Mapping Dominant Vegetation Communities in the Colorado Rocky Mountain Front Range with Landsat Thematic Mapper and Digital Terrain Data

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ABSTRACT: Landsat Thematic Mapper (TM) data have been combined with topographic and topoclimatic variables to map dominant vegetation communities in the Colorado Rocky Mountain Front Range. Landsat TM transformations, elevation, aspect, and slope-aspect index were able to distinguish among alpine and subalpine vegetation types; however, forest vegetation types in the montane zone were not distinguishable. Previous research indicated that high resolution color infrared aerial photography was necessary to map relatively small mapping units, but Landsat TM spatial resolution appears to be more suitable for mapping larger geographic areas. Alpine and subalpine vegetation distributions mapped with Landsat TM and landscape variables agree favorably with a map of dominant vegetation communities prepared from field observations and large scale color and color infrared aerial photographs.

INTRODUCTION

THIS STUDY is part of a larger effort to map vegetation in the Colorado Rocky Mountain Front Range with remotely sensed data.

Two previous studies were undertaken to map alpine vegetation with digitized color infrared aerial photography in combination with topographic data (Frank and Thorn, 1985), and in combination with topoclimatic indexes (Frank and Isard, 1986). Results from these earlier studies found that high resolution imagery was necessary to identify relatively small mapping units, but spectral observations alone were not sufficient to distinguish among alpine tundra and shrub vegetation types. Both topographic and topoclimatic measures derived from a digital elevation model (DEM) were required to characterize vegetation habitats. In this study, mapping has been extended to assess vegetation in the alpine, subalpine, and montane plant zones. The focus of this study has been on Landsat Thematic Mapper (TM) data as a means to map larger geographic regions. Landsat TM offers a better selection of spectral wavebands than color infrared imagery, particularly with the addition of middle infrared wavebands; and Landsat TM spatial resolution is more suitable than high resolution aerial imagery to map relatively large areas.

Mountain ecosystems exhibit some of the steepest environmental gradients on Earth. Vegetation distributions are controlled by environmental factors that affect soil development, moisture, and disturbance; solar radiation; and snow cover distribution and persistence. Subtle variation in vegetation type and diversity is associated with the spatial variability of pedologic, climatologic, and edaphic characteristics of the landscape. These environments are particularly difficult to map with remotely-sensed data because (1) many cover types do not exhibit unique spectral reflectance/absorptance characteristics that distinguish one cover type from another: (2) topography often affects reflectance, differentiating sunlit and shadowed slopes: and (3) even though vegetation distributions are generally related to an altitudinal gradient, recognized plant zones merge into each other on the margins, and the plants which are characteristic of one zone are often found in favorable sites in the neighboring zone above or below (Weber, 1976). Topographic data, particularly elevation and aspect, have been used in combination with spectral data to classify vegetation in mountain environments (e.g., Hoffer *et al.*, 1975; Strahler *et al.*, 1978; Frank and Thorn, 1985). More recently, variables that measure environmental effects on vegetation distributions, such as wind, snow cover, and solar insolation, have been combined with spectral data with some success in mapping difficult vegetation distributions (e.g., Cibula and Nyquist, 1987; Frank and Isard, 1986). Many of the methods for combining ancillary data with spectral data have been described by Hutchinson (1982).

In this study, Landsat TM data have been combined with topographic and topoclimatic measures to determine the best set of classification variables for mapping vegetation communities along an altitudinal gradient from alpine to subalpine to montane plant zones. A map of vegetation communities derived from this procedure is compared with a previously published map of dominant vegetation communities in the study area to assess the relative agreement of the classification against traditional mapping methods.

BACKGROUND

PLANT ZONES OF THE ROCKY MOUNTAIN FRONT RANGE

Vegetation distributions in the Rocky Mountain Front Range have been categorized along an altitudinal gradient into three primary groups (Weber, 1976): (A) alpine tundra: meadows and rocky fellfields above treeline, mostly deep rooted mat and cushion plants, dwarf willows (*Salix*), grasses, and sedges; (B) subalpine forests: *Picea engelmannii* (Engelmann spruce), *Abies Lasiocarpa* (subalpine fir), and *Pinus Flexilis* (limber pine) forests interspersed with moist meadows, ponds, and bogs; and (C) montane forests: *Pinus contorta* (lodgepole pine), *Pinus engelmannii* and *Pinus pungens* (blue spruce), *Pseudotsuga menziesii* (Douglas-fir), *Populus tremuloides* (aspen), and *Pinus ponderosa* (ponderosa pine). Vegetation mapping units within these plant zones have been delineated on the basis of relationships among plant species, and with relationships between plants and their topographic setting (Kuchler, 1967). Plant community mapping units have relatively uniform structure and floristic composition (e.g., Braun-Blanquet, 1932) while vegetation type mapping units have similar habitat and physiognomic characteristics (e.g., May and Webber, 1982). Mapping plant communities in mountain

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environments requires a method to recognize units of plant species that occur together regularly (e.g., Komarkova and Webber, 1978). Therefore, plant community mapping units are generally compiled from field observations. Vegetation type mapping units are more suitable for mapping with remote sensing (e.g., Frank and Isard, 1986). Identification of vegetation type mapping units can be attempted through a synthesis of spectral, spatial, textural, and associative characteristics (e.g., Hay, 1982; Hutchinson, 1982).

Factors Influencing Vegetation Distributions

The primary determinants of the distribution of vegetation types in the Colorado Rocky Mountain Front Range, in decreasing order of importance, are soil moisture, snow accumulation, and soil disturbance (Webber and May, 1977). Snow cover is distributed by strong winds associated with the westerly cyclone belt which create long-lasting snowbeds on leeward slopes and snow-free ground on adjacent windward slopes (Osburn, 1958; Marr, 1961; Benedict, 1970). Snowbeds protect plants from winter temperatures and desiccation, but shorten the growing season (Billings and Bliss, 1959; Marr, 1961); and provide moisture throughout the summer growing season. Soil moisture is closely associated with snow accumulation and melt, and with slope and drainage characteristics of the land.

The secondary determinants of vegetation distributions are solar radiation and wind. Solar radiation is the primary atmospheric control over soil moisture status between precipitation events in vegetation not receiving meltwater and appears to influence the local adaptation of vegetation (Isard, 1986). Relationships between slope aspect and solar radiation control the range of vegetation types along the altitudinal gradient. Wind affects vegetation distributions by controlling snow cover distributions, but wind also affects plant morphology. For example, flagged trees have branches growing only on the sides of trees facing away from the dominant wind direction, and shrubs and trees in the forest-alpine tundra ecotone often grow parallel to the ground in continuously high wind sites. Therefore, topography appears to modify the altitudinal range of vegetation types because of differential solar radiation associated with aspect, and differential plant morphology associated with wind.

Remote Sensing in Mountain Environments

Alpine environments are dominated by low herbaceous vegetation and shrubs that exist under extreme environmental conditions. Background reflectance from soil or exposed rock often dominates reflectance from alpine tundra. Subalpine environments are characterized by a mixture of open herbaceous meadows, shrubs, and coniferous forests which produce complex or hybrid reflectance patterns. Montane forests generally exhibit indistinguishable spectral reflectance patterns among coniferous species, making forest classification difficult with spectral data alone or in combination with topographic data (e.g., Strahler *et al.*, 1978; Hoffer *et al.*, 1975).

Remotely sensed imagery is commonly used to map mountain vegetation. Becking (1959) evaluated black-and-white aerial photography for mapping small tundra communities, but concluded that, even though small mapping units could be recognized on large scale photography, vegetation type could not be interpreted. Vegetation cover, or density, was the primary control over tonal variation on the photography, which is not necessarily associated with vegetation types. Keammerer (1976) mapped broad vegetation types in the Colorado Rocky Mountain Front Range with color infrared aerial photography. She was not able to distinguish vegetation type directly on the imagery, but she could infer landscape characteristics associated with vegetation distributions directly from the imagery.

Frank and Thorn (1985) found that alpine tundra distributions could be mapped using a two-stage classification system that combined digitized aerial photography with digital elevation, slope, and aspect data; however, the method was difficult to extend beyond the local study sites. Frank and Isard (1986) developed a more generalized method to combine digitized aerial photography with topoclimatic indexes to map alpine tundra, but the topoclimatic indexes were not readily transferable to surrounding areas. Cibula and Nyquist (1987) used a similar method to characterize vegetation distributions by combining Landsat MSS, topographic, and general precipitation data inferred from watershed delineations. The goal of remote sensing in mountain environments still remains to find a means for extending local scale observations and models to larger, surrounding geographic regions.

STUDY SITE

A study area in the Colorado Rocky Mountain Front Range enclosed entirely within the Ward, Colorado 7½-minute quadrangle (Figure 1) was chosen to study vegetation distributions in the alpine to montane plant zones. The area surrounding Niwot Ridge, a long-term ecological research site (LTER) for alpine tundra located along the east side of the Continental Divide approximately 50 km west of Boulder, Colorado, was selected for study because ecological surveys and vegetation maps existed for this area (e.g., Komarkova and Webber, 1978; Keammerer, 1976; Hansen-Bristow, 1981), and earlier remote sensing studies were conducted here (Frank and Thorn, 1985; Frank and Isard, 1986). This area contains a diversity of vegetation types within a relatively small area for three primary groups: alpine, subalpine, and montane ecoystems (Table 1).

Alpine Ecoystems

Niwot ridge slopes gently to the east, dropping from 3750 to 3400 m ASL. Strong prevailing winds from the west control the distribution of snow cover, producing windswept knolls and areas of deep snowpack. West-facing slopes and ridge tops are generally free of snow due to wind action, while east slopes usually accumulate snowpack. Vegetation exhibits a general change from moist communites in the west to drier communities in the east (Komarkova and Webber, 1978). Local controls on vegetation are influenced by local habitat characteristics, particularly soil moisture, snow accumulation, and soil disturbance (Webber and May, 1977). In turn, these factors are controlled by the interaction of slope and aspect. Above timberline, no trees are found; rather, deep-rooted mat and cushion plants, dwarf willows, grasses, and sedges. Grassy slopes are usually referred to as alpine meadows to distinguish them from the more rocky fellfields (Weber, 1976).

Alpine vegetation on Niwot Ridge has been mapped using three different classification systems:

(1) Webber and May (1977) identified six vegetation units (noda) that are defined by principal habitat and physiognomy: dry alpine meadow, dry fellfield, moist shrub tundra, moist alpine meadow, snowbed communities, and wet meadows. Noda are characterized by the environmental gradient based on soil moisture, snow accumulation, and soil disturbance. Noda were successfully mapped with high resolution color IR imagery and topoclimatic indexes (Frank and Isard, 1986).

(2) Komarkova (1976) mapped alpine vegetation using the hierarchical Braun-Blanquet (1932) classification system based on floristic-sociological principles. Diagnostic species were used to categorize plant communities by decreasing hierarchical levels: division, class, order, alliance, suballiance, association, subassociation, variant, and subvariant. Noda generally correspond to higher level Braun-Blanquet units, but this system has not been mapped successfully with remote sensing.

TABLE 1. DESCRIPTION OF DOMINANT VEGETATION COMMUNITIES IN THE COLORADO ROCKY MOUNTAIN FRONT RANGE (HANSEN-BRISTOW, 1981; PERS. COMM., 1987)

1. WET HERBACEOUS MEADOW (*Sedge-elephantella*). This community consists of herbaceous species which form dense cover found below timberline on both steep slopes (along a drainage or below areas of late lying snow) and on flat or gently sloping sites of poor drainage.
2. DRY HERBACEOUS MEADOW (golden banner-yarrow). This community forms an open to dense community found below timberline on both gentle and steep slopes with good drainage and low soil moisture.
3. MOIST ALPINE MEADOW (alpine avens alpine meadow). A low herbaceous community found on moist, leeward, and north-facing slopes, forming a dense, tight turf, generally with less than 25 percent exposed rock.
4. KOBRESIA ALPINE MEADOW (*Kobresia myosuroides*). This alpine community consists of small dense clumps of this sedge species. It is covered during winter with only scattered snowbanks which melt early in spring. Ecosystem is found on mesic end of the moisture gradient, found mostly on well-drained interfluves and broad ridges.
5. DRY SEDGE-KOBRESIA ALPINE MEADOW (*Carex-Kobresia*). This is a rocky community composed of low grass species found in areas of good soil drainage and sparse winter snow cover, often on ridge tops or on well stabilized talus slopes.
6. MOSS CAMPION-ROCKY ALPINE MEADOW (*Silene acaulis-Carex rupestris*). Highly tolerant community found only on extreme wind-exposed ridges, has ground surface cover 50 to 80 percent rock.
7. *SALIX* BOG (*Sphagnum-Salix-Betula*). A dense, very moist, broad-leaved deciduous shrub and moss community found in areas of excessive soil moisture below timberline.
8. *SALIX* MOIST MEADOW (*Salix*). An open to semi-dense broad-leaved deciduous shrub found in areas of mesic soil moisture below timberline where snow cover does not last long into the growing season.
9. KRUMMHOLZ (*Picea-Abies-Pinus*). Low, open krummholz interspersed with alpine meadows located where winter snow protects krummholz islands from dessicating winds. Distribution results from strong westerly winds moving downslope, over the alpine and into the forest-alpine tundra ecotone.
10. FLAG-TREE (*Picea-Abies-Pinus*). Low to medium tall open forest. Trees are flagged, supporting branches on only the leeward side of the main stem. Located within the lower zone of the forest-alpine tundra ecotone, the community lies immediately above timberline.
11. *Picea engelmannii-Abies lasiocarpa* (engelmann spruce-subalpine fir forest). A stable needle-leaved evergreen forest. Located within the upper zone of the forest, this community grades at lower elevations into the ponderosa pine and lodgepole pine forests and at higher elevations into the alpine zone. This is a climax forest, found in undisturbed areas, with small islands of flag trees, dry golden banner-yarrow meadows, wet sedge-elephantella meadows, rock outcrops, lodgepole pine, limber pine, and peat moss communities.
12. *Pinus flexilis* (limber pine forest). This open, needle-leaved evergreen forest community is found on wind-swept, dry, rocky ridges where little competition from other species exists. The community is drought tolerant and forms the uppermost treeline on windy ridges.
13. *Populus tremuloides* (quaking aspen forest). The aspen community is an open to dense, broad-leaved deciduous forest. The community ranges in elevation throughout the entire forest of the study area, and even extends to treeline on a south-east facing slope of Niwot Ridge. It is found on both wet and dry slopes. This community has variable ecotypes ranging from moist to mesic to dry soil conditions.
14. *Pinus contorta* (lodgepole pine forest). This community is a dense, successional, narrow trunk, needle-leaved evergreen forest. This community seldom occurs below 2560 m and, if lower, is usually restricted to mesic, north-facing slopes. It is found rarely at treeline and within the forest-alpine meadow ecotone, and is most frequently found below timberline, in dry soils.
15. *Pinus ponderosa* (ponderosa pine forest). This community is an open, needle-leaved evergreen forest that is found only within the lower elevations of the study area, mainly on south-facing slopes. This community is a topographic climax on hot and dry slopes, a topoedaphic climax on deep soils on the lower part of the south-facing slopes, and an edaphic climax on very coarse soils on north exposures and ridgetops (Marr, 1964).
16. *Pseudotsuga menziesii* (Douglas-fir forest). The Douglas-fir community is a fairly dense needle-leaved evergreen found mainly on north-facing slopes in moist canyons. Within the higher elevations, this community is located on the more mesic sites, and within the lower elevations it is found on steep, north-facing slopes. It is not abundant in the study area.

(3) Hanson-Bristow (1981) mapped vegetation as dominant vegetation communities. Alpine communities were characterized by moist alpine meadows (*Acomastylis rossii, Acomastylis-Kobresia*), dry alpine meadows (*Kobresia mysouroides, Carex-Kobresia*), fellfield (*Carex-Cushion* plant), and alpine *Salix* bog.

SUBALPINE COMMUNITIES

The forest-alpine tundra ecotone surrounds Niwot Ridge in a subalpine zone approximately 3400 to 2700 m ASL. Vegetation is characterized by a mosaic of *Picea engelmannii, Abies lasiocarpa, Pinus flexilis,* moist meadows, ponds, and bogs. The zone represents transitional vegetation types between the alpine and montane forests.

Vegetation in the forest-alpine tundra ecotone has been mapped using two classification systems:

(1) Structural indicators of vegetation were mapped by Hansen-Bristow (1981) into forest, flag-trees and alpine meadows, meadows below timberline, meadows above timberline, meadows with tree islands, and lichen communities on boulders.

(2) Dominant vegetation communities were mapped by Hansen-Bristow (1981) into krummholz conifers, flagged krummholz, krummholz and *Carex-Kobresia*, krummholz and alpine *Salix* bog, and *krummholz* and *Salix* moist meadow, *Picea engelmannii* and *Abies lasiocarpa,* and *Pinus flexilis.*

MONTANE FORESTS

Forest communities are found in the montane zone from approximately 2700 to 2500 m ASL. This zone is transitional between the subalpine zone above and the foothill vegetation types below. Dominant forest communiteis are *Pinus contorta, picea engelmannii* and *Picea pungens, Pseudotsuga menziesii, Populus tremuloides*, and some *Pinus ponderosa* (Weber, 1976).

Structural characteristics and habitat descriptions of the alpine, subalpine, and montane communites that were used in this study were summarized for each community by Hansen-Bristow (1981; pers. comm., 1987, Table 1):

(1) Alpine vegetation: (1) wet herbaceous meadow (*sedge-elephantella*). (2) dry herbaceous meadow (golden banner-yarrow), (3) moist alpine meadow (alpine avens alpine meadow), (4) *Kobresia* alpine meadow (dry), (5) dry *sedge-Kobresia* alpine meadow, and (6) moss campion - rocky alpine meadow (fellfield).

(2) Subalpine vegetation: (7) *Salix* bog, (8) *Salix* moist meadow, (9) krummholz (conifers in upper portion of ecotone), (10) flag-trees (in lower portion of ecotone), (11) *Picea engelmannii* and *Abies lasiocarpa*, and (12) *Pinus flexilis.*

(3) Montane vegetation: (13): *Populus tremuloides,* (14) *Pinus contorta,* (15) *Pinus ponderosa,* and (16) *Pseudotsuga menziesii.*

MATERIALS AND METHODS

A map of dominant vegetation communities (Table 1) covering the Ward, Colorado 7½-minute quadrangle (Figure 1) pre-

Fig. 1. Perspective view of Landsat TM for the Ward, Colorado 7½-minute quadrangle locating Niwot Ridge study area.

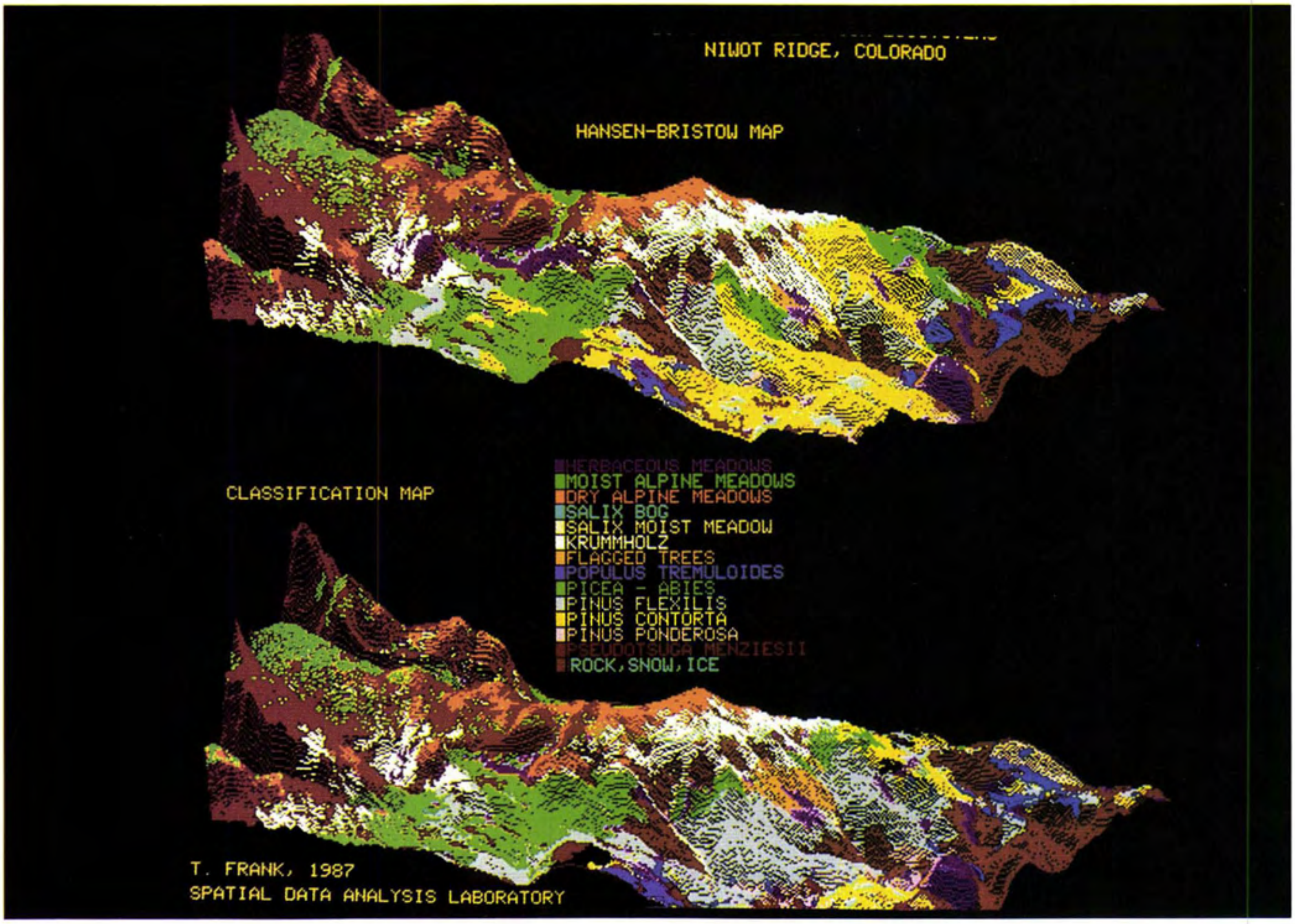

FIG. 2. Dominant vegetation ecosystems in the Niwot Ridge, Colorado study area: (Upper) Derived from traditional mapping techniques. (Lower) Derived from Landsat TM, topographic, and topoclimatic variables.

pared by Hansen-Bristow (1981) was digitized from the 1:24,000-scale sheet, and subsequently converted into raster format with 30- by 30-meter resolution. The area surrounding Niwot Ridge was extracted for the study area enclosed within a rectangle defined by Universal Transverse Mercator coordinates: 447000E to 457000E and 4437000N to 443000N (Figure 2).

Landsat TM Transformations

A Landsat-5 Thematic Mapper digital image acquired on 29 June 1984 was geographically referenced to the study area represented by the map (Graham, 1977). Landsat TM data were acquired for seven spectral bands: TM1 (0.45 to 0.52μm), TM2 (0.52 to 0.60μm), TM3 (0.63 to 0.69μm), TM4 (0.76 to 0.90μm), TM5 (1.55 to 1.75μm), TM6 (10.40 to 12.48μm), and TM7 (2.08 to 2.35μm). TM7 was found to be highly correlated (r = 0.98) with TM5 and, along with the thermal band (TM6), was not used in this study. The TM spectral bands were transformed into five band ratios and normalized difference variables to characterize the spectral patterns of vegetation community cover types:

Vegetation Index Ratio of NIR and RED bands

$$\mathrm{VI1} = \mathrm{TM4/TM3} * (\mathrm{S.D.TM4} + \mathrm{S.D.TM3}) \tag{1}$$

Normalized difference with NIR and RED bands

$$\mathrm{ND1} = ((\mathrm{TM4\text{-}TM3})/(\mathrm{TM4} + \mathrm{TM3}) + 1.) / 2. * \mathrm{K} \tag{2}$$

Vegetation Index Ratio of NIR and MIR bands

$$\mathrm{VI2} = \mathrm{TM4/TM5} * (\mathrm{S.D.TM4} + \mathrm{S.D.TM5}) \tag{3}$$

Normalized difference with NIR and MIR bands

$$\mathrm{ND2} = ((\mathrm{TM4\text{-}TM5})/(\mathrm{TM4} + \mathrm{TM5}) + 1.) / 2. * \mathrm{K} \tag{4}$$

Reflectance/absorptance ratio

$$\mathrm{R/A} = \mathrm{TM4}/(\mathrm{TM3} + \mathrm{TM5}) * (\mathrm{S.D.TM4} + ((\mathrm{SD.TM3} + \mathrm{S.D.TM5})/2.)) \tag{5}$$

where K is constant used to convert to eight-bit integer and S.D. is standard deviation.

Band ratios and transformations were used to reduce differences between illuminated and shadowed slopes, and to enhance the spectral absorption and reflectance differences of vegetation communities.

Topographic Measures Derived from DEM

Topographic effects on vegetation distributions were examined using estimates of elevation, slope, aspect, and relief to characterize vegetation community types in this study area. Digital Elevation Model (DEM) data came directly from the Ward, Colorado DEM prepared by the United States Geological Survey. The DEM contains elevation data in a UTM referenced matrix for 30- by 30-metre elements (Elassal and Caruso, 1983). Slope gradient was calculated from the partial derivatives in the east-west and north-south directions of the study area. Slope was then measured as the magnitude of the elevation gradient:

$$\mathrm{Slope} = \mathrm{SQRT}((\partial f/\partial x)**2 + (\partial f/\partial y)**2) \tag{6}$$

where

$$\partial f/\partial x = (8f(x+h) - 8f(x-h) + f(x-2h) - f(x+2h))/12h$$

$$\partial f/\partial y = (8f(y+h) - 8f(y-h) + f(y-2h) - f(y+2h))/12h$$

in which $\partial f/\partial x$ is the partial derivative in the east-west direction, $\partial f/\partial y$ is the partial derivative in the north-south direction, and h is the grid interval in metres.

Aspect, the direction of slope, was calculated from the two partial derivatives

$$\mathrm{Aspect} = \arctan((\partial f/\partial y)/(\partial f/\partial x)). \tag{7}$$

This method has been shown to approximate the true slopes and aspects in a digital elevation model (Snyder, 1983). Elevation was used to represent the altitudinal gradient of vegetation communities, and aspect was used to approximate differences in exposure to solar radiation. Elevation and aspect have been used widely to characterize vegetation distributions (Cibula and Nyquist, 1987; Frank and Thorn, 1986; Hutchinson, 1982; Strahler *et al.*, 1978, Hoffer *et al.*, 1975).

Local differences in elevation which create convex or concave slopes also characterize moisture gradients in mountain vegetation. Measures such as relief, the absolute difference between the highest elevation in the study area and the elevation at a specific location in the study area, can represent landscape drainage characteristics. In this study, local relief was used to measure variations in elevation from a general trend in the altitudinal gradient. This measure was used to characterize favorable habitats for dry or wet vegetation types. The altitudinal gradient was approximated by a polynomial function derived from the digital elevation model. Predicted elevation was a function of x, y map coordinates using a third-order polynomial. Then local relief was the difference between actual elevation and predicted elevation:

$$\mathrm{Relief} = \mathrm{Elevation} - (a_0 - a_1X + a_2Y + a_3X^2 + a_4XY + a_5Y^2) \tag{8}$$

where X and Y are DEM Cartesian coordinates and Elevation is from the DEM.

This method accounts for any general tendency in altitudinal gradient in both the east-west and north-south directions simultaneously. Consequently, the local relief is calculated for a particular study site so that the measure is sensitive to local differences that may be associated with vegetation habitats.

Topoclimatic Index Derived from DEM

A topoclimatic index was created from the digital elevation model to distinguish between favorable habitats for windblown, xeric communities and snow-covered, mesic communities. Slope-aspect index (SAI) was used in this study to characterize prevailing wind effects on soil moisture and subsequent vegetation distributions:

$$\mathrm{SAI} = \sin(\mathrm{slope}) * \mathrm{aspect} / \mathrm{max.SAI} * K \tag{9}$$

where max.SAI is maximum index value and K is constant to convert to eight bit value.

Topoclimatic conditions were defined by relationships between wind patterns and aspect and slope effects on snow accumulation for three topographic conditions:

northwest facing slopes: 270 < aspect < 360

$$\mathrm{SAI} = (90. - (360. - \mathrm{aspect})) * \sin(\mathrm{slope}) / \mathrm{max.SAI} * K$$

northeast facing slopes: 0 < aspect < 90

$$\mathrm{SAI} = (180. - (90. - \mathrm{aspect})) * \sin(\mathrm{slope}) / \mathrm{max.SAI} * K$$

south facing slopes: 90 < aspect < 270

$$\mathrm{SAI} = (270. - \mathrm{aspect}) * \sin(\mathrm{slope}) / \mathrm{max.SAI} * K$$

High values of SAI indicated areas that are generally leeward, steep slopes that usually accumulate deep, long-lasting snow banks. Low SAI values indicated areas that are windblown, snowfree, and generally highly dessicated. SAI was shown previously to be a good discriminator of alpine vegetation types on Niwot Ridge even when the types did not exhibit spectral reflectance/absorptance differences (Frank and Isard, 1986). SAI was adapted for use in this study to discriminate among communities in the forest-alpine tundra ecotone and the forest communities.

Determination of Classification Variables

Samples from the dominant vegetation communities were stratified by structural/plant zone grouping with reference to the Hansen-Bristow (1981) map. Spectral, topographic, and topoclimatic characteristics of the communities were characterized by VI1, ND1, VI2, ND2, R/A, elevation, slope, aspect, relief, and SAI. The ability of the spectral, topographic, and topoclimatic variables to discriminate among the dominant vegetation communities was examined using the statistical procedure discriminant analysis. Based on the collection of variables, the problem was to distinguish among the vegetation communities, and to identify the variables that were important for distinguishing among the groups.

Linear combinations of the predictor variables were formed from the analysis, which served to post-predict the sample memberships, and to subsequently serve as the basis for classifying new observations. Each predictor variable had a unique coefficient for each dominant vegetation community so that the original value of each variable, multiplied by the coefficient and summed over the predictor variables, provided a discriminant score for an observation for each dominant community. Then using the discriminant scores, each observation was assigned to the dominant community using the posterior probability: the probability that an observation with a discriminant score of D belonged to dominant vegetation community group G was estimated by the conditional probability, and the observation was assigned to the group which produced the largest conditional probability.

The best predictor variables were found by calculating a discriminant function value for each observation, then calculating the correlation between each predictor variable and the discriminant function values. ND1, VI2, R/A, elevation, aspect, relief, and SAI were the best predictors of vegetation communities. ND2, VI1, and slope were highly correlated with at least one other variable, and were not necessary for classification. Both topographic and topoclimatic variables were necessary, in combination with the Landsat spectral variables, to distinguish among the dominant communities because no single variable exhibited sufficient difference among all communites.

CLASSIFICATION RESULTS

The study area was stratified into three structural groups for classification. First, alpine meadow observations were assigned to one of the six dominant alpine meadow vegetation community classes using the set of predictor variables. The classification was repeated for subalpine and montane forests. Therefore, three separate classification maps were derived independently, eliminating classification error between groups. The three maps were overlayed to produce a composite map (Figure 2). Prior to comparing the classification map to the Hansen-Bristow (1981) map, the classification map was filtered to eliminate small classification errors. This step was necessary because Landsat derived-maps exhibit spatial variability not usually evident on manually-derived maps. The degree to which this is a problem depends on (1) the level of detail expressed on the map, and subsequent pattern sizes selected for display at various scales of published maps; and (2) the spatial diversity identified within the image, controlled primarily by the resolution of the data in the image.

A neighborhood filter was applied to the classification map, thereby removing some spatial diversity from the classification (Guptill, 1978). Let K, a vegetation community state, and J, a neighbor vegetation community state, be events in a sample space made up of a finite number of elementary events. Then the conditional probability of K occurring on the classification map given that neighbor J occurs, denoted by $p(K|J)$, was

$$p(K|J) = p(K\Omega J) / p(J) \quad (10)$$

where $p(K\Omega J)$ is the joint probability of center state K and neighbor J, and $p(J)$ is the probability of neighbor J.

Then for an N by N neighborhood, the conditional probability of vegetation community K occurring given each of the surrounding eight neighbors, was

$$p(K_c|N) = \prod_{i=1}^{J} p(K_c|N_j) \quad (11)$$

Assessing Agreement between Classification and Map

Evaluation of the classification was conducted by comparing the predicted dominant vegetation community classification against the Hansen-Bristow (1981) map. Site-specific comparisons were made by calculating the frequency of coincident classes, point by point, on the map and the classification, and reporting coincident frequencies in an error matrix (Table 2). The row sums on the right edge of the error matrix give the total number of observations for each community from the map, and column totals along the bottom of the error matrix give the total number of observations for each community from the classification. Elements along the diagonal of the error matrix indicate the frequency of agreement between the classification and the map. For each vegetation community, percent correct, percent commission, and percent ommission errors were calculated from the error matrix. These are widely used measures for assessing classifications against maps (Campbell, 1987). Overall percent agreement was averaged from the individual percent correct measures.

$$\text{Percent correct} = \frac{\text{Diagonal element from classification}}{\text{Row sum for map community}} \quad (12)$$

$$\text{Percent commission error} = \frac{\text{Column sum} - \text{Diagonal}}{\text{Column sum}} \quad (13)$$

$$\text{Percent ommission error} = \frac{\text{Row sum} - \text{Diagonal}}{\text{Row sum}} \quad (14)$$

$$\text{Overall agreement} = \frac{\text{Total of Diagonal Elements}}{\text{Total Number of Observations}} \quad (15)$$

A better measure of overall agreement between the map and the classification was the Kappa statistic (Congalton and Mead, 1983; Bishop *et al.*, 1975; Cohen, 1960). Kappa adjusts the overall percent correct measure by subtracting the estimated contribution of chance agreement. Kappa, the maximum likelihood estimate from the multinomial distribution and a measure of the actual agreement of two maps minus the chance agreement, is (Congalton and Mead, 1983)

$$K = \frac{\sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r} (X_{i+} * X_{+i})}{N^2 - \sum_{i=1}^{r} (X_{i+} * X_{+i})} \quad (16)$$

where r = number of rows and columns in error matrix,
X_{ii} = number of observations in row i and column i,
X_{i+} = marginal total of row i,
X_{+i} = marginal total of column i, and
N = total number of observations.

Not all vegetation community classes could be identified with certainty, so classes were aggregated together within structural groups, but not between structural groups. The aggregation

TABLE 2. COINCIDENT FREQUENCY MATRIX AND ACCURACY ASSESSMENT FOR DOMINANT VEGETATION COMMUNITIES FROM HANSEN-BRISTOW (1981) MAP AND CLASSIFICATION RESULTS

	CLASSIFICATION RESULTS								
	Dominant Meadow Communities								
HANSEN-BRISTOW MAP	1	2	3				%CORR	%COMM	%OMM
1. Herbaceous meadows	2279	93	327				84.44	7.77	15.56
2. Moist alpine meadows	74	1628	753				66.31	20.16	33.69
3. Dry alpine meadows	118	318	2849				86.73	27.49	13.27
Kappa 0.6954 % Overall agreement 80.06									
	Dominant Subalpine Communities								
	4	5	6	7	8	9	%CORR	%COMM	%OMM
4. *Salix* bog	109	0	1	0	0	0	99.09	30.13	0.91
5. *Salix* meadow	0	335	3	2	0	0	98.53	32.87	1.47
6. Krummholz	47	164	4410	430	0	0	87.31	0.09	12.69
7. Flagged trees	0	0	0	177	0	0	100.00	70.94	0.00
8. *Picea-Abies*	0	0	0	0	10448	3171	76.72	15.21	23.28
9. *Pinus flexilis*	0	0	0	0	1874	2880	60.58	52.40	39.42
Kappa 0.6190 % Overall agreement 76.33									
	Dominant Montane Communities								
	10	11	12	13			%CORR	%COMM	%OMM
10. *Populus tremuloides*	1328	135	57	268			61.34	37.15	38.66
11. *Pinus contorta*	646	1986	656	1185			18.44	35.73	81.56
12. *Pinus ponderosa*	11	5	293	38			77.51	74.76	22.49
13. *Pseudotsuga menziessi*	3	3	51	259			75.95	86.74	24.05
Kappa 0.3762 % Overall agreement 55.83									

resulted in three alpine meadow classes, four subalpine classes, and seven montane classes (Table 2). The areal proportions of dominant vegetation communities were then calculated for the aggregated classes from both the map and the classification (Table 3).

DISCUSSION OF RESULTS

The results of this study suggest that Landsat Thematic Mapper data, in combination with topographic and topoclimatic indexes, can be used to map dominant vegetation communities in the Colorado Rocky Mountain Front Range. Alpine, subalpine, and montane communities were identifiable when compared to a manually derived vegetation map.

Herbaceous meadows (84.44 percent), moist alpine meadows (66.31 percent), and dry alpine meadows (86.73 percent) compared favorably with the map, and errors of commission and ommission were not a significant problem. However, fellfield communities were not distinguishable from dry alpine meadows because spectral and topographic differences were not sufficiently different at the resolution of the database. Wet alpine meadows were not distinguishable from wet herbaceous meadows because the spectral characteristics of wet communities were similar even though elevation differences existed between the communities.

Six subalpine communities could be mapped accurately; however, flagged-trees and *Pinus flexilis* had high errors of commission. Flagged-trees were predominantly a structural difference among *Picea*, *Abies*, and *Pinus* communities; therefore, high errors of commission were not unexpected. *Pinus flexilis* did not occur frequently in the study area, and spectral differences were

TABLE 3. AREAL COVERAGE ESTIMATES OF DOMINANT COMMUNITIES FROM MAP (HANSEN-BRISTOW, 1981) AND RESULTS OF CLASSIFICATION

	Map		Classification	
	Ha	%	Ha	%
MEADOW COMMUNITIES				
1. Herbaceous meadows	242.91	5.50	222.39	5.10
2. Moist alpine meadows	220.95	5.00	183.51	4.21
3. Dry alpine meadows	295.65	6.69	353.61	8.11
SUBALPINE COMMUNITIES				
4. *Salix* bog	9.90	0.22	14.04	0.32
5. *Salix* moist meadow	32.85	0.74	44.91	1.03
6. Krummholz	457.20	10.34	397.26	9.11
7. Flagged trees	15.93	0.36	54.81	1.26
8. *Picea - Abies*	1241.19	62.04	947.43	47.35
9. *Pinus flexilis*	277.65	13.88	358.65	17.93
MONTANE COMMUNITIES				
10. *Populus tremuloides*	12.68	6.08	120.69	6.03
11. *Pinus contorta*	325.17	16.25	357.39	17.86
12. *Pinus ponderosa*	6.03	0.30	86.94	4.35
13. *Pseudotsuga menziesii*	28.98	1.45	129.60	6.48
Kappa 0.6828 % Overall agreement 73.56				

not apparent between this community and *Picea engelmannii* and *Abies lasiocarpa*.

Four montane forest communities were difficult to map. A deciduous-coniferous distinction was obvious, yet each community had unique problems. *Populus tremuloides* was not confused often with other forest communities, but then it was only correctly identified 61.34 percent of the time. *Pinus contorta* was identified poorly (18.44 percent correct) due to high errors of ommission (81.56 percent). *Pinus ponderosa* was the most distinguishable forest community (77.51 percent correct), but this community had a high error of commission (74.76 percent). *Pseduotsuga menziesii* also had a high correct classification (75.95 percent) and a high error of commission (86.74 percent).

Areal comparisons between communities estimated from the classification and the map (Table 3) indicated that alpine meadow communities compare favorably overall; subalpine communities compare favorably with the exception of *Picea-Abies* and *Pinus flexilis*; and montane forest communities do not compare favorably, even though *Populus tremuloides* and *Pinus contorta* appear to have approximately similar distributions. The two distributons do not coincide spatially (Table 2).

The results of this study suggest that Landsat TM, in combination with topograpic and topoclimatic indexes, may be useful to map some dominant vegetation communities in the Colorado Rocky Mountain Front Range. Alpine meadow and subalpine communities were identified more accurately than expected using the spatial resolution of Landsat TM and USGS digital elevation data. Results for meadow and subalpine communities suggest that the models used in this study should be useful for mapping other alpine and subalpine communities in the Front Range. The results for forest communities suggest that topographic effects on forest community distributions and the influence of topography on forest reflectance in mountain environments must be assessed further (Leprieur *et al.*, 1988).

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