Terrain Analysis from Digital Patterns in Geomorphometry and Landsat MSS Spectral Response

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ABSTRACT: Digital Landsat multispectral images are used with elevation model variables in high relief terrain analysis. An integrated terrain map from conventional photomorphic methods (based on aerial photointerpretation) is compared with the results of digital processing methods. The objective is to show that there will be a reasonable correspondence between the analogue and digital mappings, and that digital data and methods offer significant advantages in terms of survey reliability, accuracy, and repeatability.

Digital patterns in spectral response and geomorphometry are shown to capture those attributes of the surface necessary for classification of landscape units. Classification of the MSS digital patterns showed up to 46 percent agreement with photomorphic survey methods. Agreement rose up to 75 percent as the MSS data were augmented with the geomorphometric patterns. Maps produced using this enhanced discrimination technique are 70 percent accurate when the classes are weighted by area and compared to the photointerpretation on a pixel-by-pixel basis at field-checked test areas. Greater overall interpretation accuracy might have been obtained with more precise digital class description, greater rigor in the conventional survey, or both.

INTRODUCTION

LANDSCAPE UNITS are composed of recurring patterns in vegetation, soils, landform, and lithology. These units have been used in terrain analysis based on metric aerial photointerpretation and field observation for over 30 years in many parts of the world (Christian and Stewart, 1968; Townshend, 1981; Franklin, 1985). These integrated, or landscape, surveys have sometimes been criticized (Hutchinson, 1978; Story *et al.*, 1976) as a consequence of the lack of objectivity and repeatability of survey results.

Recently, digital data from sensors on platforms such as Landsat have been used to increase landscape survey reliability. The research of Robinove (1979) and Hutchinson (1978) in arid lands survey was based on the hypothesis that mapping integrated characteristics of land can be done by computer analysis of multispectral images. Those studies built on earlier discussion and research in the landscape approach (Mabbutt, 1968; Story *et al.*, 1976). They emphasized the problems in subjectivity of analog image interpretations, survey repeatability and accuracy, and the selection of descriptor variables, such as Landsat MSS spectral response patterns, for use in representing landscape criteria. These are continuing problems in terrain analysis and classification.

The research described here was designed to address some of these methodological problems in the analysis of a subarctic, alpine region in Northern Canada. The main hypothesis is that, in this high relief environment, the discrimination and mapping of landscape units can be done accurately through the classification of multispectral images with elevation model variables. To test this research hypothesis, digital Landsat MSS data were acquired for 1 August 1978. The image has a sun elevation of 43 degrees and sun azimuth of 154 degrees, and is cloudfree. An elevation model was generated from August 1979 metric aerial photographs (scale 1:60 000) on the Gestalt Photomapper II (an image correlator). The variables extracted from this model conform to the general system of geomorphometry (Evans, 1972) and provide a quantitative basis for topographic descriptions of terrain surfaces and landforms.

The digital analysis of these data is described in two stages. The first stage, correlation analysis, is used to document the nature of the relationships between spectral response patterns and surface elevation and geometry. The second stage is a discriminant analysis in which we use field observations to determine class structures and supervise the classification. The resulting digital maps are used in an assessment of the correspondence between analog and digital interpretations of terrain phenomena generalized into the nine landscape classes of interest.

THE STUDY AREA

The study area encompasses an area of 100 square kilometres within the Ruby Range near Aishihik Lake in southwestern Yukon Territory (Figure 1). This range is one of a series of grandiorite-schist plateaux. During the last (Wisconsin) ice maximum, lobes extended northward from the St. Elias Ice Sheet along valleys now occupied by Aishihik Lake and Sekulmun Lake. Moraine deposits dominate the surficial geology, and postglacial alluvial and lacustrine deposits are evident in floodplains and fans. Because the till covering varies considerably in texture and thickness, bedrock and volcanic outcropping is common. Several such features are visible in the orthophotograph shown in Figure 2.

The region has a continental and semi-arid climate with mean daily temperatures in the past three decades of −24.3°C (January) and +12.1°C (July). A mean annual precipitation of 248.3 mm was recorded with the greatest amount occuring in summer. On north facing slopes in the Ruby Range, perennial snow is common, though not within the confines of the present study site.

During two field seasons with an interdisciplinary field team, strong structural control and altitudinal zonation on the growth of vegetation species were noted (Franklin, 1985). In the valleys the dominant vegetation is white spruce. With increasing elevation, a mixed woodland cover containing deciduous species is present. A patchy upland shrub cover is found up to approximately 1500 metres elevation; and above, a bryoid mat consisting of lichens and mosses is found in conjunction with tundra and alpine barrens. The elevation ranges from 812 to 1755 metres above sea level. Low gradient slopes extend the width of the major river valleys. In general, as elevation increases, slopes become steeper and more variable (Figure 3).

THE INTEGRATED APPROACH

In the integrated approach to terrain classification, landscape units are described as areas having unique combination of topography, soils, vegetation, and lithology. Many surveys using

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FIG. 1. Study area in the Ruby Range, Yukon Territory.

such landscape criteria were conducted by interdisciplinary mapping teams (Townshend, 1981; Hutchinson, 1978; Bastedo and Theberge, 1983). The Australian Surveys are perhaps the best well known and documented examples of this approach, illustrating practical mapping results, philosophy, and methods of terrain classification (Christian and Stewart, 1968; Paijmans, 1970; Story *et al.*, 1976; Robinove, 1979). An evaluation of these methods and an application using landscape units in the U.S. was recently provided by Ackerson and Fish (1980).

A crucial methodological assumption in the integrated or landscape approach was that areas on aerial photographs delineated on the basis of tone, texture, pattern, shape, site association, and dimension could be related to natural terrain units having corresponding unique combinations of topography, soils, vegetation, and lithology (Ackerson and Fish, 1980). In many cases, such aerial photointerpretation was conducted for final mapping scales of 1:100 000 or smaller. That interpretation and mapping process has since become widely known as photomorphic mapping (MacPhail, 1971; Nichol, 1975) in which the distinctive photographic image is considered the analog of the natural terrain unit. Field observations to establish that relationship were an integral part of the proper and consistent application of the integrated approach (Paijmans, 1970; Ackerson and Fish, 1980; Hutchinson, 1978). Despite some advances in quantifying mapping accuracy (e.g., Ackerson and Fish, 1980), the subjectivity of the analog extension from aerial photographs has been considered a constraint in some applications (Robinove, 1979; Franklin, 1985).

The digital method developed in this study describes landscape units using parametric measures of spectral response and geomorphometry. These also are descriptors of the landscape unit that are highly correlated with vegetation, soils, landform, and lithology. In a supervised classification, the extension of these parameters to describe other terrain areas is controlled objectively by computer analysis. After an accurate prediction (using the parametric criteria) of the given (analog) classification scheme in training areas has been made, the decision rule is applied to areas where the classes are known, but where little is known of the terrain attributes themselves. The power of the digital method is twofold: (1) the limitation of analog subjectivity explicitly in training areas; and (2) the use of a repeatable, consistent extension to other areas.

Other studies have illustrated the suitability of Landsat MSS data in classification of certain terrain types according to the landscape approach (Robinove, 1979, 1981). Spectral response patterns are surrogates for some of the attributes (e.g., vegetation cover, soils) that are combined to describe landscape units on the ground and in aerial photographs. However, in high relief, topographic expression (landform) can be a critical component in classification (Hutchinson, 1978; Franklin and LeDrew, 1984; Christian and Stewart, 1968). Such descriptions are not available in a generally usable form in the MSS spectral response patterns; they must be generated from ancillary sources such as digital elevation models (DEM).

GENERAL GEOMORPHOMETRY AND DIGITAL ELEVATION MODELS

Terrain descriptors extracted from digital elevation models may be related to the specific morphometry of landforms or the general geomorphometric characteristics of land surfaces. Specific geomorphometry is used to describe landforms that have been delineated from adjacent parcels of land using clear and recognized geomorphological or genetic criteria. Examples can be found in analyses of cirques, drumlins, and stream channels. The system of general geomorphometry (Evans, 1972; Franklin, 1985) consists of measures of elevation, slope (first derivative of elevation), aspect (directional component of slope), convexity (surface curvature or the second derivative of elevation), and relief (surface variability).

Analysis results when subsets of such geomorphometric data are integrated with Landsat MSS images have been discussed by Justice (1978), Fleming and Hoffer (1979), and Bonner *et al.* (1982), among others, for specific applications such as forest typing. In the present study, we discuss the significance of the full range of general geomorphometric terrain descriptors. Those terrain descriptors may contribute insight into the spectral and spatial linkages in the environment viewed in the interpretative landscape approach. For example, in subarctic high relief environments, landscape classes can be expected to display a relatively simple ecosystem structure, but the spatial arrangement of these systems may be complex. This may be a result of the environmental gradients associated with high relief morphometry such as wind exposure, drainage, and incident irradiance.

The general geomorphometric variables were extracted from a dense-grid DEM of the Aishihik Lake area (Figure 3) after error-checking routines (Hannah, 1981) and geometric registration to the MSS image were applied.

RELATIONSHIPS AMONG TERRAIN DESCRIPTORS

In this section the statistically significant relationships between attributes of terrain that are described by the MSS and geomorphometric surrogates are interpreted using a canonical correlation model. This analysis constitutes a methodology for the selection of discriminating variables to be used in terrain classification (Justice, 1978; Franklin, 1985).

A lack of significant correlation between MSS and DEM data would suggest little could be gained through data set integration for this region. There may be no similarity in the structure of land phenomena as it is defined using the two data sets, and the model will fail to integrate meaningfully the variations in spectral response and geomorphometry. If, on the other hand, the patterns in spectral response display a simple one-to-one correspondence with patterns in geomorphometry, the model will show that variations in surface elevation and geometry covary perfectly with spectral response patterns. They may con-

FIG. 2. Orthophotograph of the study site. The image area is approximately 9.8 km by 10.1 km. The orthophotograph was generated from metric aerial photography, acquired in August 1979, using the Gestalt Photomapper II spatial correlation machine. Locational error is less than 12 m (determined from 18 ground control points at the time of model generation). North is to the top of the image.

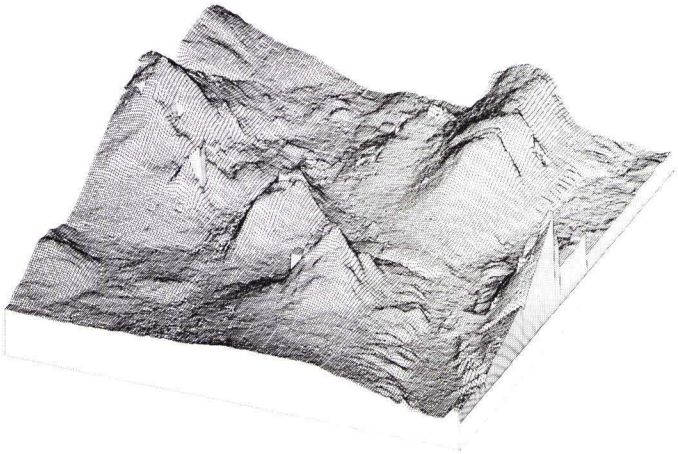


FIG. 3. Isometric view of the digital elevation model. The image area is approximately 9.8 km by 10.1 km. This view is from the southwest, with an elevation angle of 30° and a vertical exaggeration of 2×. Regions where the stereocorrelations are inaccurate are masked with an allowable change-of-slope algorithm (after Hannah, 1981).

tribute little surface discriminatory power, but may still be of interest for landforms. If the data contain more complex relationships, they may be expressed in the statistical model as significant canonical correlation.

In previous communications (Franklin and LeDrew, 1984; Franklin, 1985) samples extracted from the registered MSS and DEM data set were discussed in detail. Some of those results are summarized in Table 1. Geomorphometry was extracted from the DEM in the area of each MSS pixel, and 9973 MSS pixels were sampled randomly from the image. The canonical correlation (R_c = 0.51), shown with the structure matrix, is used to interpret the amount of variance in each variable that is explained given the linear combination of variables from the same data set (r), and given the linear combination of variables from the other data set (r_z). This pattern represents the major associations between spectral response and geomorphometric characteristics of the surfaces.

All spectral bands and all geomorphometric variables except convexity are involved in the pattern shown in Table 1. Elevation is clearly the dominant attribute from the geomorphometric side. As expected, there is empirical information contained in first- and second-order elevation descriptors that is not found in other (MSS or DEM) descriptors, but the variations in elevation overlap the variations in spectral response. One simple way to

TABLE 1. CANONICAL CORRELATION AND STRUCTURE MATRICES FOR SPECTRAL DATA AND GEOMORPHOMETRY

First Vector Pair			$F = 163.22$		
$R_c = 0.51$					
MSS All	r	r_z	Geomorphometry	r	r_z
Band 7	0.97	0.50	elevation	0.91	0.46
Band 6	0.99	0.51	relief	0.06	0.03
Band 5	0.81	0.41	convexity	0.02	0.11
Band 4	0.75	0.38	slope	0.22	0.11
			incidence	−0.43	−0.22

R_c = canonical correlation coefficient.
r = correlation between the variable and the canonical vector composed of a linear combination of variables from the same data set.
r_z = correlation between the variable and the canonical vector composed of a linear combination of variables from the other data set.

(all correlations significant at 0.001).

describe the pattern is to total the variance explained and divide by the number of variables in the model. Thus, 20 percent of the variance in spectral bands is explained by a linear combination of four geomorphometric variables that account for an average of 27 percent of the variance in geomorphometry. In essence, this pattern illustrates and confirms the elevational controls on those attributes quantified by the MSS data. The strongest correlation occurs with infrared channels which are sensitive to vegetation cover type and density. In this region the pattern represents heavily forested valleys at low elevations, through sparsely vegetated slopes and tundra plateaux at mid-elevation, through alpine barrens and denuded, exposed slopes at mountain peaks.

The landscape approach relies on such knowledge of the association between terrain attributes. That knowledge is applied in an informal (analog) fashion during photointerpretation where the elements of the analysis, such as image tone and texture, incorporate the known (i.e., fieldchecked) or surmised recurring patterns in the environment (Townshend, 1981; Ackerson and Fish, 1980; Christian and Stewart, 1968; Nichol, 1975). These analog landscape criteria appear to be captured in statistical patterns of geomorphometry and spectral response; at least, this is one interpretation that is consistent with field observation and the nature of the digital data. Based on the observed significant correlation, we would expect that a discriminant strategy using the integrated digital patterns can be successful in separating landscape units.

TERRAIN CLASSIFICATION AND MAPPING ACCURACY

The application of digital patterns in prediction of the results of a conventional photomorphic survey is documented in this section as classification accuracy (650 pixels in training samples) and interpretation accuracy (375 pixels in independent test samples). For discussion purposes, accuracy and percentage correct statements are here defined to be *agreement* of digital classification with field-checked photointerpretation on a pixel-by-pixel basis (after Pettinger, 1982). It was necessary to use blocks of pixels (3 by 3 and 5 by 5) in the sampling because there was no way to be sure that the pixel area corresponded exactly with the area on the ground during our field data collection.

We use *classification accuracy* as a response to the question: How well do the MSS and geomorphometric variables describe and separate the classes? Then, we use *interpretation accuracy* as a measure of "how well the classification rule performs in areas not used in class description or the determination of classification criteria." The second measure is the more powerful of the two because bias is minimized; precision in digital class description is directly related to the interpretation accuracy. Precision refers to the clustering of sample values about their own average, a class characteristic which can be inferred from,

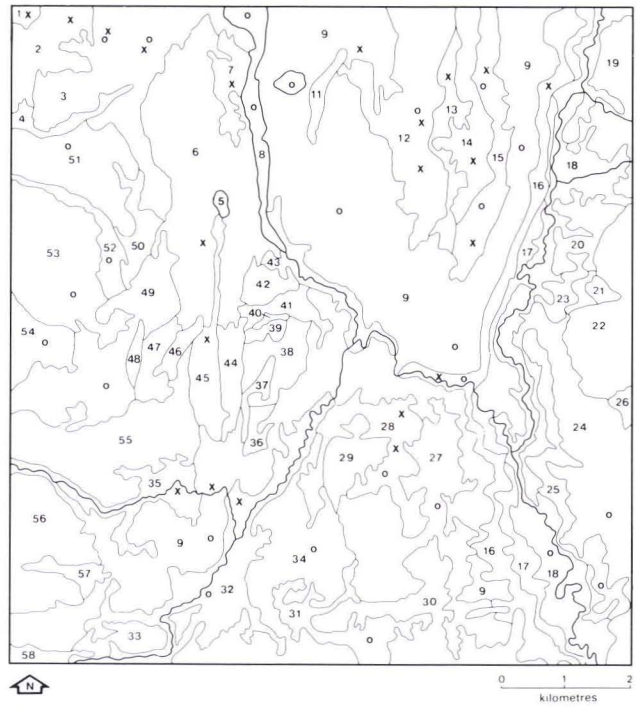


FIG. 4. Landscape unit boundaries generalized from aerial photography. Test sites (x) and training sites (o). Landscape units are labeled from 1 to 58 as follows: water 5, 8, 10; forest 9, 17, 21, 24, 30, 33, 34; woodland 3, 12, 27, 38, 42, 55; upland shrub 2, 13, 19, 26, 41, 46, 49, 51, 56; alpine shrub 7, 28, 31, 36, 45; alpine tundra 14, 52, 54; alpine barrens 15, 37, 39, 47, 50, 53; marshland 18, 32, 43; exposed slopes 4, 16; shadows 11, 22, 29, 40, 48. North is to the top of the map.

but is not synonymous with, class accuracy. For example, a class may be very precisely described with biased samples which are inaccurate. But, it follows that class descriptions cannot be accurate without also being precise. In remote sensing analysis, another way to view this is as follows: training areas, because they are selected on the basis of personal judgement, are areas *thought* to represent the landscape classes, while test areas, because they are sampled randomly, *actually do* represent them (if they are logical and consistent generalizations of terrain phenomena).

The classes used in these tests are outlined briefly in Table 2 and mapped in Figure 4 (conventional) and Plate 1 (digital) for the Yukon study area. With the relative weights by area, they include water (0.01), forest (0.41), woodland (0.20), upland shrub (0.10), alpine shrub (0.10), alpine tundra (0.04), alpine barrens (0.06), marshland (0.04) and exposed slopes (0.04). The classification accuracy (training areas) is documented in Table 3.

Results are poor using MSS data alone in training areas: 58 percent classification accuracy. The addition of elevation increases accuracy to 79 percent and the addition of the other four geomorphometric variables yields 87 percent classification accuracy. Only the selection of variables in the discrimination has been altered; thus, it is reasonable to conclude that the choice of discriminating variables underlies the differences in classification results observed in training areas. Now, the precision with which classes have been described must be validated using samples that are free of the bias used in training the classifier. This validation process can be construed as a test of the rigor and consistency with which (analog) landscape criteria have been applied.

Table 4 contains the interpretation accuracy estimates for the successful discriminant combinations also expressed as class accuracy weighted by map area. Plate 1 shows the digital classification for MSS data alone and MSS data plus elevation. It is

TABLE 2. LANDSCAPE CLASSES - AISHIHIK LAKE STUDY SITE

Class	Description
1 Water	- water table at or above the surface
2 Forest	- greater than 25% tree cover; tree height greater than 3m - white spruce dominant; sites well drained
3 Woodland	- 10 to 25% tree cover; tree height greater than 2m - white spruce dominant; poplar understory, deciduous shrubs
4 Upland Shrub	- deciduous dominant; shrubs 0.5 to 5m height - well drained upper slopes; plateaux
5 Alpine Shrub	- deciduous dominant; shrubs 0.1 to 0.5m height - greater than 25% shrub cover
6 Alpine Tundra	- bryoid mat consisting of lichens, mosses, woody plants - less than 10% deciduous shrub cover; less than 25% exposed soil
7 Alpine Barrens	- nonvegetated; bedrock outcropping; talus slopes
8 Marshland	- water table near the surface; fen - deciduous shrub dominant; sedges; flat lowland
9 Exposed Slopes	- eroded hillslopes; exposed soil; sedges and low shrubs - high slope; in valley aspect-oriented to southeast

TABLE 3. SUMMARY OF CLASSIFICATION ACCURACY

	Percent* Classified Accurately in Class:									
Function	1	2	3	4	5	6	7	8	9	Mean
MSS Band 7	72	76	52	80	0	68	18	32	0	44
MSS Band 5	80	3	61	90	0	42	40	0	10	36
MSS 7 & 5	73	70	67	86	6	64	38	54	20	53
MSS All	76	74	65	90	18	62	43	68	24	58
DEM All	92	63	87	92	16	94	45	94	68	72
MSS & Elevation	80	83	87	100	60	86	67	90	64	79
MSS & Relief	75	70	73	92	28	68	53	82	44	65
MSS & Convexity	75	69	65	90	16	68	40	60	26	56
MSS & Slope	73	73	73	92	34	72	52	68	36	63
MSS & Incidence	73	74	61	90	26	70	49	70	42	61
MSS & DEM	88	87	97	100	64	98	70	100	80	87

*Subject to Rounding Errors

TABLE 4. SUMMARY OF MAPPING ACCURACY

	Percent* Classified Accurately in Class:										
Function	1	2	3	4	5	6	7	8	9	Overall	Mean
MSS All	67	31	45	92	32	52	30	40	28	41	46
MSS & Elevation	84	48	68	88	56	84	68	76	56	61	70
MSS & DEM	87	64	70	76	68	92	86	56	74	70	75

*Subject to Rounding Errors

worthwhile noting that the statistical accuracies associated with these maps are based on *samples within landscape units* and do not refer to the correspondence *between boundaries of landscape units* in the mappings. That correspondence involves more complex analysis (see Hutchinson, 1978; Ackerson and Fish, 1980).

The MSS data alone yield maps that are 46 percent accurate (Plate 1a). The results using the MSS and geomorphometric data are significantly better; up to 75 percent accurate. The single largest increase in interpretation accuracy, as in training areas, is noticed when elevation is added to the spectral decision rule (Plate 1b). This trend was suggested by the canonical analysis. However, the addition of geomorphometry (map not shown) in the form of slope, incidence, relief, and convexity provides significant improvement over the simple addition of elevation. The relative improvement over the MSS discrimination is 29 percent.

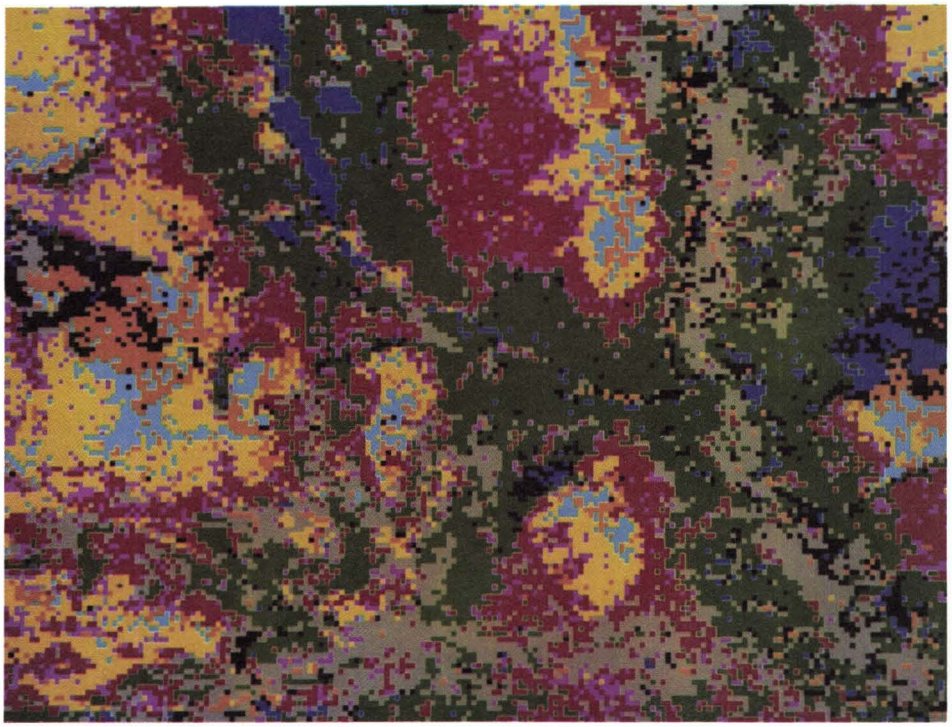
These levels of accuracy are consistent with those published by researchers integrating elevation and first-order derivatives of elevation and spectral information for other resource mappings. For example, Fleming and Hoffer (1979) improved accuracy in forest typing from approximately 49 percent to 66 percent, and Bonner *et al.* (1982) found improvement from 54 percent to 73 percent in desert land classification.

DISCUSSION OF CLASSIFIER RESULTS

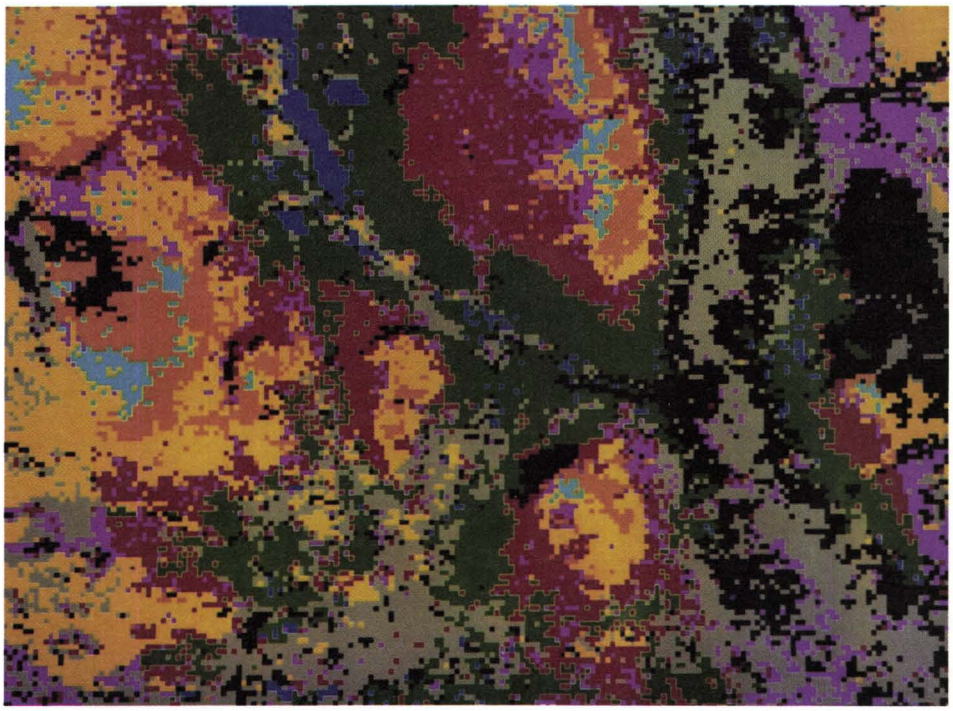
In this study, accuracies are expressed as the percent agreement between digital and photomorphic landscape classifications. In general, the failure to obtain higher classification and interpretation accuracies of the landscape units is a consequence of a lack of precision in the digital class description if the photointerpretation results are considered the only correct possibility for pixel identification. If this assumption is relaxed, the discrepancy may be a result of a lack of precision, the presence of bias, or both.

Relatively low interpretation accuracy cannot be attributed to classification criteria if the *a priori* class system used is logical and consistent. If the utility of the training data is granted (up to 87 percent correct), then the digital patterns represent the landscape classes. In that case, it is probable that the interpretation accuracy (75 percent) represents the best possible agreement between photointerpretation and digital classifications in light of several practical and theoretical considerations, some of which are characteristic of any such classifications, and some of which are specific to the present methodology. For example:

- Single pixel test areas often cannot be identified on the ground or in supplemental aerial photographs because of relief displacement



(a)



(b)

PLATE 1. Digital classification maps. Pixels are registered to UTM coordinates with 44 metre RMS error. Color/Class legend: blue, water; light green, forest; red, woodland; yellow, upland shrub; magenta, alpine shrub; cyan, alpine tundra; orange, alpine barrens; gray, marshland; dark green, eroded slopes; black, shadows and unclassified. (a) MSS data alone. Map accuracy tested using 375 pixels is 46 percent in comparison to the unit identification by conventional survey shown in Figure 4. (b) MSS data plus elevation. Map accuracy tested using 375 pixels is 70 percent in comparison to the unit identification by conventional survey shown in Figure 4.

and geometric errors in data set registration. However, blocks of test pixels represent a generalization of the continuum of variability in terrain attributes. Additional problems can be traced to the possibility of training and testing using mixed pixels, which are inherently difficult to classify. The area on the ground used to calculate geomorphometry may not coincide exactly with the area in the MSS instantaneous field of view which contributes spectral response.

- The concept of acceptable heterogeneity in landscape units as a characteristic of a class in aerial photointerpretation does not translate directly into the concept of statistical precision in digital data. For example, sample areas from anywhere in the unit are assumed to represent the class equally well. Although this is easily handled using analogs, it is difficult to reconcile increasing class generalization with loss of precision in digital classification.
- Analog procedures, such as photomorphic mapping, always involve some errors of judgement in the assignment of a given area of land to a landscape unit, and the naming of a unit using the class structures. These errors are usually minimized in training areas. However, test data can be significantly biased in other ways. For example, they are usually less well known and cover pixels of a mixed nature over a wider range of terrain conditions (they are randomly sampled).
- Classification results should not be considered absolute if they are presented in terms of differences between two classifications where one (conventional) must be called correct and the other (digital) must be called incorrect. Logical comparison of classifications may not be totally valid because both interpretations may represent reasonable generalization of the terrain phenomena of interest.

CONCLUSIONS

The geomorphometric system of terrain descriptors has been used to augment the accuracy with which terrain classification in the landscape approach can be done using surrogate multispectral images. The increase is from 46 percent (MSS alone) to 75 percent (MSS plus elevation, slope, incidence, relief, and convexity) in a high relief environment in southwestern Yukon. The measured landscape unit map accuracy is reasonable when compared to photomorphic units. Of course, the final accuracy test in terrain analysis is utility, a test which is beyond the scope of this paper.

The digital method of terrain analysis using geomorphometric and spectral response patterns offers significant advantages over generalization based on aerial photointerpretation. These advantages include solutions to some methodological problems noticed by researchers working in the landscape approach using conventional data and methods, such as the photomorphic procedures discussed by Nichol (1975), Ackerson and Fish (1980), Franklin (1985), and Hutchinson (1978), among others. They are

- Parametric reliability of classification results based on an objective extension from training data to other areas;
- Objective evaluation of decision rules (landscape criteria) used to assign parcels of land to landscape units, and the naming and description of such units using an *a priori* class structure;
- Assessment of surrogate variable selection using quantitative methods (statistical or deterministic); and
- Automation in the mapping and analysis process providing ready interface to other developing technologies such as geographic information systems.

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