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Title: Relationships Between Grass Canopy Characteristics and Landsat Thematic Mapper Bands
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The relationships between spectral reflectance in the Landsat Thematic Mapper (TM) bands and grass canopy variables were evaluated using *in situ* remote sensing techniques. Reflectance data were collected from experimental plots of annual ryegrass (*Lolium multiflorum*) and tall fescue (*Festuca arundinacea*) using a Barnes Modular Multiband Radiometer (MMR). The canopy variables used were canopy height, canopy cover, total wet biomass, total dry biomass, aboveground plant water, and leaf area index.

Statistically significant relationships were found between the spectral bands and the canopy variables. Inverse relationships in the visible (TM1, TM2, TM3) and middle infrared (TM5, TM7) regions were related to spectral absorption by plant pigments (visible) and moisture within plant tissue (middle infrared). Direct relationships in the near infrared (TM4, MMR5) were attributed to enhanced reflectance resulting from spectral scattering. Overall, no one spectral

band was found to be superior in all situations, but TM5 consistently showed the lowest correlations with the canopy variables.

Data sets were collected during three annual ryegrass phenological stages: early stem extension (June), anthesis (July), and senescence (August). The most significant correlations between reflectance and the canopy variables were found for the June data. High levels of biomass in July and plant senescence in August adversely affected the spectral reflectance/canopy relationships.

Data from the tall fescue plots were obtained from a wide range of total wet biomass levels (16.5 - 1677.9 g/m2). The asymptotic limits, or the biomass range for which the reflectance could be used to predict changes in the canopy variables, were studied. The reflection asymptotes were nearly twice as high for the near infrared (TM4) as for the visible and middle infrared bands (TM1, TM2, TM3, TM7).

The use of band ratios and normalized difference transformations did not consistantly increase correlations of spectral reflectance with the grass canopy variables. Logarithmic transformations of both the spectral bands and the canopy variables were successfully used to linearize the spectral reflectance/canopy regression functions. Redundancy was found among the absorption bands (TM1, TM2, TM3, TM7) and between the near infrared bands (TM4, MMR5). Principal component transformations were utilized to eliminate these spectral band redundancies. The seven spectral bands were reduced to two principal components, while maintaining nearly all of the variability found in the original bands.

Relationships Between Grass Canopy Characteristics and Landsat Thematic Mapper Bands

by

William J. Ripple

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CHAPTER I

INTRODUCTION

Two very important variables in grassland ecosystems are the spatial distribution and the temporal differences in the amount of vegetation. For example, quantitative estimates of the amount of above-ground biomass are needed for studies in primary productivity, evapotranspiration, forage availability, and rangeland condition and trend. Biomass estimates from grasslands have traditionally been determined by clipping plots and calculating the biomass per unit area. This method is very time-consuming and is difficult to apply over large geographic areas. As a result, remote sensing methods have been developed to monitor vegetation. The Landsat satellite system has been an important source of remotely sensed data for vegetation studies since the launch of the first satellite in 1972.

Biomass Mapping with Landsat

Landsat Multispectral Scanner (MSS) data have been used in several investigations concerned with grassland biomass estimation. The methods used in these studies typically involve locating sample plots on the ground, determining the amount of green biomass in these plots, and correlating these biomass measurements with digital values from the corresponding Landsat MSS pixels. Along with the individual band values, the ratio of two bands or other more complex vegetation indices are commonly correlated with biomass. Biomass maps are then developed using simple or multiple regression models based on the relationships between sample plot biomass and Landsat radiance values.

Researchers at Texas A&M University used digital Landsat MSS radiance data to produce maps of the amount of rangeland vegetation in the Great Plains (Rouse et al., 1973). Multiple regression models were developed from satellite (MSS radiance) and ground truth (green biomass) data collected repetitively during the growing season. Carneggie et al. (1974) found that Landsat MSS data provided information on plant growth stages, along with information on the differences in forage production on California's annual grassland. Bently et al. (1976) conducted research on ephemeral rangeland in Arizona and perennial rangeland in Montana on methods of processing Landsat MSS data for mapping vegetation characteristics. Their study indicated that Landsat MSS data were more sensitive to differences based on the total percentage of vigorous vegetation than to actual physical or spectral differences among plant species. Several methods for assessing natural vegetation conditions with landsat MSS data were reviewed by McDaniel and Haas (1982). They reported on techniques involving repetitive monitoring, band ratioing, regression analysis, and vegetation index modeling. Landsat MSS data were found to be sensitive to seasonal changes in vegetation growth conditions within relatively uniform vegetation/soil systems.

Significance and Objectives of Research

In 1982, Landsat 4, with the new Thematic Mapper sensor system, was launched by the National Aeronautics and Space Administration (NASA). This new system was designed with increased spatial resolution and improved spectral separation when compared to the previous Landsat systems (Table I.1). The Thematic Mapper uses narrower bands in the green (0.52 - 0.6 µm vs. 0.5 - 0.6 µm), red (0.63 - 0.69 µm vs. 0.6 - 0.7 µm), and near infrared (0.76 - 0.9 µm vs. 0.7 - 1.1 µm) as compared to the multispectral scanner. These narrower bands should allow vegetation parameters to be measured more precisely by the Thematic Mapper. Also, four new bands have been added to the Thematic Mapper, including 1 bluegreen band, 2 middle infrared bands and 1 thermal infrared band. The bluegreen band (0.45 - 0.52 µm) will supplement the red band in detecting differences in vegetation chlorophyll absorption. The new middle infrared bands (1.55 - 1.75 µm and 2.08 - 2.35 µm) are sensitive to the amount of moisture present in plants, and should be useful in monitoring vegetation.

The Thematic Mapper band designations and spectral ranges discussed above were developed primarily for applications in vegetation monitoring. Central to these applications is the requirement of detecting the presence of vegetation, monitoring its development, and predicting the quantity present. This requirement can only be met if the specific relationships between vegetation characteristics and reflected energy as acquired by the Thematic Mapper are understood.

Table I.1

Comparison of Landsat Multispectral Scanner (MSS) Bands With Landsat Thematic Mapper (TM) Bands

Band	Landsat MSS Bands Spectral Region (μm)	Band	Thematic Mapper Bands Spectral Region (μm)
4	0.5 - 0.6 (green)	1	0.45 - 0.52 (blue-green)
5	0.6 - 0.7 (red)	2	0.52 - 0.60 (green)
6	0.7 - 0.8 (near IR)	3	0.63 - 0.69 (red)
7	0.8 - 1.1 (near IR)	4	0.76 - 0.90 (near IR)
		5	1.55 - 1.75 (middle IR)
		6	10.40 - 12.50 (thermal IR)
		7	2.08 - 2.35 (middle IR)

The objectives of this research were to:

1. Study the statistical relationships between in situ measured spectral reflectance of grass canopies with selected grass canopy variables using correlation and regression techniques.
2. Develop spectral reflectance graphs for various grass phenological stages.
3. Determine the asymptotic limits or the biomass range for which the spectral data can be used to predict changes in grass canopy characteristics.

4. Test the utility of band ratios and other transformations for use in monitoring grass canopies.

The Study Area and Research Plots

Experimental grass plots were established at the Oregon State University Experimental Farm, located approximately 1 mile east of Corvallis, Oregon. Two 13m x 13m parcels were seeded; one to annual ryegrass (*Lolium multiflorum*), and one to tall fescue (*Festuca arundinacea*). Each parcel was divided into 120 square, 0.86 m^2 plots. Figure I.1 illustrates the plot layout scheme.

The plots were located on Chehalis silty clay loam, which occupies a large portion of the land along the Willamette River. The Chehalis series consists of deep, well drained soils formed in recent alluvium. The surface soil of the Chehalis silty clay loam is smooth-textured and of a brown or dark brown color (Kocher et al., 1924).

The Willamette Valley has a warm temperate climate which is characterized by cool winters and dry warm summers. Precipitation averages approximately 100 cm per year. Winds are commonly from the north in the summer and from the southwest in the winter.

Interaction of Radiation with Vegetation

Information relating to the physical factors affecting the spectral properties of individual leaves is needed before attempting to study the spectral response of vegetation canopies. In addition

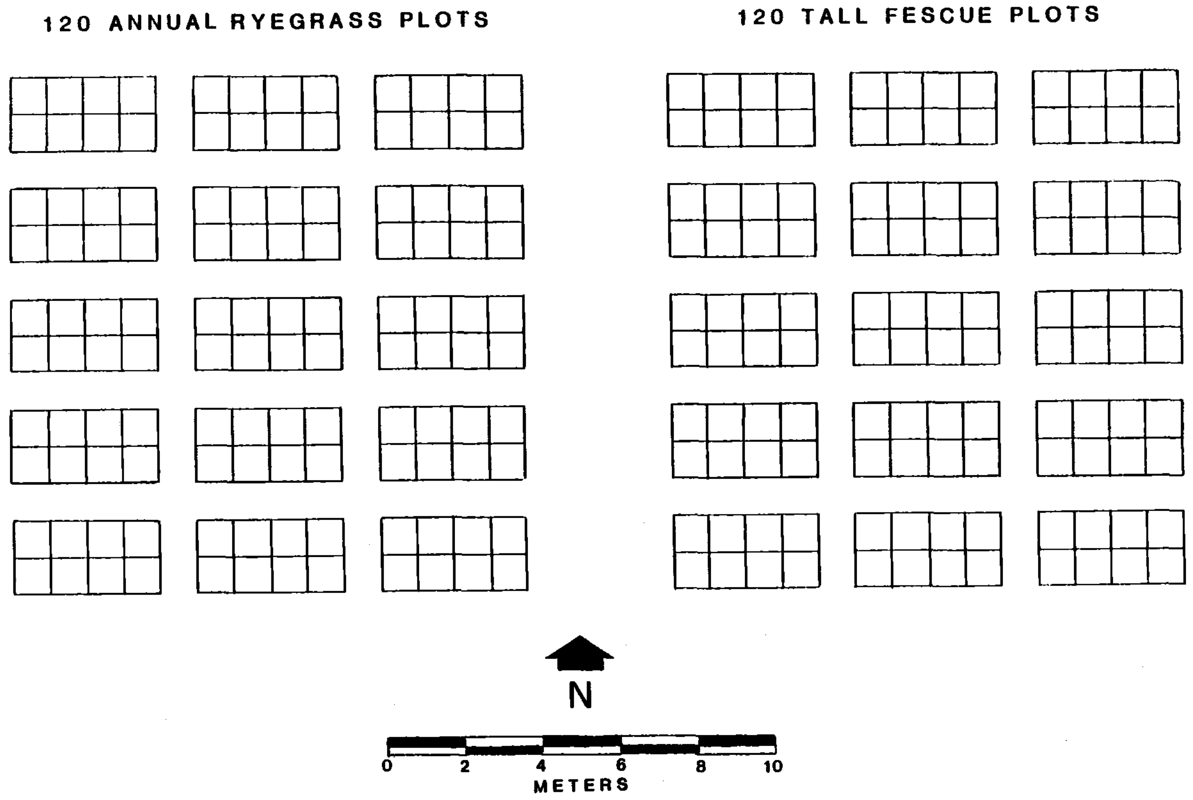

Figure I.1. Plot layout scheme.

to reflection, leaves also transmit and absorb light (radiant energy). For any wavelength (λ), the interaction of light with a leaf can be expressed as (LARS, 1968):

$$R_\lambda + T_\lambda + A_\lambda = 1$$

where R_λ, T_λ, and A_λ represent reflectance, transmittance, and absorptance, respectively. All incoming radiation is either reflected, transmitted, or absorbed by the leaf surface.

The 0.4 - 2.6 µm region of the electromagnetic spectrum can be divided up into three distinct spectral areas based on the response of leaves to incoming light. These three spectral regions include the visible (0.4 - 0.7 µm), the near infrared (0.7 - 1.3 µm) and the middle infrared (1.3 - 2.6 µm) portions of the spectrum. The interaction of radiation with leaves in the 0.4 - 2.6 µm range is well documented (Gates, 1970; Gates et al., 1965; Jenson, 1983; Knipling, 1970; LARS, 1968; Woolley, 1971). The typical spectral response of a green healthy leaf is shown in Figure I.2. In the visible region, absorptance is high while reflectance and transmittance are low. Conversely, reflectance and transmittance are high in the near infrared region, resulting in low levels of absorptance. In the middle infrared region, absorptance is relatively high, with low or moderate levels of reflectance and transmittance.

The study of the physical nature of light interactions with leaf tissue can aid in the understanding of the spectral differences introduced above. Within the visible region, most of the light striking the leaf is transmitted through the cuticle and epidermis to

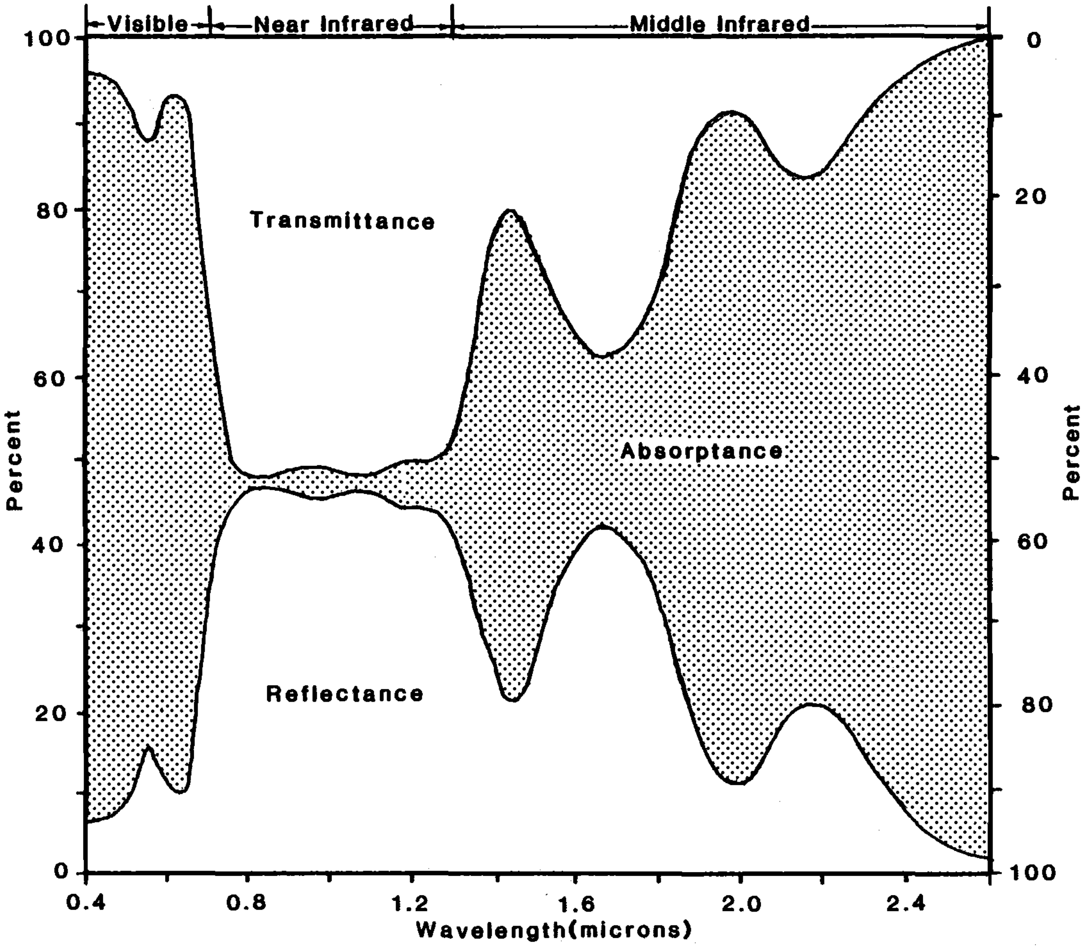

Figure I.2 Absorptance, transmittance, and reflectance from a green leaf; adapted from Knipling (1970).

the underlying layers of mesophyll cells, where the majority of the chlorophyll pigment is located (Jenson, 1983). These chlorophyll pigments absorb much of the visible light and photochemically, via photosynthesis, convert this light energy into stored energy in the form of organic compounds (Gates et al., 1965). This high absorptance accounts for the low reflectance and transmittance within the visible region. Reflectance is highest for the green portion (0.55 µm) of the visible spectrum, which explains the perceived green color of plants.

Very little radiation is absorbed by the leaf in the near infrared region (0.7 - 1.3 µm). High reflectance in the near infrared is caused by scattering at the interfaces of the spongy mesophyll cells, this tissue having many intercellular air spaces (Knipling, 1970). This scattering results in approximately one-half of the near infrared light reflected up, and the other one-half transmitted down, through the leaf. In a plant canopy with several layers of leaves present, the transmittance becomes important. Near infrared radiation transmitted through the uppermost leaves in a canopy is reflected from the lower leaves and re-transmitted through the upper leaves to increase reflectance from the canopy.

Reflectance in the middle infrared range beyond 1.3 µm is largely governed by water (Knipling, 1970; Myers, 1970; Woolley, 1971). Knipling (1970) compared the spectral curve of a dehydrated leaf to that of a fresh leaf and found the reflectance of the fresh leaf to be much lower than that of the dried leaf. Myers (1970) found that middle infrared reflectance for very small glass beads in water was about the same as the reflectance from a fresh leaf, but the spectral responses for dried leaves and glass beads in air were completely dissimilar. Within the middle infrared, as the moisture content in the leaf decreases, reflectance generally increases (Knipling, 1970).

Organization of Dissertation

This dissertation has been organized using the manuscript format. Oregon State University encourages this format to facilitate the publication of research results in professional journals. Each manuscript is a separate chapter in the dissertation, and each includes title page, abstract, introduction, body, summary, and reference sections. The body of each manuscript consists of a literature review, materials and methods used, and a results and discussion section. In addition to the reference sections at the end of each manuscript, a single comprehensive bibliography is included at the end of the dissertation. It should be noted that the use of the manuscript format results in the repetition of certain concepts, tables, and equations throughout the dissertation.

The following topics are addressed in the manuscripts:

1. The functional relationships between the spectral bands and the grass canopy variables are discussed for annual ryegrass in Chapter II and for tall fescue in Chapter III
2. The reflectance characteristics of annual ryegrass at

three different phenelogical stages are presented in Chapter II. Analysis was conducted on data obtained during the stem extension, anthesis, and senescence stages.

3. Spectral band ratios and other transformations were applied to the data and are discussed in Chapters II and III.
4. Correlation analysis was used to identify redundancies among the spectral variables and among the grass canopy variables. These correlation results are presented in Chapters II and III. Principal component analysis is also discussed in Chapters II and III as a method for reducing spectral band redundancy.
5. Chapter IV describes a methodology to explain the asymptotic relationships between the spectral bands and the tall fescue canopy variables. The limits of the amount of vegetation spectrally detectable are discussed.
6. Chapter V contains concluding remarks which summarize the findings of the entire research project and a section on recommendations for further research.

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CHAPTER II

MONITORING ANNUAL RYEGRASS WITH THE LANDSAT THEMATIC MAPPER BANDS

Abstract

The utility of the Landsat Thematic Mapper bands for estimating grass canopy variables was studied. Spectral data were collected from annual ryegrass (Lolium multiforum) plots using in situ remote sensing techniques with a Barnes Modular Multiband Radiometer. Data sets were collected at three plant phenological stages; early stem extension (June), anthesis (July), and senescence (August). The most significant correlations between the spectral and canopy variables were found for the June data set while the August data set yielded the poorest relationships. High levels of biomass (July) and plant senescence (August) both adversely affected the reflectance/canopy relationships. The application of band ratios and normalized difference transformations did not improve the relationships between the spectral and canopy variables. Principal component analysis was successful at reducing the seven original spectral bands to only two dimensions while maintaining nearly all of the variability found in the original data.

Introduction

A major goal in the remote sensing of grassland vegetation is to spectrally estimate the quantity of vegetation present. The quantity of vegetation is typically expressed in terms of percent canopy cover, leaf area index, or biomass. The spatial and temporal distribution of this quantity is a very important property of grassland ecosystems. Traditional methods of grass canopy data collection are time-consuming and often involve clipping, weighing, and measuring the surface area of leaves. As a result, remote sensing methods to monitor grass canopy variables are being developed utilizing the Thematic Mapper data from the Landsat satellite. If these canopy variabiles can be accurately estimated from Landsat Thematic Mapper data, they could be input into large area models concerned with primary productivity, evapotranspiration, carrying capacity, or rangeland condition.

Knowledge of the relationships between the grass canopy variables and the reflectance associated with the wavelengths of the Thematic Mapper bands is necessary for the accurate interpretation of the data acquired by the satellite. Actual Landsat imagery is not well suited for this type of research. Difficulties are encountered with Landsat imagery when variation is introduced from atmospheric conditions, sun angle, sensor reponse, and sampling areas the size of a pixel, approximately 0.4 hectares (Tucker et al., 1981).

To develop the potential of the Thematic Mapper data, ground-based experiments are needed to determine the quantitative relationships between the characteristics of the grass canopy and the corresponding spectral response of the Thematic Mapper bands.

The research described in this paper assessed the utility of the Landsat Thematic Mapper bands for estimating grass canopy variables. This research was entirely ground-based and relied on *in situ* remote sensing techniques using a spectral radiometer. Statistical relationships between variables were studied using correlation and regression techniques.

Literature Review

Knowledge of the physical factors affecting the spectral properties of individual leaves is needed in order to interpret the reflectance from vegetation canopies. The electromagnetic spectrum between the wavelengths of 0.4 µm and 2.6 µm can be divided into three spectral regions of interest. These three regions are the visible (0.4 - 0.7 µm), the near infrared (0.7 - 1.3 µm), and the middle infrared (1.3 - 2.6 µm), portion of the spectrum (Figure II.1). The interaction of radiant energy with plant leaves in the 0.4 µm to 2.6 µm region is well documented (Gates et al., 1965; LARS, 1968; Knipling, 1970; Woolley, 1971). In the visible region, absorption of radiant energy by a leaf is high while reflectance and transmittance are low. This high absorption of radiation in the visible region is mainly caused by leaf pigments, primarily the chlorophylls (Gates et al., 1965). The Thematic Mapper has three bands in the visible range which are sensitive to chlorophyll concentrations. These include a blue-green band (TM1) in the 0.45 - 0.52 µm range, the green band (TM2) in the 0.52 - 0.60 µm range, and the red band (TM3) in the 0.63

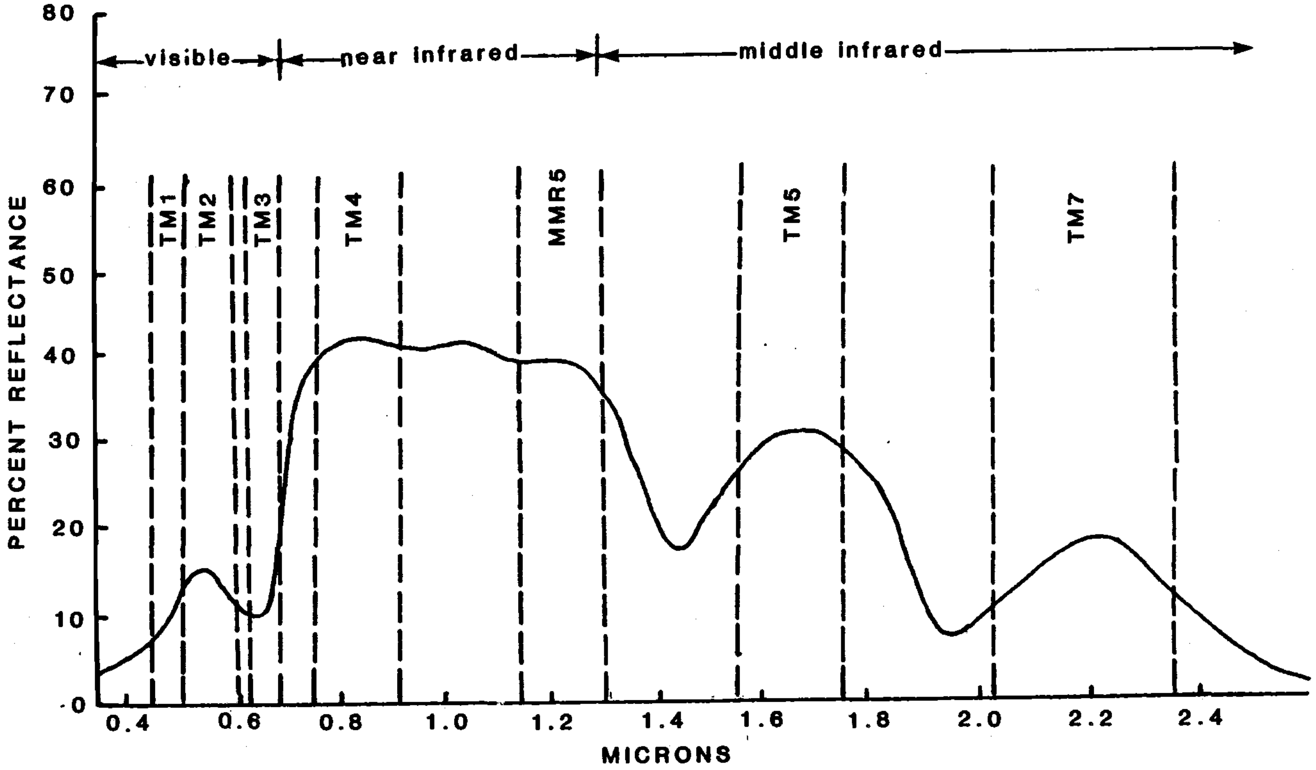

Figure II.1. Spectral reflectance curve for a green leaf showing the location of the Thematic Mapper bands; adapted from LARS (1970).

- 0.69 µm region. Reflectance is normally higher in TM2 than in TM1 and TM3 due to a decreased level of chlorophyll pigment absorption in TM2 (Tucker, 1978). In the near infrared region, reflectance and transmittance are relatively high along with little or no absorption by the leaf. This reflectance increase in the near infrared is caused by scattering at the interfaces of the spongy mesophyll cell walls (Gates et al., 1965; Knipling, 1970). The Thematic Mapper has one band (TM4) in the near infrared region which lies between 0.76 - 0.90 µm. Absorption is high in the middle infrared beyond the 1.3 µm wavelength. Liquid water in the leaf is the primary cause for high levels of absorption in the middle infrared region (Gates, 1970; Myers, 1970). The Thematic Mapper has two middle infrared bands (TM5 and TM7) which are located at the 1.55 - 1.75 µm and 2.08 - 2.35 µm regions, respectively.

Several studies have been published describing ground-based research on the spectral characteristics of grass canopies. Much of the published work has been produced by Tucker who studied the spectral response of blue grama (Bouteloua gracilis). Tucker (1977a) found the 0.62 - 0.69 µm region (red) to be best for estimating low levels of biomass, chlorophyll, and leaf water content for a grass canopy with mostly green biomass. The 0.74 - 1.00 µm region was found to be the best suited for estimating moderate to high levels of dry biomass (285-435 g/m^2) and leaf water (400-600 g/m^2). Tucker (1977b) also collected data late in the growing season when approximately 50 percent of the standing biomass was dead vegetation. He found that leaf water content, which represented the photosnythetically active vegetation present, had significant correlations with spectral data collected in the 0.45 - 0.50, 0.63 - 0.69, and 0.74 - 0.80 μm regions.

Colwell (1974) studied spectral reflectance of grass canopies in the green, red, and near infrared regions to assess the feasibility of using remote sensing techniques to estimate grassland biomass. He also concluded that the red spectral region was most sensitive to changes in biomass at low to intermediate biomass levels while the near infrared region was most sensitive to changes in biomass at high levels of biomass. Colwell demonstrated that the relationship between reflectance and biomass was generally curvilinear for the full range of biomass levels. He suggested that the near infrared region was the best "all season" spectral band for determining biomass since it varied the least with canopy senescence. The infrared/red reflectance ratio was found to be effective in normalizing the effect of soil background reflectance, but less effective in normalizing the effects of canopy shadow and standing dead vegetation.

The first four Thematic Mapper bands have been evaluated with regard to their ability to discriminate vegetation biomass from blue grama plots (Tucker, 1978). The grass canopy variables were total wet biomass, total dry biomass, dry green biomass, dry brown biomass, leaf water, and chlorophyll content. For a mostly green canopy, Tucker (1978) found TM3 to have the highest correlation with all of the canopy variables (R^2 = 0.80 - 0.91) with the exception of dry brown biomass in which TM4 had the highest correlation (R^2 = 0.63).

Brown et al. (1983) studied spectral reflectance of mixed grass and rough fescue prairies in southern Alberta using a radiometer that simulated the Thematic Mapper bands. They reported no strong quantitative relationships between vegetation biomass and spectral reflectance and suggested this was caused by the heterogeneous nature of their rangeland sites. The authors did find a high level of redundancy in the visible bands TM1, TM2, and TM3. The two water absorption bands, TM5 and TM7, were also found to be highly correlated. They concluded that most of the spectral information about grasslands is present in a three band subset of the six Thematic Mapper bands (i.e. visible, near infrared, and middle infrared bands).

Materials and Methods

This research was based on the analysis of data from experimental grass plots to relate grass canopy variables with spectral response. Grass plots were established for annual ryegrass (Lolium multiforum) at the experimental farm owned by Oregon State University. The treatment involved using the broadcast seeding method in order to acquire a large range of seed densities. This produced a high variability of canopy cover and biomass within the seeded parcel. The seeded parcel was divided into 120 square 0.86 m^2 plots. Three data sets were acquired from the parcel during the 1983 summer field season. This multidate coverage allowed data to be obtained during three plant phenological stages which included early stem extension (June 7), anthesis (July 10), and senescence (August 9). A data set consisted of twenty-two 0.2 m^2 circular spectral plots randomly selected from within the parcel. The 0.2 m^2 spectral plots were centered within the larger 0.86 m^2 plots to allow for a buffer zone between spectral plots.

The spectral data collection system consisted of a Barnes Modular Multiband Radiometer (MMR), an Omnidata Polycorder, a barium sulfate coated calibration panel, and a 7 meter telescoping boom mounted on a pickup truck (Figure II.2). The standard bands for the Barnes radiometer were designed to simulate the spectral bands of the Thematic Mapper (Table II.1). The thermal band (10.40 - 12.50 μm) was not considered for this paper. In addition to all of the Thematic Mapper bands, the Barnes radiometer has an additional near infrared band in the 1.15 - 1.30 μm region which will be referred to as MMR5.

The spectral data were collected on clear days between 1000 and 1500 hours. The radiometer's 15^o field-of-view allowed measuring each 0.2 m^2 plot at 1.92 m above the ground. Therefore, the radiometer had a field of view approximately equivalent to the plot area. Data were collected and stored in the polycorder with the radiometer mounted on the boom and independently recentered for each of the three readings per plot. Reflectance calibrations were taken approximately every 20 minutes using the calibration panel. The radiance

Figure II.2 Collection of spectral data from annual ryegrass on August 9, 1983.

Table II.1 Wavelengths for the Barnes Modular Multispectral Radiometer (MMR) and Corresponding Thematic Mapper Bands (TM).

Radiometer Bands (MMR)	Thematic Mapper Bands (TM)	Wavelength (µm)
MMR1	TM1	0.45 - 0.52 (blue-green)
MMR2	TM2	0.52 - 0.60 (green)
MMR3	TM3	0.62 - 0.69 (red)
MMR4	TM4	0.76 - 0.90 (near infrared)
MMR5		1.15 - 1.30 (near infrared)
MMR6	TM5	1.15 - 1.75 (middle infrared)
MMR7	TM7	2.08 - 2.35 (middle infrared)
MMR8	TM6	10.40 -12.50 (thermal ")

data collected were converted to percent reflectance for each spectral band according to the following equation (Biehl, 1981):

$$R_s = \frac{(D_s - d_s)}{(D_r - d_s)} \times 100$$

Where R_s - spectral bidirectional reflectance factor of scene (%)

D_s - spectral response of instrument to scene

d_s - dark level response of instrument

D_r - spectral response of instrument to reference standard (i.e. barium sulfate calibration panel)

A linear interpolation routine was used to calibrate the spectral data between any two reference calibration observations. The grass canopy variables selected for inclusion in the analysis were canopy height (cm), canopy cover (%), total wet biomass (g/m^2), total dry biomass (g/m^2), above ground plant moisture (g/m^2), and leaf area index (Table II.2). After the spectral data were obtained for the selected plots, the height of each plot canopy was measured and a vertical photograph was taken. All of the above-ground vegetation was then clipped, bagged, and taken to the laboratory for wet weight measurement. Dry weights were obtained after drying the vegetation in an oven at 60° C for 48 hours. Above ground plant moisture was determined by subtracting the dry weight from the wet weight. Percent canopy cover was determined by the use of the dot count method with the vertical photographs of the plots. A small subsample of grass from each plot was used to estimate leaf area index (LAI) which is the total area of all the leaves in the plot divided by the total ground area in the plot. First, the leaf area (cm^2) of the wet leaf

Table II.2. Summary of Annual Ryegrass Canopy Variables

	June 7 (Stem extension)				July 10 (Anthesis)				August 9 (Senescence)			
	Mean	Min.	Max.	C.V.*	Mean	Min.	Max.	C.V.	Mean	Min.	Max.	C.V.
Height (cm)	18.5	14.5	26.0	.16	44.9	33.5	59.0	.14	53.8	41.0	64.5	.10
Cover (%)	62.7	18.6	89.0	.35	89.5	61.3	100.0	.14	76.2	48.4	96.7	.16
Total Wet Biomass (g/m^2)	335.7	89.7	618.8	.47	829.4	512.9	1146.4	.20	437.3	298.5	588.1	.22
Total Dry Biomass (g/m^2)	79.4	18.4	148.1	.48	263.2	154.8	351.3	.21	92.3	58.4	140.1	.22
Plant Water (g/m^2)	256.3	71.4	470.7	.46	566.2	358.2	795.1	.20	80.8	38.4	186.1	.48
Leaf Area Index	0.6	0.2	1.3	.47	1.1	0.6	1.8	.29	0.1	0.0	0.3	.75

*C.V. = Coefficient of Variation

subsample was determined using an optical leaf area meter. The leaf area index was then computed using the following equation:

$$LAI = \frac{L_a/(L_b/P_b)}{P_a}$$

where L_a is the leaf area of the subsample

L_b is the wet leaf biomass of the subsample

P_b is the total plot biomass

P_a is the ground area in the plot

Results and Discussion

The correlation analysis was conducted using correlation coefficients (r) rather than coefficients of determination (R^2) to illustrate whether relationships were direct or inverse. Due to the physical nature of plant growth, high positive correlation coefficients were found among the grass canopy variables (Table II.3). Strong relationships were observed between total wet biomass, total dry biomass, and above ground plant water ($r \geq .98$). Leaf area index also had a high correlation with these variables ($r \geq 0.91$). Figure II.3 illustrates the positive linear relationship between leaf area and wet leaf weight for the data collected from annual ryegrass leaves on June 7th. These results indicated that leaf weight could be used to estimate leaf area or leaf area index.

Mean spectral reflectance was computed for the June, July, and August data sets (Figure II.4). On June 7, the entire canopy was nearly all green with the ryegrass in the early stem extension stage.

Table II.3. Mean Correlation Coefficients(r) for the Annual Ryegrass Canopy Variables for the June 7 and July 10 Data.

	Height	Cover	Total Wet Biomass	Total Dry Biomass	Plant Water	Leaf Area Index
Height	1.00	.37	.47	.46	.47	.47
Cover		1.00	.69	.70	.69	.69
Total Wet Biomass			1.00	.99	.99	.92
Total Dry Biomass				1.00	.98	.91
Plant Water					1.00	.92
Leaf Area Index						1.00

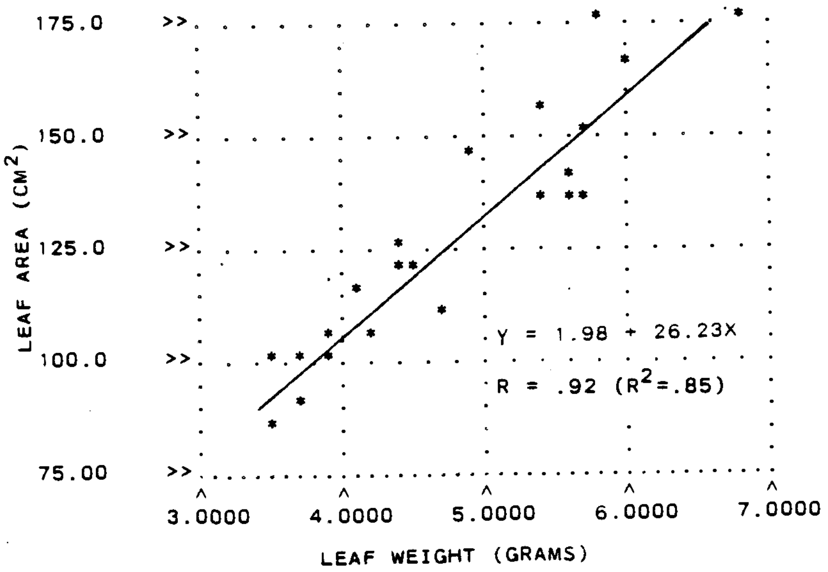

Figure II.3. Scatter diagram showing the relationship between leaf weight and leaf area.

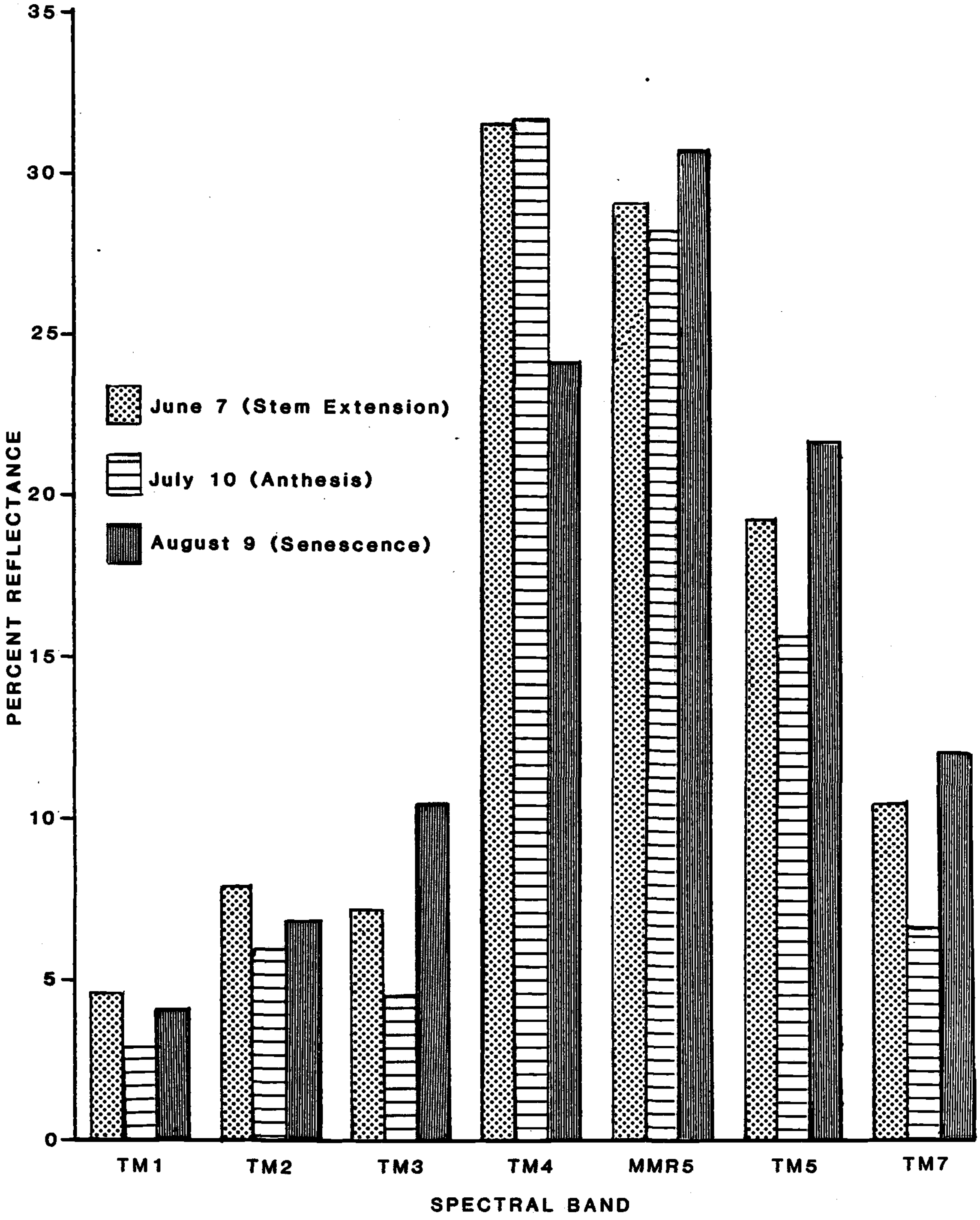

Figure II.4. Bar graph showing mean spectral reflectance from annual ryegrass on June 7, July 10, and August 9.

Reflectance was low in the visible bands (TM1, TM2, TM3) due to absorption by plant pigments. Reflectance values were much higher in the near infrared region (TM4, MMR5) due to enhanced reflectance caused by infrared scattering. MMR5 values were slightly lower than TM4 because of minor water absorption characteristics of the MMR5 spectral region (Hoffer, 1978). Due to water absorption, reflectance values in the middle infrared (TM5 and TM7) were lower than the values for the near infrared. The reflectance values recorded during anthesis, on July 10, followed a pattern very similar to the June data. Mean reflectance values were lower in July for TM1, TM2, TM3, TM5, and TM7 due to an increase in total biomass causing additional pigment and water absorption in these bands. Overall, the reflectance for the June and July data closely followed the spectral reflectance curve for a green leaf as displayed in Figure II.1.

On August 9, the annual ryegrass was undergoing senescence with most of the canopy brown. When compared to the July values, mean reflectance increased in all bands except TM4. The reason for lower reflectance in TM4 was unclear. Sinclair et al. (1971) reported an increase in reflectance at all wavelengths during senescence. They stated that the increase in reflectance for visible and middle infrared bands was due to a decrease in chlorophyll and plant water and the increase in the near infrared was caused by changes in the internal leaf structure which accompanies senescence.

Numerous statistically significant relationships were found between the spectral bands and the grass canopy variables (Table

II.4). Direct relationships were found when the infrared bands were correlated with the canopy variables, while inverse relationships generally existed between the absorption bands and the canopy variables. The relationships were most significant for the June data set (stem extension) and least significant for the August data set (senescence). There were only two significant relationships from the data set collected in August. These included the correlation of TM4 with canopy height ($r = .52$) and MMR5 with total wet biomass ($r = .52$).

Figure II.5 illustrates the relationships between total wet biomass and the seven spectral bands for the June, July, and August data sets. With the exception of TM5, the correlation coefficients (r) were high for all bands ($r \geq .90$) on June 7. On July 10, TM3 ($r = -.77$), and TM7 ($r = -.73$) were superior to the rest of the bands for estimating total wet biomass. The weaker relationships for the July data when compared to the June data can be related to the asymptotic nature of the spectral response. Tucker (1977a) described the upper spectral asymptote as the point which indicates so much vegetation that additional vegetation will result in no detectible change in reflectance. Tucker found the upper asymptote for total wet biomass to be between 293 and 374 g/m^2 for red reflectance and between 634 and 975 g/m^2 for the near infrared region. For this study, the upper limits of biomass detectability were probably exceeded. The average total wet biomass for the July data was 829.4

Table II.4. Correlation Coefficients(r) Between Spectral Bands and Annual Ryegrass Canopy Variables for Data Collected on June 7 and July 10.

	June 7						July 10					
	Height	Cover	Total Wet Biomass	Total Dry Biomass	Plant Water	Leaf Area Index	Height	Cover	Total Wet Biomass	Total Dry Biomass	Plant Water	Leaf Area Index
TM1	-.67**	-.93**	-.91**	-.93**	-.90**	-.91**	-.06	-.49*	-.36	-.41	-.33	-.25
TM2	-.69**	-.92**	-.91**	-.92**	-.90**	-.90**	-.15	-.20	-.60**	-.66**	-.57**	-.42
TM3	-.67**	-.94**	-.92**	-.93**	-.91**	-.90**	-.24	-.34	-.77**	-.79**	-.75**	-.54**
TM4	.63**	.93**	.95**	.95**	.95**	.92**	.51*	.26	.51*	.45*	.53*	.37
MMR5	.59**	.91**	.93**	.92**	.94**	.90**	.51*	.30	.57**	.51*	.59**	.39
TM5	-.58**	-.47*	-.43*	-.47*	-.42	-.48*	.15	-.50*	-.52*	-.60**	-.47*	-.40
TM7	-.68**	-.91**	-.90**	-.91**	-.89**	-.90**	-.08	-.61**	-.73**	-.77**	-.71**	-.51*

**Significant at 99% Confidence Level

*Significant at 95% Confidence Level

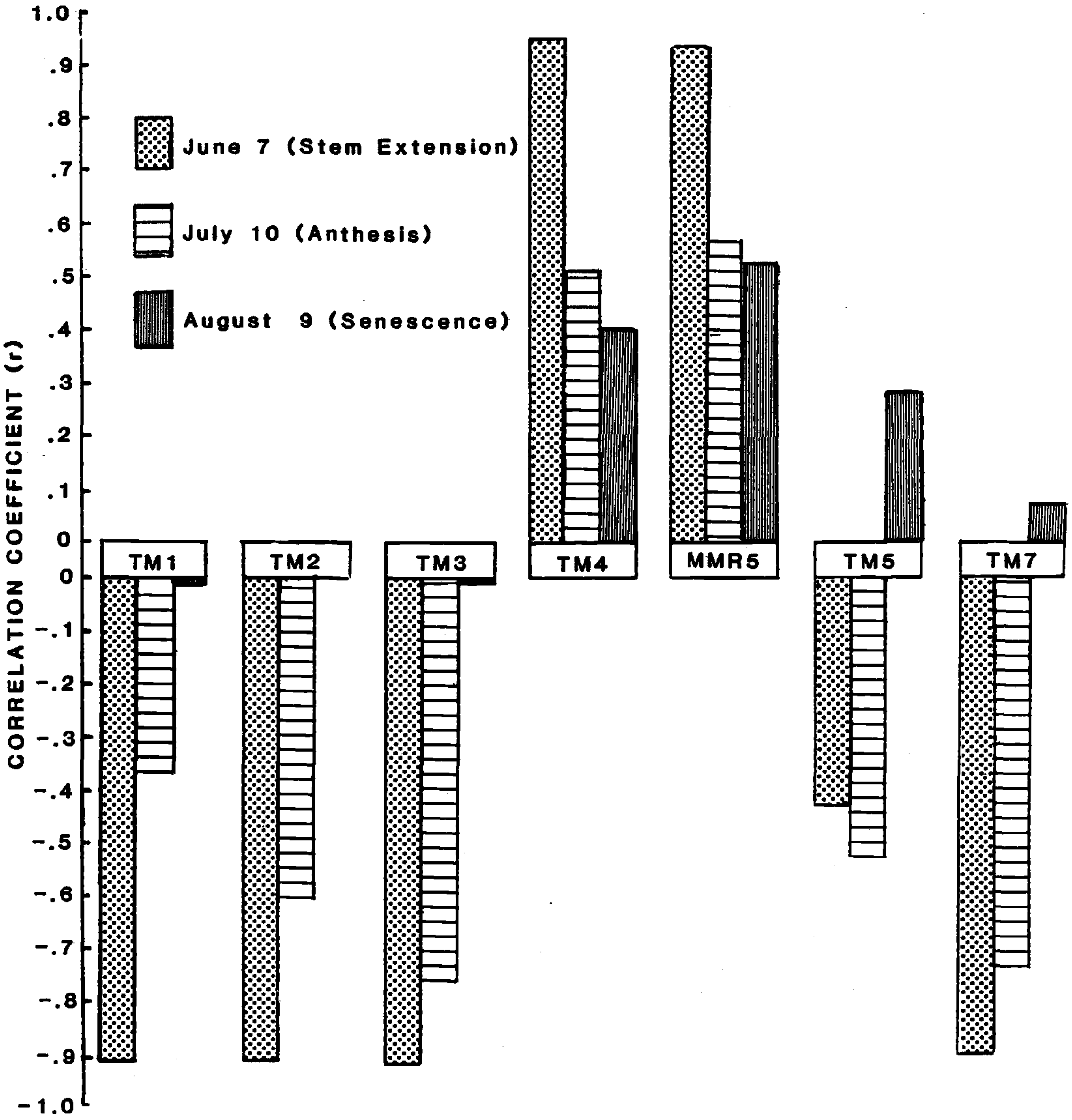

Figure II.5. Bar graph showing the correlations between total wet biomass and reflectance from annual ryegrass on June 7, July 10, and August 9.

g/m^2 which was substantially above Tucker's red reflectance asymptote and in the range of his near infrared asymptote.

The correlation coefficients between the spectral variables and total wet biomass were lowest for the August data when photosynthesis was no longer taking place in most of the canopy. A decrease in biomass estimation capabilities was also reported by Tucker (1978) when much of the canopy turned brown. He found lower correlations between spectral data and canopy variables for September data when the canopy was approximately 50 percent brown compared to June data when the canopy was greater than 80 percent green. Figure II.5 shows that the infrared bands (MMR5 and TM4) were the best, although relatively low, for estimating total wet biomass for the August data.

The linear correlation coefficients computed for each spectral band with the various canopy variables were not sufficient to determine if the function was linear. For example, the correlation coefficient between total wet biomass and TM3 was -0.92, which indicates a strong inverse relationship. An examination of the corresponding scatter plot clearly shows a non-linear inverse relationship (Figure II.6). In constrast, the functional relationship between TM4 and total wet biomass was linear for the June 7 biomass range (Figure II.7).

The relationship between TM3 and total wet biomass for the July data set can also be examined using a scatter plot (Figure II.8). The shape of the July curve (Figure II.8) is similar to the shape of the June curve (Figure II.6) although the upper asymptote seemed to

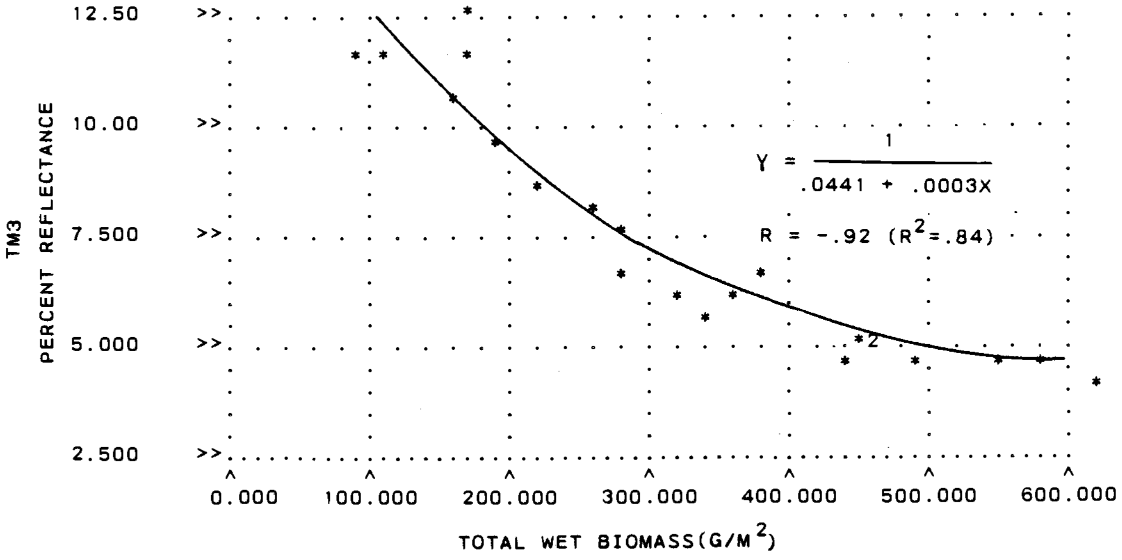

Figure II.6 Scatter diagram of total wet biomass (g/m^2) and TM3 reflectance from annual ryegrass on June 7.

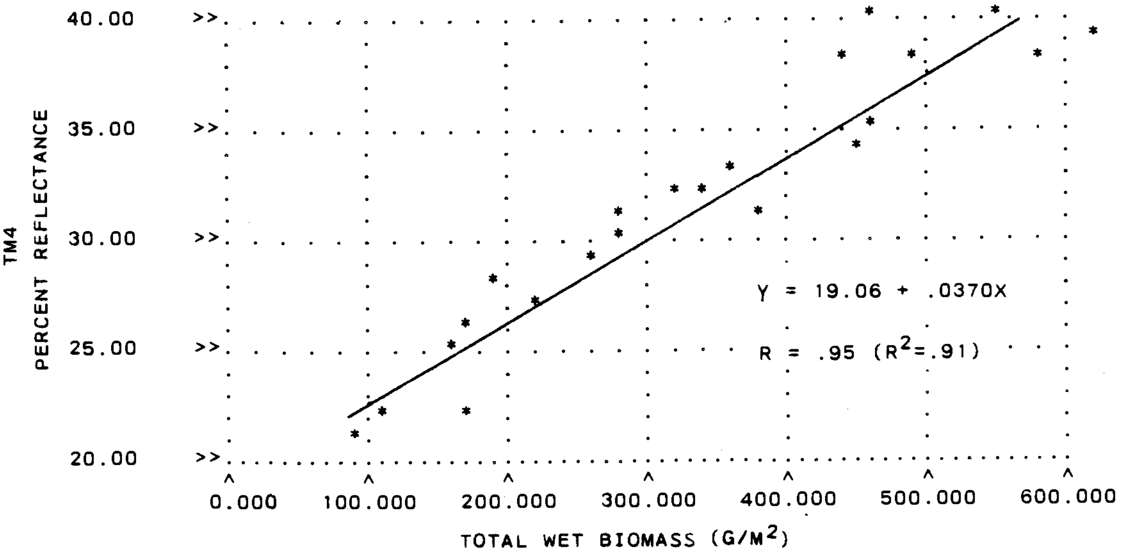

Figure II.7. Scatter diagram of total wet biomass (g/m^2) and TM4 reflectance from annual ryegrass on June 7.

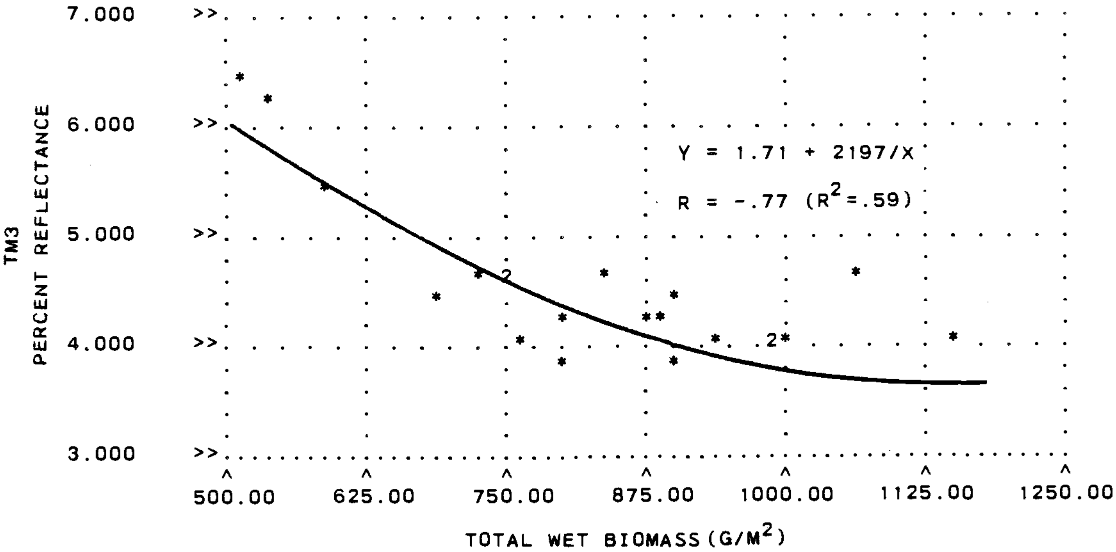

Figure II.8. Scatter diagram of total wet biomass (g/m^2) and TM3 reflectance from annual ryegrass on July 10.

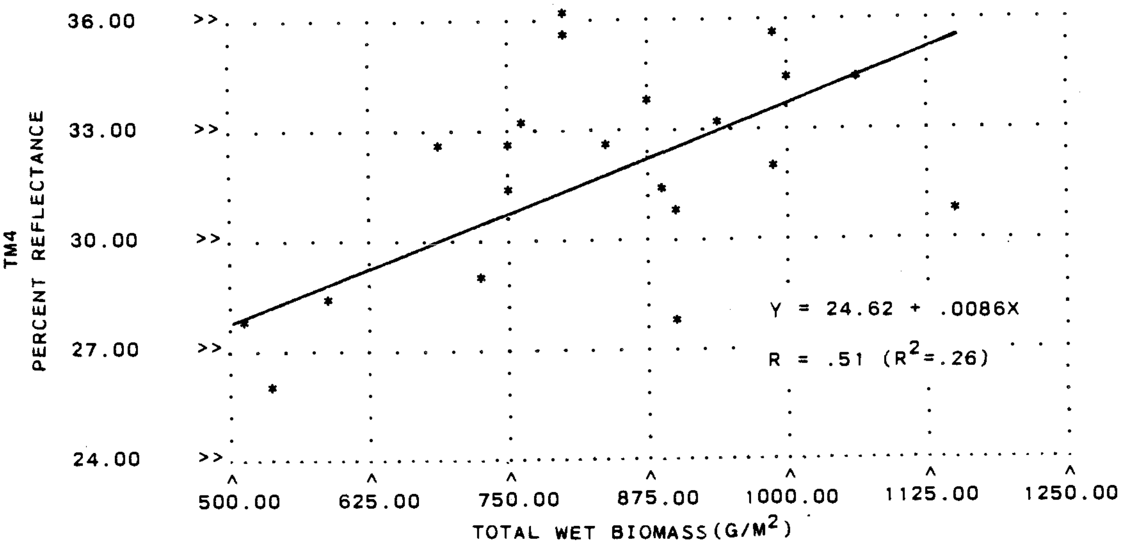

Figure II.9. Scatter diagram of total wet biomass (g/m^2) and TM4 reflectance from annual ryegrass on July 10.

be at higher total biomass level for the July data. The reason for the asymptote being at a higher level in July was due to a change in plant structure. Most of the July biomass was contained in the elongated stems which have only a minor affect on reflectance.

The regression of TM4 with total wet biomass for the July data indicates a relatively linear relationship but very large residual errors when the observed points are compared to the prediction line (Figure II.9). It is possible that this high variability in TM4 response was caused by transmittance and reflectance of near infrared energy through the canopy layers. Much of the near infrared energy is transmitted through the upper canopy leaves and reflected from the lower canopy leaves back through the upper canopy leaves to enhance total canopy reflectance (Knipling, 1970). The variations in the TM4 data could have been caused by variations in the geometry of the canopy layers, especially leaf orientation.

All possible combinations of band ratios (Band A/Band B) along with all possible normalized difference transformations (Band A-Band B/Band A+Band B) were computed from the original seven spectral bands. These transformations generally have the effect of normalizing spectral data that are acquired under varying irradiational conditions. For this study, these transformations provided little or no increase in the correlations with the canopy variables for all three data sets. The advantage of these transformations was minimized since the raw radiance data were calibrated and converted to percent reflectance and only collected on clear days, near solar noon and with very similar soil conditions.

The redundancy between some of the spectral bands was high as a result of the plant canopy and radiant energy relationships involving absorption and scattering. Table II.5 reveals a high positive correlation between the absorption bands TM1, TM2, TM3, and TM7 ($r \geq .81$). The spectral response between the two near infrared bands was very similar ($r = .97$). In order to reduce the redundancy caused by high between band correlations, a principal component analysis was conducted. Miller et al. (1983) described principal component analysis as providing a means to determine the contributions of each spectral band to the overall variability caused by all of the spectral bands. The first principal component is associated with an eigenvector pointing in the direction of maximum variation within the data, while the subsequent principal components are associated with eigenvectors that lie in the directions seeking maximum residue variations not accounted for by the previous principal components. Table II.6 shows the percent of variance accounted for by each of the principal components for the June, July, and August data sets. For these three data sets, the first two principal components accounted for 99, 97, and 91 percent of the original variance, respectively. This indicated that the seven dimensions of the original data could be reduced to only two dimensions while maintaining most of the variability in the data.

For all three data sets, the first principal component was highly related to the near infrared bands (TM4 and TM5) since these

Table II.5. Mean Correlation Coefficients(r) between the Spectral Bands for the June 7 and July 10 Data.

	TM1	TM2	TM3	TM4	MMR5	TM5	TM7
TM1	1.00	.81	.84	-.67	-.65	.61	.85
TM2		1.00	.91	-.62	-.62	.69	.85
TM3			1.00	-.86	-.78	.65	.94
TM4				1.00	.97	-.24	-.75
MMR5					1.00	-.18	-.73
TM5						1.00	.76
TM7							1.00

Table II.6. Percentage of the Original Variance Accounted for by the First Two Principal Components (PC) and the Coefficients for Associated Eigenvectors from Annual Ryegrass Spectral Data Collected on June 7, July 10, and August 9.

	% of Variance	TM1	TM2	TM3	TM4	MMR5	TM5	TM 7
June 7								
PC1	95.72	-.14	-.15	-.34	.74	.44	-.04	-.29
PC2	3.53	.24	.24	.44	.28	.40	.43	.52
July 10								
PC1	84.13	-.07	-.04	-.16	.81	.52	-.04	-.23
PC2	12.63	.21	.19	.31	.21	.14	.59	.64
August 9								
PC1	82.13	.08	.14	.28	.53	.58	.45	.28
PC2	9.03	-.22	-.25	-.35	.39	.43	-.33	-.56

bands had the highest range of reflectance values. The second principal component was more difficult to interpret, but overall, it seemed to give considerable weight to the middle infrared bands (TM7). Within the visible region, TM3 was given the most weight in both the first and second principal components.

Summary

Under the conditions of this study, the following conclusions can be made:

1. A strong relationship was found between leaf weight and leaf area. This suggests that leaf biomass measurements could be used to estimate leaf area index which is much more difficult to measure. Leaf area index could be estimated using regression techniques with leaf biomass as the independent variable.
2. A high level of redundancy existed among several of the grass canopy variables, especially total wet biomass, total dry biomass, and above ground plant water ($r \geq .98$). This suggests that it would only be necessary to collect data on one of these redundant canopy variables for monitoring grass canopies with Landsat.
3. Strong relationships were found between the grass canopy variables and the Thematic Mapper spectral bands. The most significant relationships were found before the occurence of high biomass levels or canopy

senescence both of which adversly affected these relationships. Landsat imagery acquired early in the growing season may result in the highest possible biomass mapping accuracies.

4. Overall, no spectral band(s) was found to be superior for explaining the variation in the canopy variables for all three different phenological stages. Since the spectral bands respond differently to different canopy conditions, it would be desirable, when mapping vegetation with satellite data, to be able to select from bands in all important regions of the spectrum.
5. The examination of the correlation coefficients alone was not sufficient to determine if the relationships between the spectral variables and the canopy variables was linear. It was found that scatter diagrams were needed to determine these functional relationships.
6. When compared to the original bands, the use of band ratios and normalized difference transformations did not significantly increase correlations with the grass canopy variables. This lack of improvement was attributed to the calibration of the radiance data along with minimal variations in sun angle, atmosphere, and soil conditions.
7. For all three data sets, the first two principal components accounted for at least 91 percent of the

variability found in the seven original spectral bands. This indicated that the original seven band data set could be reduced to a two dimensional data set while maintaining nearly all of the original variability.

8. The first principal component, which accounted for at least 82 percent of the original variance in the three data sets, was most highly related to near infrared reflectance (TM4 and MMR5). The second principal component was more difficult to interpret but weighted the middle infrared band (TM7) slightly higher than the other bands.

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CHAPTER III

LANDSAT THEMATIC MAPPER BAND TRANSFORMATIONS FOR CHARACTERIZING GRASS VEGETATION

Abstract

The relationships between reflectance in the Landsat Thematic Mapper (TM) bands and grass canopy characteristics were studied. Data were collected from a total of 107 tall fescue (Festuca arundinacia) plots ($0.2m^2$) during the 1983 growing season. Canopy height, percent cover, total wet biomass, total dry biomass, plant water, and leaf area index were correlated with spectral data obtained from a Barnes Modular Multiband Radiometer. The near infrared wavelength region corresponding to TM4 band appeared to be the best estimator of total wet biomass ($r = .80$) and canopy height ($r = .82$). Percent canopy cover had the highest correlation coefficients with TM7 ($r = -.95$) and TM1, TM2, and TM3 ($r \geq -.93$). All canopy variables showed a curvilinear relationship with the spectral bands, except canopy cover, which showed a near linear relationship, for the biomass range in this study. Linear transformations were obtained using natural logarithms of the grass canopy variables and the spectral bands. Band ratios were more significant than individual bands when correlated with the canopy variables. The relationship between the normalized difference transformation and total wet biomass was linear for low biomass situations. The normalized difference values were constant for high biomass levels. Redundancy

was found in several of the canopy variables and several of the spectral variables. Principal component transformations were effective in reducing the seven spectral bands to two principal components, while maintaining nearly all of the variance of the seven bands.

Introduction

The data from the Landsat Thematic Mapper can only be interpreted if it is known how the energy recorded by the spectral bands interacts with the vegetation. This knowledge can be used to develop new applications for Thematic Mapper data and aid in the choice of spectral bands for future satellite remote sensing systems designed for monitoring vegetation.

Knowledge of the complex relationships between the biophysical characteristics of vegetation canopies and reflectance from these canopies is needed. The quantity of vegetation present is a principal characteristic affecting reflectance from vegetation canopies. This study was undertaken to evaluate the relationships between the quantity of grass vegetation and reflectance recorded in the Thematic Mapper bands. The variables used to quantify the amount of vegetation were canopy height, canopy cover, biomass, plant water, and leaf area index. Correlation, regression, and principal components analysis were used to explain the functional relationships between the Thematic Mapper bands and the grass canopy variables.

This study was ground-based and used in situ remote sensing techniques with a portable spectral radiometer.

Literature Review

Knowledge of how light interacts with a green leaf can aid in the understanding of reflectance from grass canopies. The 0.4 - 2.6 μm spectral range can be divided into three regions of interest: the visible, near infrared, and middle infrared regions. Reflectance from a leaf in the visible region (0.4 - 0.7 μm) is low due to high levels of absorptions by plant pigments, primarily the chlorophylls (Gates et al., 1965). Little or no absorption occurs in the near infrared region (0.7 - 1.3 μm). High levels of reflectance and transmittance in the near infrared are caused by the scattering of energy at the interfaces of the spongy mesophyll cells (Knipling, 1970). Reflectance in the middle infrared region (1.3 - 2.6 μm) is governed primarily by water within the leaf tissue; as leaf moisture content decreases absorption decreases and reflectance increases (Myers, 1970).

Colwell (1974) studied reflectance from grass canopies in the green (0.55 μm), red (0.65 μm), and near infrared (0.75 μm) wavelengths. He concluded that no single wavelength could be considered effective for monitoring grass in all situations. He did find the red region to possess the greatest sensitivity to changes in biomass for low to intermediate biomass levels. The near infrared region was most sensitive to changes in biomass at high biomass levels.

The spectral reflectance from blue grama (Bouteloua gracilis) grass canopies was studied extensively by Tucker (1977, 1978, 1979). He found the red region (0.63 - 0.69 µm) to be superior for estimating low levels of green biomass and the near infrared region (0.74 - 1.00 µm) to be the best for estimating moderate to high densities of biomass (Tucker, 1977). Tucker (1978) evaluated the usefulness of the first four Thematic Mapper bands for discriminating green grass biomass, chlorophyll concentration, and leaf water content. For a mostly green canopy with a high range of wet biomass (52 - 1230 g/m^2), he found TM3 (0.63 - 0.69 µm) to have the highest correlations with the above canopy variables.

Much research concerning spectral analysis of grass canopies has utilized spectral ratios and vegetation index models. A spectral ratio or a vegetation index model is a formula that transforms multidimensional spectral data into a single real number (Miller, 1981). This real number is derived from reflectance values from two or more spectral wavelengths or bands. Generally, the greater the amount of vegetation, the greater the vegetation index number. Researchers have formulated vegetation index models that can be used to predict biomass, vegetation condition, or yield.

Pearson and Miller (1973) were the first to use the spectral ratio method for estimating biomass. In their study of reflectance from grass plots, they found 0.68 µm (red) and 0.78 µm (near infrared) to be two optimal wavelengths for detecting green vegetation. Their ratioing method was based on the fact that an inverse relationship exists between reflectance and vegetation at 0.68 µm, while a direct relationship exists between reflectance and vegetation at the 0.78 µm wavelength. They found that a ratio of these two wavelengths yielded higher correlations with biomass than either individual wavelength.

Carneggie et al. (1974) used the infrared/red ratio to correlate spectral data with biomass production using Landsat multispectral scanner (MSS) data. The ratio of the Landsat bands MSS7 and MSS5 was compared with range condition, phenologic change, and biomass. Results indicated it was possible to monitor stages of growth of annual forage within and between seasons using band ratios.

Rouse et al. (1973) developed the transformed vegetation index (TVI) to monitor rangeland vegetation in the great plains using Landsat MSS data. This index, which was based on the ratioing concept, also included a normalizing procedure to reduce extraneous effects caused by variations in atmospheric conditions and sun angle. The procedure involves dividing the difference of the near infrared (MMS7) and red (MSS5) bands by the sum of the near infrared and red bands:

$$\mathrm{TVI} = \sqrt{\frac{\mathrm{MSS7} - \mathrm{MSS5}}{\mathrm{MSS7} + \mathrm{MSS5}} + .5}$$

Many researchers (Miller, 1981; Tucker, 1979) currently use the vegetation index (VI), which is based on the TVI developed by Rouse et al. (1973):

$$\text{VI} = \frac{\text{Near Infrared Band} - \text{Red Band}}{\text{Near Infrared Band} + \text{Red Band}}$$

This vegetation index is often referred to as the normalized difference index in the literature (Gardner et al., 1982).

Various linear combinations of red and near infrared (NIR) radiance were evaluated by Tucker (1979) in an attempt to quantify the relationships between spectral radiance and grass canopy variables. The NIR/red ratio, square root of the NIR/red ratio, NIR-red difference, VI, and the TVI were all found to have approximately the same sensitivity to the amount of green biomass present. For a June data set, all of these transformations had a similar curvilinear response to total wet biomass.

A high level of redundancy among several of the Thematic Mapper spectral bands has been reported. Budd and Milton (1982) used a portable radiometer to monitor salt marsh vegetation with the first four Thematic Mapper bands. They found TM1 (0.45 - 0.52 µm), TM2 (0.52 - 0.60 µm), and TM3 (0.63 - 0.69 µm) to have high between-band correlations. They used a principal component analysis to eliminate this spectral redundancy and simplify the relationship between reflectance and surface conditions. The first and second principal components accounted for 97 percent of the variability, with the first component highly related to near infrared reflectance (TM4), and the second to the visible region, primarily green (TM2) reflectance. Miller et al. (1983) also found redundancy among the visible Thematic Mapper bands in their study of reflectance from small grain canopies. They executed a principal component analysis on the six reflective Thematic Mapper bands and also found the distribution of the data to be two-dimensional. The first two principal components accounted for 96 percent of the original variance in the spectral data. The first principal component was highly related to near infrared reflectance.

Materials and Methods

Experimental plots of tall fescue (Festuca arundinacea) were planted at the Oregon State University Experimental Farm on April 14, 1983. This perennial grass was established using the broadcast seeding method in order to acquire a large range of seed densities. High variability in biomass and canopy cover resulted from the variability in seed density.

Data were collected from the tall fescue plots on June 7, July 10, August 9, and September 12. This sampling scheme allowed data to be obtained from low to high levels of biomass (16.5 - 1,677.9 g/m^2 wet biomass). A total of 107 plots (0.2 m^2) were spectrally measured during the growing season. Spectral reflectance data were obtained with a Barnes Modular Multiband Radiometer (MMR) mounted on a boom truck. The Barnes radiometer bands were designed to simulate the Landsat Thematic Mapper bands (Table III.1). The Thematic Mapper has three bands in the visible region, one near infrared band, two middle infrared bands, and one thermal band. The thermal band, located in the 10.40 - 12.50 μm region, was not considered in this study. It should be noted that the Barnes radiometer has an additional band (MMR5) in the near infrared which was not included on the Thematic Mapper, but which was included in this study.

Table III.1

Wavelengths for the Barnes Modular Multispectral Radiometer (MMR) and Corresponding Thematic Mapper Bands (TM)

Barnes Radiometer Bands (MMR)	Thematic Mapper Bands (TM)	Wavelength (μm)
MMR1	TM1	0.45-0.52 (blue-green)
MMR2	TM2	0.52-0.60 (green)
MMR3	TM3	0.63-0.69 (red)
MMR4	TM4	0.76-0.90 (near infrared)
MMR5		1.15-1.30 (near infrared)
MMR6	TM5	1.55-1.75 (middle ")
MMR7	TM7	2.08-2.35 (middle ")
MMR8	TM6	10.40-12.50 (thermal ")

The Spectral data were collected only on sunny clear days during mid-day hours. Spectral data were collected with the radiometer aimed in a vertical position approximately 1.92 m above the ground. The instruments 15^{0} field-of-view was approximately equivalent to the plot area (0.2 m^{2}). The radiometer was independently centered over each plot three times. Mean reflectance was computed from these three replications. Reflectance calibrations were taken approximately every 20 minutes from a panel coated with barium sulfate.

Six plant canopy variables were selected for inclusion in the analysis. These were canopy height (cm), canopy cover (%), total wet biomass (g/m^2), total dry biomass (g/m^2), above ground plant water (g/m^2), and leaf area index (Table III.2). Immediately after collecting spectral data for each plot, the canopy height was measured and a vertical photograph was taken. Next, all above ground plant material was harvested, bagged, and taken to the Laboratory for total wet biomass measurements. Total dry biomass data were obtained after drying the samples in an oven for 48 hours at 60^o C. Above ground plant water was determined by subtracting the dry weights from the wet weights. Percent canopy cover was estimated using the dot count method with the vertical photographs. Leaf area index was calculated by dividing the total area of all the leaves in the plot by the total ground area in the plot. The total area of all the leaves in the plot was estimated from a leaf subsample. The leaf area of this subsample was determined through the use of an optical leaf area meter. Leaf area index (LAI) was calculated as follows:

$$LAI = \frac{L_a/(L_b/P_b)}{P_a}$$

where L_a = the leaf area of the subsample

L_b = the wet leaf biomass of the subsample

P_b = the total wet biomass of the plot

P_a = the ground area in the plot

Table III.2

Summary of Tall Fescue Canopy Variables

	Mean	Min.	Max.	S.E.*	S.D.**	C.V.***
Height (cm)	24.7	7.5	57.5	1.2	12.2	0.49
Cover (%)	63.5	4.1	100.0	2.8	28.5	0.45
Total wet Biomass (g/m^2)	523.3	16.5	1,677.9	45.3	468.8	0.90
Total Dry Biomass (g/m^2)	146.4	6.5	502.5	12.5	129.7	0.89
Plant water (g/m^2)	376.9	9.9	1,312.4	33.0	340.9	0.90
Leaf Area Index	1.06	0.03	4.32	0.09	0.98	0.92

*S.E. = Standard Error of the Mean

**S.D. = Standard Deviation

***C.V. = Coefficient of Variation

Correlation and regression techniques were used to examine relationships between the spectral data and the canopy variables. Several numerical transformations were applied to the spectral and canopy variables, and the resulting transformed relationships were studied.

Results and Discussion

The correlation analysis was conducted using correlation coefficients (r) rather than coefficients of determination (R^2) to illustrate whether relationships were direct or inverse. The linear correlation coefficients(r) between the various canopy variables and the spectral bands are shown in Table III.3. The relationships with the canopy variables were moderate to strong for all of the bands with the exception of TM5. The reasons for weaker TM5/canopy relationships are unclear. Theoretically, TM5 should respond to the canopy in a similar fashion as TM7, since both bands are located in the middle infrared water absorption region (Gates, 1970; Knipling, 1970). Direct relationships were found between the near infrared bands (TM4 and MMR5) and the canopy variables, while inverse relationships were found between the chlorophyll/water absorption bands (TM1-TM3, MMR5 and TM7) and the canopy variables.

Due to the physical nature of plant growth, several of the canopy variables were highly correlated with each other. Table III.4 shows a high level of redundancy among the variables of total wet biomass, total dry biomass, above ground plant water, and leaf area index ($r \geq .94$). The following discussion will focus on the grass canopy variables of total wet biomass, canopy height, and canopy cover. Total wet biomass will be used to represent the four highly redundant canopy variables listed above. Generally, the findings relating to total wet biomass also hold true for total dry biomass, plant water, and leaf area index.

The near infrared band, TM4, was found to have the highest correlation with total wet biomass ($r = .80$). This higher near infrared correlation can be attributed to the ability of energy in this

Table III.3. Correlation Coefficients(r) between the Spectral Bands and the Tall Fescue Canopy Variables.

	Height	Percent Cover	Total Wet Biomass	Total Dry Biomass	Plant Water	Leaf Area Index
TM1	-.75	-.94	-.75	-.77	-.74	-.73
TM2	-.77	-.93	-.77	-.78	-.76	-.74
TM3	-.75	-.94	-.75	-.75	-.74	-.73
TM4	.82	.84	.80	.76	.80	.75
MMR5	.80	.77	.77	.75	.77	.70
TM5	-.39	-.71	-.49	-.50	-.47	-.53
TM7	-.72	-.95	-.75	-.76	-.75	-.74

Table III.4. Correlation Coefficient(r) Matrix for the Tall Fescue Canopy Variables.

	Height	Cover	Total Wet Biomass	Total Dry Biomass	Plant Water	Leaf Area Index
Height	1.00	.82	.91	.90	.91	.85
Cover		1.00	.87	.87	.86	.85
Total Wet Biomass			1.00	.99	.99	.96
Total Dry Biomass				1.00	.98	.94
Plant Water					1.00	.96
Leaf Area Index						1.00

spectral region to penetrate a multiple-layered canopy. In the near infrared region much of the energy is transmitted through the uppermost canopy leaves, then reflected from the lower canopy leaves back through the upper canopy, to increase total reflectance (Knipling, 1970). Conversely, the canopy leaves are less transparent to energy in the visible and middle infrared bands, making these wavebands less sensitive to multiple layered canopies.

Overall, the relationships between total wet biomass and the spectral bands were curvilinear due to the asymptotic characteristics of spectral response for moderate to high biomass levels. Tucker (1977) described the upper asymptote as the point reached when so much vegetation is present that any increase does not cause a detectable change in spectral reflectance. This results in a curvilinear response.

A number of logarithmic and reciprocal transformations were applied to the data set in an attempt to linearize the regression functions between total wet biomass and the spectral bands. The choice of the most appropriate model was aided by calculating the correlation coefficients between logarithmic/reciprocal transformations of the seven spectral bands (Y) and total wet biomass (X). The transformations included X against log Y, log X against Y, log X against log Y, X against reciprocal Y, reciprocal X against Y, and reciprocal X against reciprocal Y (Table III.5). Overall, the log X against log Y transformations exhibited the most linear pattern. The lower correlations for the reciprocal transformations were unexpected, since these transformations have been reported to be useful when upper asymptotes are found in the data (Neter and Wasserman, 1974).

Table III.5

Correlation Coefficients (r) between Logarithmic/Reciprocal Transformations of Total Wet Biomass (x) and the Spectral Bands (y)

	X & Y	X & Log Y	Log X & Y	Log X & Log Y	X & 1/Y	1/X & & Y	1/X & 1/Y
TM1	-.75	-.81	-.92	-.92	.84	.70	-.55
TM2	-.77	-.82	-.92	-.92	.83	.78	-.56
TM3	-.75	-.83	-.93	-.93	.86	.71	-.53
TM4	.80	.79	.85	.88	-.77	-.55	.67
MMR5	.77	.76	.80	.82	-.75	-.51	.56
TM5	-.49	-.48	-.63	-.62	.48	.52	-.48
TM7	-.75	-.81	-.92	-.92	.84	.71	-.57

A simple linear regression model was developed for the transformed variables of log X with log Y. The model took the form:

$$LnY = Lna + b(LnX)$$

where LnY is the natural logarithm of reflectance in a selected band, Lna and b are coefficients, and LnX is the natural logarithm of the grass canopy variable.

A curvilinear model was developed from the above linearized equation and was expressed as:

$$Y = aX^b$$

where Y is reflectance in a selected band, X is the canopy variable, and a and b are coefficients determined from the linearized equation above.

Figure III.1 shows the fitted regression line and the relationship between total wet biomass the TM4. Figure III.2 illustrates the linearized relationship between the natural logarithm of total wet biomass and the natural logarithm of TM4. Figure III.3 and Figure III.4 are corresponding examples for an absorption band (TM7) and total wet biomass, with the data expressed in the original and transformed scales, respectively.

The relationships between canopy height and the spectral bands were strongest for the near infrared bands TM4 ($r = .82$) and MMR5 ($r = .80$). Figure III.5 illustrates a curvilinear relationship between TM4 and height for canopies between 7.5 cm and 57.5 cm tall. The reason for the higher correlation coefficients in the near infrared can be attributed to the ability of energy in this spectral region to penetrate a multiple layered canopy as described previously.

The variable percent cover consistently had the highest correlation coefficients with the spectral bands. The middle infrared band (TM7) and the visible bands (TM1-TM3) were found to have the strongest relationships with percent cover ($r \geq .93$). When studying percent cover for this project, the multiple layers of the canopy were not considered, since canopy cover could not exceed one complete layer or 100 percent. Therefore, the visible and middle infrared

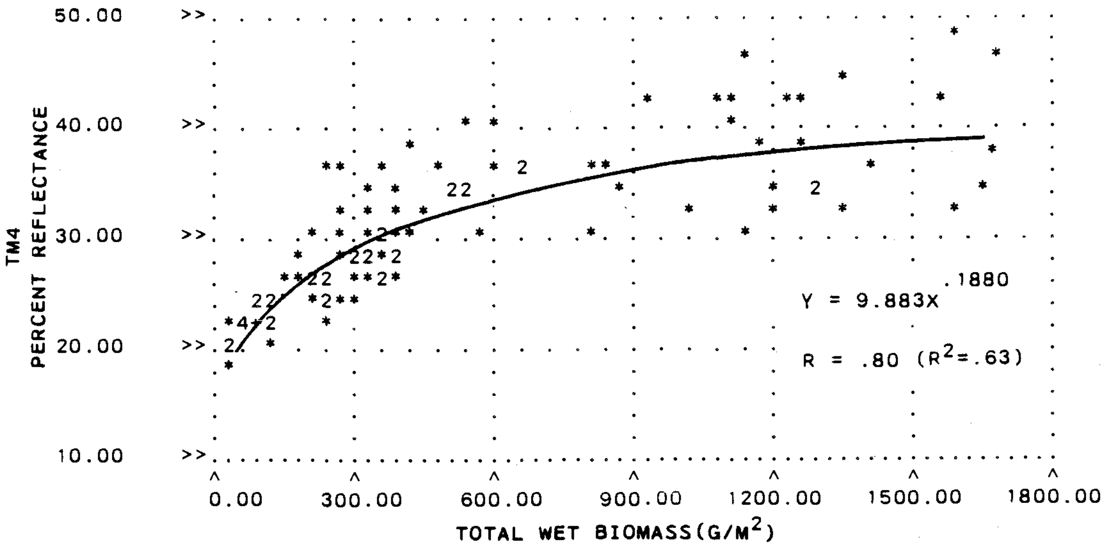

Figure III.1. Scatter diagram of total wet biomass (g/m^2) and TM4 reflectance from tall fescue.

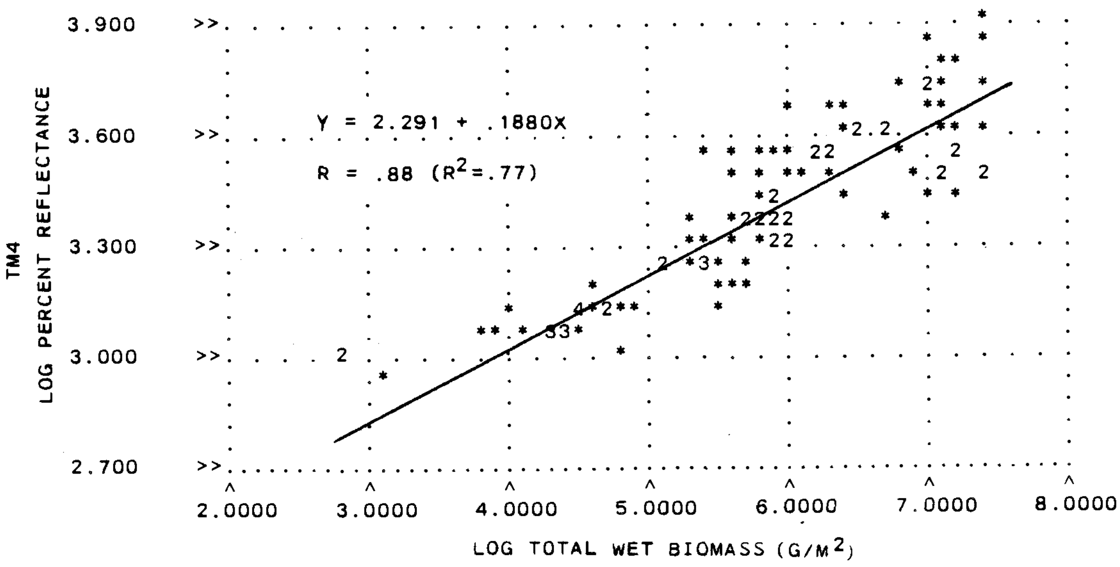

Figure III.2. Scatter diagram of the natural logarithm of total wet biomass (g/m^2) and the natural logarithm of TM4 reflectance from tall fescue.

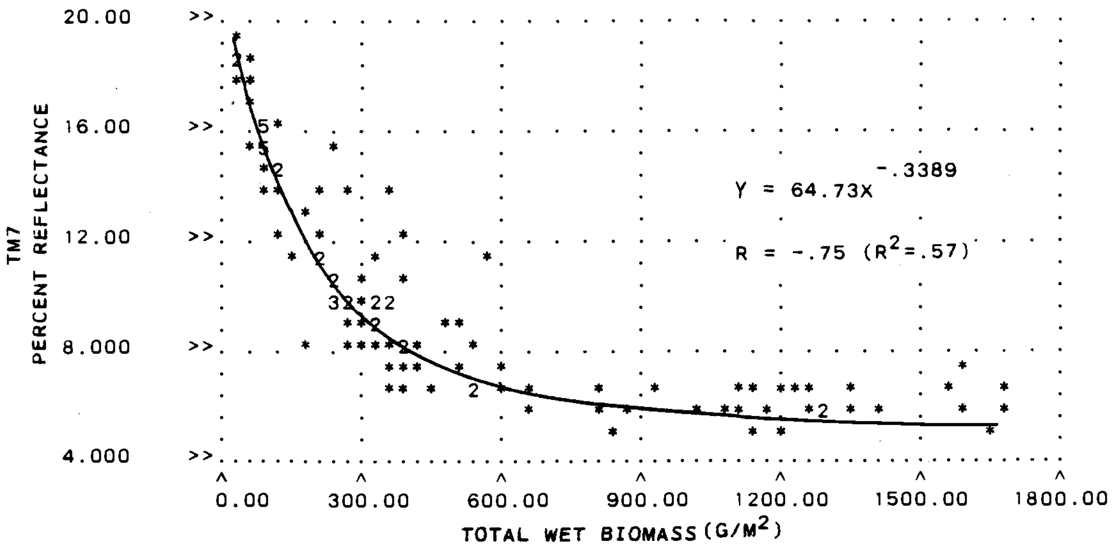

Figure III.3 Scatter diagram of total wet biomass (g/m^2) and TM7 reflectance from tall fescue.

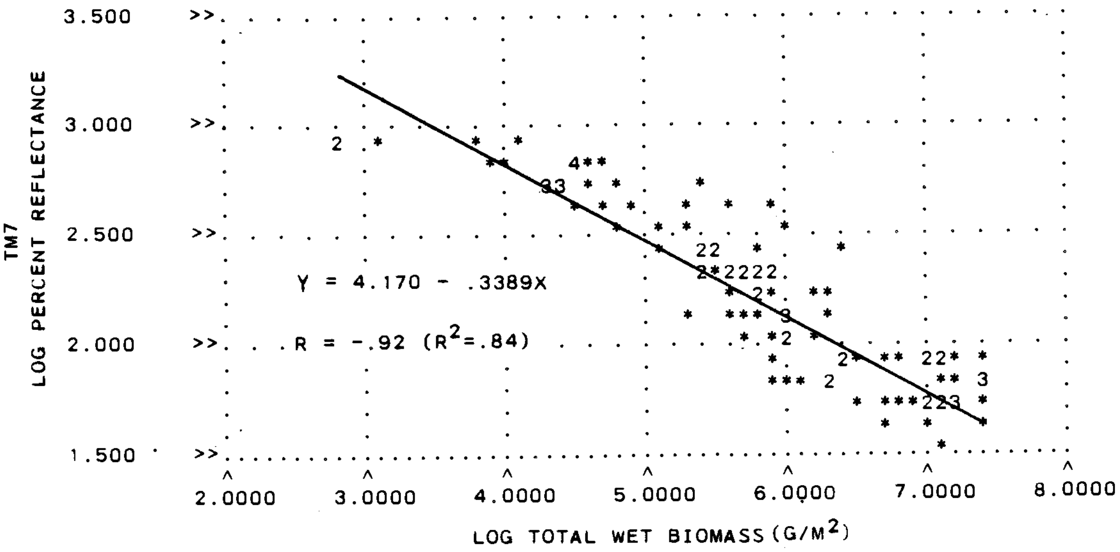

Figure III.4. Scatter diagram of the natural logarithm of total wet biomass (g/m^2) and the natural logarithm of TM7 reflectance from tall fescue.

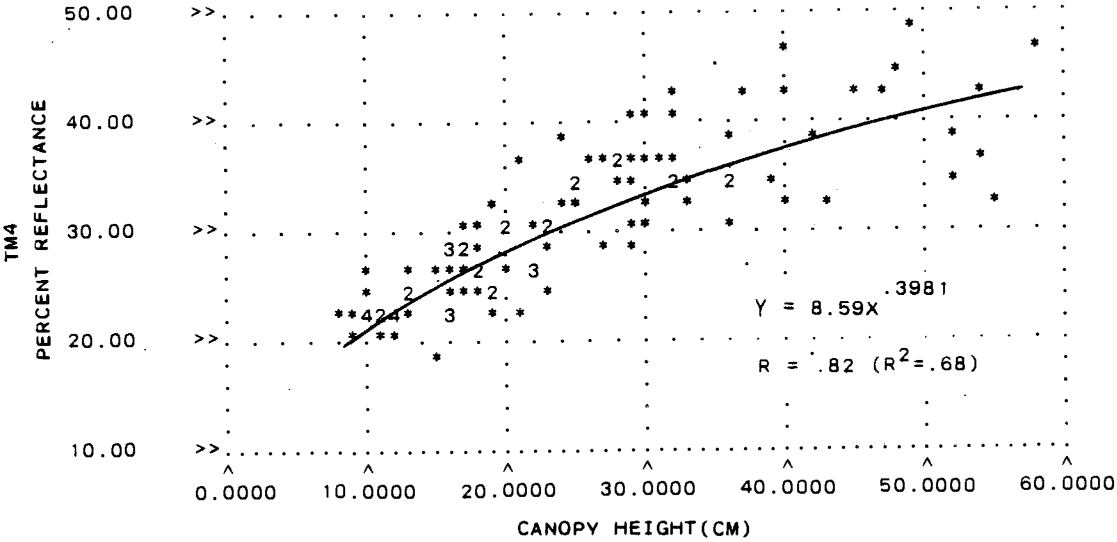

Figure III.5. Scatter diagram of canopy height (cm) and TM4 reflectance from tall fescue.

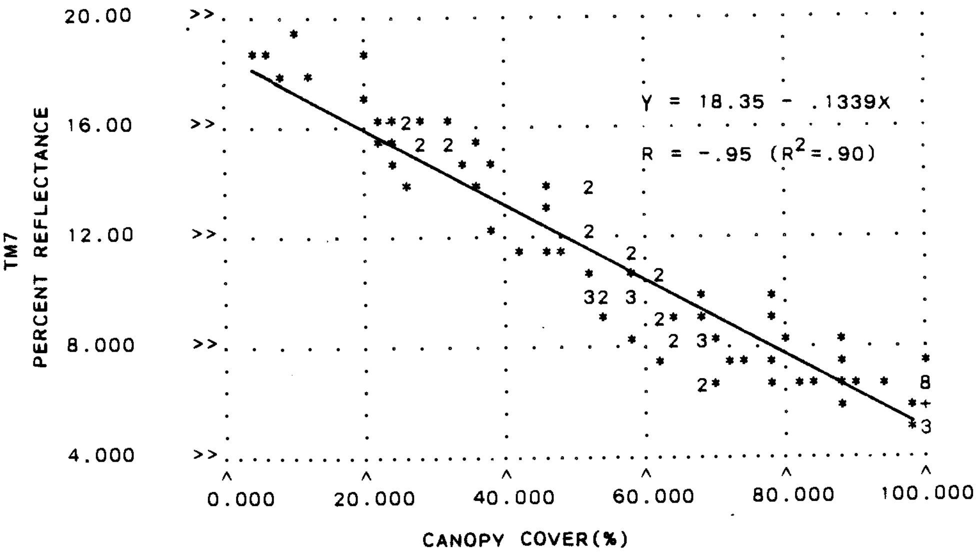

Figure III.6. Scatter diagram of canopy cover (%) and TM7 reflectance from tall fescue.

successfully in estimating percent cover. Figure III.6 illustrates the linear nature of the relationship between the spectral data (TM7) and percent canopy cover.

All possible band ratios (Band a/Band b) were tested for significant correlations with the canopy variables. The correlation coefficients for the band ratios were generally higher than the individual bands (Table III.6). The most significant ratios resulted from dividing near infrared reflectance values by middle infrared reflectance values. The interpretation of these ratios can be related to the strong inverse relationship between middle infrared reflectance and the amount of vegetation, along with the direct relationship between near infrared reflectance and the amount of vegetation. Figure III.7 is an illustration of how the near infrared/middle infrared ratio (TM4/TM7) became larger as total wet biomass increased. The normalized difference transformation (TM4-TM7/TM4+TM7) was also plotted against total wet biomass (Figure III.8). The relationship between the normalized difference and total wet biomass was very linear until the upper asymptote was reached at approximately 600 g/m^2 of total wet biomass. For biomass values between 600 g/m^2 and 1678 g/m^2, normalized difference values remained relatively constant. These results indicate that the normalized difference index would be an excellent predictor of biomass at low to moderate biomass levels using simple linear regression. For higher biomass levels, the normalzied difference index could have useful applications in classifying cover types using automated data handing techniques with digital remote sensing data. After the normalized difference index becomes asymptotic, within-cover type differences in biomass would no longer affect the normalized difference index. This uniform response could result in higher cover type classification accuracies.

Table III.6

Spectral Bands and Band Ratios Exhibiting the Highest Correlation Coefficients(r) with the Tall Fescue Canopy Variables

	Band	r	Band Ratio	r
Height	TM4	.82	TM4/TM7	.85
Cover	TM7	-.95	TM4/TM5	.95
Total Wet Biomass	TM4	.80	TM4/TM7	.89
Total Dry Biomass	TM2	-.78	MMR5/TM7	.88
Plant Water	TM4	.80	MMR5/TM7	.89
Leaf Area Index	TM4	.75	TM4/TM7	.86

High positive correlation coefficients were found among several of the spectral bands. Table III.7 shows the high redundancy for spectral bands TM1, TM2, and TM3 (r = .99). TM7 also exhibited a strong direct relationship with the visible bands ($r \geq .96$). A high correlation coefficient was found between the two near infrared bands, TM4 and MMR5 (r = .97).

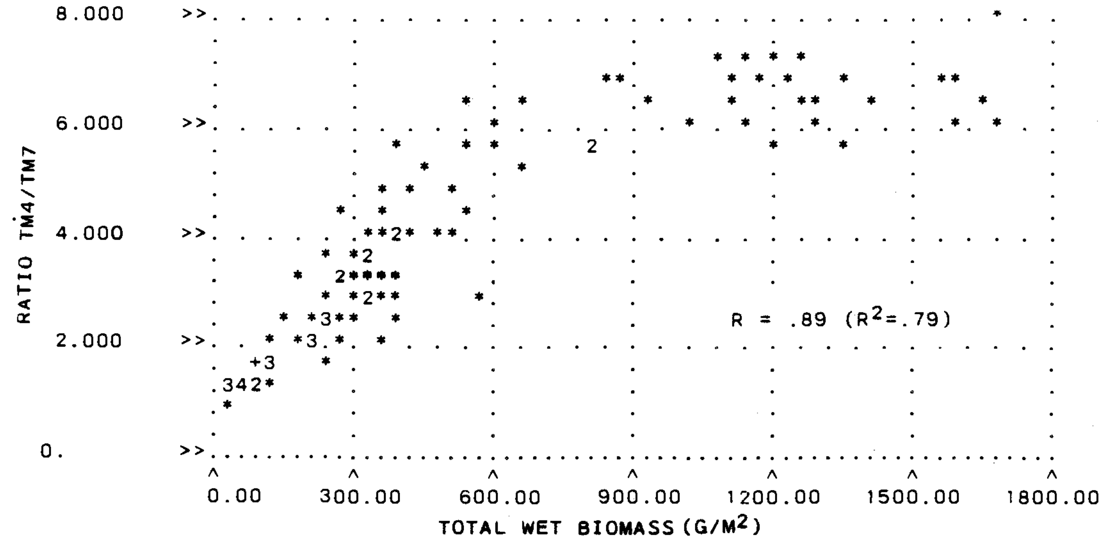

Figure III.7. Scatter diagram of total wet biomass (g/m^2) and the TM4/TM7 reflectance ratio from tall fescue.

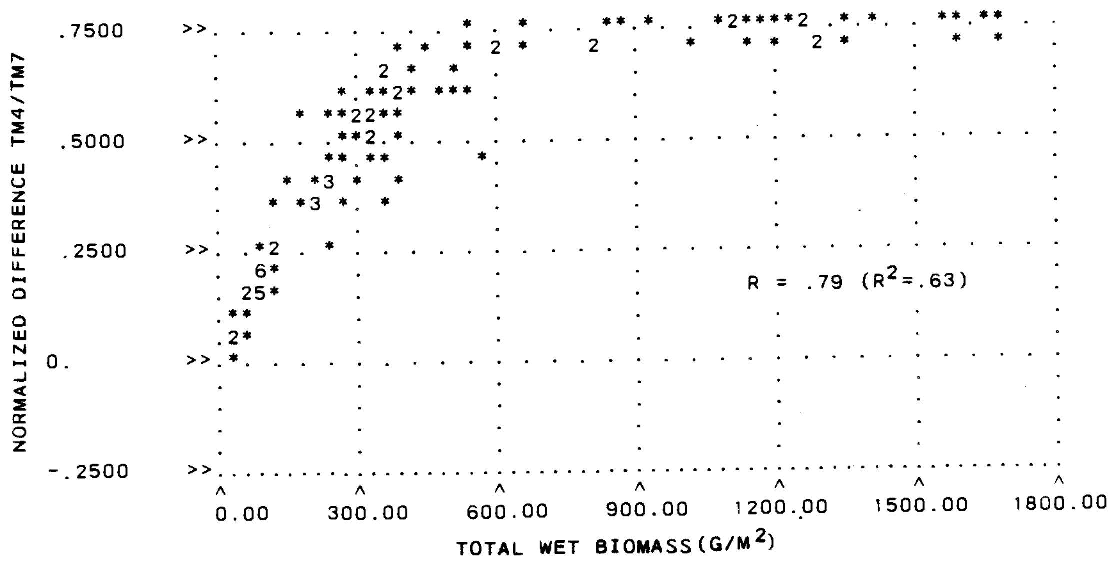

Figure III.8. Scatter diagram of total wet biomass (g/m^2) and the normalized difference of TM4 and TM7 reflectance from tall fescue.

Table III.7 Correlation Coefficient(r) Matrix for the Seven Spectral Bands

	TM1	TM2	TM3	TM4	MMR5	TM5	TM7
TM1	1.00	.99	.99	-.79	-.74	.74	.97
TM2		1.00	.99	-.81	-.76	.71	.96
TM3			1.00	-.83	-.76	.73	.97
TM4				1.00	.97	-.32	-.79
MMR5					1.00	-.18	-.70
TM5						1.00	.82
TM7							1.00

Table III.8. Percent of Variance Accounted for by the First Two Principal Components (PC) and Coefficients for Associated Eigenvectors for the Tall Fescue Spectral Data.

	Percent of Variance	TM1	TM2	TM3	TM4	MMR5	TM5	TM7
PC1	86.9	-.16	-.21	-.34	.67	.48	-.10	-.35
PC2	11.7	.20	.23	.38	.34	.41	.49	.49

A principal component analysis was conducted on the seven spectral bands in an attempt to reduce band redundancies and reduce the dimensionality of the data. The seven bands were reduced to two principal components while maintaining 99 percent of the variance contained in the original spectral bands. The first principal component is defined by an eigenvector pointing in the direction of maximum variation within the data. Subsequent principal components are defined by eigenvectors that lie in directions seeking maximum residual variations from the previous components (Miller et al., 1983). The coefficients for the eigenvectors associated with each principal component provide a means to determine the contributions of each spectral band to the overall variability caused by all of the spectral bands.

Table III.8 shows the first principal component being primarily related to near infrared reflectance (TM4 and MMR5). The second principal component is more difficult to interpret but is weighted toward the middle infrared bands (TM5 and TM7). The results of the analysis reported here and by Budd and Milton (1982) and Miller et al. (1983) indicate that principal component analysis has good potential in providing for Thematic Mapper data reduction in vegetation studies.

Summary

The following conclusions can be made under the conditions of this study:

1. There was a direct relationship between the near infrared bands and the canopy variables, along with an inverse relationship between the visible/middle infrared bands and the canopy variables.
2. A high level of redundancy was found among the canopy variables of total wet biomass, total dry biomass, above ground plant water, and leaf area index. This suggests that data on only one of these variables needs to be collected for studies concerned with remote sensing of grass canopies.
3. The near infrared region was best suited for estimating vertical biomass density in multiple-layered canopies. TM4 was the best estimator of total wet biomass and canopy height.
4. The middle infrared region (TM7) and the visible region (TM1-TM3) were superior to the near infrared bands for estimating percent canopy cover.
5. The relationship between the spectral bands and the canopy variables of total wet biomass, total dry biomass, plant water, and leaf area index was curvilinear for the biomass range in this study.
6. Logarithmic transformations linearized the regression functions between total wet biomass and the spectral bands. Overall, the transformations involving both the natural logarithm of the grass canopy variable and the

natural logarithm of the spectral band provided the most linear results.

7. Band ratios were more significant than individual bands when correlated with the canopy variables. The ratios of near infrared band values to middle infrared band values were most significant. This near infrared/middle infrared ratio should be treated as a potentially useful vegetation index for future thematic Mapper studies.
8. The relationship between the normalized difference transformation of TM4 and TM7 with total wet biomass was linear for total wet biomass levels of less than 600 g/m^2. For higher biomass situations of greater than 600 g/m^2, the values for the normalized difference index were relatively constant.
9. A high level of redundancy was found among four of the absorption bands (TM1, TM2, TM3, and TM7). The two near infrared bands (TM4 and MMR5) were also found to be highly correlated.
10. The seven spectral bands were reduced to two dimensions using principal components analysis. The first principal component was mostly related to near infrared reflectance and accounted for 87 percent of the variability of the original seven bands. With the

inclusion of the second principal component, 99 percent of the original variance was explained.

11. The high correlation among the Thematic Mapper bands and the principal component analysis indicates that a two or three band subset of the original spectral bands may be sufficient for mapping vegetation characteristics with Landsat Thematic Mapper imagery. Important biophysical regions for the spectral analysis of vegetation include the visible (TM1-TM3), the near infrared (TM4,MMR5), and the middle infrared (TM5,TM7).

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CHAPTER IV

ASYMPTOTIC CHARACTERISTICS OF LANDSAT THEMATIC MAPPER BANDS FOR MONITORING VEGETATION

Abstract

The asymptotic relationships between the Thematic Mapper Spectral bands and grass canopy variables were studied. Spectral data were obtained using in situ remote sensing techniques on 107 tall fescue (Festuca arundinacea) plots. Estimates of the asymptotic limits were based on a regression model, which showed the curvilinear nature of the spectral response to the grass canopy variables. The reflectance asymptotes for the near infrared band (TM4) were up to twice as high as the asymptotes for the redundant absorption bands (TM1, TM2, TM3, and TM7). The TM4 asymptotes were estimated to be between 270-375 g/m^2 of the total dry biomass, which was equivalent to a leaf area index of 2.45 - 3.25. The asymptote for the normalized difference index was lower than the near infrared asymptotes, but similar to the asymptotes for TM1, TM2, TM3, and TM7.

Introduction

The spectral band locations for the Landsat Thematic Mapper were chosen primarily for applications in monitoring vegetation. A knowledge of the asymptotic characteristics of the Thematic Mapper bands is important for studies in biomass estimation and vegetative cover mapping.

Allen and Richardson (1968) were the first to report on the asymptotic nature of reflectance from a plant canopy. They increased the number of plant leaf layers in the canopy until a stable or constant reflectance was reached. This asymptotic limit was termed "infinite reflectance." Tucker (1977) defined asymptotic spectral reflectance as the point reached when so much vegetation is present that the addition of more vegetation ceases to cause a detectable change in reflectance.

The research reported here is concerned with the asymptotic relationships between the Landsat Thematic Mapper bands and grass canopy variables. *In situ* remote sensing techniques were used to collect spectral data from grass plots representing a large range of biomass levels. The procedure utilized the results of regression models to estimate asymptotes for the Thematic Mapper bands.

Literature Review

Different spectral asymptotes at various wavelengths are caused by differing amounts of absorption, transmittance, and reflectance from leaves in the plant canopy. In the visible region (0.4 - 0.7 μm), low levels of reflectance and transmittance are caused by highly absorbing plant pigments, mainly the chlorophylls (Gates et al., 1965). Conversely, both reflectance and transmittance are very high in the near infrared (0.7 - 1.3 μm), with little or no absorption.

This is caused by the scattering of near infrared energy at the interfaces of the spongy mesophyll cell walls (Gates et al., 1965; Knipling, 1970). In the middle infrared (1.3 - 2.6 μm), relatively low reflectance is governed by strong absorption from liquid water in the leaves (Gates, 1970; Myers, 1970).

The importance of the relationship between transmittance and spectral asymptotes was demonstrated by Myers (1970). He obtained laboratory reflectance measurements from cotton leaves stacked on one another, up to six deep. No differences in reflectance were found in the visible wavelengths from any combination of stacked leaves. Near infrared reflectance changes occurred for up to six stacked leaves. This higher asymptote was attributed to the transmittance of near infrared energy through the upper leaves, and multiple reflectance from the lower leaves back through the upper leaves. Leaf stacking did not significantly affect reflectance in the middle infrared region, although reflectance for six stacked layers was approximately ten percent higher than reflectance for one leaf at 1.60 μm wavelength.

The nature of asymptotic reflectance in corn leaves was studied in the laboratory by Gausman et al. (1976). Spectral asymptotes resulted from stacking two leaves for visible reflectance (0.5 - .75 μm), eight leaves for the near infrared (0.75 - 1.35 μm), and three leaves for the middle infrared (1.35 - 2.5 μm).

Tucker (1977) investigated the asymptotic characteristics of grass canopies. He obtained *in situ* reflectance measurements from thirty-five blue grama grass (Bouteloua gracilis) plots. Spectral asymptotes were estimated for both red (.680 μm) and near infrared (0.775 μm) wavelengths using a stepwise curvilinear regression method. The criterion for the asymptotes was as follows. When the change in predicted reflectance, utilizing a regression equation and incrementally increased values for a canopy variable, from step to step, was less than an assigned minimum, the asymptote was reached. This methodology was expressed in the following way:

if $|RFL(i) - RFL(i-1)| < min$, then ΔX was not detectable,

where RFL(i) was predicted reflectance for the ith increment and ΔX was the corresponding step change for the canopy variable.

Tucker (1977) found the near infrared reflectance asymptote to be two to three times higher than the red reflectance asymptote. For total dry biomass, the red asymptote was calculated to be between 97.5 - 127.5 g/m^2, while the near infrared asymptote was reported to be between 285 - 435 g/m^2.

Materials and Methods

This research was based on the analysis of data from 107 tall fescue (Festuca arundinacea) grass plots. Experimental plots were planted on April 14, 1983 using the broadcast seeding method in order to acquire a large range of seed densities. This resulted in a high variability of biomass and canopy cover within the seeded plots.

Data were collected from green grass canopies on June 7 (n = 22), July 10 (n = 22), August 9 (n = 30), and September 12 (n = 33).

This sampling scheme allowed for a large range of plot biomass levels (6.5 - 502.5 g/m^2 total dry biomass). The spectral data were collected using a Barnes Multiband Modular Radiometer (MMR) with a seven meter telescoping boom mounted on a pickup truck. This radiometer was designed to simulate the spectral bands of the Landsat Thematic Mapper (Table IV.1). The Thematic Mapper has three bands in the visible region (TM1, TM2, and TM3), one band in the near infrared (TM4), two in the middle infrared (TM5 and TM7), and one in the thermal infrared (TM6). The thermal band was not included in this study, but a second near infrared band (1.55 - 1.30 µm) was included and will be referred to as MMR5.

The spectral data were collected only on clear sunny days during the mid-day hours. Vertical spectral readings were recorded with the radiometer 1.92 m above the ground. The radiometer's circular field-of-view was approximately equivalent to the plot area (0.2 m^2). The instrument was independently centered over each plot three times and a mean reflectance was calculated from the three readings. The spectral data were referenced to a barium sulfate calibration panel approximately every 20 minutes.

The grass canopy variables included in the analysis were canopy height (cm), total wet biomass (g/m^2), total dry biomass (g/m^2), above ground plant water (g/m^2), and leaf area index (Table IV.2). After each plot was spectrally measured, canopy height was measured and all above ground biomass was harvested and taken to the Laboratory for wet biomass measurements. Dry biomass data were obtained

Table IV.1. Wavelengths for the Barnes Modular Multispectral Radiometer (MMR) and Corresponding Thematic Mapper Bands (TM)

Barnes Radiometer Bands (MMR)	Thematic Mapper Bands (TM)	Wavelength (μm)
MMR1	TM1	0.45 - 0.52 (Blue-green)
MMR2	TM2	0.52 - 0.60 (green)
MMR3	TM3	0.63 - 0.69 (red)
MMR4	TM4	0.76 - 0.90 (near infrared)
MMR5		1.15 - 1.30 (near infrared)
MMR6	TM5	1.55 - 1.75 (middle infrared)
MMR7	TM7	2.08 - 2.35 (middle infrared)
MMR8	TM6	10.40 -12.50 (thermal infrared)

Table IV.2. Summary of Tall Fescue Canopy Variables

	Mean	Min.	Max.	S.E.*	S.D.**	C.V.***
Height (cm)	24.7	7.5	57.5	1.2	12.2	.49
Total Wet Biomass (g/m^2)	523.3	16.5	1677.9	45.3	468.8	.90
Total Dry Biomass (g/m^2)	146.4	6.5	502.5	12.5	129.7	.89
Plant Water (g/m^2)	367.9	9.9	1312.4	33.0	340.9	.90
Leaf Area Index	1.06	.03	4.32	.09	.98	.92

*S.E. = Standard Error of Mean

**S.D. = Standard Deviation

***C.V. = Coefficient of Variation

after the grass was dried in an oven for 48 hours at 60^{o} C. Aboveground plant water was calculated by subtracting the dry weights from the wet weights. Leaf area index was estimated from a subsample of grass from each plot. Leaf area index is the area of all the leaves in the plot divided by the ground area in the plot. After calculating the leaf area and leaf weight of the subsample, extrapolations were made to estimate the leaf area index of the plot, since both total plot biomass and total plot area were known.

A regression approach was used to explain the asymptotic characteristics of the spectral response. A simple linear regression model was developed for the natural logarithms of both the spectral and grass canopy variables:

$$\mathrm{Ln}Y = \mathrm{Ln}a + b(\mathrm{Ln}X)$$

where LnY is the natural logarithm of a selected spectral band, Lna and b are coefficients, and LnX is the natural logarithm of the grass canopy variable. A curvilinear model was developed from the above linearized equation and was expressed as:

$$Y = aX^{b}$$

where Y is reflectance in a selected band, X is the canopy variable, and a and b are coefficients determined from the linearized equation above.

A quantitative approach similar to the methodology developed by Tucker (1977) was used to estimate the asymptote for each spectral band. Equations to predict reflectance were developed from the above curvilinear regression model. Reflectance was predicted for each of thirty-three incremental changes in the canopy variable. The upper asymptote was reached when percent change in predicted reflectance was less than an assigned minimum for a corresponding incremental change in the canopy variable. The model took the form:

$$\text{if } \frac{|\hat{Y}_i - \hat{Y}_{i-1}|}{\hat{Y}_{max} - \hat{Y}_{min}} \times 100 < \text{min, then } \Delta X \text{ is not detectable,}$$

where $\hat{y}_i$ is predicted reflectance for the ith iteration; $\hat{y}_{max}$ is predicted reflectance for the highest iteration; $\hat{y}_{min}$ is predicted reflectance for the lowest iteration; min is the assigned minimum percent change in reflectance; and ΔX is the corresponding incremental change for the canopy variable.

The increments for the grass canopy variables were set at 2.5 cm for canopy height, 50 g/m^2 for total wet biomass, 15 g/m^2 for total dry biomass, 40 g/m^2 for plant water, and 0.13 for leaf area index. The asymptotes were calculated using three different criteria for the assigned minimum percent change in reflectance (1.50%, 1.75%, and 2.00%).

Results and Discussion

The correlation analysis was conducted using correlation coefficients (r) rather than coefficients of determination (R^2) to illustrate whether relationships were direct or inverse. Correlation coefficients were computed for the transformed (i.e., natural logarithms) spectral and canopy data (Table IV.3). The pigment/water absorption bands (TM1, TM2, TM3, TM5, and TM7) exhibited an inverse relationship with the canopy variables, while the near infrared bands showed a direct relationship with the canopy variables. Overall, the correlation coefficients(r) were highest for TM1, TM2, TM3, and TM7, and lowest for TM5. The reason for the weak TM5/canopy relationship is unclear. TM5 should have characteristics similar to TM7, since both bands are located in the water absorption region of the spectrum (Gates, 1970; Knipling, 1970).

Table IV.3.

Correlation Coefficients(r) between the Transformed Spectral Bands and the Transformed Canopy Variables (Logarithmic transformations were used).

	Height	Total Wet Biomass	Total Dry Biomass	Plant Water	Leaf Area Index
TM1	-.85	-.92	-.93	-.91	-.91
TM2	-.85	-.92	-.92	-.91	-.90
TM3	-.86	-.93	-.92	-.92	-.92
TM4	.86	.88	.87	.88	.84
MMR5	.84	.82	.82	.81	.75
TM5	NS	-.62	-.62	-.62	-.69
TM7	-.81	-.92	-.91	-.91	-.92

NS = not significant

Table IV.4 shows an example of the asymptotic modeling technique used for this study. Presented are the results of 33 regression iterations, using total dry biomass as the independent variable and TM4 reflectance as the dependent variable. The model was used to predict TM4 reflectance (Y) from total dry biomass (X), which varied from 15 g/m^2 to 495 g/m^2 in 15 g/m^2 (ΔX) increments. When the relative incremental change in TM4 reflectance was less than the assigned minimum (2.00%, 1.75%, or 1.50%), the spectral asymptote was reached. This procedure was repeated for all possible spectral band/canopy variable combinations.

Estimates of the spectral asymptotes for the canopy variables are shown in Table IV.5. The asymptotes for TM4 were nearly twice as high as the asymptotes for the absorption bands (TM1, TM2, TM3, and TM7). The MMR5 asymptotes were slightly lower than those for TM4. The high near infrared asymptotes resulted from the ability of near infrared energy to penetrate multilayered canopies, as discussed by Myers (1970). The TM4 asymptote for total dry biomass was between 270 g/m^2 - 375 g/m^2, which was equivalent to a leaf area index (LAI) of 2.34 - 3.25 for this study. These near infrared asymptotes were similar to those found by Tucker (1977).

The lower asymptotes for the pigment and water absorption bands can be explained by the opaque nature of the canopy to energy in these wavebands. Reflectance asymptotes for TM1, TM2, TM3, and TM7 were between 165 g/m^2 - 225 g/m^2 of total dry biomass (LAI 1.43 - 1.95). The asymptote for red reflectance with total dry biomass (165

Table IV.4. Results of 33 Regression Interations ($\hat{y}$ = 13.02 $X^{.1806}$) Showing the Asymptotic Characteristics of TM4 Reflectance (Y) Regressed Against Total Dry Biomass (X).

Iteration	$\hat{y}$	x(g/m^2)	Δx(g/m^2)	$\lvert\hat{y}_i-\hat{y}_{i-1}\rvert$	$\frac{\lvert\hat{y}_i-\hat{y}_{i-1}\rvert}{\hat{y}_{max}-\hat{y}_{min}} \times 100$
1	21.240	15			
2	24.072	30	15	2.832	15.03
3	25.900	45	15	1.828	9.70
4	27.282	60	15	1.382	7.34
5	28.403	75	15	1.121	5.95
6	29.354	90	15	.951	5.05
7	30.183	105	15	.829	4.40
8	30.919	120	15	.736	3.90
9	31.584	135	15	.665	3.53
10	32.191	150	15	.607	3.22
11	32.750	165	15	.559	2.97
12	33.268	180	15	.518	2.75
13	33.753	195	15	.485	2.57
14	34.207	210	15	.454	2.41
15	34.636	225	15	.429	2.29
16	35.042	240	15	.406	2.17
17	35.428	255	15	.386	2.06
18	35.796	270	15	.368	1.97
19	36.147	285	15	.351	1.87
20	36.483	300	15	.336	1.80
21	36.806	315	15	.323	1.73
22	37.117	330	15	.311	1.66
23	37.416	345	15	.299	1.60
24	37.705	360	15	.289	1.55
25	37.983	375	15	.278	1.49
26	38.253	390	15	.270	1.44
27	38.515	405	15	.262	1.40
28	38.769	420	15	.254	1.36
29	39.015	435	15	.246	1.32
30	39.255	450	15	.240	1.28
31	39.489	465	15	.234	1.25
32	39.715	480	15	.226	1.21
33	39.936	495	15	.221	1.18

Table IV.5. Estimates of Spectral Asymptotes for Five Grass Canopy Variables Using Three Different Criteria.

	% Change Criteria	Height (cm)	Total Wet Biomass (g/m^2)	Total Dry Biomass (g/m^2)	Plant Water (g/m^2)	Leaf Area Index
TM1	2.00	31.5	550	180	480	1.56
TM1	1.75	34.5	650	195	520	1.69
TM1	1.50	37.5	700	210	560	1.82
TM2	2.00	33.0	600	180	480	1.56
TM2	1.75	36.0	650	195	560	1.69
TM2	1.50	37.5	750	225	600	1.95
TM3	2.00	33.0	550	165	440	1.43
TM3	1.75	34.5	550	180	480	1.56
TM3	1.50	37.5	650	195	520	1.69
TM4	2.00	>57.5	900	270	720	2.34
TM4	1.75	>57.5	1050	315	840	2.73
TM4	1.50	>57.5	1300	375	1040	3.25
MMR5	2.00	53.0	850	255	680	2.21
MMR5	1.75	>57.5	950	300	800	2.60
MMR5	1.50	>57.5	1200	345	960	2.99
TM5	2.00	Not Significant	750	210	560	1.82
TM5	1.75		850	240	640	2.08
TM5	1.50		900	285	760	2.34
TM7	2.00	33.0	600	180	480	1.56
TM7	1.75	36.0	650	195	520	1.69
TM7	1.50	39.0	750	225	560	1.82

- 195 g/m^2) was higher than Tucker (1977) reported (97.5 - 127.5 g/m^2).

The curvilinear nature of the relationship between the spectral data and the canopy data is illustrated with scatter diagrams (Figures IV.1-IV.7). The estimated asymptote (1.75% criterion) is depicted by the arrow in each scatter diagram. The scatter diagrams show the redundancies found in TM1, TM2, TM3, and TM7. The scatter diagrams also show how the residuals from the fitted regression lines for the near infrared bands (TM4 and MMR5) increased as biomass increased. This nonconstant error term was probably caused by variable scattering resulting from variations in leaf orientation within the multilayered canopies.

The normalized difference index (TM4-TM3/TM4+TM3) was plotted against total dry biomass (Figure IV.8). The spectral response was linear until the upper asymptote was reached at approximately 180 g/m^2. The normalized difference asymptote was lower than the near infrared asymptotes, but similar to the asymptotes for the absorption bands (TM1, TM2, TM3, and TM7).

Summary

The following conclusions can be made concerning the asymptotic characteristics of the spectral bands used in this study:

1. The relationships between the spectral bands and the canopy variables were curvilinear for the biomass range in this study.

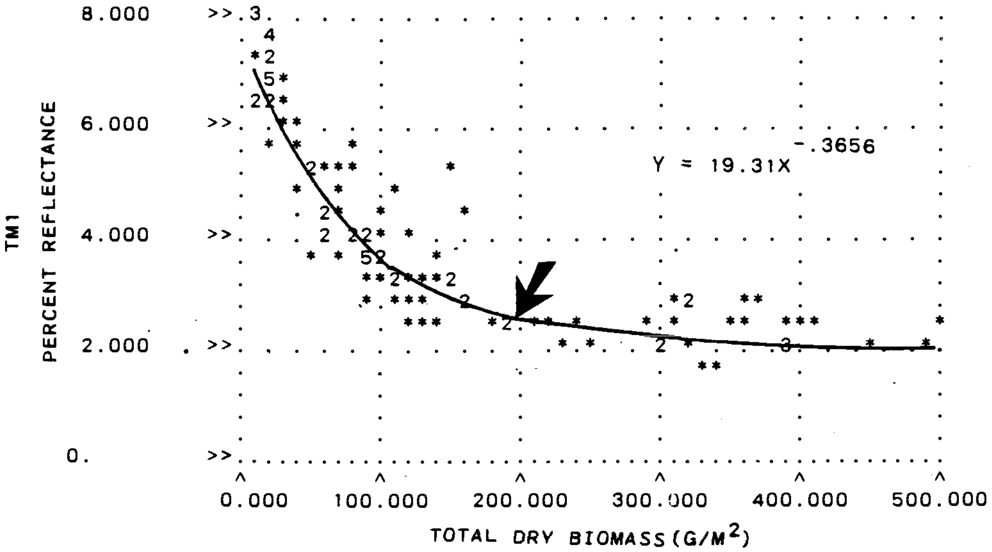

Figure IV.1. Scatter diagram of total dry biomass (g/m^2) and TM1 reflectance from tall fescue showing the reflectance asymptote (arrow).

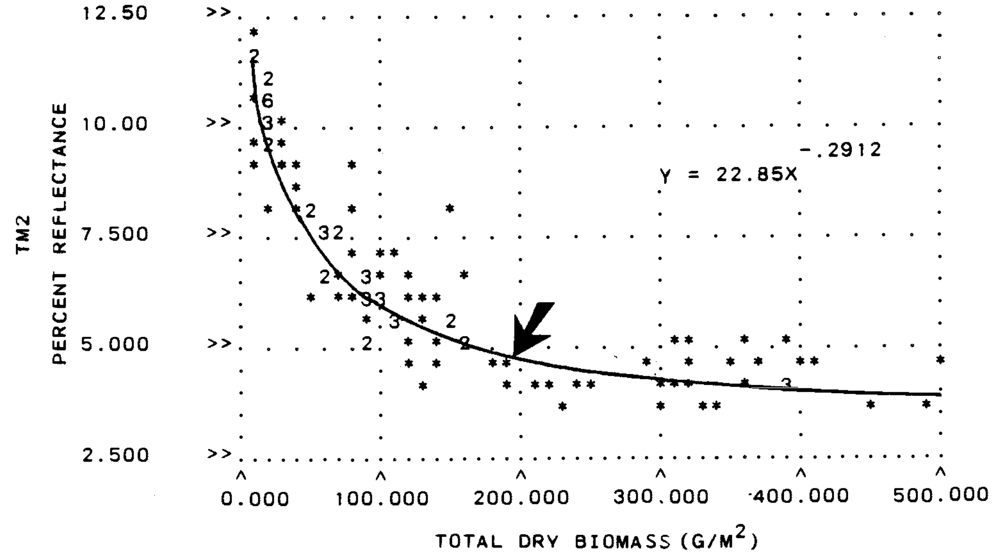

Figure IV.2. Scatter diagram of total dry biomass (g/m^2) and TM2 reflectance from tall fescue showing the reflectance asymptote (arrow).

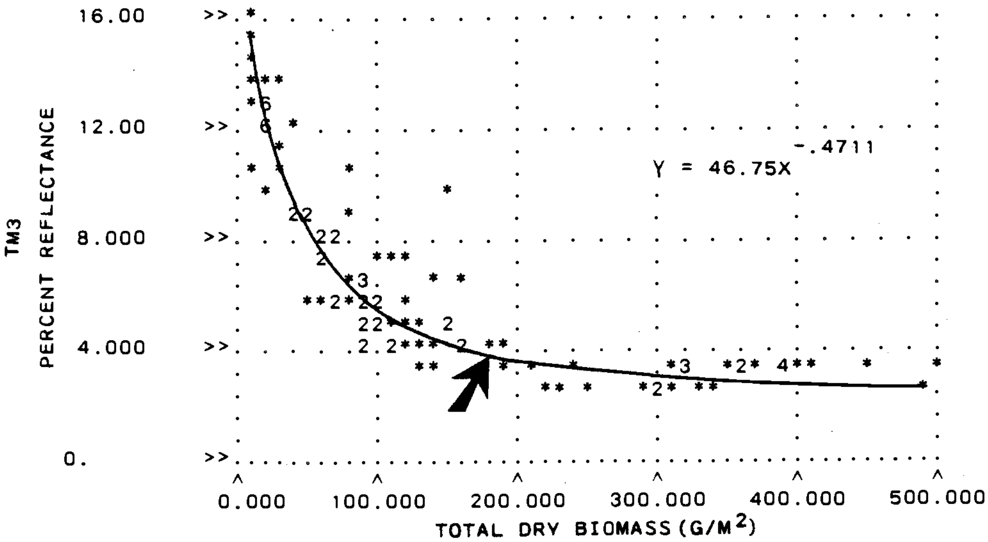

Figure IV.3. Scatter diagram of total dry biomass (g/m^2) and TM3 reflectance from tall fescue showing the reflectance asymptote (arrow).

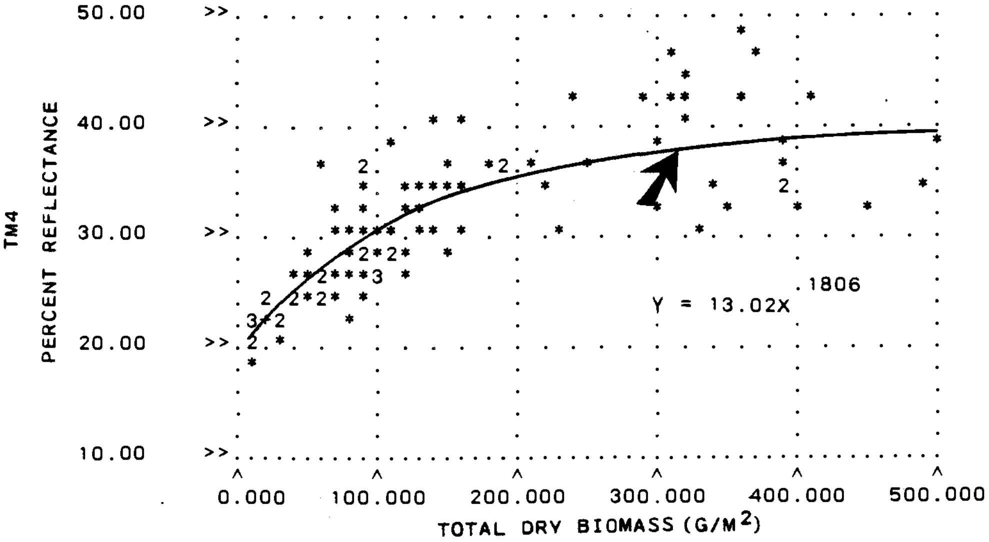

Figure IV.4. Scatter diagram of total dry biomass (g/m^2) and TM4 reflectance from tall fescue showing the reflectance asymptote (arrow).

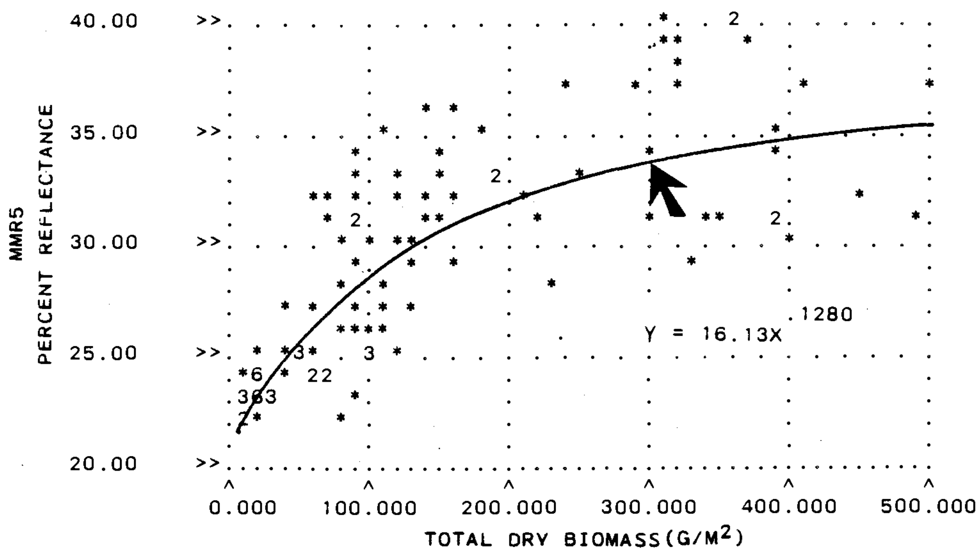

Figure IV.5. Scatter diagram of total dry biomass (g/m^2) and MMR5 reflectance from tall fescue showing the reflectance asymptote (arrow).

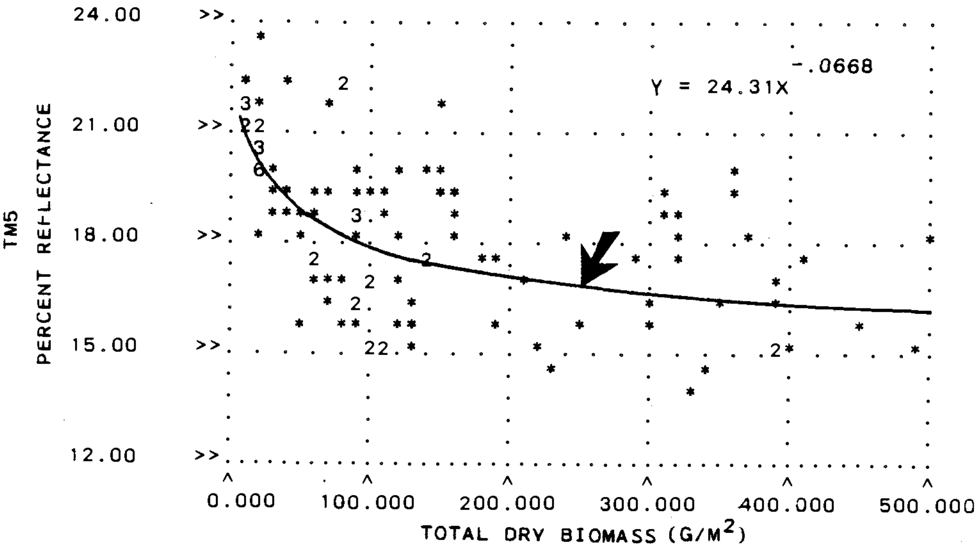

Figure IV.6. Scatter diagram of total dry biomass (g/m^2) and TM5 reflectance from tall fescue showing the reflectance asymptote (arrow).

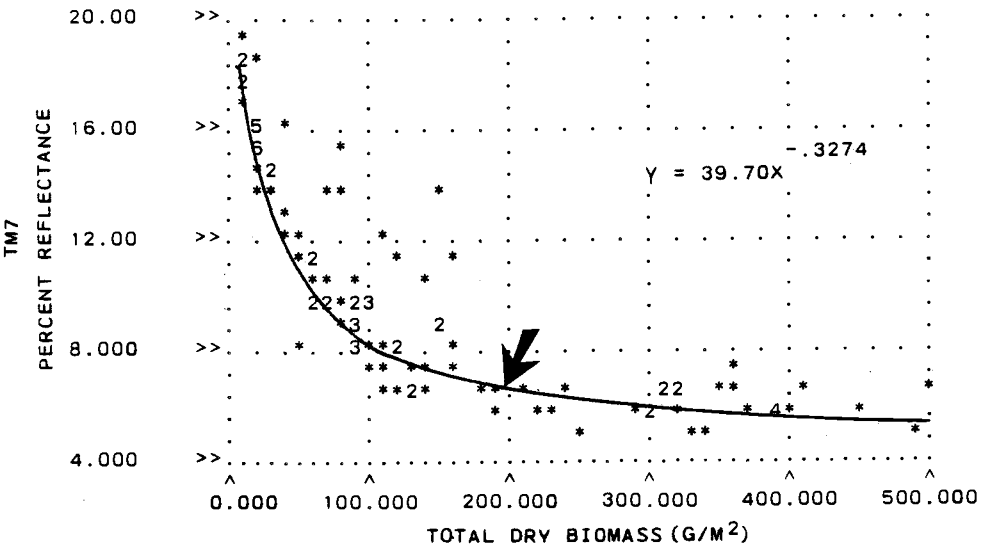

Figure IV.7. Scatter diagram of total dry biomass (g/m^2) and TM7 reflectance from tall fescue showing the reflectance asymptote (arrow).

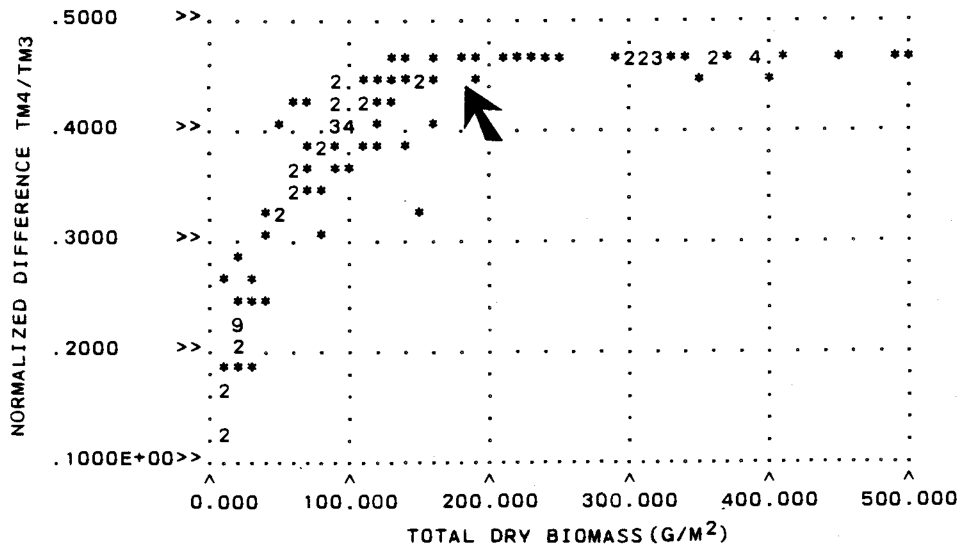

Figure IV.8. Scatter diagram of total dry biomass (g/m^2) and the normalized difference of TM4/TM3 reflectance from tall fescue showing the reflectance asymptote (arrow).

2. The spectral bands showed regression sensitivity to changes in canopy height, total wet biomass, total dry biomass, above ground plant water, and leaf area index. TM5 was the least sensitive spectral band tested.
3. The reflectance asymptotes for the near infrared bands were as much as twice as high as the asymptotes for the absorption bands. The asymptotic levels were very similar for absorption bands TM1, TM2, TM3, and TM7.
4. The residuals from the fitted regression lines for the near infrared bands increased as biomass increased. This nonconstant error term was attributed to differential scattering caused by variations in canopy geometry primarily leaf orientation.
5. The normalized difference index asymptote was less than the near infrared asymptotes, but similar to the asymptotes found for TM1, TM2, TM3, and TM7.
6. Determining the asymptotic limits of the Thematic Mapper bands has implications for monitoring vegetation with the Landsat Satellite. For conditions below the reflectance asymptotes, regression equations could be used to estimate biomass on a pixel-by-pixel basis, since the relationship between reflectance and biomass would be linear. Vegetation biomass maps could then be constructed using digital mapping techniques. Conversely, in higher biomass situations, when the

asymptotic limits are exceeded, differences in biomass within vegetative cover types would no longer affect reflectance values. This stable reflectance should result in higher cover type mapping accuracies using Landsat image classification methods.

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CHAPTER V

CONCLUSIONS

The functional relationships between the Landsat Thematic Mapper bands and grass canopy variables were studied using both annual and perennial grasses: annual ryegrass (*Lolium multiforum*) and tall fescue (*Festuca arundinacea*). Data sets were obtained for three annual ryegrass phenological stages: early stem extension (n = 22), anthesis (n = 21), and senescence (n = 22). Data were collected from the tall fescue plots (n = 107) representing a range of 16.5 - 1,677.9 g/m^2 of total wet biomass. It should be noted that the results presented in this dissertation are from a relatively small data base and caution should be exercised in extrapolation of these results and their interpretation to different situations. Additional verification is needed to evaluate the relationships between the Thematic Mapper bands and grass canopy variables under various conditions. The following conclusions can be made from the results of this study:

1. Redundancy was found to exist for several of the canopy variables in both the ryegrass and fescue data sets. The correlation analysis indicated a high redundancy for the variables of total wet biomass, total dry biomass, plant water, and leaf area index. The results of this study indicate that biomass measurements could be substituted for the more tedious leaf area

measurements. Leaf area index could be predicted from biomass using double sampling and regression techniques.

2. All of the data indicated a direct relationship between the near infrared bands and the canopy variables, and an inverse relationship between the visible/middle infrared bands and the canopy variables. This was attributed to near infrared scattering and chlorophyll/water absorption, respectively.
3. The most significant relationships between the spectral and canopy variables were found before the occurrence of high biomass levels or canopy senescence, both of which adversely affected these relationships. This suggests that Thematic Mapper imagery acquired early in the growing season may provide the best results for mapping biomass and other canopy characteristics.
4. Overall, no one spectral band(s) was found to be superior for explaining the variation in the canopy variables in all situations. Since the spectral bands respond differently to different biophysical canopy characteristics it would be desirable to select bands from all important regions of the spectrum for satellite monitoring applications. For the tall fescue data, the near infrared was superior for estimating biomass in multi-layered canopies. The visible (TM1-

TM3) and middle infrared (TM7) were superior to the near infrared bands for estimating percent cover. TM5 consistently exhibited the lowest correlation with the canopy variables.

5. The examination of the correlation coefficients alone was not sufficient to determine whether the relationships were linear. Scatter Diagrams were needed to illustrate the functional relationships. The relationship between near infrared reflectance (TM4 and MMR5) and biomass was linear for low to moderate biomass levels for both the annual ryegrass and the tall fescue data sets. Linear relationships were found between the spectral data and canopy cover. All other spectral reflectance/canopy relationships were curvilinear for this study.
6. The results of band ratioing were inconclusive. When compared to the original bands, the use of band ratios did not significantly increase correlations with the grass canopy variables for the annual ryegrass data. This lack of improvement was attributed to the calibration of the radiance data, along with minimal variations in sum angle, atmosphere, and soil conditions. Band ratios for the tall fescue data were more significant than individual bands. The near infrared/middle infrared ratio was most significant and potentially

could be useful as a vegetation index for future Thematic Mapper studies.

7. The absorption bands TM1, TM2, TM3, and TM7 were found to be highly correlated with each other. A high level of redundancy was also found for the two near infrared bands (TM4 and MMR5). A principal component analysis was used to eliminate spectral band redundancies. The seven spectral bands were reduced to two principal components, while maintaining nearly all of the variability contained in the original seven bands. These results indicate that a two-variable subset of the original spectral bands would be sufficient for mapping vegetation characteristics with Landsat Thematic Mapper imagery.
8. Reflectance asymptotes were estimated for each spectral band using the tall fescue data. Asymptotes for the near infrared (TM4) were nearly twice as high as the asymptotes for the absorption bands (TM1, TM2, TM3, and TM7). The TM4 asymptotes were found to be between 270 - 357 g/m^2 of total dry biomass, which is equivalent to a leaf area index of 2.45 - 3.25.
9. Reflectance asymptotes have important implications for monitoring vegetation with the Landsat Satellite. For biomass situations below the asymptotes, linear models could be used to produce maps of biomass. Conversely, for higher biomass situations when the asymptoes are

exceeded, differences in biomass within vegetative cover types would not cause changes in reflectance. This should result in higher cover type mapping accuracies.

10. The normalized difference transformation did not significantly improve the spectral reflectance canopy relationship. The relationship between the normalized difference transformation was linear for low biomass situations. The normalized difference asymptote was found to be at approximately the same biomass level as the asymptotes found for TM1, TM2, TM3, and TM7.
11. Logarithmic transformations for both the spectral variables and canopy variables were found to linearize the regression functions for the tall fescue data.
12. Residuals from the fitted regression lines for the near infrared bands increased as tall fescue biomass increased. It is believed that this non-constant error term was caused by differential near infrared scattering within the canopy.

Recommendations for Further Research

Controlled ground-based radiometer studies provide for a basic understanding of the relationships between reflectance and grass canopy variables. Additional *in-situ* studies of Thematic Mapper band reflectance from grass canopies under various conditions are needed for independent verification of the results of this dissertation. Research involving actual Thematic Mapper data obtained from the Landsat Satellite is also needed. The following discussion describes a methodology which could be adapted to test the feasibility of mapping grassland canopy variables with data from the Landsat Thematic Mapper sensor.

A grassland study area would be chosen and stratified into homogeneous regions based on vegetation, soil, and slope characteristics. Numerous sample plots could be located within each stratified area and vegetation would be sampled at the time of a Landsat overpass. Circular $0.2 m^2$ plots would be used to sample the grass canopy variables of biomass, plant moisture, leaf area index, canopy cover, and canopy height. These data could be collected using the same field and laboratory methods as discussed here for _in situ_ remote sensing analysis. The mean would be obtained for each canopy variable from the sample plots in each stratified area, to characterize each stratum. For example, average biomass yield could be determined by calculating the average yield per unit area of all of the sample plots located within a given stratum.

Landsat Thematic Mapper data would be obtained from a cloud-free satellite overpass of the study area. The data from the Thematic Mapper are stored on magnetic tapes with a pixel resolution of 30 m by 30 m. The boundaries of each stratified area would need to be precisely located on line-printer maps produced from the magnetic tapes. The digital values for each pixel within each stratified area would also be averaged to represent a mean reflectance, by band, for each stratum.

Spectral reflectance curves would be developed from the satellite data and compared with the curves developed from the *in situ* remote sensing data. Correlation and regression analysis could be conducted based on the relationships between the Thematic Mapper digital values and the field data. Multiple regression models would be employed which combine grass canopy parameters, or use several spectral bands, as independent variables in the models. These regression models could be used spatially to produce maps which show estimates of biomass, leaf area index, and canopy cover. Finally, comparisons could be made between results of the Landsat analysis and the *in situ* remote sensing analysis, to determine if the statistical relationships are similar.

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APPENDICIES

APPENDIX A

REFLECTANCE DATA TABLES

ANNUAL RYEGRASS REFLECTANCE ON JUNE 7,1983

DATE	TIME	OBS.	PLOT	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6	BAND 7
607	1850	1	117R	.0433	.0741	.0593	.3213	.2890	.1866	.0996
607	1852	2	99R	.0404	.0736	.0666	.2962	.2832	.1866	.0949
607	1856	3	98R	.0360	.0687	.0535	.3241	.2961	.1862	.0893
607	1859	4	94R	.0347	.0663	.0451	.4129	.3608	.1980	.0822
607	1902	5	92R	.0328	.0638	.0415	.3940	.3406	.1931	.0813
607	1905	6	68R	.0356	.0642	.0439	.3774	.3335	.1930	.0851
607	1908	7	52R	.0647	.1012	.1277	.2175	.2424	.2060	.1458
607	1911	8	45R	.0434	.0742	.0604	.3306	.2945	.1932	.1027
607	1914	9	1R	.0680	.0986	.1169	.2197	.2365	.1991	.1492
607	1932	10	30R	.0617	.0939	.1169	.2142	.2300	.1937	.1367
607	1935	11	5R	.0547	.0852	.0872	.2713	.2520	.1931	.1289
607	1940	12	113R	.0355	.0681	.0494	.3496	.3058	.1834	.0805
607	1944	13	107R	.0488	.0817	.0731	.3065	.2812	.1936	.1077
607	1946	14	87R	.0376	.0694	.0492	.3995	.3454	.1985	.0871
607	1948	15	86R	.0422	.0756	.0671	.3067	.2881	.1928	.0993
607	1950	16	65R	.0341	.0657	.0435	.3832	.3196	.1818	.0754
607	1952	17	64R	.0346	.0642	.0435	.3790	.3199	.1873	.0829
607	1955	18	63R	.0364	.0664	.0509	.3434	.2991	.1807	.0841
607	1958	19	42R	.0477	.0822	.0814	.2921	.2759	.1842	.0964
607	2000	20	41R	.0574	.0910	.1029	.2510	.2465	.1936	.1288
607	2002	21	8R	.0578	.0890	.0944	.2810	.2695	.2029	.1342
607	2005	22	14R	.0667	.1017	.1163	.2581	.2599	.2102	.1445
607	2011	23	SOIL	.0817	.1152	.1540	.1854	.2077	.2055	.1851

ANNUAL RYEGRASS REFLECTANCE ON JULY 10,1983

DATE	TIME	OBS.	PLOT	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6	BAND 7
710	2023	1	77R	.0276	.0573	.0393	.3402	.3003	.1524	.0585
710	2026	2	53R	.0313	.0639	.0470	.3144	.2775	.1557	.0663
710	2030	3	74R	.0279	.0572	.0398	.3314	.2908	.1524	.0601
710	2032	4	72R	.0125	.0576	.0436	.3244	.2866	.1554	.0643
710	2035	5	50R	.0278	.0596	.0424	.3340	.2908	.1454	.0553
170	2036	6	51R	.0281	.0590	.0456	.3250	.2901	.1511	.0600
710	2038	7	25R	.0356	.0664	.0621	.2602	.2428	.1587	.0837
710	2040	8	27R	.0262	.0536	.0433	.2751	.2623	.1413	.0579
710	2044	9	20R	.0297	.0613	.0461	.3266	.2939	.1594	.0663
710	2046	10	31R	.0266	.0556	.0403	.3199	.2881	.1502	.0593
710	2058	11	114R	.0643	.0967	.1261	.2187	.1867	.2084	.1630
710	2100	12	112R	.0344	.0626	.0545	.2808	.2622	.1671	.0863
710	2102	13	89R	.0416	.0650	.0647	.2779	.2614	.1768	.1037
710	2105	14	88R	.0289	.0580	.0398	.3549	.3003	.1593	.0684
710	2107	15	81R	.0268	.0552	.0384	.3656	.3141	.1537	.0569
710	2110	16	55R	.0278	.0592	.0415	.3526	.2988	.1528	.0604
710	2113	17	62R	.0295	.0572	.0422	.3134	.2806	.1498	.0639
710	2116	18	61R	.0260	.0527	.0387	.3072	.2813	.1466	.0591
710	2119	19	34R	.0304	.0622	.0456	.3434	.3075	.1660	.0673
710	2121	20	35R	.0279	.0561	.0398	.3064	.2788	.1458	.0571
710	2123	21	36R	.0301	.0584	.0451	.2883	.2500	.1487	.0720
710	2125	22	37R	.0284	.0572	.0409	.3306	.2871	.1592	.0679

ANNUAL RYEGRASS REFLECTANCE ON AUGUST 9,1983

DATE	TIME	OBS.	PLOT	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6	BAND 7
809	1907	1	116R	.0405	.0663	.1064	.2508	.3190	.2226	.1212
809	1909	2	101R	.0382	.0615	.0962	.2219	.2984	.2149	.1203
809	1912	3	118R	.0457	.0712	.1075	.2291	.2953	.2236	.1375
809	1913	4	119R	.0448	.0727	.1086	.2456	.3113	.2214	.1240
809	1917	5	70R	.0423	.0698	.1077	.2546	.3188	.2156	.1159
809	1919	6	71R	.0433	.0684	.1064	.2335	.2935	.2088	.1208
809	1921	7	48R	.0441	.0702	.1107	.2464	.2998	.2055	.1144
809	1923	8	46R	.0447	.0735	.1201	.2539	.3237	.2359	.1351
809	1926	9	28R	.0384	.0628	.0994	.2336	.2940	.1991	.1072
809	1929	10	26R	.0381	.0623	.0937	.2077	.2638	.1815	.1012
809	1931	11	3R	.0396	.0651	.0987	.2269	.2838	.1928	.1047
809	1939	12	106R	.0369	.0595	.0959	.2251	.3078	.2077	.1108
809	1941	13	108R	.0387	.0613	.0939	.2085	.2923	.2146	.1227
809	1946	14	84R	.0494	.0789	.1247	.2582	.3188	.2325	.1352
809	1948	15	60R	.0380	.0640	.0928	.2405	.3139	.2143	.1149
809	1951	16	40R	.0376	.0624	.0909	.2410	.2957	.1988	.1076
809	1952	17	33R	.0380	.0653	.1021	.2468	.3115	.2135	.1151
809	1954	18	16R	.0504	.0814	.1189	.2560	.2985	.2158	.1270
809	1957	19	15R	.0390	.0623	.1001	.2427	.3068	.2118	.1190
809	2000	20	19R	.0415	.0689	.1113	.2680	.3374	.2324	.1293
809	2004	21	17R	.0482	.0770	.1266	.2818	.3588	.2502	.1405
809	2007	22	7R	.0387	.0611	.0921	.2244	.2959	.2066	.1156
809	2018	23	SOIL	.0999	.1407	.1870	.2282	.2585	.2562	.2295

TALL FESCUE REFLECTANCE ON JUNE 7,1983

DATE	TIME	OBS.	PLOT	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6	BAND 7
607	2016	24	99F	.0691	.1006	.1231	.2168	.2288	.1985	.1533
607	2019	25	94F	.0807	.1135	.1432	.2143	.2292	.2105	.1748
607	2021	26	92F	.0729	.1055	.1353	.2134	.2301	.2111	.1727
607	2023	27	68F	.0519	.0816	.0873	.2488	.2476	.1828	.1145
607	2025	28	52F	.0619	.0936	.1130	.2250	.2338	.1896	.1362
607	2029	29	49F	.0683	.1022	.1321	.2042	.2258	.1960	.1460
607	2033	30	3F	.0849	.1202	.1580	.2031	.2291	.2191	.1856
607	2034	31	5F	.0697	.1032	.1273	.2220	.2382	.2061	.1571
607	2036	32	20F	.0745	.1086	.1318	.2320	.2446	.2090	.1597
607	2040	33	43F	.0746	.1098	.1383	.2246	.2412	.2134	.1633
607	2041	34	31F	.0559	.0855	.0907	.2522	.2495	.1900	.1247
607	2044	35	8F	.0834	.1165	.1526	.2003	.2211	.2131	.1837
607	2052	36	103F	.0635	.0918	.1053	.2280	.2328	.1886	.1401
607	2054	37	79F	.0524	.0809	.0880	.2506	.2479	.1845	.1184
607	2057	38	112F	.0740	.1064	.1294	.2256	.2387	.2074	.1616
607	2100	39	107F	.0706	.1042	.1264	.2192	.2350	.1990	.1466
607	2103	40	81F	.0687	.1031	.1231	.2352	.2435	.2021	.1492
607	2105	41	64F	.0667	.0980	.1191	.2168	.2322	.1983	.1481
607	2107	42	63F	.0655	.0964	.1165	.2122	.2274	.1956	.1488
607	2111	43	36F	.0667	.0976	.1184	.2138	.2305	.1979	.1513
607	2113	44	14F	.0724	.1028	.1239	.2129	.2271	.1966	.1540
607	2115	45	11F	.0754	.1066	.1267	.2289	.2407	.2048	.1588

TALL FESCUE REFLECTANCE ON JULY 10,1983

DATE	TIME	OBS.	PLOT	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6	BAND 7
710	2139	23	115F	.0426	.0724	.0710	.2634	.2540	.1708	.0978
710	2142	24	91F	.0403	.0669	.0589	.2824	.2605	.1696	.0950
710	2145	25	77F	.0333	.0611	.0509	.2960	.2734	.1615	.0753
710	2146	26	76F	.0352	.0668	.0639	.2596	.2577	.1583	.0768
710	2149	27	95F	.0460	.0746	.0819	.2420	.2417	.1755	.1066
710	2153	28	73F	.0400	.0685	.0645	.2745	.2619	.1692	.0890
710	2156	29	50F	.0350	.0607	.0487	.2697	.2455	.1515	.0782
710	2158	30	28F	.0316	.0582	.0497	.2642	.2502	.1492	.0692
710	2200	31	21F	.0311	.0552	.0438	.2852	.2647	.1504	.0704
710	2204	32	23F	.0502	.0726	.0714	.2566	.2414	.1736	.1137
710	2209	33	19F	.0465	.0737	.0775	.2474	.2401	.1637	.0971
710	2210	34	17F	.0552	.0820	.0977	.2153	.2175	.1819	.1344
710	2223	35	90F	.0291	.0553	.0388	.3277	.2873	.1512	.0610
710	2225	36	105F	.0384	.0648	.0542	.2890	.2689	.1645	.0844
710	2230	37	109F	.0497	.0792	.0891	.2327	.2448	.1854	.1176
710	2234	38	87F	.0393	.0651	.0635	.2378	.2320	.1641	.0983
710	2235	39	82F	.0449	.0758	.0793	.2491	.2451	.1680	.0953
710	2237	40	61F	.0352	.0622	.0544	.2737	.2550	.1580	.0838
710	2239	41	38F	.0427	.0650	.0594	.2571	.2442	.1660	.1057
710	2243	42	66F	.0328	.0600	.0528	.2656	.2485	.1558	.0791
710	2244	43	42F	.0297	.0572	.0442	.3019	.2775	.1486	.0610
710	2247	44	33F	.0388	.0616	.0585	.2262	.2230	.1546	.0971
710	2251	45	SOIL	.0651	.0938	.1275	.1590	.1771	.1747	.1529

TALL FESCUE REFLECTANCE ON AUGUST 9,1983

DATE	TIME	OBS.	PLOT	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6	BAND 7
809	1744	1	92F	.0249	.0416	.0292	.4245	.3716	.1814	.0650
809	1746	2	78F	.0258	.0466	.0366	.3687	.3453	.1741	.0659
809	1747	3	68F	.0241	.0437	.0379	.3439	.3281	.1662	.0631
809	1750	4	94F	.0338	.0540	.0425	.3798	.3457	.1885	.0815
809	1752	5	74F	.0401	.0648	.0723	.2532	.2680	.1855	.1112
809	1755	6	49F	.0371	.0583	.0542	.3187	.3181	.1936	.0950
809	1757	7	51F	.0357	.0564	.0486	.3185	.3114	.1884	.0895
809	1758	8	52F	.0241	.0444	.0298	.3908	.3557	.1716	.0605
809	1802	9	47F	.0276	.0485	.0366	.3985	.3619	.1833	.0687
809	1803	10	46F	.0325	.0521	.0432	.3507	.3327	.1867	.0829
809	1805	11	27F	.0279	.0488	.0351	.4665	.4056	.1917	.0653
809	1806	12	26F	.0229	.0416	.0298	.3678	.3283	.1582	.0569
809	1809	13	25F	.0329	.0535	.0472	.3501	.3439	.1980	.0882
809	1815	14	43F	.0253	.0431	.0365	.3573	.3330	.1725	.0674
809	1817	15	30F	.0324	.0529	.0457	.3305	.3288	.1909	.0862
809	1821	16	3F	.0519	.0797	.0886	.2902	.3014	.2198	.1395
809	1823	17	4F	.0367	.0601	.0569	.2872	.2902	.1847	.1005
809	1827	18	20F	.0299	.0506	.0469	.3276	.3205	.1793	.0813
809	1828	19	5F	.0414	.0657	.0704	.2888	.3032	.2000	.1109
809	1830	20	6F	.0577	.0887	.1062	.2644	.2766	.2198	.1554
809	1831	21	7F	.0366	.0619	.0649	.2914	.3085	.1959	.1020
809	1838	22	107F	.0524	.0809	.0973	.2846	.3085	.2150	.1367
809	1840	23	87F	.0300	.0511	.0405	.3551	.3220	.1794	.0776
809	1842	24	82F	.0365	.0602	.0604	.3085	.3058	.1892	.0937
809	1846	25	84F	.0658	.0940	.1266	.1845	.2219	.2179	.1886
809	1848	26	63F	.0274	.0478	.0386	.3427	.3156	.1774	.0800
809	1850	27	58F	.0359	.0611	.0579	.2978	.3024	.1947	.0973
809	1854	28	14F	.0508	.0755	.0798	.2910	.3055	.2131	.1334
809	1855	29	13F	.0648	.0967	.1311	.2107	.2520	.2339	.1861
809	1857	30	12F	.0589	.0915	.1187	.2311	.2684	.2199	.1579

TALL FESCUE REFLECTANCE ON SEPTEMBER 12,1983

DATE	TIME	OBS.	PLOT	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 6	BAND 7
912	1842	1	116F	.0261	.0445	.0290	.4680	.3902	.1806	.0600
912	1844	2	101F	.0271	.0482	.0337	.4259	.3713	.1815	.0639
912	1847	3	91F	.0188	.0366	.0260	.3305	.3128	.1492	.0515
912	1849	4	77F	.0209	.0382	.0257	.3711	.3447	.1625	.0548
912	1853	5	100F	.0173	.0332	.0227	.3327	.3112	.1453	.0468
912	1855	6	93F	.0186	.0357	.0291	.3253	.3222	.1541	.0536
912	1859	7	67F	.0241	.0420	.0280	.4138	.3871	.1882	.0647
912	1901	8	53F	.0246	.0455	.0336	.3768	.3653	.1798	.0635
912	1906	9	69F	.0194	.0376	.0305	.3458	.3509	.1678	.0587
912	1908	10	70F	.0223	.0394	.0298	.4232	.4016	.1907	.0643
912	1910	11	71F	.0211	.0412	.0295	.3970	.3765	.1744	.0571
912	1912	12	72F	.0207	.0395	.0278	.3610	.3331	.1553	.0517
912	1915	13	50F	.0265	.0459	.0289	.4408	.3888	.1871	.0643
912	1922	14	25F	.0259	.0494	.0350	.3900	.3438	.1608	.0550
912	1924	15	26F	.0253	.0454	.0295	.4133	.3692	.1767	.0615
912	1926	16	28F	.0210	.0407	.0300	.3350	.3090	.1517	.0536
912	1929	17	24F	.0191	.0335	.0239	.2908	.2758	.1412	.0527
912	1931	18	23F	.0236	.0415	.0292	.3411	.3049	.1560	.0609
912	1934	19	31F	.0233	.0439	.0345	.3117	.2954	.1504	.0557
912	1936	20	41F	.0410	.0649	.0578	.3514	.3201	.1942	.0959
912	1939	21	19F	.0245	.0420	.0323	.3619	.3222	.1685	.0663
912	1941	22	18F	.0209	.0372	.0264	.3270	.3055	.1546	.0556
912	1948	23	87F	.0299	.0502	.0316	.4862	.4108	.1985	.0702
912	1950	24	88F	.0244	.0441	.0329	.3281	.3149	.1593	.0607
912	1952	25	66F	.0227	.0440	.0272	.4211	.3693	.1722	.0570
912	1954	26	54F	.0201	.0381	.0282	.3588	.3145	.1529	.0548
912	1957	27	84F	.0640	.0895	.1049	.2230	.2438	.2156	.1720
912	1959	28	62F	.0169	.0326	.0228	.2980	.2890	.1391	.0484
912	2002	29	38F	.0312	.0501	.0387	.3405	.3246	.1734	.0715
912	2004	30	34F	.0346	.0591	.0503	.3425	.3352	.1961	.0868
912	2006	31	33F	.0231	.0405	.0264	.3497	.3099	.1502	.0521
912	2007	32	9F	.0450	.0671	.0623	.2995	.2947	.1940	.1093
912	2010	33	8F	.0462	.0681	.0715	.2754	.2660	.1914	.1229

APPENDIX B

GRASS CANOPY DATA TABLES

ANNUAL RYEGRASS CANOPY DATA FOR JUNE 7,1983

OBS	PLOT#	HEIGHT CM	COVER %	WET TOTAL BIOMASS	DRY TOTAL BIOMASS	PLANT WATER	LAI (WET)
1	117R	21.00	74.80	324.70	72.20	252.50	.6594
2	99R	19.50	70.00	275.80	67.90	207.90	.6093
3	98R	21.00	69.50	337.50	87.70	249.80	.6258
4	94R	22.50	88.60	554.00	122.10	431.90	.9343
5	92R	17.00	82.90	618.75	148.10	470.65	1.2552
6	68R	20.50	78.60	443.40	105.70	337.70	.7576
7	52R	16.50	41.90	171.80	36.60	135.20	.3555
8	45R	16.50	69.00	362.45	84.35	278.10	.6451
9	1R	18.50	18.60	105.30	23.30	82.00	.1650
10	30R	15.50	20.50	89.70	18.35	71.35	.2176
11	5R	16.00	54.80	220.30	52.10	168.20	.3234
12	113R	21.00	81.00	462.10	108.90	353.20	.8750
13	107R	17.00	66.20	276.35	65.70	210.65	.5406
14	87R	18.50	86.70	462.20	108.80	353.40	.8535
15	86R	17.50	71.00	380.25	95.70	284.55	.7115
16	65R	26.00	85.70	490.05	128.00	362.05	.9529
17	64R	23.00	89.00	581.35	136.35	445.00	1.1248
18	63R	23.00	67.10	450.50	110.65	339.85	.8334
19	42R	18.00	49.60	259.40	55.50	203.90	.5326
20	41R	14.50	32.50	161.45	38.55	122.90	.3308
21	8R	20.00	46.30	186.50	43.95	142.55	.3577
22	14R	14.50	34.10	171.80	37.15	134.65	.2867

ANNUAL RYEGRASS CANOPY DATA FOR JULY 10,1983

OBS	PLOT#	HEIGHT CM	COVER %	WET TOTAL BIOMASS	DRY TOTAL BIOMASS	PLANT WATER	LAI (WET)
1	77R	54.00	100.00	1003.25	326.50	676.75	1.3168
2	53R	39.00	93.00	745.80	236.35	509.45	.8869
3	74R	40.00	100.00	937.05	283.95	653.10	1.0999
4	72R	44.00	100.00	686.70	225.10	461.60	.8858
5	50R	44.00	100.00	877.20	287.80	589.40	1.0756
6	51R	47.00	100.00	834.25	258.35	575.90	1.1491
7	25R	33.50	100.00	532.65	166.50	366.15	.8619
8	27R	41.50	100.00	894.40	300.85	593.55	1.0856
9	20R	51.50	82.00	745.50	227.80	517.70	.6583
10	31R	49.00	100.00	988.40	320.70	667.70	1.3917
11	114R	24.50	22.60	115.55	41.50	74.05	.2673
12	112R	33.50	77.40	588.50	180.40	408.10	.6978
13	89R	53.00	61.50	512.90	154.75	358.15	.6375
14	88R	59.00	87.00	982.40	304.85	677.55	1.6981
15	81R	44.00	80.60	803.25	249.55	553.70	1.0150
16	55R	50.00	96.70	798.30	249.90	548.40	1.0331
17	62R	38.50	87.10	887.00	300.40	586.60	1.1096
18	61R	45.00	90.30	894.45	295.60	598.85	.9919
19	34R	47.50	93.80	1065.80	329.70	736.10	1.3096
20	35R	42.00	93.50	1146.35	351.30	795.05	1.8067
21	36R	44.50	61.30	724.50	240.35	484.15	.8600
22	37R	41.50	74.40	768.10	236.55	531.55	.7589

ANNUAL RYEGRASS CANOPY DATA FOR AUGUST 9,1983

OBS	PLOT#	HEIGHT CM	COVER %	WET TOTAL BIOMASS	DRY TOTAL BIOMASS	PLANT WATER	LAI (WET)
31	116R	54.50	87.10	463.35	86.10	45.30	.0910
32	101R	48.50	77.40	324.65	75.07	48.55	.0298
33	118R	47.00	48.40	372.00	82.06	79.05	.1509
34	119R	53.50	77.40	466.25	102.07	118.90	.0429
35	70R	55.50	74.20	325.95	83.03	86.85	.1049
36	71R	54.00	77.40	417.80	99.47	66.30	.0714
37	48R	53.00	61.30	379.15	81.19	82.25	.0532
38	46R	58.50	67.70	367.95	78.65	56.55	.0200
39	28R	52.50	87.10	549.40	99.48	70.55	.0965
40	26R	41.00	64.50	301.45	58.42	51.15	.0823
41	3R	50.50	90.00	298.50	66.84	47.30	.0506
42	106R	54.50	96.70	576.95	112.40	81.45	.1211
43	108R	52.00	83.90	338.50	72.24	54.80	.0656
44	84R	57.50	77.40	492.55	81.66	38.40	.0259
45	60R	60.00	77.40	588.10	133.75	177.50	.2983
46	40R	62.50	67.70	512.10	140.11	185.95	.2649
47	33R	53.50	80.60	515.75	101.35	92.25	.2768
48	16R	64.50	54.80	383.45	99.23	93.30	.1700
49	15R	53.50	71.00	358.50	73.43	61.20	.1032
50	19R	50.00	93.50	531.40	107.59	99.25	.0530
51	17R	55.00	80.60	566.80	108.07	89.65	.1224
52	7R	51.00	80.60	491.10	87.74	51.85	.0575

TALL FESCUE CANOPY DATA FOR JUNE 7.1983

OBS	PLOT#	HEIGHT CM	COVER %	WET TOTAL BIOMASS	DRY TOTAL BIOMASS	PLANT WATER	LAI (WET)
24	99F	7.50	24.40	76.25	17.90	58.35	.1265
25	94F	9.50	11.40	43.90	8.35	35.55	.1059
26	92F	11.50	8.90	49.95	9.80	40.15	.0964
27	68F	13.00	48.80	213.15	49.25	163.90	.4157
28	52F	12.00	36.60	132.75	29.65	103.10	.2639
29	49F	11.50	33.30	118.80	25.90	92.90	.2235
30	3F	8.50	5.40	16.55	6.60	9.95	.0407
31	5F	11.00	25.20	90.45	19.75	70.70	.1836
32	20F	10.00	26.80	91.80	20.55	71.25	.2009
33	43F	12.00	21.70	89.20	18.10	71.10	.2057
34	31F	12.50	45.10	170.10	42.40	127.70	.3166
35	8F	10.50	4.10	16.75	6.90	9.85	.0312
36	103F	9.50	38.20	110.15	25.25	84.90	.2287
37	79F	10.00	52.00	195.90	51.30	144.60	.3790
38	112F	11.50	27.60	99.65	22.95	76.70	.1928
39	107F	11.00	24.40	80.95	18.15	62.80	.1618
40	81F	15.50	32.50	98.30	20.05	78.25	.2338
41	64F	10.00	27.60	83.80	18.95	64.85	.1661
42	63F	15.50	35.70	79.50	16.45	63.05	.1817
43	36F	10.00	27.60	75.10	19.25	55.85	.1755
44	14F	9.00	22.00	71.75	16.80	54.95	.1442
45	11F	12.50	23.60	89.10	21.25	67.85	.1903

TALL FESCUE CANOPY DATA FOR JULY 10.1983

OBS	PLOT#	HEIGHT CM	COVER %	WET TOTAL BIOMASS	DRY TOTAL BIOMASS	PLANT WATER	LAI (WET)
23	115F	17.00	58.30	359.30	103.55	255.75	1.0817
24	91F	17.00	77.10	324.90	97.65	227.25	.9374
25	77F	21.50	77.40	418.50	125.80	292.70	1.0289
26	76F	20.00	80.60	298.15	91.25	206.90	.6989
27	95F	19.00	58.10	233.65	63.25	170.40	.6743
28	73F	16.00	54.80	283.65	79.40	204.25	.8101
29	50F	17.50	64.50	337.95	100.00	237.95	.9689
30	28F	21.50	61.30	351.25	102.40	248.85	.8730
31	21F	16.00	74.20	394.55	114.50	280.05	1.2410
32	23F	16.00	58.00	223.90	57.75	166.15	.5888
33	19F	18.50	51.40	274.20	72.90	201.30	.5174
34	17F	16.00	25.10	90.95	24.40	66.55	.2750
35	90F	18.50	78.30	439.50	125.80	313.70	1.2157
36	105F	17.00	64.50	312.70	90.05	222.65	.8344
37	109F	12.50	38.70	124.75	35.05	89.70	.3445
38	87F	22.50	58.10	294.20	87.90	206.30	.7388
39	82F	18.00	51.60	230.85	61.70	169.15	.6133
40	61F	16.00	58.10	194.90	54.90	140.00	.5386
41	38F	14.50	61.30	248.50	73.40	175.10	.6060
42	66F	18.00	87.10	399.20	117.75	281.45	1.0945
43	42F	17.00	67.70	371.75	106.00	265.75	.9251
44	33F	20.50	54.80	254.60	75.15	179.45	.6240

TALL FESCUE CANOPY DATA FOR AUGUST 9,1983

OBS	PLOT#	HEIGHT CM	COVER %	WET TOTAL BIOMASS	DRY TOTAL BIOMASS	PLANT WATER	LAI (WET)
1	92F	31.50	89.00	931.50	239.75	691.75	1.6653
2	78F	25.50	82.00	612.40	181.50	430.90	1.0681
3	68F	24.50	68.00	390.75	116.85	273.90	.5851
4	94F	23.50	70.00	414.25	112.25	302.00	.7609
5	74F	21.50	45.20	160.10	55.10	105.00	.2402
6	49F	23.50	54.80	283.20	74.20	209.00	.5321
7	51F	30.00	61.30	340.70	90.95	249.75	.6976
8	52F	28.50	83.80	550.15	141.80	408.35	.9985
9	47F	31.50	72.90	587.65	164.15	423.50	1.0466
10	46F	29.50	64.50	281.60	85.75	195.85	.4191
11	27F	40.00	100.00	1144.90	312.55	832.35	2.1964
12	26F	29.00	87.10	666.00	185.65	480.35	1.3094
13	25F	21.00	61.00	493.75	154.75	339.00	.8950
14	43F	27.00	70.90	645.25	189.15	456.10	1.0281
15	30F	29.00	67.70	522.05	150.90	371.15	.8378
16	3F	19.50	45.20	271.15	82.15	189.00	.4212
17	4F	22.50	51.60	304.50	92.30	212.20	.5945
18	20F	24.50	67.70	385.20	120.20	265.00	.6851
19	5F	17.50	42.90	343.15	116.40	226.75	.5375
20	6F	22.00	32.30	225.15	77.40	147.75	.3135
21	7F	22.50	61.30	378.50	141.05	237.45	.5702
22	107F	26.50	51.60	358.75	152.65	206.10	.5800
23	87F	31.50	67.70	357.05	87.35	269.70	.6769
24	82F	19.50	51.60	357.10	93.15	263.95	.6422
25	84F	15.00	9.60	22.00	6.45	15.55	.0399
26	63F	27.50	67.70	527.70	155.85	371.85	.8517
27	58F	29.00	67.70	330.35	102.20	228.15	.5984
28	14F	17.50	51.60	201.95	72.35	129.60	.3359
29	13F	18.50	19.40	63.20	19.95	43.25	.0983
30	12F	16.50	32.30	113.60	40.70	72.90	.1657

TALL FESCUE CANOPY DATA FOR SEPTEMBER 12,1983

OBS	PLOT#	HEIGHT CM	COVER %	WET TOTAL BIOMASS	DRY TOTAL BIOMASS	PLANT WATER	LAI (WET)
1	116F	57.50	100.00	1677.85	365.50	1312.35	3.8275
2	101F	45.00	100.00	1238.75	317.80	920.95	2.4461
3	91F	39.00	100.00	1642.65	486.85	1155.80	2.5861
4	77F	35.50	100.00	1184.50	303.95	880.55	2.4187
5	100F	35.50	100.00	1214.60	340.90	873.70	3.4264
6	93F	39.50	100.00	1577.50	454.60	1122.90	3.9191
7	67F	47.00	100.00	1119.55	310.95	808.60	1.9304
8	53F	42.00	100.00	1665.15	502.45	1162.70	2.7270
9	69F	35.50	100.00	1289.20	392.90	896.30	2.0089
10	70F	36.50	100.00	1260.00	359.00	901.00	2.7509
11	71F	29.50	100.00	1102.65	315.95	786.70	2.5015
12	72F	30.50	98.00	839.15	249.85	589.30	1.8383
13	50F	48.00	100.00	1344.60	322.15	1022.45	2.3002
14	25F	51.50	100.00	1271.05	387.80	883.25	2.0705
15	26F	53.50	100.00	1559.80	411.15	1148.65	2.4318
16	28F	52.00	100.00	1296.25	386.75	909.50	2.2374
17	24F	22.50	97.00	804.05	228.30	575.75	1.5500
18	23F	32.50	88.60	551.50	134.30	417.20	1.1947
19	31F	55.00	100.00	1347.60	398.50	949.10	3.1149
20	41F	27.50	58.10	232.00	61.10	170.90	.4445
21	19F	28.00	93.50	816.65	212.70	603.95	1.5497
22	18F	32.50	100.00	1012.50	304.10	708.40	2.1566
23	87F	49.00	100.00	1580.75	362.90	1217.85	4.3232
24	88F	42.50	100.00	1202.20	350.05	852.15	2.7604
25	66F	39.50	100.00	1080.95	287.05	793.90	2.4079
26	54F	53.50	100.00	1400.80	394.65	1006.15	2.7478
27	84F	15.50	19.40	55.75	13.10	42.65	.1260
28	62F	35.50	99.00	1134.65	326.50	808.15	2.3152
29	38F	24.50	87.10	509.80	141.70	368.10	.8511
30	34F	32.00	77.40	334.15	91.30	242.85	.4394
31	33F	32.00	100.00	863.10	215.90	647.20	1.8002
32	9F	30.00	58.10	573.20	155.50	417.70	.7106
33	8F	28.50	51.60	388.75	112.90	275.85	.8433