Alpine Vegetation Classification Using High Resolution Aerial Imagery and Topoclimatic Index Values

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ABSTRACT: Topoclimatic index values, representing the primary direct determinants of vegetation distribution in the mid-latitude alpine tundra, are combined with film density data from a color infrared aerial photograph to numerically derive a vegetation map of the Saddle area on Niwot Ridge, Colorado. Film density is used to distinguish between moist or wet vegetation that receives a continuous supply of meltwater and dry vegetation types that rely on precipitation water input. Topoclimatic index values represent (1) the effect of slope-aspect in relation to prevailing wind direction on snow accumulation and (2) the effect of isolation on evapotranspiration and, consequently, soil moisture status. The vegetation classification reveals that combining topoclimatic and film density data produces an alpine map of high categorical accuracy.

INTRODUCTION

MAPS THAT REPRESENT spatial aggregations of vegetation cover are important tools for studying alpine environments. Order of magnitude differences in surficial geomorphic process rates are found when data are stratified by vegetation type. For example, rates of soil delivery to sediment traps (Bovis and Thorn, 1981), pedogenesis (Burns and Tonkin, 1982), and soil disturbance (Thorn, 1978; 1982) exhibit differences among alpine vegetation units. Traditionally, vegetation has been mapped in mid-latitude alpine tundra by scientists who simultaneously evaluate the biotic, edaphic, and topographic characteristics of the landscape. Although vegetation exhibits infinite variability, alpine vegetation is delineated into homogeneous mapping units based upon (1) relationships among plant species and (2) 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)). Ideally, mapping decisions are made in accordance with pre-specified criteria. Knowledge of the study area and personal experience often affect the interpreter's perception of the relationship between vegetation pattern and the landscape. Vegetation maps compiled from field data generally provide detailed descriptions of plant communities (e.g., May (1973) and Komarkova and Webber (1978), but alpine field surveys require extensive observations for even small areas since vegetation gradients are steep in rugged terrain (e.g., Komárková (1976)).

Aerial photographs have been employed to directly map alpine vegetation (Becking, 1959; Keammerer, 1976) and to supplement field mapping (Komárková and Webber, 1978). Large areas of alpine tundra have been mapped successfully with aerial photographs (e.g., Keammerer (1976)); however, the resulting maps only depict general vegetation patterns. Tonal and color variations on aerial photographs are related to vegetation density, morphology, and physiological condition (e.g., Curran (1980)), but correspond poorly with vegetation type in low herbaceous environments such as the alpine tundra. Accurate measurement of topographic setting is necessary to distinguish between many alpine vegetation types because local topograhic site factors influence plant distribution. Therefore, visual interpretation of aerial imagery alone often does not provide sufficient categorical detail for scientists studying alpine environments.

Topographic data have been incorporated into airphoto analysis using elevation, ground slope, and aspect measured from stereoscopic aerial images (e.g., Avery (1985)). Frank and Thorn (1985) have shown that the relationship between topographic setting and the spatial distribution of vegetation types can be quantified with conditional probabilities ("topographic context distribution model"). Climatic data in the form of isolation estimates have also been combined with spectral reflectance measurements to distinguish among surface features (e.g., Tom and Miller (1984)). However, inclusion

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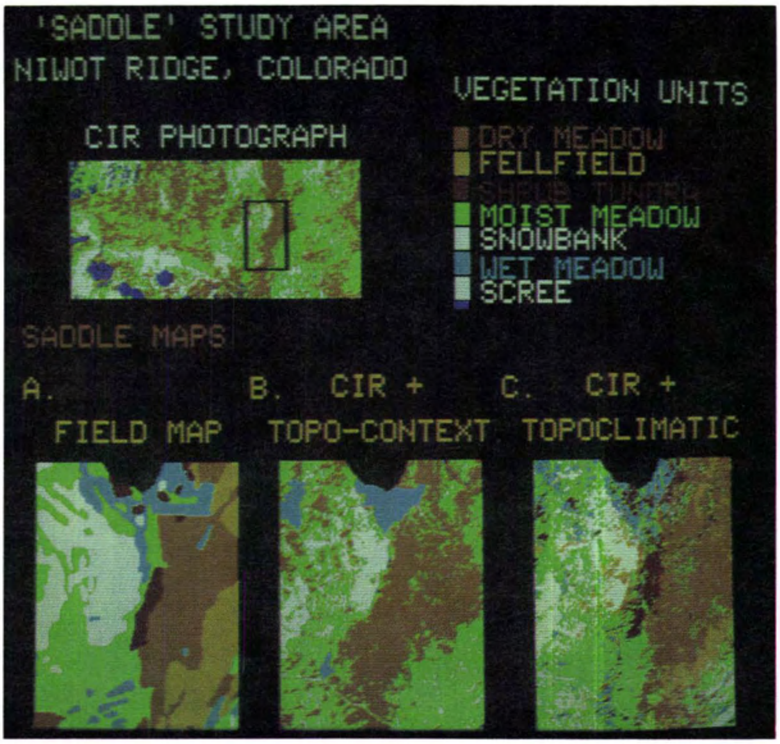

PLATE 1. Vegetation maps of Saddle area and Niwot Ridge in the Indian Peaks section of the Colorado Front Range. The CIR photograph (upper left) shows lakes (dark blue), dry-sparse vegetation (orange), moist-more dense vegetation (green), and snowbanks-scree (white). Insert below displays vegetation units in the Saddle area (see legend). The detailed field map (a) was digitized from May and Webber (1982). The CIR + topo-context numerically derived map (b) is from Frank and Thorn (1985) and the CIR + topoclimatic map (c) was developed in this study.

of the effects of topographic setting in vegetation classification by numerical analysis of aerial imagery is complex (e.g., Hutchinson (1982)), especially in the alpine tundra where slope-aspect and ambient atmospheric conditions interact to influence the distribution of vegetation types. To date, a numerical technique that combines the interaction of topograhy and climate with aerial photography in order to classify alpine vegetation has not been developed.

In this paper, we present a procedure to map alpine vegetation using a color infrared (CIR) aerial photograph and knowledge of topoclimatic conditions. The technique is similar to the "logical channel" approach for combining spectral and ancillary data (Strahler *et al.*, 1978). Film density measurements from a digitized color infrared aerial photograph and topoclimatic index values calculated from an elevation matrix are used to characterize site conditions of alpine vegetation types. The topoclimatic index values characterize the interaction among several important climatic and topographic factors, specifically, prevailing wind direction, insolation, ground slope, and aspect. Evaluation of the vegetation classification reveals that the combination of topoclimatic index values and film density data produces an alpine vegetation map of high categorical similarity to field maps (Plate 1).

FACTORS INFLUENCING VEGETATION TYPE DISTRIBUTION IN THE STUDY AREA

The Saddle area on Niwot Ridge in the Indian Peaks section of the Colorado Front Range is an intensive study site for the University of Colorado Long-Term Ecological Research (LTER) program. Six vegetation types defined by principal habitat and physiognomy (noda) have been identified in the Saddle (May, 1973). Names and characteristic species for the noda are listed in Table 1. A second mapping system, utilizing the Braun-Blanquet classification method, emphasizes the importance of floristic-sociological principles to define a hierarchical relationship among plant species (Komárková, 1976). A cursory comparison of noda and Braun-Blanquet units (Webber and May, 1977; Komárková

TABLE 1. NODUM, CHARACTERISTIC SPECIES AND CORRELATION WITH BRAUN-BLANQUET MAPPING UNITS[a]

Nodum (Braun-Blanquet mapping units)[b]	Topoclimatic setting and Characteristic species
Dry meadow (1 and 6)	Occupies positions on windward west facing exposures where snow accumulation is light. *Kobresia myosuroides*, the dominant species, forms dense grass turf which blocks wind and traps snow within the clumps. Winter snow cover is continuous and the growing season is typically bound by snowmelt in mid-June to early July and freezing air temperatures during mid-September. *Selaginella densa, Acomastylis rossii, Tortula ruralis, Dactylina madreporiformis*
Dry fellfield (2–5 and 7)	Established on wind-swept ridge crests and west facing slopes. Relatively snow-free throughout winter with the growing season generally limited to between early June and mid-September. *Trifolium dasyphyllum, Silene acaulis, Carex rupestris, Polytrichum piliferum, Alectoria minuscula*
Moist shrub tundra (20)	Inhabits depressions which provide *Salix planifolia*, the characteristic species, with protection from strong winds and where the water table is close to the surface. Winter snow cover is moderate and the growing season length is slightly shorter than in the dry meadow. *Lophozia hatcheri, Peltigera aphthosa*
Moist meadow (8–13)	Found on leeward east facing slopes that receive moderate to heavy snow cover. Meltwater is plentiful during the early growing season which usually lasts from the end of June to mid-September. *Acomastylis rossii, Deschampsia caespitosa, Desmatodon latifolia*
Snowbed (14–17)	Located on steep leeward east facing slopes among stone stripes and scree. Deep long-lasting snow results in a very short growing season (typically late July to mid-September). Soil moisture is abundant after snowmelt but decreases rapidly in the sandy soil once the supply of meltwater from upslope ceases. *Sibbaldia procumbens, Carex pyrenaica, Anthelia juratzkana, Toninia cumulata*
Wet meadow (18 and 19)	Situated where drainage is impeded by terraces and winter snow cover is continuous. Snow depth and length of growing season are highly variable. *Caltha leptosepala, Carex scopulorum, Aulacomnium palustre*

[a] Adapted from Komárková and Webber (1978), May and Webber (1982), and May (personal communication, 1984).

[b] Braun-Blanquet mapping units; 1 is Association *Caricetum elynoidis*, 2 is Alliance *Kobresio-Caricion rupestris*, 3 is Association *Trifolietum dasyphyllum*, 4 is Association *Sileno-Paronychietum*, 5 is Association *Eritricho-Dryadetum octopetalae*, 6 is Association *Selaginello-Kobresietum myosuroidis*, 7 is Alliance *Kobresio-Caricion rupestris* and Association *Eritricho-Dryadetum octopetalae*, 8 is Alliance *Deschampsio-Trifolion parryi*, 9 is Association *Acomastylidetum rossii*, 10 is Association *Deschampsio-Trifolietum parryi*, 11 is Association *Stellario-Deschampsietum caespitosae*, 12 is Association *Vaccinietum scoparium-cespitosum*, 13 is Association *Solidagini-Danthonietum intermediae*, 14 is Order *Sibbaldio-Caricetalia pyrenaicae*, 15 is Association *Toninio-Sibbaldietum*, 16 is Association *Caricetum pyrenaicae*, 17 is Association *Juncetum drummondii*, 18 is Order *Pediculari-Caricetalia scopulorum*, 19 is Association *Caricetum-scopulorum*, and 20 is Alliance *Salicion planifolio-villosae*.

and Webber, 1978; May, personal communication, 1984) is presented in Table 1. Extensive biotic and abiotic information for these mapping units is found in May (1973), Komárková (1976), May (1976), Webber and May (1977), Komárková and Webber (1978), May and Webber (1982), and Webber *et al.* (1984).

Relationships among relief, wind, insolation, snow cover, soil moisture, and alpine tundra vegetation on Niwot Ridge have been repeatedly presented (see May and Webber (1982) and Isard (1984)) and provide the foundation for the vegetation mapping procedure. Snow cover and soil moisture are the primary direct determinants of the distribution of vegetation types in the Saddle area on Niwot Ridge (May, 1973; May and Webber, 1982). Strong winds, associated with the westerly cyclone belt, redistribute snow, creating long-lasting snowbanks on leeward slopes, while leaving adjacent windward slopes snow-free (Osburn, 1958; Marr, 1961; Benedict, 1970). Snowbanks affect vegetation in a complex manner: they protect plants from winter temperatures and desiccation, but shorten the growing season (Billings and Bliss, 1959; Marr, 1961). Meltwater from late-lying snowfields is a primary source of moisture to areas directly downslope in the alpine tundra (Billings and Bliss, 1959; Holway and Ward, 1963). The distribution of soil moisture is also sensitive to topoclimatic variations because insolation and wind influence both snowmelt and evapotranspiration (Sellers, 1965; Gates and Janke, 1965). Solar radiation is the primary atmospheric control over soil moisture status between precipitation events in vegetation not receiving meltwater and appears to influence vegetation distribution on Niwot Ridge (Isard, 1984).

Film density data distinguish between mesic and xeric vegetation types, i.e., plants that receive a continuous supply of meltwater from late-lying snowbanks in addition to summer precipitation and those that rely only on precipitation for water input during the growing season. Topoclimatic index values represent additional factors governing the distribution of alpine vegetation types: (1) the effect of slope-aspect in relation to prevailing wind direction on snow accumulation and (2) the effect of insolation on evapotranspiration and soil moisture status.

METHODS

FILM DENSITY MEASUREMENTS FROM A DIGITIZED PHOTOGRAPH

A vegetation map was created for the Saddle area on Niwot Ridge from film density and topoclimatic index values. Film density was measured by optically scanning (digitizing) three emulsion layers of a color infrared aerial photograph (1:113,950 scale, positive transparency) on an Optronics P-1700 microdensitometer. The CIR photograph was taken August 1973. Film density values were calculated for each emulsion layer at 100-μm sampling intervals (called pixels) from

$$D_p = \log_{10}(O_p) = \log_{10}(1/T_p) \quad (1)$$

where D_p, O_p, and T_p are film density, opacity, and transmittance at a pixel. Transmittance is the ratio of light passing through the film to the total light incident on the film. Film density has been inverted from a range of 0 to 3 into a range of 0 to 255 (8-bit digital numbers) where high digital numbers indicate high relative reflectance from the ground and low digital numbers indicate low relative reflectance from the ground (Lillesand and Kiefer, 1979).

Jensen *et al.* (1978) indicate that digitized aerial photographs often exhibit exposure variability through the image as a result of vignetting and directional reflectance within the camera's large field of view. These sources of exposure variation are considered minor in this study because Niwot Ridge is encompassed within a small area on the photograph near its principal point.

RELATIONSHIP BETWEEN FILM DENSITY MEASUREMENTS AND VEGETATION

Film density (relative reflectance) is related to vegetation density, morphological characteristics, and physiological condition of vegetation. Tucker (1979) has shown that green, healthy vegetation on a uniform soil generally exhibits high reflectance in the near-infrared wavelength interval (0.69 to 0.90 μm) and relatively low reflectance in the red wavelengths (0.63 to 0.69 μm). Individual vegetation types can be identified with film density data alone if they exhibit sufficiently unique reflectance characteristics and if reflectance contrasts are manifested in the film density. In low herbaceous vegetation cover, reflectance and consequently film density is generally related to vegetation density and the soil background reflectance (e.g., Robinove *et al.* (1981) and Frank (1985)). Film density is also affected by floristic composition, topography, solar illumination angle, atmospheric composition, and camera angle. Film density from the photograph used in this study appears to be primarily associated with vegetation density and soil moisture. Classification using the CIR photograph (Plate 1) results in the delineation of two vegetation units: dry, sparse vegetation and moist, more dense vegetation. Therefore, additional observations of topographic setting and microclimate are necessary to discriminate between alpine vegetation types.

TOPOCLIMATIC INDEX VALUES

A digital elevation matrix was created for the Saddle area by interpolating the elevation for a uniform grid from digitized contours on a topographic map (1:24,000 scale). Slope and aspect were calculated from the elevation matrix using the method of Snyder (1983). SA, an index of slope-aspect relative to the prevailing westerly wind direction, was computed for each pixel in the study area from

$$SA = \beta\,\theta \quad (2)$$

where β is ground slope (degrees) and θ is the difference in degrees between the aspect of ground slope and due east. Consequently, high *SA* values are associated with wind-blown, snow-free west facing slopes within the Saddle area, while sites that experience heavy winter snow accumulation (level and east facing slopes) are represented by low *SA* values.

Daily insolation for a typical summer day was calculated to represent the climate controls over soil moisture status between water inputs in the alpine tundra. Instantaneous global insolation ($K\downarrow$ in ly/min; direct beam plus diffuse sky radiation) was computed for each pixel in the terrain model from

$$K\downarrow = \tau_K S_o\,[(1-\kappa)\cos z \cos z_o^{-1} + \kappa \cos^2(0.5\beta)] \quad (3)$$

where global transmission (τ_K) is defined as (Liu and Jordan, 1960)

$$\tau_k = K\downarrow_o S_o^{-1} \quad (4)$$

$K\downarrow_o$ is global insolation (ly/min) to an unobstructed horizontal plane at the surface of the Earth, and S_o is extraterrestrial solar flux density (ly/min) corrected for incidence angle. κ is the ratio between diffuse sky radiation to an unobstructed horizontal plane at the Earth's surface and $K\downarrow_o$ (Orgill and Hollands, 1977; Erbs *et al.*, 1982), and z and z_o are angles of direct beam incidence (measured from the local zenith) to sloping and horizontal surfaces, respectively. Global transmission and $\kappa = f(\tau_K)$ are given for Niwot Ridge by Olyphant (1984; Figures 2 and 3). On average summer days the proportion of insolation reaching the surface decreases drastically in the afternoon due to intense convective activity which enhances cumulus cloud development. As a result, the daily insolation load (instantaneous values integrated from sunrise to sunset) is typically greatest at east and south facing sites during the growing season (Isard, 1984).

VEGETATION CLASSIFICATION

Film density, the *SA* index, and insolation were spatially registered in an image stack (assemblage of spatially registered images). Training samples for the permanent LTER research plots for each vegetation type (see May and Webber (1982)) were extracted from the image stack to derive quantitative signatures. Signatures were characterized by average film density, insolation, *SA* index, and estimates of variance and covariance among the variables. Classification over the image stack for the Saddle area was conducted by assigning each pixel to the vegetation type associated with the signature that maximized its discriminant function score (e.g., Swain (1978)).

A combination of two independently compiled field vegetation surveys of Niwot Ridge (May, 1973; Komárková and Webber, 1978) was used to evaluate the categorical accuracy of our vegetation map (Plate 1). Mapping units representing vegetation types were compiled from the May and Webber (1982) detailed noda map of the Saddle area and correlated to the Komárková and Webber (1978) map of Niwot Ridge by aggregating lower level Braun-Blanquet mapping units using the cross-reference list in Table 1. The vegetation types were delineated with a Cartesian coordinate digitizer and subsequently encoded into image stack format to overlay the aerial photograph and topoclimatic layers of Niwot Ridge.

RESULTS

Comparison of the vegetation map derived in this study with the detailed field map for the Saddle area on Niwot Ridge (May and Webber, 1982) reveals that combining topoclimatic information with film density data produces an alpine vegetation map of high categorical fidelity to results of previous studies (Plate 1). It should be noted that snowbed and scree cover categories were combined in the analysis because snow blanketed portions of both categories when the aerial photograph was taken. The insolation variable did not improve the distinction among mapping units and subsequently was excluded from the analysis. Although insolation directly affects plants by providing light and influencing leaf temperature, its impact on soil moisture relations (through evapotranspiration and snowmelt), and consequently the distribution of vegetation types in the alpine tundra, is indirect. Perhaps for this reason insolation did not help discriminate between alpine vegetation types. Average film density and *SA* index values for the six vegetation types are presented in Table 2.

Areal size of the mapping units was calculated for (a) the detailed field survey (May and Webber, 1982), (b) the CIR + topo-context vegetation classification (Frank and Thorn, 1985), and (c) the CIR + topoclimatic map (Table 3). Categorical accuracy is higher for all mapping units in the Saddle with the CIR + topoclimatic site factors than with the CIR + topo-context analysis. Demarcation of dry meadow from fellfield and moist shrub tundra from moist meadow is greatly improved through the incorporation of topoclimatic data. Absolute difference in percentage cover between the field and CIR + topoclimatic maps for the six categories range from a minimum of 1.4 percent for dry meadow to 7.2 percent for moist meadow.

Comparison of vegetation types from the map produced by the CIR + topoclimatic index values with the vegetation types from the field map in the Saddle provides an estimate of the categorical accuracy of our map (Table 4). For example, 61.3 percent of dry meadow pixels (CIR + topoclimatic map) are classified dry meadow by May and Webber (1982), while 24.5 percent of the dry meadow pixels are designated fellfield vegetation on the field map. The snowbed was excluded from the analysis because it could not be distinguished from scree, due to snow cover. The principal diagonal of the matrix represents the percentage of pixels classified correctly. Moist shrub tundra is frequently classified as moist meadow (32.2 percent) or wet meadow (21.5 percent), and wet meadow is primarily confused with moist meadow (36.9 percent). Although these percentages are large, moist shrub tundra and wet meadow vegetation types represent only 3.3 percent and 9.9 percent of the Saddle area, respectively (Table 3). The relative poor ability to distinguish between dry meadow and fellfield is the greatest inadequacy of the CIR + topoclimatic mapping procedure.

DISCUSSION OF RESULTS

The vegetation classification for the Saddle area using CIR and topoclimatic site factors not only results in improved categorical accuracy, but this procedure is more efficient to imlement than the numerical analysis of Frank and Thorn (1985). In that study, an elaborate method was used to distinguish between mesic and xeric vegetation types with density measurements from a color infrared photograph; and between moist and wet vegetation types using conditional probabilities to relate elevation, ground slope, and aspect with vegetation type. The procedure was useful for mapping alpine vegetation

TABLE 2. AVERAGE DIGITAL NUMBERS AND SA INDEX VALUES FOR SIX VEGETATION MAPPING UNITS IN THE SADDLE AREA ON NIWOT RIDGE

Mapping unit	Training sample size	Digital numbers from CIR image[a]			
		Green	Red	Near-infrared	*SA* index[b]
Dry meadow	272	118.11	84.37	145.39	116.96
		(9.49)	(19.32)	(13.31)	(28.98)
Fellfield	184	125.12	129.91	174.36	189.20
		(11.45)	(15.13)	(8.82)	(14.95)
Moist shrub tundra	71	186.15	37.66	113.90	138.23
		(5.10)	(7.71)	(7.72)	(71.22)
Moist meadow	177	172.77	63.45	131.93	198.85
		(8.92)	(13.53)	(10.41)	(7.74)
Snowbed	83	202.86	209.01	211.39	212.70
		(14.91)	(15.65)	(6.34)	(3.96)
Wet meadow	22	190.59	72.59	141.50	159.09
		(4.60)	(14.71)	(10.81)	(52.54)

[a] Numbers in parentheses represent standard error.
[b] *SA* index has been compressed into a range of 0–255.

TABLE 3. MAPPING UNIT AREA CALCULATED FROM THE MAY AND WEBBER SADDLE FIELD SURVEY, CIR + TOPO-CONTEXT AND CIR + TOPOCLIMATIC MAPS[a]

Mapping unit	a. May and Webber field survey			b. CIR + topo-context			c. CIR + topoclimate		
	pixels	ha[b]	%	pixels	ha[b]	%	pixels	ha[b]	%
Dry meadow	5923	14.8	24.1	9010	22.5	36.6	6294	15.7	25.6
Fellfield	3547	8.9	14.4	0	0	0	2000	5.0	8.1
Moist shrub tundra	804	2.0	3.3	0	0	0	1598	4.0	6.5
Moist meadow	7140	17.9	29.1	11494	28.7	46.8	8914	22.3	36.3
Snowbed, snow and scree	4744	11.9	19.3	2907	7.3	11.8	4297	10.7	17.5
Wet meadow	2422	6.1	9.9	1143	2.9	4.7	1473	3.7	6.0

[a] CIR + topo-context map from Frank and Thorn (1985); Saddle field map from May and Webber (1982); letters refer to Plate 1.
[b] ha is hectare.

TABLE 4. CONFUSION MATRIX FOR MAY AND WEBBER FIELD AND CIR + TOPOCLIMATIC SITE FACTOR MAPS[a]

CIR-topoclimatic site factor map	May and Webber field map				
	Dry meadow	Fellfield	Moist shrub tundra	Moist meadow	Wet meadow
Dry meadow	61.3	24.5	1.3	6.0	7.0
Fellfield	19.2	64.2	0.6	6.9	9.2
Moist shrub tundra	15.6	1.4	29.5	32.2	21.5
Moist meadow	17.3	9.5	3.0	58.7	11.5
Wet meadow	6.2	4.4	7.3	45.1	36.9

[a] Numbers represent percentage of pixels for each vegetation type classified by the CIR + topoclimatic procedure that correspond to each field mapping unit of May and Webber (1982).

on Niwot Ridge, but the technique may be too cumbersome to be practical for mapping larger areas of alpine tundra. In contrast, the topoclimatic index values used in this study were computed directly from the elevation matrix.

Our method demonstrates that a conceptual model of environmental controls on vegetation distribution can be used to characterize alpine vegetation mapping units. Although field based maps are considered more accurate than maps generated from aerial photographs and topoclimatic site factors, the latter may provide sufficient categorical detail for many physical process studies in alpine environments. The map presented in this paper is not yet adequate to support plant ecology and botanical studies in the alpine tundra; however, the improvement in vegetation mapping indicates that continued research is warranted.

The greatest inaccuracy of the method developed in this study is its relatively poor ability to distinguish between dry meadow and fellfield vegetation types. We expect that greater accuracy can be achieved by using (1) larger scale imagery and (2) a temporal series of color infrared aerial photographs. In addition to the aerial photograph taken during the growing season, an image collected in winter should reveal snow cover contrasts between dry meadow and fellfield vegetation, and consequently increase categorical accuracy. Dry tundra vegetation requires snowcover to protect against winter desiccation, while fellfield vegetation can only compete successfully with other vegetation types in windblown locations that experience discontinuous winter snow cover (Marr, 1961). Color differences between the two vegetation types may also be apparent on aerial imagery during September when the dry meadow turns golden brown.

SUMMARY

Three alpine vegetation maps have been compared in this study: (1) vegetation mapping units compiled in the field (May and Webber, 1982), (2) vegetation mapping units characterized with a digitized color infrared aerial photograph and a "topographic context distribution model" (CIR + topocontext; Frank and Thorn (1985)), and (3) vegetation units derived from the aerial photograph and topoclimatic index (CIR + topoclimate). Inspection of the three maps for the Saddle on Niwot Ridge (Plate 1) and area calculations for each mapping unit (Table 3) indicate that combining topoclimatic information with film density data improves alpine tundra vegetation classification to a larger extent than does inclusion of the "topographic context distribution model." Comparison of individual pixels from the CIR + topoclimatic and field vegetation maps, however, reveals considerable differences. Steep environmental gradients within alpine tundra create complex vegetation patterns and make generalization of vegetation into relatively large homogeneous vegetation types an arduous task in the field. In contrast, the procedure presented in this paper may have potential for efficiently mapping large areas of alpine tundra.

REFERENCES

Avery, T., 1985. *Interpretation of Aerial Photographs*, Minneapolis, Burgess Publishing Co., 4th edition, 392 p.

Becking, R. W., 1959. Forestry applications of aerial color photography, *Photogrammetric Engineering and Remote Sensing*, 25:559–565.

Benedict, J. B., 1970. Downslope soil movement in a Colorado alpine region: rates, processes and climatic significance, *Arctic and Alpine Research*, 2:165–226.

Billings, W. D., and L. C. Bliss, 1959. An alpine snowbank environment and its effects on vegetation, plant development, and productivity, *Ecology*, 40:388–397.

Bovis, M. J., and C. E. Thorn, 1981. Soil loss variation within a Colorado alpine area, *Earth Surface Processes and Landforms*, 6:151–163.

Braun-Blanquet, J., 1932. *Plant Sociology: the study of plant communities*, (Translated by G. D. F. Fuller and H. S. Conrad), McGraw-Hill Book Co., Inc. New York, 439 p.

Burns, S. F., and P. J. Tonkin, 1982. Soil geomorphic models and the spatial distribution and development of alpine soils. In Thorn, C. E. (ed.), *Space and Time in Geomorphology*, Allen and Unwin Ltd., London, pp. 25–43.

Curran, P. J., 1980. Multispectral remote sensing of vegetation amount, *Progress in Physical Geography*, 4:315–341.

Erbs, D. G., S. A. Klein, and J. S. Duffie, 1982. Estimation of the diffuse radiation fraction for hourly, daily, and monthly-average global radiation, *Solar Energy*, 28:293–302.

Frank, T. D., 1985. Differentiating semiarid environments using Landsat reflectance indexes, *Professional Geographer*, 37:36–46.

Frank, T. D., and C. E. Thorn, 1985. Stratifying alpine tundra for geomorphic studies using digitized aerial imagery, *Arctic and Alpine Research*, 17:179–188.

Gates, D. M., and R. Janke, 1965. The energy environment of the alpine tundra, *Oecologia Plantarum*, 1:39–62.

Holway, J. G., and R. T. Ward, 1963. Snow and meltwater effects in an area of Colorado alpine, *The American Midland Naturalist*, 69:189–197.

Hutchinson, C. F., 1982. Techniques for combining Landsat and ancillary data for digital classification improvement, *Photogrammetric Engineering and Remote Sensing*, 48:123–130.

Isard, S. A., 1984. *Factors controlling soil moisture and evapotranspiration within alpine vegetation communities, Niwot Ridge, Colorado*, Ph.D. thesis, Indiana University, 97 p.

Jensen, J. J., J. E. Estes, and L. R. Tinney, 1978. High-altitude versus Landsat imagery for digital crop identification, *Photogrammetric Engineering and Remote Sensing*, 6:723–733.

Keammerer, D. B., 1976. Niwot Ridge vegetation map 1:24,000. Unpublished manuscript on file at Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, 80309.

Komárková, V., 1976. *Alpine vegetation of the Indian Peaks area, Front Range, Colorado Rocky Mountains*, Ph.D. thesis, University of Colorado, Boulder, 655 p.

Komárková, V., and P. J. Webber, 1978. An alpine vegetation map of Niwot Ridge, Colorado, *Arctic and Alpine Research*, 10:1–29.

Kuchler, A. W., 1967. *Vegetation Mapping*, Ronald Press, New York, 472 p.

Lillesand, T. M., and R. W. Kiefer, 1979. *Remote Sensing* *and Image Interpretation*, John Wiley and Sons, New York, 612 p.

Liu, Y. H., and R. C. Jordan, 1960. The interrelationships and characteristic distribution of direct, diffuse and total solar radiation, *Solar Energy*, 4:1–19.

Marr, J. W., 1961. *Ecosystems of the east slope of the Front Range in Colorado*, University of Colorado, Series in Biology, No. 8, 134 p.

May, D. E., 1973. *Models for predicting composition and primary production of alpine tundra vegetation from Niwot Ridge, Colorado*, M. A. thesis, University of Colorado, 99 p.

———, 1976, *The response of alpine tundra vegetation in Colorado to environmental change*, Ph.D. thesis, University of Colorado, Boulder, 164 p.

May, D. E., and P. J. Webber, 1982. Spatial and temporal variation of the vegetation and its productivity, Niwot Ridge, Colorado, In Halfpenny, J. C., (ed.), *Ecological Studies in the Colorado Alpine*, Occasional Paper No. 37, Institute of Arctic and Alpine Research, University of Colorado, Boulder, pp. 35–62.

Olyphant, G. A., 1984. Insolation topoclimates and potential ablation in alpine snow accumulation basins: Front Range, Colorado, *Water Resources Research*, 20:491–498.

Orgill, J. F., and K. G. Hollands, 1977. Correlation equation for hourly diffuse radiation on a horizontal surface, *Solar Energy*, 19:357–359.

Osburn, W. S., Jr., 1958. *Ecology of winter snow-free areas on alpine tundra of Niwot Ridge, Boulder County, Colorado*, Ph.D. thesis, University of Colorado, 76 p.

Robinove, C. J., P. S. Chavez, D. Gehring, and R. Holmgren, 1981. Arid land monitoring using Landsat albedo difference images, *Remote Sensing of Environment*, 11:133–156.

Sellers, W. D., 1965. *Physical Climatology*, University of Chicago Press, Chicago, 272 p.

Snyder, M. J., 1983. *A comparison of four techniques for the calculation of slope and aspect from digital terrain matrices*, M.S. thesis, University of Illinois, 85 p.

Strahler, A. H., T. L. Logan, and N. A. Bryant, 1978. Improving forest cover classification accuracy from Landsat by incorporating topographic information, *Proceedings of the Twelfth International Symposium on Remote Sensing of Environment*, Environmental Research Institute of Michigan, pp. 927–942.

Swain, P. H., 1978. *Remote Sensing: The Quantitative Approach*, Chapter 3, (Swain, P. H. and S. M. Davis, ed.), McGraw-Hill, New York, 396 p.

Thorn, C. E., 1978. A preliminary assessment of the geomorphic role of pocket gophers on the alpine zone of the Colorado Front Range, *Geografiska Annaler*, Series A, 60:181–187.

———, 1982. Gopher disturbance: Its variability by Braun-Blanquet vegetation units in the Niwot Ridge alpine tundra zone, Colorado Front Range, USA., *Arctic and Alpine Research*, 14:45–51.

Tom, C. H., and L. E. Miller, 1984. An automated land-use mapping comparison of the Bayesian maximum likelihood and linear discriminant analysis algorithms, *Photogrammetric Engineering and Remote Sensing*, 50:193–207.

Tucker, C. J., 1979. Red and Photographic Infrared linear combinations for monitoring vegetation, *Remote Sensing of Environment*, 8:127–150.

Webber, P. J., and D. E. May, 1977. The distribution and magnitude of belowground plant structures in the alpine tundra of Niwot Ridge, Colorado, *Arctic and Alpine Research*, 9:155–166.

Webber, P. J., O. D. Pollack, and N. D. Lederer, 1984. *Peak season standing crop and annual production data for six alpine plant communities from the Saddle, Niwot Ridge—1982 and 1983*, University of Colorado Long-Term Ecological Research Data Report, 21 p.

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