Utility of Landsat Thematic Mapper Data for Mapping Site Productivity in Tropical Moist Forests

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ABSTRACT: Regression analysis was used to develop a relationship between Landsat 5 Thematic Mapper data and site quality of permanent sample plots. The thermal band (6) produced misleading results, but the ratio of band 4 on 5 showed promise when combined with geological information. Best results were obtained when regression analysis was restricted to ensure that at least one each of the visible (1 to 3), mid-infrared (5 and 7) and near-infrared (4) bands were included. Results suggest that Landsat TM may be useful for mapping site quality in tropical moist forest in north Queensland. Interpolation of site productivity within a single pass seems feasible, but attempts to extrapolate results to other passes or to imagery obtained on different dates may be unreliable

INTRODUCTION

ONE OF THE GREAT CHALLENGES in managing the tropical moist forest (TMF) is efficient multiresource inventory in these areas of rugged, inaccessible, and often poorly mapped terrain. One of the key steps in this process is defining homogeneous units for sampling, mapping, and planning. Although this is conceptually simple and is easily completed for well surveyed and mapped forests such as industrial plantations, it remains a costly and difficult exercise in the TMF. Where cloud free satellite imagery is available, remote sensing may provide a solution.

Stratification into homogeneous units for multiresource inventory is often on the basis of stand density, productivity, and accessibility, although other factors may also be considered. Spectral analysis of remote sensing imagery provides little help with assessing accessibility; this is the domain of geographic information systems and digital terrain models where suitable data are available, and of air photo interpretation and local knowledge elsewhere.

Forest managers are interested in several measures of stand density. Numbers and volumes per unit area of certain species (usually commercial) are often desired, but cannot readily be determined by remote sensing. Stand basal area, a forester's measure of biomass of trees, may be significantly correlated with spectral signature, but the correlation is often so weak that the relationships so established are of little practical use. Total (above ground) biomass may exhibit a stronger correlation in temperate forests, but the correlation remains weak in TMF (Sader *et al.*, 1989). In any case, total biomass is notoriously difficult to measure in TMF and is rarely used in management and planning.

Site productivity is of economic and ecological importance, indicating the potential for commercial timber production as well as giving an indication of the species composition of the forest. Cook *et al.* (1989) report a significant correlation between Landsat Thematic Mapper (TM) data and biomass production in three temperature forests. Vanclay (1989) devised an objective measure of site productivity for TMF in north east Queensland, and found a correlation between site quality and Landsat TM data. The present study addresses whether those correlations are specific to Vanclay's (1989) data or are more widely applicable, whether they can be extrapolated from pass to pass, and how sensitive they are to season.

DATA

The present study concerns the TMF of northeast Queensland, between 16 and 19° S (Figure 1). The environment and dynamics of these forests have been described by Stocker and Unwin (1989). These forests have been managed for conservation and timber production for more than 80 years, and the Queensland Department of Forestry's (1983) research program has provided a database of 250 permanent sample plots with a measurement history of up to 40 years (Vanclay, 1990b). The plots range in size from 0.04 to 0.5 hectares and sample virgin, logged, and silviculturally treated forests on a variety of soil types. Soil type is difficult to map, but geological data are readily available, are correlated with growth patterns, and may be used as an indicator of soil type (Queensland Department of Forestry, 1983, 1985). Vanclay's (1989) index of site quality has been found to be significant in predicting the growth of these forest stands (Vanclay, 1990a), and has been operationally proven in yield forecasting (Vanclay and Preston, 1989).

Site quality was estimated for each plot using Vanclay's (1989) Equation 13: i.e.,

$$GI=\frac{\sum_{ij}\mathrm{Log}(DI_{ij}+\alpha)-\sum_{ij}(\beta_{0i}+\beta_{1i}D_{ij}+\beta_{2i}\mathrm{Log}(D_{ij})+\beta_{3i}\mathrm{Log}(BA)+\beta_{4i}OBA_{ij})}{0.08808\times\sum_{ij}\mathrm{Log}(D_{ij})}$$

where GI is the growth index of the plot; D_{ij} is the diameter (breast high or above buttress, over bark, in cm) of tree j of species i; DI_{ij} is its diameter increment (cm/ann); OBA_{ij} is its "overtopping basal area," the basal area of trees within the plot that are bigger than tree ij (m²/ha); BA is the plot basal area (m²/ha); and α, β are parameters estimated by linear regression. This equation estimates growth index, a measure of site productivity based on the diameter increment adjusted for tree size and competition, of all trees of 18 reference species (*Acronychia acidula, Alphitonia whitei, Argyrodendron trifoliolatum, Cardwellia sublimis, Castanospora alphandii, Cryptocarya angulata, C. mackinnoniana, Darlingia darlingiana, Elaeocarpus largiflorens, Endiandra* sp. aff. *E. hypotephra, Flindersia bourjotiana, F. brayleyana, F. pimenteliana, Litsea leefeana, Sterculia laurifolia, Syzygium kuranda, Toechima erythrocarpum,* and *Xanthophyllum octandrum*) using all available remeasures for the plot (except that, where plots were remeasured more frequently, remeasurements were selected to achieve approximately 5-year intervals). The βs were estimated by fitting the equation

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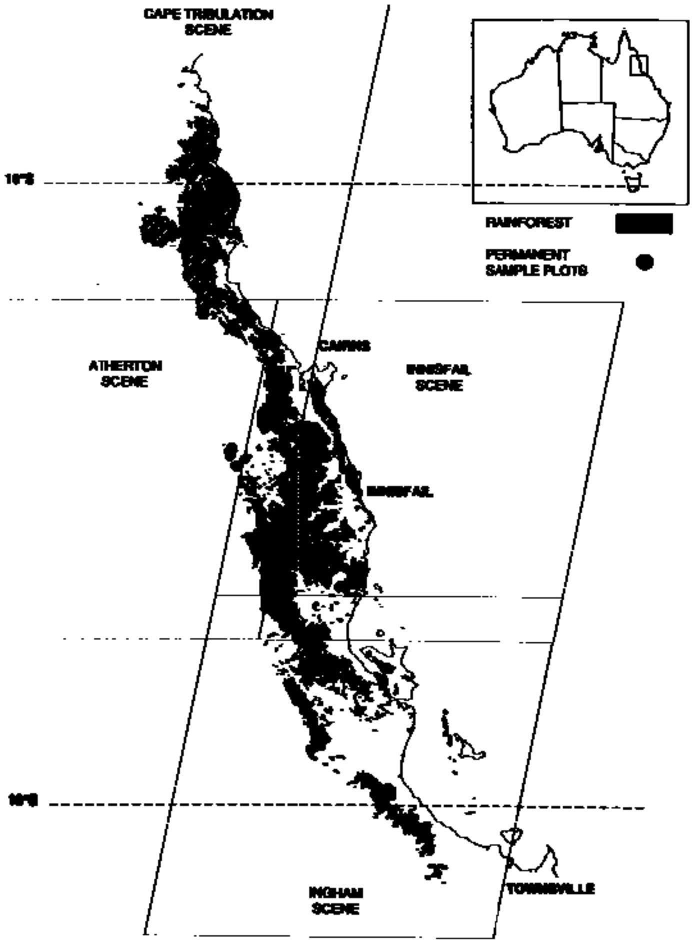

FIG. 1. Location of study and permanent growth plots.

$$\mathrm{Log}\,(DI+\alpha)=Spp+D.Spp+\mathrm{Log}(D).Spp+\mathrm{Log}(BA).Spp+OBA.Spp+\mathrm{Log}\,(D).Plot$$

(where *Spp* and *Plot* are qualitative variables) simultaneously for all these reference species in the development data set (80 plots; a further 64 plots were used for validation studies). The value 0.08808 was subjectively determined to scale the growth indices into the range 0 to 10.

Fifteen plots were rejected and omitted from this analysis because the standard error associated with the estimate of growth index exceeded 2 or because the growth index exceeded the reasonable range (0 to 10). Other plots had insufficient reference species for the growth index and its error to be computed. Six valid plots were outside the Landsat coverage, leaving 215 plots for the present analysis.

Clearly, one cannot afford to maintain a permanent plot on each site for 30 years in order to estimate the growth index, so more immediate methods for estimating and mapping site quality are required. Vanclay (1989) developed equations to enable the growth index to be predicted from the presence or absence of indicator species recorded at the site, e.g.,

$$GI=5.882+0.973S_1+2.514S_2+1.545S_3+1.352S_4-0.970S_5+1.253S_6-0.951S_7-1.523S_8$$

where S_i, $i=1,2,\ldots,8$ are dummy variable which take the value one if present, zero if absent, and represent the tree species *Beilschmiedia obtusifolia*, *Helicia australasica*, *Lethedon setosa*, *Opisthiolepis heterophylla*, *Podocarpus neriifolius*, *Scolopia braunii*, *Syzygium wesa*, and *Xylopia maccreai*, respectively. Vanclay (1989) also estimated growth index from Landsat TM data, suggesting that strata for timber inventory and yield forecasting could be prepared from Landsat images. The present study further examines the utility of Landsat to stratify on the basis of site quality.

Four Landsat scenes from two passes were available to the present study. These scenes were not specifically selected for the study, but were two cloud-free scenes freely available to the authors. The eastern pass included the Innisfail (95–72) and Ingham (95–73) scenes captured on 7 October 1987, and the western pass recorded the Cape Tribulation (96-71) and Atherton (96-72) scenes on 24 August 1986. None of the plots were logged during the period between the two passes. The region experienced a cyclone during February 1986, in which some of the forest in the eastern pass was damaged (Preston, 1987). The forests in the western pass suffered no damage, but received widespread rain. Rainfall during March to August 1986 was erratic and below average, with July particularly dry. August 1986 experienced average rainfall and temperature (Anon., 1986). Good rainfall was experienced during the months prior to the October 1987 image, with the four months June to September all experiencing above average rainfall (Anon., 1987). Natural color images prepared from the three visible bands (1 to 3) revealed the October 1987 images to be much greener, particularly for the pastoral country to the west of the TME.

Ninety-six of the permanent sample plots with valid estimates of site quality occurred in the overlap region of the two Landsat passes, 20 plots were to the east of the overlap region, and 99 plots were to the west. Thus, the data enabled an analysis of both the spatial and temporal portability of equations predicting site quality from Landsat TM data. Parameters for equations were estimated using the 96 plots from the overlap region, and the remaining 119 plots were used to validate the utility of the equations. Only four of the six geological types recorded on permanent sample plots occur in the overlap region. Thus, extrapolations to other geological types inevitably result in a poor correlation. This is a realistic test of efficacy, as few managers are fortunate enough to have complete information for all geographic data, as well as reliable sample data in all strata.

Vanclay (1989) used 44 plots develop his equations, and a further 12 to validate them. All these plots are included in the present database, and all but eight of his development plots lie in the overlap region.

ANALYSIS

It is common practice to register remotely sensed images onto a map, and to transform the image to the appropriate projection. However, to avoid the possible loss of spectral integrity, the Landsat scenes were not transformed. Rather, the back-transformations were applied to the map projection (UTM) to determine the locations of the permanent plots on the untransformed images.

Most remote sensing analyses employ classification to interpret and extrapolate images, but regression analysis and other approaches can also be used (e.g., Cook *et al.*, 1989; Sader *et al.*, 1989; Vanclay, 1989). For data such as site quality, regression analyses provide the advantage of predicting a continuum of values rather than a number of discrete classes. Cook *et al.* (1989) used the average reflectance values from nine pixels comprising a 3-by 3-pixel window surrounding and including the ground truth plot. Vanclay (1989) examined the use of the individual pixel reflectance values, the average and median for a cluster of pixels about the plots, and the use of some textural measures, but obtained the best results from the median of a 3 by 3 window centered on the study plot. Thus, for each of the seven bands, the median of the nine pixels centered on each plot was computed and used in these analyses. Basic manipulation of the Landsat data was conducted using the DISIMP image processing system (CSIRO, 1988). Data were then transferred to a general computer system, and were analyzed using two general purpose statistical packages, GLIM (Payne, 1986) and Genstat (Payne *et al.*, 1987).

Table 1 indicates the correlation matrices for the data derived from overlapping region of the Landsat scenes. All the correlations between raw bands are significant ($p<0.05$), and this may cause problems with stepwise regression analysis. Such correlation among the "independent" or regressor variables results in a non-orthogonal design matrix. This means that parameter estimates may change significantly when an additional variable is included in the model, and detracts from the interpretation of parameter estimates (Neter and Wasserman, 1974). Using the ratios of the bands reduces these correlations, reducing the problems with multicollinearity. It also reduces the variation in illumination caused by topography and sun angle and, thus, in reflectance recorded by Landsat TM, enhancing the portability of results.

The rightmost column of Table 1 shows the correlations between the raw reflectance values and the estimates of site quality. Two of the bands in each pass show a significant correlation. The thermal band (6) is significant in both, band 1 is significant in the October 1987 pass, and band 2 is significant in the August 1986 pass. It is not clear whether the correlation with band 6 reflects a true relationship with site quality. The TMF in north Queensland occur in a region of strong relief, and plots used in the compilation of Table 1 range in altitude from sea level to 1200 metres. In the lowlands, forests are confined to the poorer soils, the better soils having been converted to agriculture, whereas in the higher more rugged areas, better soils are still dominated by forests. The correlation between altitude and site quality for the 96 plots in the overlap region was $+0.14$, and $+0.39$ for all 215 plots. As band 6 may reflect altitude ($r=+0.23$ in the October 1987 pass, $r=-0.07$ in the August 1986 pass for the overlap region; $r=-0.29$ in the October 1987 pass, $r=-0.30$ in the August 1986 pass for the whole study region), it may be correlated with site quality because of historical land-patterns rather than any causal relationship.

The bottom line of Table 1 shows how the reflectance spectra changed over time. All bands were significantly correlated with the previous/subsequent image. The most similar reflectance was in band 5 ($r=0.719$), and the greatest difference in band 1 ($r=0.293$).

Vanclay (1989) reported two equations for estimating site quality from Landsat TM. One was based on a stepwise regression analysis of all raw bands, several transformations of these bands, and all possible ratios of bands: i.e.,

$$GI = -41.9 - \frac{5755}{TM_6} + 0.872 \times \frac{TM_4}{TM_3} \qquad (1)$$

where *GI* is the growth index, TM_6 is the thermal Landsat TM band, and TM_3 and TM_4 are the red and near-infrared bands, respectively. Estimates derived from this equation were found to reflect altitude and this was thought to be an artifact of the distribution of the permanent plots. This equation performed poorly in the validation using independent data, and Vanclay (1989) does not recommend its use.

Vanclay's (1989) preferred equation incorporated geology and used only ratios of Landsat bands: i.e.,

$$GI = \left(\begin{array}{l} -0.66 \times AL \\ -2.47 \times AV \\ +0.07 \times BV \\ +1.72 \times CG \\ -1.11 \times SM \\ -0.59 \times TG \end{array} \right) + 9.19 \times \frac{TM_4}{TM_5} - 1.42 \times \frac{TM_4}{TM_7} \qquad (2)$$

where *AL*, *AV*, *BV*, *CG*, *SM*, *TG* are dummy (0,1) variables representing Alluvial, Acid Volcanic, Basic Volcanic, Coarse grained Granite, Sedimentary-Metamorphic, and Tully (fine grained) Granite geology, respectively, and where TM_4, TM_5, and TM_7 are the near-infrared, and two mid-infrared Landsat TM bands, respectively. This equation provided a better fit to his data (44 plots) than did Equation 1, and performed well in the independent validation. Vanclay (1989) suggested that this equation may be useful for mapping site quality in the Landsat scene used in his study.

TABLE 1. CORRELATION MATRIX FOR THE OVERLAP DATA SET ($n=96$)

			Correlations for the October 1987 Data Set					
TM_1	TM_2	TM_3	TM_4	TM_5	TM_6	TM_7	Site Quality	
1.000	0.550^{***}	0.697^{***}	0.236^{*}	0.363^{***}	0.385^{***}	0.388^{***}	-0.285^{**}	TM_1
	1.000	0.818^{***}	0.679^{***}	0.713^{***}	0.429^{***}	0.609^{***}	-0.033	TM_2
		1.000	0.534^{***}	0.681^{***}	0.424^{***}	0.656^{***}	-0.132	TM_3
			1.000	0.841^{***}	0.212^{*}	0.595^{***}	0.137	TM_4
				1.000	0.487^{***}	0.888^{***}	-0.078	TM_5
					1.000	0.550^{***}	-0.233^{*}	TM_6
						1.000	-0.178	TM_7
							1.000	Site Quality
			Correlations for the August 1986 Data Set					
1.000	0.632^{***}	0.619^{***}	0.508^{***}	0.388^{***}	0.216^{*}	0.326^{***}	-0.160	TM_1
	1.000	0.734^{***}	0.646^{***}	0.652^{***}	0.360^{***}	0.495^{***}	-0.212^{*}	TM_2
		1.000	0.416^{***}	0.471^{***}	0.220^{*}	0.348^{***}	-0.009	TM_3
			1.000	0.896^{***}	0.269^{**}	0.813^{***}	-0.130	TM_4
				1.000	0.412^{***}	0.883^{***}	-0.133	TM_5
					1.000	0.351^{***}	-0.294^{**}	TM_6
						1.000	-0.166	TM_7
							1.000	Site Quality
			Correlations of individual bands between Data Sets					
0.293^{**}	0.474^{***}	0.529^{***}	0.584^{***}	0.719^{***}	0.396^{***}	0.640^{***}	1.000	TM_i
TM_1	TM_2	TM_3	TM_4	TM_5	TM_6	TM_7	Site Quality	

***significant at $P<0.0001$, $^{**}P<0.01$, $^{*}P<0.05$

The ability of these equations to predict site quality from other Landsat scenes is indicated in Table 2. The leftmost column of correlations in Table 2 (overlapping region, some pass) indicates the goodness-of-fit of the model to the calibration data. The four rightmost columns test the validity of the calibrated equation under different scenarios: a different image over the same plots (overlapping region, other pass), a different part of the same image (non-overlapping, same pass), a different location and different image (non-overlapping, other pass) (i.e., extrapolating results to the west or south-east of the study region, as well as using image recorded in a different season), and an overall correlation using all data (including calibration data) (overall, both passes). It is obvious that Equation 1 cannot be relied upon to provide accurate estimates of site quality, except for the particular part of the image for which it was developed. Even within an image, Equation 1 may not give reliable results when extrapolated beyond the immediate locality of the ground truth data. Table 2 supports Vanclay's (1989) contention that Equation 1 is unreliable.

New parameters were estimated for Equation 1 by fitting it to the database for the overlap region. Parameters were estimated separately for both passes, to enable validation of the relationship using data from the other pass. Parameters were also estimated using the pooled data set for the overlap region, but the results were disappointing, and equations based on a single pass generally performed better. The correlation coefficients obtained for these fits were not as good as those previously obtained. This is probably due to the larger and more diverse data set used in the present study (96 plots versus 44 used by Vanclay 1989). The resulting equations, when extrapolated to other times and locations, provided rather low correlations (median 0.14), but they were all positive, an improvement on Equation 1.

Equation 2, which includes geology, provided better results than Equation 1, although the correlations are still not high. Equation 2 provides a reasonable estimate of site quality for areas within the same pass, and within the same region in other passes, but cannot be reliably determined in the west of the study region. Equation 2 performs better than estimates based solely on geology (Vanclay, 1989, Equation 7), which also cannot be extrapolated to the west.

There were some difficulties in estimating new parameters for Equation 2 from the current database, as two of the six geological types known to occur in the study area were not represented in the data from the overlap region used to calibrate equations. The missing types (Alluvial and Tully fine-grained Granite) were assumed to have the same characteristics as the Sedimentary-Metamorphics, the default provided by the statistical package used and a reasonable assumption (see Equation 2). Estimates prepared from the two re-calibrated versions of Equation 2 provided rather good estimates on four of the geological types, but negative correlations where the two missing types were included. This suggests that the two ratios, band 4 on band 5 and band 4 on band 7, may provide useful results for investigating site quality, but only where reliable ground truth and accurate geological maps are available. Figure 2 illustrates the correlation between site quality and the ratio of band 4 on band 5.

New stepwise regression analyses were performed to investigate different formulations which may provide better predictions. These regressions were performed on the data from the overlap region only, for data from both passes separately, and the results validated with data from the other pass, and from the non-overlapping region. Initially, regression analyses were performed with only the ratios of bands. Additional analyses examined the use of raw reflectances, and of several transfor-

TABLE 2. CORRELATIONS BETWEEN PREDICTED AND ACTUAL SITE QUALITY

	Calibration	Overlapping Region		Non-overlapping Region		Overall
Equation	Data	Same Pass	Other Pass	Same Pass	Other Pass	Both Passes
		Using Landsat Data Only				
Equation 1	44 plots (r = .51***)	.02	−.28**	−.31†	−.23*	−.10
Equation 1	October 1987	.32***	.19*	.14†	.08	.10
Equation 1	August 1986	.31**	.14	.16	.28†	.10
New Best Fit Equation						
T4/T5 + T5/T4	October 1987	.45***	.002	−.11†	−.02	.10
T2/T3 + T3/T1	August 1986	.26**	−.10	−.23*	.002†	−.02
1/T6 + T6	August 1986	.41***	−.21*	.05	−.25†	−.06
Mid-infrared, Near-infrared, Visible						
T4/T5 + T1 (Eqn 3)	October 1987	.45***	.14	.13†	.25**	.16
1/T2 + T5/T7§	August 1986	.26**	.11	.41***	.12†	.18
T4/T5 + T4/T2§	October 1987	.39***	.04	.03†	.19*	.01
T7/T3 + T2/T4§	August 1986	.21*	.20*	−.13	.31†	.03
		Using Landsat and Geographical (Geology) Data				
Equation 2	44 plots (r = .75***)	.35***	.27**	.46*†	−.16	.12
Vanclay's (1989) Eqn 7	44 plots (r = .47**)	.35***	.35***	.44*†	−.21*	.11
Equation 2	October 1986	.45***	.27**	.50*†	−.22*†	.09
Equation 2	August 1986	.38***	.41***	−.19‡	.46*†	.15
New Best Fit Equation						
Geol + T4/T5 + T5/T4	October 1987	.53***	.14	−.42†	−.20	.15
Geol + T7/T3 + T2/T3	August 1986	.48***	.30***	−.25**‡	.40†	−.08
Geol + 1/T6 + T2/T3 + T/6	August 1986	.56***	−.16	−.0002‡	−.08†	−.04
Mid-infrared, Near-infrared, Visible						
Geol + T4/T5 + T1 (Eqn 4)	October 1987	.50***	.33***	.47*†	.22*†	.19*
Geol + T7/T3 + T4/T2§	August 1986	.47***	.39***	−.20*‡	.54*†	.11
Geol + T4/T5 + T4/T2§	October 1987	.46***	.30**	.52*†	−.21*†	.10
Geol + T7/T3 + T2/T4§	August 1986	.46***	.39***	−.17‡	.52†	.12

§ These variables not significant ($p > 0.05$)
† These values based on 20 plots only; all others >95 plots.
‡ These values include estimates for "unknown" geological types.
*** Significant at $P < 0.0001$, ** $P < 0.01$, * $P < 0.05$

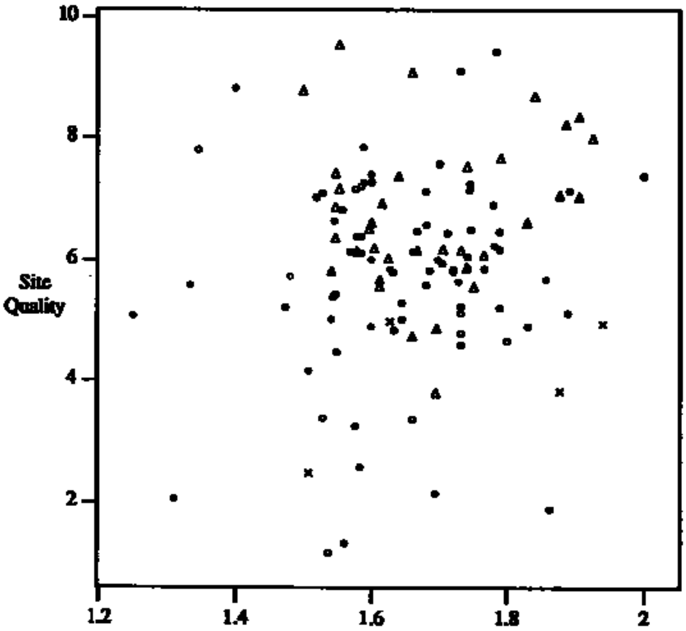

FIG. 2. Scatterplot of site quality and ratio of bands 4/5 (October 1987). (× acid volcanic, ○ basic volcanic, Δ coarse granite, ● sedimentary-metamorphic)

mations of these. For the October 1987 data set, only the ratios were significant, but the thermal band (6) featured prominently in the August 1986 data set.

The new "best fit" equations (Table 2) provide rather poor estimates. The equations containing the thermal band (6) are unreliable, and it is suggested that this band should not be used when using Landsat data to map site quality in the TMF of Queensland. The equations employing geology give better results than those based solely on Landsat data, and allow more robust estimates when extrapolated to other images. If prediction equations employ geology, it is essential that training sites encompass the full range of geology in the region, as reliable predictions cannot be made for the missing geological types.

Previous researchers (Badhwar *et al.*, 1986; Benson and DeGloria, 1985; Sheffield, 1985) have recommended one each of a mid-infrared (5 and 7), near-infrared (4), and visible (1 to 3) band be employed to maximize information on an ecosystem. When regression analyses were constrained to include at least one and not more than two terms containing these bands, the results were markedly better. The best two equations were derived from the October 1987 scene: i.e.,

$$GI = 19.12 + 3.866 \times \frac{\mathrm{TM}_4}{\mathrm{TM}_5} - 0.324 \times \mathrm{TM}_1 \qquad (3)$$

and

$$GI = \begin{pmatrix} 15.75 \times AV \\ 18.13 \times BV \\ 18.42 \times CG \\ 17.59 \times SM \end{pmatrix} + 3.017 \times \frac{\mathrm{TM}_4}{\mathrm{TM}_5} - 0.284 \times \mathrm{TM}_1 \qquad (4)$$

where AV, BV, CG, and SM are dummy (0,1) variables representing Acid Volcanic, Basic Volcanic, Coarse grained Granite, and Sedimentary-Metamorphic geology, respectively, and where TM_1, TM_4, and TM_5 are the blue, near-infrared, and mid-infrared Landsat TM bands, respectively. The goodness-of-fit to the calibration data was only slightly worse than the best unrestricted stepwise regression result, but these equations performed much better in validation with data from different passes and different locations. This procedure also minimized bias due to incorrectly classified geology. Although there are some advantages with using ratios of bands, no advantage accrued from further restricting the regression analysis to include only ratios of bands. The last two equations reported in each part of Table 2 were restricted to ratios, excluding ratios of visible bands and of the mid-infrared bands, but provided no advantage or improvement.

Cook *et al.* (1989) found the ratio of like bands from different passes helpful. They used the ratio of the June band 3 to the September band 3 reflectance which has a correlation of +0.379 with biomass production. In the present study, band 4 provided the only such ratio from the pooled overlap data set. It exhibited a significant correlation (+0.319, $p<0.01$) but did not enter the regression analysis as a significant variable.

Table 2 shows some differences in predictions based on the two passes. Generally, the October 1987 pass seems to provide better results. It consistently provides a better correlation coefficient for the initial fit to the data. These equations also perform well when validated with independent data, especially the equations including geology. Equations based on data from the August 1986 pass provided good results when validated against data from the October 1987 pass. This could imply that October may be a more favorable time for assessing site quality, it may be an artifact of the February 1986 cyclone, or it could imply that better results can be obtained when the forests are not suffering moisture stress.

CONCLUSION

This study demonstrates that regression analysis approaches may be a useful way to analyze, interpret, and extrapolate Landsat TM data when ground truth is available. It suggests that Landsat TM may offer potential for mapping site productivity in TMF, but that the results may depend upon the season. Best results may be obtained when other data sources (e.g., geology) are also employed. The Landsat TM thermal band 6 produced misleading results in Queensland TMF, and should not be used to extrapolate site quality data without independent validation studies. The ratio of band 4 on 5 seemed to show most promise for site quality mapping, especially when used in conjunction with geology. Best results were obtained when simple stepwise regression was not used, but when regression analysis was restricted to ensure that at least one each of the visible (1 to 3), mid-infrared (5 and 7), and near-infrared (4) bands were included. The resulting equations could be expected to give reasonable site quality estimates within the pass for which they were calibrated, but should not be extrapolated to other passes without further validation.

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