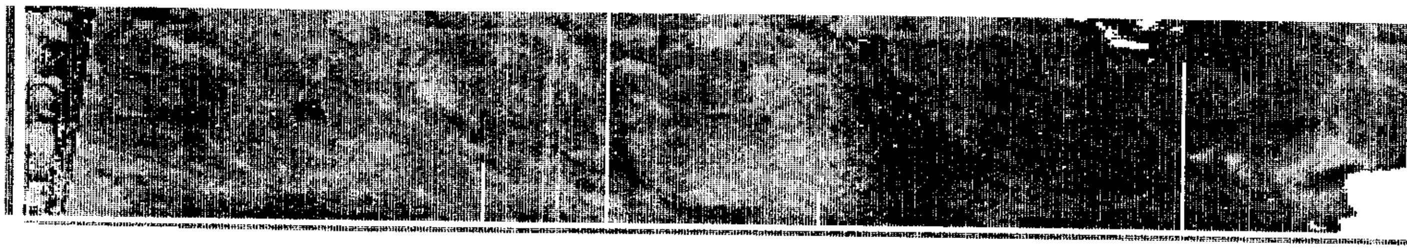


ass class.

s determined by the digital computer to belong to the particular
. The scale is approximately 1/25000.



a) Class soil (0 g/m^2 biomass).



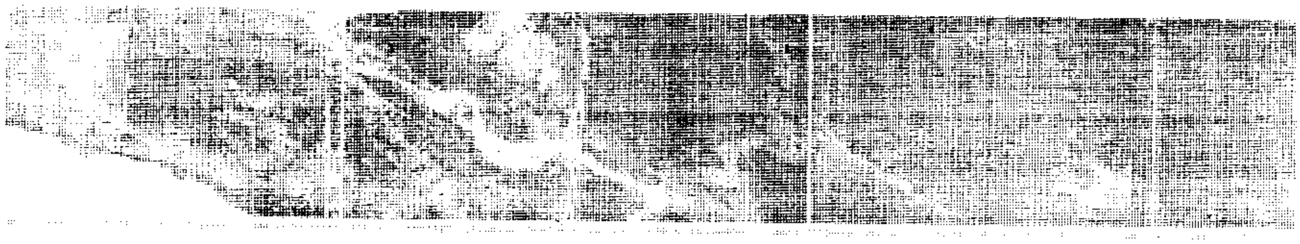
b) Composite recognition map of all classes.

c) Ratio of wavelength band .8 to 1.0 μm (channel 10) to

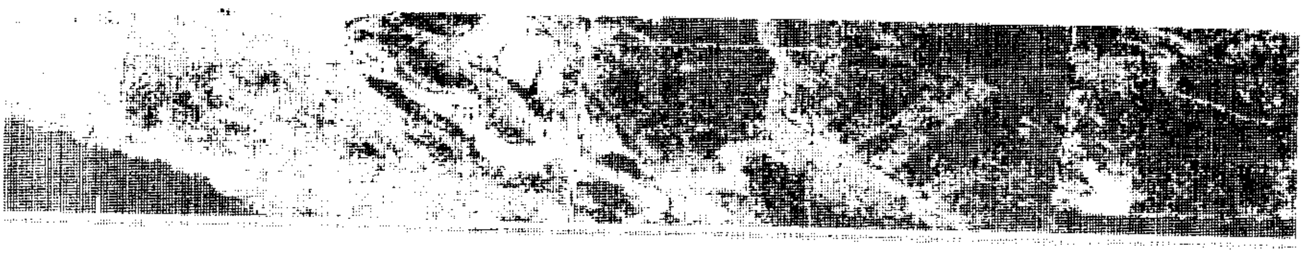
d) Digital grey map of multispectral scanner wavelength b

e) Digital grey map of multispectral scanner wavelength b

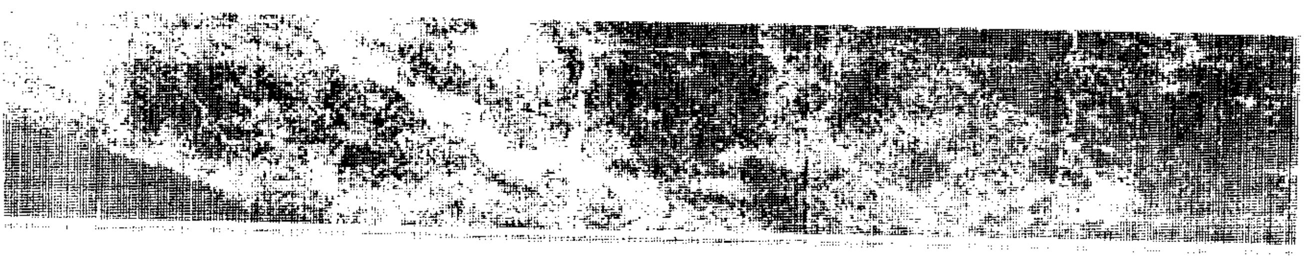
Fig. 8. Multispectral data processing maps. In sections b and c above, darker sy
of the line) represent higher amounts of biomass. The scale is approxima



ıvelength band .66 to .72 µm (channel 8).



ıd .66 to .72 µm (channel 8, same as Fig. 5h).



ıd .8 to 1.0 µm (channel 10, same as Fig. 5j).

ols (except for the area recognized as cloud shadow in the center
ly 1/25000.

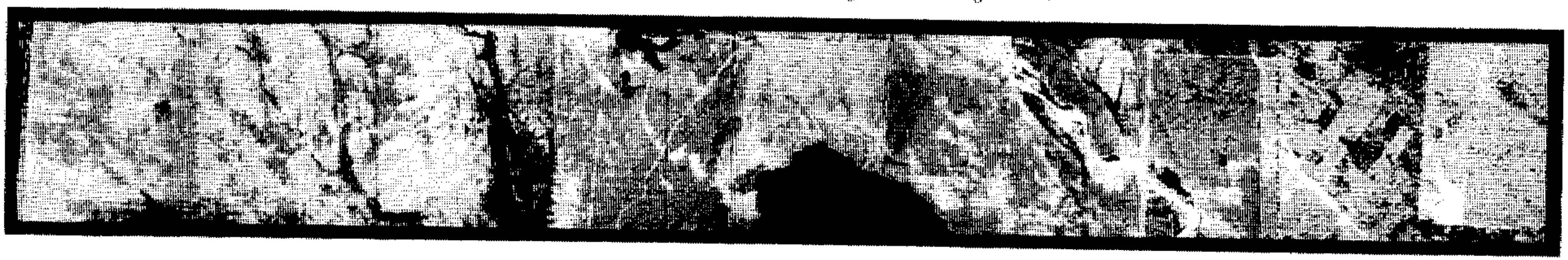
color class displayed separately over the grey map of channel 6 (0.58 - 0.62 μm) on the CSU digital color television display (Smith et al., 1972) Each frame of the color coded recognition maps was photographed from the color monitor, printed and mosaicked together to produce single images of the color recognition maps (Fig. 9).

One area contained in the processed flight line has been subjected to a seasonal grazing study for several years by the Central Plains Experiment station. The area is subdivided into 24 pastures each 1.9 ha (3.5 acres) in size (Fig. 10). The pastures are each grazed for one month each year. One of the two pastures grazed each month is annually fertilized with 40 pounds of nitrogen fertilizer per acre to study the combined effect of grazing and fertilizing the range vegetation (personal communication during 1972 with R. E. Bement, range scientist in charge of Forage and Range Branch, Agricultural Research Service, USDA).

The color RECOG map (Fig. 10) clearly shows the different biomass levels detected on each of the pastures. Pastures 5, 7, 8, 11, 12, 22 and 24 are detected as being high in biomass, which can be correlated to the fact that each of these pastures is nitrogen fertilized and grazed before or during June of each year. June is the principal month of biomass production on the shortgrass prairie and these pastures have recovered from the grazing. Pasture 3, which was unfertilized and grazed in the month of August just prior to the scanner flight, shows a low average biomass representing a grazed condition. The pastures which were fertilized consistently show a higher biomass than those which were not fertilized for a particular month, and pastures which were grazed previous to midsummer show higher average biomass at the time of the overflight than those which were grazed during or after midsummer (Fig. 11).

(a) Grey map of 0.58 to 0.62 µm radiance.

(b) Green is area classified as 250 g/m² of standing biomass.



(c) Classification of entire area into five standing biomass levels.

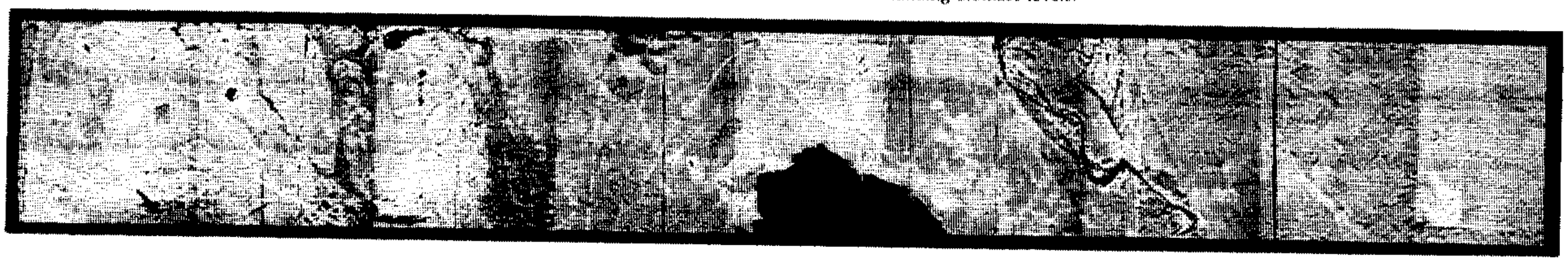


Figure 9.

Multispectral scanner images from the Pawnee National Grassland. All images were photographed from the CSU digital color television display as separate frames and mosaicked together to form the strips shown. Scale is approximately 1/30,000. (a) Grey map of the radiance from 0.58 to 0.62 µm of the multispectral scanner (channel 6). Note the rectangular grazing exclosure in the left end of the image and the large cloud shadow in the center. (b) 250 g/m² biomass class recognized by RECOG displayed as green overlaid on the grey map of radiance from 0.58 to 0.62 µm. (c) Recognition map of standing crop biomass. Black represents cloud shadow, blue represents 400 g/m² biomass, green represents 250 g/m² biomass, brown represents 100 g/m² biomass, yellow represents 50 g/m² biomass, and red represents bare soil. Note the linear boundary between areas of essentially green and brown color in the center of the image above the cloud shadow which corresponds to a section boundary between two pastures of different grazing teatments and biomass. (From Pearson and Miller, 1972*b*).

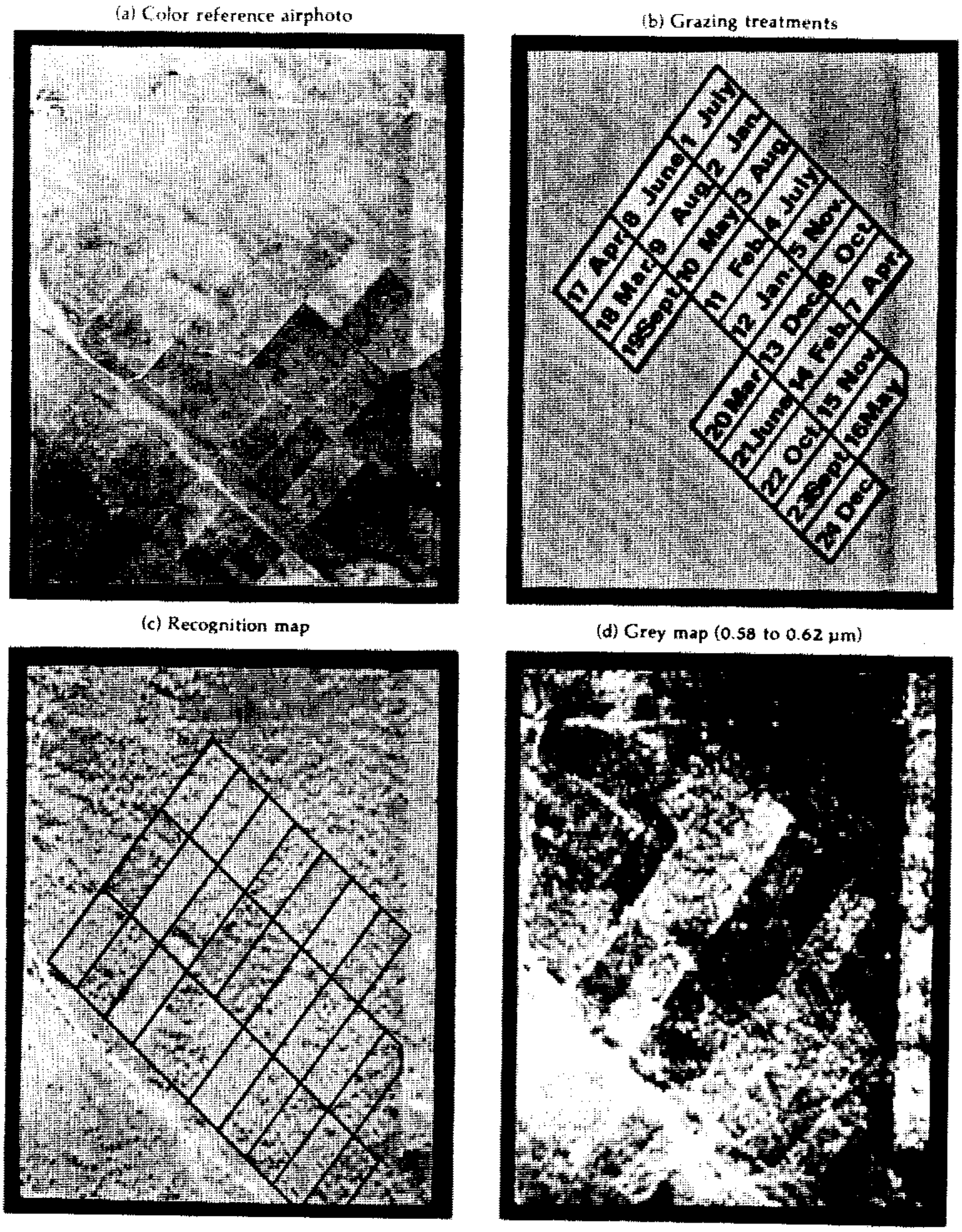


Figure 10.

Detailed analysis of imagery taken over month-of-grazing treatment pastures, Pawnee National Grassland. Each rectangular area represents a single 1.9 hectare pasture which is intensely grazed for only one month each year. (a) Color aerial photograph of the set of grazing treatment pastures taken on 19 June 1972, by CSU RC-8 mapping camera at 10:18 AM (personal communication during 1972 with W. J. McGuinnies and R. E. Bement, range scientists for the Forage and Range Branch, Agricultural Research Service, USDA). (b) Schematic diagram of pasture treatment. Each pasture is grazed for the one month shown. The green pastures are annually fertilized with nitrogen; the orange ones are not fertilized. (c) RECOGnition map of pastures. This figure is an enlargement of the right end of Fig. 9c. (d) Grey map of the radiance from the pastures in the 0.58 to 0.62 μm spectral band. This figure is an enlargement of the right end of Fig. 9a. (From Pearson and Miller, 1972*b*).

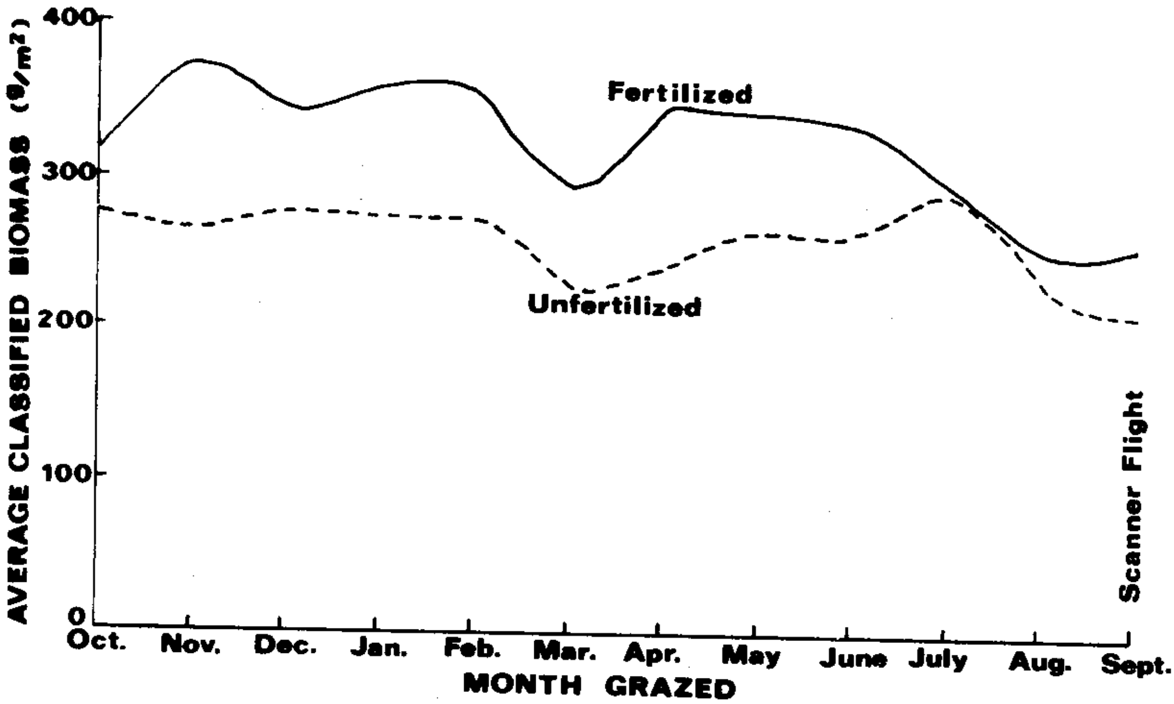


Fig. 11. Average mid-September biomass determined multispectrally for seasonal grazing study pastures. This average biomass was computed from the recognition map of grazing pastures (Fig. 10) by converting the symbols occurring in each pasture to biomass and computing their average.

Similar effects can be seen in the large grazing plots covered by the rest of the flight line. Each large pasture occupies an entire section or portion of a section and is subjected to different grazing pressures (Table 4). A very striking boundary can be seen in Fig. 9 in the central portion of the strip just above the black cloud shadow. The boundary between the brown and yellow pasture on the left and the green region on the right corresponds to the section boundary between a section which has a heavy summer grazing pressure to the west (23E) and a section which has moderate summer grazing pressure to the east (24). As Fig. 9 indicates, there is a marked biomass difference across the section boundary which is recognized and graphically displayed in the RECOG output. Biomass maps of this type can be very useful to the range manager in monitoring the condition of the range being grazed.

COMPARISON OF AUTOMATICALLY MAPPED BIOMASS WITH GROUND TRUTH DATA

The data processing and analysis which took place using RECOG did so without the a priori knowledge of the actual conditions on most of the ground images made by the flight line (except the information input into the processing when the training sets were chosen from the grey maps). The accuracy of the biomass mapping was checked by comparing the final biomass class estimated (Fig. 9) for actual ground truth locations sampled at the time of the scanner flight in areas other than in the training test fields used in RECOG.

The first step in correlating ground and aerial data was the identification of the ground truth sampling points in the multispectral imagery. During the week of the scanner overflight, a total of 87 ground plots of

Table 4. 1968 grazing treatments.

Section	Grazing Intensity Yearlings Section	Season
21 N	Heavy--72/section	Summer (May through October
21 S	Moderate--50/section	Summer
22 NW	Light--30/section	Year long
22 SW	Moderate--47/section	Summer
22 E	Heavy--75/section	Winter
23 W	Moderate--44/section	Summer
23 E	Heavy--84/section	Summer
24	Moderate--43/section	Summer

one square meter was clipped and the wet forb biomass, wet grass biomass, dry forb biomass, dry grass biomass, and percent soil water, soil type, etc. were determined. The position of each of these sampling points was annotated in the field on aerial photographs (Fig. 3) for later reference. These sample positions were subsequently located on the grey maps of the unprocessed multispectral images of the flight line displayed in Phase 1 of RECOG. Some 35 of the 87 ground truth points were in the area covered by the selected flight line.

It was estimated by careful examination of the digitally displayed imagery that a ground point could only be located within 15 m (approximately one Instantaneous Field-of-View [IFOV] or image cell) of its true location. Therefore, in obtaining the characteristics of the sample point from the imagery, the values for the IFOV or image cell thought to be the best estimated location of the ground truth point were averaged with values of their eight adjacent neighbor IFOV's. The image properties tested thus represent the average of nine IFOV's of the ground defining an area approximately 30 m on a side and centered at the best estimated position of the ground truth point. Occasionally, the ground truth points happened to lie on a boundary such as a narrow road which was easily recognizable on the digital images. The nine IFOV's used for averaging purposes in this case were selected from a rectangle whose center was at the estimated location of the ground truth point and whose long sides were parallel to the boundary detected in the imagery. These averaging methods were used to obtain the average scanner radiances from each of the 10 images and the computer classified biomass output by RECOG for each of the 35 ground points.

The correlation between ground truth data and the image values for the 35 available points was performed using a stepwise linear regression routine. The average radiances for each of the ground truth points for the two scanner channels which most closely sampled the wavelength bands used in the ground tests referred to earlier were converted to ratios, i.e., the average scanner radiances for channel 10 (0.8 - 1.0 μm) were divided by the radiances for channel 8 (0.66 - 0.72 μm) for each ground truth point. This radiance ratio, which can be used to estimate biomass, was regressed against the actual biomass clipped from each of the 35 one square meter ground points with a resulting correlation coefficient of 0.81. A correlation coefficient of 0.84 was calculated between the RECOG multispectral classification and the total dry clipped biomass of each ground point. The multiple regression of all of the 10 averaged radiance values representing each available spectral image with the total dry biomass on the plots gave a correlation of 0.74.

The plotted regression data showed that most of the outlying data values were from ground truth points taken from small anomalous areas of the grassland (such as narrow ridgetops, along narrow roads, etc.). The attempts to average using an elongated rectangle of nine points to handle ground truth points located along the recognizable boundaries in the imagery were not entirely successful. The nine ground truth points which were of this type were thrown out and the linear regression computations were repeated for the remaining 26 points. The resulting imagery-biomass correlations were far improved. The final correlation between the RECOG multispectral classification and the dry total biomass was 0.98. The least squares linear equation between clipped biomass and RECOG estimated biomass for the 26 ground truth points demonstrates almost a unity relationship between the two methods of biomass determination (bottom of Table 5). For the same set of 26 ground points the correlation between the channel ratio and dry total biomass was reduced slightly to 0.79.

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Table 5. Statistical results of the methods of biomass prediction from multispectral scanner data.

Ch 1 for 0.40 - 0.44 μm, Ch 2 for 0.46 - 0.48 μm, Ch 3 for 0.50 - 0.52 μm, Ch 4 for 0.52 - 0.55 μm, Ch 5 for 0.55 - 0.58 μm, Ch 6 for 0.58 - 0.62 μm, Ch 7 for 0.62 - 0.66 μm, Ch 8 for 0.66 - 0.72 μm, Ch 9 for 0.72 - 0.80 μm, Ch 10 for 0.80 - 1.0 μm.

Multiple regression of all scanner channels

Correlation Coefficient (R) = 0.79
N = 35

Dry Biomass = -18.8 + 32.6 Ch 1 - 66.3 Ch 2 + 14.6 Ch 3 + 102.8 Ch 4 - 80.9 Ch 5 + 7.2 Ch 6 - 9.3 Ch 7 - 7.9 Ch 8 + 50 Ch 9 + 11.1 Ch 10

Two channel ratio

Correlation Coefficient (R) = 0.79
N = 26

$$\text{Dry Biomass} = -327.7 + 429.2 \frac{\text{Ch } 10}{\text{Ch } 8}$$

RECOG spectrum matching

Correlation Coefficient (R) = 0.98
N = 26

Dry Biomass = 0.867 (Spectrum matching classification)

These results indicate that the recognition classes which were mapped by RECOG are representative of the actual biomass present on the plot. The channel ratio and multiple regression methods of biomass prediction from spectral data were also representative of the actual biomass present (Table 5).

ESTIMATION OF TOTAL DRY BIOMASS

Establishment of the relationship between the processed multispectral imagery and the actual biomass enabled one final simple computation to be made to estimate the total standing crop for the entire area sampled by the particular flight strip. This was done by counting the number of occurrences of each biomass classification in the flight line (Fig. 9) and by multiplying by the corresponding biomass values to yield the total biomass for each class. The class totals were then summed to give an estimate of total biomass in the area covered by the flight strip. The counting of symbols was actually done by the computer during the RECOG classification of the imagery so that the biomass prediction process could have been performed automatically by the computer for any smaller sub-areas covered by the imagery. This total biomass computation was not rigorous in that it did not account for the variation of ground area viewed (IFOV) at various scan angles. Since the spatial variation in biomass in fields imaged is random and the fields were wider than the width of the imagery, it was assumed that using an average ground area viewed, rather than an area adjusted for scan angle, would give a reasonable estimate of total biomass per field.

The simple calculations (Table 6) estimate the total biomass in the entire flight line and for a particular field within the flight line. These

Table 6. Computation of total dry biomass. Number of occurrences counted by the computer for the flight strip shown in Fig. 9.

Class Biomass (g/m^2)	Average Ground Cell Area (m^2)	Number of Occurrences	Total Mass of Standing Crop Biomass (kg)
Entire flight line shown in Fig. 9 (includes grazed and ungrazed pastures)			
400	100	10305	4.12×10^5
250	100	35208	8.80×10^5
100	100	33145	3.31×10^5
50	100	14493	0.72×10^5
	Average biomass per hectare		1.696×10^6 kg
	$\frac{1.696 \times 10^6 \text{ kg}}{936 \text{ ha}} = 1812$ kg/ha		
NW 1/4 Section 22 (lightly grazed year long)			
400	100	116	4640
250	100	661	16525
100	100	4018	40180
50	100	3188	15940
	Average biomass per hectare		77285 kg
	$\frac{77285 \text{ kg}}{65 \text{ ha}} = 1189$ kg/ha		

computed biomass or standing crop estimates can be compared with other estimates of aboveground biomass from other primary producer studies of the same area of the shortgrass prairie by other Grassland Biome program investigators (Sims and Singh 1971). They measured 2600 kg/ha for ungrazed pastures and 1690 kg/ha for grazed pastures at approximately the same time period as the overflight, but in a later year. The differences between their estimates and the multispectral aircraft estimates (Table 6) can readily be accounted for in the differences in precipitation (the latter year was more moist) (personal communication during 1972 of unpublished meteorological data from Pawnee National Grassland with D. Swift, Programming Coordinator, U.S. IBP Grassland Biome).

CONCLUSION

A definite relationship has been demonstrated between the amount of green vegetation present on a plot and the spectroradiance from that plot. This relationship has been of considerable value in devising a method of nondestructive measurement of percent cover and standing crop biomass in the shortgrass prairie. These biomass estimation methods are based on the basic biophysiological properties of the leaves of living green plants and will work in plant communities different than the shortgrass prairie, though they remain to be tested. The spectral bands in which the needed radiance data are measured are sampled by many present and future remote sensing data gathering systems such as Earth Resources Technology Satellite (ERTS) and SKYLAB satellite systems, as well as aircraft multispectral scanners. This indicates that a determination of the quantity of vegetation, in addition to its type and condition, may be possible on a worldwide, synoptic, timely basis.

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