Asymptotic Reflectance Characteristics of Grass Vegetation

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ABSTRACT: The asymptotic relationships between spectral reflectance 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 nearly 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 and 375 g/m^2 of the total dry biomass, which was equivalent to a leaf area index of 2.45 to 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. Calculations were also made to determine the effects of atmospheric factors on the actual asymptotic limits that would be encountered if the data were obtained at satellite altitudes.

INTRODUCTION

LANDSAT DATA have been used in a number of investigations concerned with grassland biomass estimation (Bentley *et al.*, 1976; Carneggie *et al.*, 1974; McDaniel and Haas, 1982; Rouse *et al.*, 1973). The methods used in these types of studies typically involve locating sample plots on the ground, determining the amount of biomass in these plots, and correlating these biomass measurements with the digital values from the corresponding Landsat pixels. Biomass maps are then developed using regression models which are based on the relationships between sample plot biomass and Landsat radiance values.

A knowledge of the asymptotic characteristics of the spectral bands is important for studies in biomass mapping using Landsat digital data. Tucker (1977) described asymptotic spectral reflectance as the point reached when so much biomass is present that the addition of more biomass ceases to cause a detectible change in reflectance. The nature of these asymptotic characteristics needs to be known for the successful development of regression models to estimate biomass. For biomass mapping with conditions below the reflectance asymptotes, linear regression equations can be used to estimate biomass on a pixel-by-pixel basis.

Information on the spectral asymptote limits can also be useful in vegetative cover type mapping through the reduction of within-cover-type reflectance variability. In situations where the asymptotes are exceeded, minor differences in biomass within vegetative cover types will not cause variability in reflectance values. For example, Tucker (1977) has noted that asymptotic spectral reflectance can be readily observed with multispectral imagery over uniform fields of various crops. At the point in the growing season when the spectral response becomes asymptotic, minor biomass differences within a field will no longer affect canopy reflectance. This stable reflectance can result in higher crop type mapping accuracies using image classification methods.

The objective of the research reported here was to examine the asymptotic relationships between spectral reflectance and grass canopy variables. *In situ* remote sensing techniques were used to collect spectral data from grass plots representing a wide range of biomass levels. The procedure utilized the results of an easy-to-use regression model to estimate the spectral reflectance asymptotes. Consideration was also given to the effects of the atmosphere on the asymptotic characteristics of data obtained at satellite altitudes.

LITERATURE REVIEW

Different spectral asymptotes at various wavelengths are caused by differing amounts of absorptance, transmittance, and reflectance from leaves in the plant canopy. In the visible region (0.4 to 0.7 μm), low levels of reflectance and transmittance are caused by highly absorbing plant pigments, mainly the chlorophylls (Gates *et al.*, 1965). Conversely, scattering causes both reflectance and transmittance to be very high in the near infrared (0.7 to 1.3 μm), with little or no absorptance (Knipling, 1970). In the middle infrared (1.3 to 2.6 μm), relatively low reflectance is governed by strong absorption from

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liquid water in the leaves (Gates, 1970; Myers, 1970).

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 to 0.75 μm), eight leaves for the near infrared (0.75 to 1.35 μm), and three leaves for the middle infrared (1.35 to 2.5 μm). These results were similar to the reflectance asymptotes determined for cotton leaves by Myers (1970).

Tucker (1977) investigated the asymptotic characteristics of grass canopies. He obtained *in situ* reflectance measurements from 35 blue grama grass (*Bouteloua gracilis*) plots. Spectral asymptotes were estimated for both red (0.680 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 $|\text{RFL}(i) - \text{RFL}(i-1)| < \text{min}$, 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 and 127.5 g/m², while the near infrared asymptote was reported to be between 285.0 and 435.0 g/m².

MATERIALS AND METHODS

This research was based on the analysis of data from 107 tall fescue (*Festuca arundinacea*) grass plots located at the Oregon State University Agricultural Experiment Farm near Corvallis, Oregon. The area is characterized by a Marine Mediterranean climate with mild wet winters and warm dry summers. The grass was established on a dark brown cumulic ultic haploxeroll soil formed in recent alluvium with a silty clay loam texture. An experimental parcel was planted on 14 April 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 parcel.

Data were collected from green grass canopies on 7 June (n = 22), 10 July (n = 22), 9 August (n = 30), and 12 September (n = 33). This sampling scheme allowed for a large range of plot biomass levels (6.5 to 502.5 g/m² 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 with the same radiometric response as the spectral bands of the Landsat Thematic Mapper (Table 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 (1.15 to 1.30 μm) was included and will be referred to as MMR5.

The spectral data were collected only on clear, sunny days during the midday 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 m²). 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/m²), total dry biomass (g/m²), above ground plant water (g/m²), and leaf area index (Table 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 after the grass was dried in an oven for 48 hours at 60°C. Above-ground plant water was calculated by subtracting the dry weights from the wet weights. Leaf area index was estimated from a subsample of the harvested grass from each plot using a leaf area meter. Leaf area index is the area of all the leaves in a plot divided by the ground area in the plot. After calculating the ratio of leaf area to leaf biomass of the subsample, extrapolations were made to estimate the leaf area index of the plot because both total plot leaf 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:

TABLE 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 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
Total Wet Biomass (g/m^2)	523.3	16.5	1677.9	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)	367.9	9.9	1312.4	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 Mean
** S.D. = Standard Deviation
*** C.V. = Coefficient of Variation

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

where Ln Y is the natural logarithm of a selected spectral band, Ln a and b are coefficients, and Ln X 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. This model was selected because it accurately represents the nonlinear canopy/reflectance relationship and is easy to understand and use.

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 33 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

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

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 percentage change in reflectance; and ΔX is the corresponding incremental change for the canopy variable.

The increments for the grass canopy variables were set a 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 percent, 1.75 percent, and 2.00 percent).

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 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, because both bands are located in the water absorption region of the spectrum (Gates, 1970; Knipling, 1970).

Estimates of the spectral asymptotes for the canopy variables are shown in Table 4. The asymptotes for TM4 were nearly twice as high as the asymptotes for the absorption bands (TM1, TM2, TM3, and

TABLE 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	−0.85	−0.92	−0.93	−0.91	−0.91
TM2	−0.85	−0.92	−0.92	−0.91	−0.90
TM3	−0.86	−0.93	−0.92	−0.92	−0.92
TM4	0.86	0.88	0.87	0.88	0.84
MMR5	0.84	0.82	0.82	0.81	0.75
TM5	NS	−0.62	−0.62	−0.62	−0.69
TM7	−0.81	−0.92	−0.91	−0.91	−0.92

NS = not significant.

TABLE 4. 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	750	210	560	1.82
TM5	1.75	Significant	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

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 and 375 g/m^2, which was equivalent to a leaf area index (LAI) of 2.34 to 3.25 for this study. 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 and 225 g/m^2 of total dry biomass (LAI 1.43 to 1.95).

The curvilinear nature of the relationship between the spectral data and the canopy data is illustrated with scatter diagrams (Figures 1 to 4). The estimated asymptote (1.75 percent criterion) is depicted by the arrow in each scatter diagram. Figures 1 and 2 show an example of the redundancies found between the visible and middle infrared bands. Figure 3 illustrates how the residuals from the fitted regression line for the near infrared (TM4) increased as biomass increased. This nonconstant error term was probably caused by variable scattering resulting from variations in leaf orientation within the multilayered canopies.

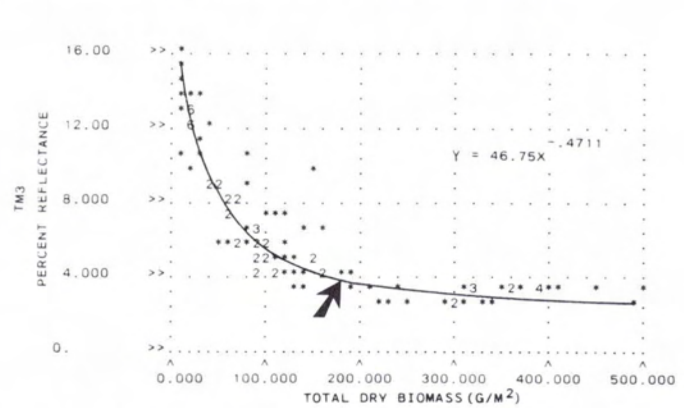

FIG. 1. Scatter diagram of total dry biomass (g/m^2) and TM3 reflectance from tall fescue showing the reflectance asymptote (arrow).

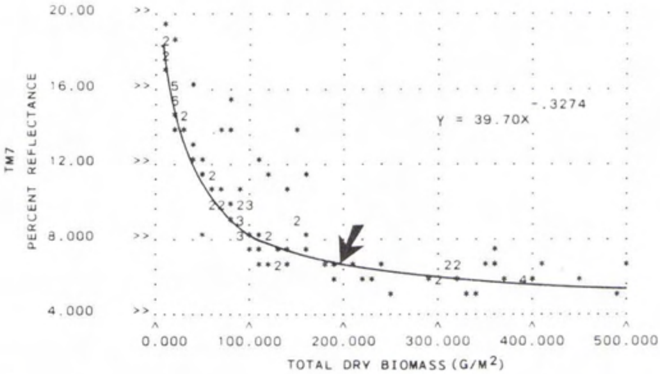

FIG. 2. Scatter diagram of total dry biomass (g/m²) and TM7 reflectance from tall fescue showing the reflectance asymptote (arrow).

The normalized difference index [(TM4 − TM3)/(TM4 + TM3)] was plotted against total dry biomass (Figure 4). The spectral response was very linear until the upper asymptote was reached at approximately 180 g/m². 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).

Some comparisons can be made between the results of this study and the results reported by Tucker (1977). The asymptote for red reflectance with total dry biomass (165 to 195 g/m²) was higher than Tucker reported (97.5 to 127.5 g/m²). Conversely, the near infrared asymptote for total dry biomass (270 to 375 g/m²) was slightly lower than the 285 to 435 g/m² found by Tucker. This study indicated that the asymptotes were approximately 1.7 times greater in the near infrared when compared to the visible, while Tucker found the near infrared asymptote to be two to three times greater than the visible asymptote. Similar asymptotic results were obtained for the other canopy variables in both studies. The results found here confirm Tucker's overall conclusion that the near infrared region is best suited for estimating biomass in moderate to high biomass situations and the red region is best for estimating biomass in low biomass situations. The results of this study indicate that the middle infrared region, along with the normalized difference index, would also be suitable for estimating biomass in low biomass situations.

The comparison differences described above may be partially caused by radiometric differences in the radiometers employed for each study. The research reported here was based on a broad-band radiometer (Barnes 12-1000), while Tucker utilized a narrow band radiometer (EG&G 580-585). The differences may also be caused by the empirical nature of each study in terms of site, species, and canopy geometry differences.

Consideration was given to the effects of atmospheric factors on the actual asymptotic limits that would be encountered if the data were obtained at satellite altitudes. The atmosphere was accounted for in a manner similar to the technique used for the Landsat Multispectral Scanner bands by Jackson *et al.* (1983). An algorithm was used which determined the normalized radiance at the top of the atmosphere for the midpoints of each of the seven bands for both clear and turbid atmospheres having

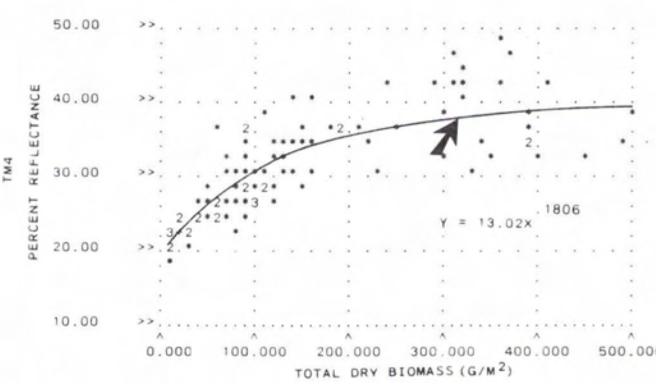

FIG. 3. Scatter diagram of total dry biomass (g/m²) and TM4 reflectance from tall fescue showing the reflectance asymptote (arrow).

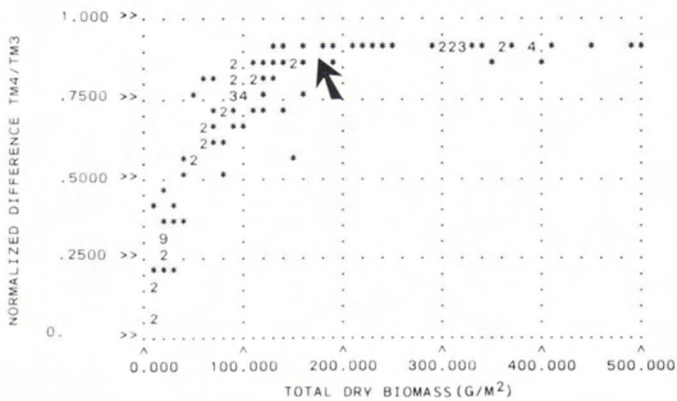

FIG. 4. Scatter diagram of total dry biomass (g/m^2) and the normalized difference [(TM4 − TM3)/(TM4 + TM3)] of reflectance from tall fescue showing the reflectance asymptote (arrow).

meteorological ranges of 100 km and 10 km, respectively. The ratio (L) of the radiance at satellite altitudes to the irradiance at the top of the atmosphere was calculated as follows:

$$L = a + bp_i + cp_i^2$$

where p is ground reflectance for a given wavelength and a, b, and c are regression coefficients provided by Jackson and Slater (personal communication) which were determined using a radiative transfer model (Slater and Jackson, 1982).

Band ratios (TM4/TM3) and normalized difference values [(TM4 − TM3)/(TM4 + TM3)] were calculated for the ground reflectance measurements along with the values simulating clear and turbid atmospheres (Table 5). Significant absolute differences were found between the ground values and the values calculated for the top of the atmophere. The magnitude of the differences was higher for the band ratios when compared to the normalized difference values. The differences found here and by Jackson *et al.* (1983) indicate the need for the application of atmospheric corrections to satellite data. Correlation coefficients were computed between the ground reflectance values and the values for the two simulated atmospheric conditions. Correlation results were very strong (r = >0.99), suggesting that the relationships and asymptotic limits determined from ground reflectance measurements should hold for data obtained at satellite altitudes.

TABLE 5. AVERAGE VALUES FOR BOTH BAND RATIOS AND NORMALIZED DIFFERENCES FOR GROUND REFLECTANCE AND TWO SIMULATED ATMOSPHERES

Band Transformation	Ground Reflectance	Clear Atmosphere	Turbid Atmosphere
$\frac{TM4}{TM3}$	6.805	4.463	3.429
$\frac{TM4 - TM3}{TM4 + TM3}$	0.626	0.550	0.487

SUMMARY

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

- The relationships between the spectral bands and the canopy variables were curvilinear for the biomass range in this study.
- 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.
- The reflectance asymptotes for the near infrared bands were approximately 1.7 times higher than the asymptotes for the absorption bands. The asymptotic levels were very similar for absorption bands TM1, TM2, TM3, and TM7.
- The differences between the near infrared band asymptotes and the visible band asymptotes were less than those described by Tucker (1977).
- 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 variation in canopy geometry, primarily in leaf orientation.
- The normalized difference index asymptote was less than the near infrared asymptotes, but similar to the asymptotes found for TM1, TM2, TM3, and TM7.
- The results of an atmospheric path radiance model suggest that the asymptotic limits determined by ground measurements would not change for data obtained at satellite altitudes.
- It should be noted that the results presented in this study are from a relatively small data base, and caution should be exercised in the extrapolation of these results to different situations. Additional empirical studies are needed to determine if these asymptotic characteristics are area specific and/or species specific. Research is also needed on the

predicted effects of spatial resolution and natural site variability on the asymptotic limits.

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