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Testing an Ecosystem Regionalization

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As a means of developing reliable estimates of ecosystem productivity, landscapes need to be stratified into homogeneous geographic regions. Such ecosystem regions are hypothesized to be productively different in important ways. One measure of the difference is hydrologic productivity (i.e. runoff per unit area). To test the hypothesis that hydrologic productivity is significantly different from region to region, data from 53 hydrologic bench-mark stations within major ecosystem regions of the conterminous United States were subjected to discriminant analysis. The ecosystem regions tested in this study exhibit a high degree of ability to circumscribe stations with similar hydrologic productivity. Discriminant analysis seems to be a particularly appropriate method for testing the validity of land units at all scales of interest.

Keywords: ecosystem, region, ecological land classification, landscape ecology, discriminant analysis, productivity.

1. Introduction

Land management deals with productivity systems, that is ecosystems, from which it attempts to extract efficiently and continuously a product, such as wood or water. These products are commonly referred to as renewable resources.

Estimates of ecosystem productivity are required for the purpose of assessment and management of these resources. In order to make such estimates, relationships between the needed production information and ecosystem classes must be developed. These relationships are called rules (Davis, 1980). Rules take on many forms, from simple experience-based judgments to multivariate regression models and complex mathematical simulations. Application of these rules is based upon concepts of transfer by analogy. Thus, the rules necessary for estimation of productivity are extrapolated from experimental sites or from management experience to analogous areas defined by classification.

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Such methods are based on the hypothesis that all replications of a particular ecosystem class will have fairly similar productivity. This hypothesis has been questioned by a number of workers on the grounds that correlations between ecosystem classes and production are generally low.

One way to establish reliable ecosystem–production relationships is to stratify the landscape into "relatively homogeneous" geographic regions where similar ecosystems have developed on sites having similar properties (Rowe, 1962). For example, similar sites (i.e. those having the same landform, slope, parent material and drainage characteristics) may be found in several climatic regions. Within a region, these sites will support the same vegetation communities, but in other regions vegetation on the sites will be different. Thus, beach ridges in the tundra climatic region support low-growing shrubs and forbs, whereas beaches in the subarctic region usually have dense growth of black spruce or jack pine. Soils display similar trends, as the kind and development of soil properties vary from region to region on similar sites.

Such ecosystem regions, or ecoregions, have at least two important functions for management. First, a map of such regions suggests over what area the productivity relationships derived from experiments and experience can be applied without too much adjustment. Second, they provide the necessary geographical stratification for designing cost-efficient sampling programs to estimate ecosystem productivity.

The mapping of these regions has been worked out in a preliminary way by Bailey (1976) from concepts advanced by Crowley (1967). Subdivisions on the map show units that (theoretically) should be relatively homogeneous. This homogeneity has been partially tested using biophysical parameters (Olson *et al.*, 1982), aquatic ecosystems (Omernik *et al.*, 1982) and wildlife communities (Inkley and Anderson, 1982). However, the degree of correlation between these regions and productivity has not been determined. The objective of this study was to use actual data to determine the degree to which ecosystem regions represent productivity regions. Effective resource management based on ecosystem–production relationships requires that productivity be distributed in a manner similar to the ecosystem regionalization used.

2. Approach to testing

As Rowe and Sheard (1981) point out, maps are hypotheses to be tested and improved. The units express a sense of what is theorized to be important in the landscape. Regional boundaries on Bailey's map are based on climatic and vegetational features (Bailey, 1983). The approach rests upon the hypothesis of a relationship between the features of the environment used to delimit the region and the properties of the region. In this case, regions bounded by changes in macro-features of the climate and vegetation are hypothesized to be productively different in important ways. If actual data on productivity are assembled for the regions, this hypothesis can be tested statistically and the validity of the regional structure (map) can be evaluated objectively. This test is independent inasmuch as productivity did not enter into the initial regionalization.

The use of statistical tests which analyse or test previously developed regional structures was pioneered by Zobler (1957). These tests involve the use of a significance test—chi square or variance analysis—to ascertain if an association exists between the spatial frame, which is the way an area has been partitioned, and the areal dispersion of specific properties of this frame. Recently, the use of multivariate discriminant analysis to test the validity of land units is attracting attention (Casetti, 1964; Steiner, 1965; Pavlik and Hole, 1977; Omi *et al.*, 1979; Rowe and Sheard, 1981). This method of analysis was viewed as the statistical method best suited for this study.

There are different approaches for measuring ecosystem productivity. The question is then: what measure of productivity is to be used for testing?

The traditional measure of productivity is net primary productivity. It is defined as the total amount of organic matter produced annually by an ecosystem (Sharpe, 1975). It is an expression of a combination of vegetation and environmental site characteristics. Because it can be applied to a wide range of ecosystems, at many levels, it is extremely useful in comparing structure and dynamics of ecosystems which differ in floristics and physiognomy. Analysis of regional structure necessitates productivity data that are not only accurate, but cover large geographic areas. The existence of such data, however, is limited. Actual measurements of primary productivity are difficult to make and are usually taken from small areas. Different methods of measurement make data comparison difficult, if not impossible. Thus, there does not exist a comprehensive data base on primary productivity that is suitable for nationwide testing.

Another measure of ecosystem productivity is the normal runoff—the amount of water runoff, on average, produced during a period from a unit area of land surface. Because runoff data are readily available for the entire country, this measure of productivity was used in this study, and is referred to here as *hydrologic productivity*.

3. Data and methods

To make unbiased comparisons of hydrologic productivity, data are needed on the runoff characteristics of "natural" basins which are unaffected by urbanization, man-made storage, diversion, or ground water pumping. The data used were the streamflow observations collected by the U.S. Geological Survey at 57 hydrologic bench-mark stations (Cobb and Biesecker, 1971). These data for stations from all over the United States are available in a computerized data library called WATSTORE at the USGS computer in Reston, Virginia (Hutchison, 1975). Locations of the stations are shown in Figure 1 and listed in Table 1.

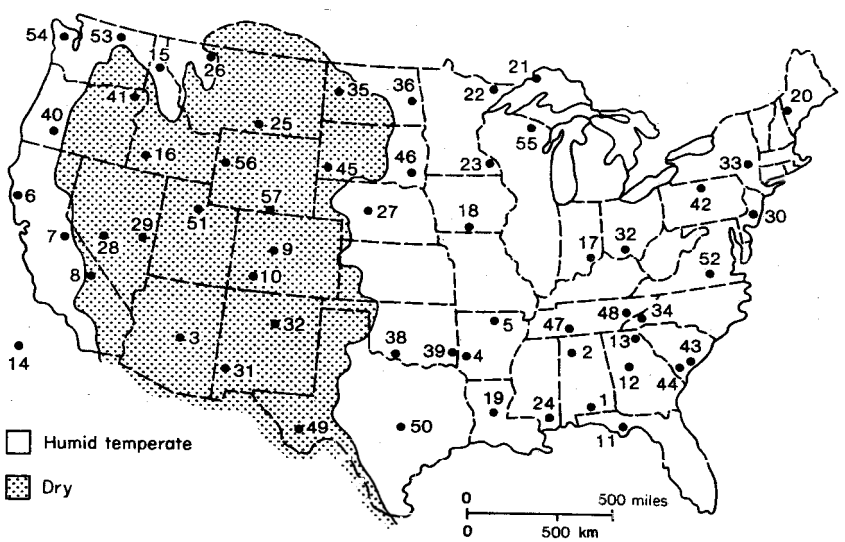

Figure Locations of hydrologic bench-mark stations and ecodomains of the conterminous United States of America.

TABLE 1. Locations of hydrologic bench-mark stations

Station No. and basin location	Station No. and basin location
1. Blackwater River near Bradley, Alabama	31. Mogollon Creek near Cliff, New Mexico
2. Sipsey Fork near Grayson, Alabama	32. Rio Mora near Tererro, New Mexico
3. Wet Bottom Creek near Childs, Arizona	33. Esopus Creek at Shandaken, New York
4. Cossatot River near Vandervoort, Arkansas	34. Cataloochee Creek near Cataloochee, North Carolina
5. North Sylamore Creek near Fifty Six, Arkansas	35. Bear Den Creek near Mandaree, North Dakota
6. Elder Creek near Branscomb, California	36. Beaver Creek near Finley, North Dakota
7. Merced River near Yosemite, California	37. Upper Twin Creek at McGaw, Ohio
8. Wildrose Creek near Wildrose Station, California	38. Blue Beaver Creek near Cache, Oklahoma
9. Halfmoon Creek near Malta, Colorado	39. Kiamichi River near Big Cedar, Oklahoma
10. Vallecito Creek near Bayfield, Colorado	40. Crater Lake near Crater Lake, Oregon
11. Sopchoppy River near Sopchoppy, Florida	41. Minam River at Minam, Oregon
12. Falling Creek near Juliette, Georgia	42. Young Woman's Creek near Renova, Pennsylvania
13. Tallulah River near Clayton, Georgia	43. Scape Ore Swamp near Bishopville, South Carolina
14. Honolii Stream near Papaikou, Hawaii	44. Upper Three Runs near New Ellenton, South Carolina
15. Hayden Creek below North Fork, near Hayden Lake, Idaho	45. Castle Creek near Hill City, South Dakota
16. Wickahoney Creek near Bruneau, Idaho	46. Little Vermillion River near Salen, South Dakota
17. South Hogan Creek near Dillsboro, Indiana	47. Buffalo River near Flat Woods, Tennessee
18. Elk Creek near Decatur City, Iowa	48. Little River above Townsend, Tennessee
19. Big Creek at Pollock, Louisiana	49. Limpia Creek above Fort Davis, Texas
20. Wild River at Gilead, Maine	50. South Fork Rocky Creek near Briggs, Texas
21. Washington Creek at Windigo, Isle Royale, Michigan	51. Red Butte Creek near Salt Lake City, Utah
22. Kawishiwi River near Ely, Minnesota	52. Holiday Creek near Andersonville, Virginia
23. North Fork Whitewater River near Elba, Minnesota	53. Andrews Creek near Mazama, Washington
24. Cypress Creek near Janice, Mississippi	54. North Fork Quinault River near Amanda Park, Washington
25. Beauvais Creek near St. Xavier, Montana	55. Popple River near Fence, Wisconsin
26. Swiftcurrent Creek at Many Glacier, Montana	56. Cache Creek near Jackson, Wyoming
27. Dismal River near Thedford, Nebraska	57. Encampment River near Encampment, Wyoming
28. South Twin River near Round Mountain, Nevada	
29. Steptoe Creek near Ely, Nevada	
30. McDonalds Branch in Lebanon State Forest, New Jersey	

For this study, data from 53 stations were analysed. Station Nos 8, 25, and 40 were not included in the analysis because the station records were incomplete. Station No. 14 (Hawaii) was not included because it is outside the study area. Mean monthly runoff values, in inches per square mile, were calculated for the period 1971–80 for each station (Table 2). Each station was placed into one of two ecoregion groups as described below. The 12 variables (monthly averages of the runoff) for each station, along with the ecoregion group of the station, constituted the data for analysis.

The ecoregion system is organized into a four-level hierarchy, each level representing

a subdivision of the area encompassed by the preceding hierarchical level. These levels, from upper to lower, are ecodomain, ecodivision, ecoprovince and ecosection. For the purposes of this analysis, the ecodomain level, which differentiates regions primarily according to broad climatic similarity, was chosen because of the small sample size. With a sample of 53 stations and 12 variables, only two groups could be properly analysed (Lachenbruch, 1975). Excluding the southern tip of Florida, the conterminous United States is partitioned into two ecoregions at the ecodomain level—dry and humid temperate. The two ecodomains of the conterminous United States are shown in Figure 1, which also shows the location of the hydrologic bench-mark stations. Fifteen stations comprised the dry group; 38 stations comprised the humid temperate group.

Discriminant analysis, a technique for analysing *a priori* grouped data, was used to test whether the two ecoregions were different on the basis of hydrologic productivity. Discriminating variables (those characteristics on which groups are hypothesized to differ) are linearly combined and weighted. The analysis tests how successful the discriminating variables are in significantly distinguishing between groups. Once a significant ($P<0{\cdot}05$) set of discriminating variables has been found, the original set of cases (stations) is classified as to group membership, given those variables and weights. This classification is done by calculating a discriminant score for each case and then comparing it to the mean (average) score for each of the two groups. By comparing predicted versus actual group membership, one can measure the success of group discrimination.

The two ecoregions were analysed via the computer program BMDP designed for multivariate discriminant analysis (Dixon, 1981). All of the discriminating variables except August were significant and were used in the analysis.

4. Results and discussion

Calculations of the discriminant scores for the 15 dry and 38 humid temperate stations gave values ranging from $-3{\cdot}06$ to $+2{\cdot}99$ (Table 2). In general, the lower values of the discriminant score represent dry stations, and the higher values represent humid temperate stations. The frequencies of stations for various levels of discriminant scores are shown in Table 3. Although there is overlapping of discriminant scores for dry and humid temperate groups, this table clearly shows the clustering within the two groups.

The mean value of the discriminant scores for the two groups was:

dry	$-1{\cdot}29$
humid temperate	$0{\cdot}51$
midpoint value	$-0{\cdot}39$.

In theory, when the discriminant score is less than the midpoint value $-0{\cdot}39$, the station will be classified as dry, and when the score is greater than $-0{\cdot}39$ the station will be classified as humid temperate.

The classification results are shown in Table 4. The numbers of stations that were correctly classified are given as diagonal elements of the matrix and the numbers of incorrectly classified stations appear as off-diagonal elements. Seven of 53 stations were misclassified. The misclassified stations include 23, 27, 32, 36, 46, 50, and 53 (Figure 2). All but one (Station No. 32) of these are in the humid temperate ecodomain. The overall

TABLE 2. Average monthly runoff (inch/mile²), hydrologic bench-mark stations, 1971–80†

Station No.	Group‡	Month												Discriminant score
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	
		1·36	1·47	2·39	2·80	2·51	3·65	3·07	2·83	1·73	1·65	1·99	1·81	1·66
		0·76	1·50	2·25	4·96	3·84	6·54	3·51	2·12	0·97	0·45	0·23	0·53	1·35
		0·35	0·30	0·57	1·05	1·95	1·82	0·38	0·02	0·00	0·01	0·01	0·02	−1·36
		1·33	2·47	3·85	2.34	2·54	5·37	3·81	2·42	2·23	0·59	0·39	1·13	1·68
		0·42	1·04	1·13	0·64	1·04	2·41	2·09	1·54	0·62	0·20	0·13	0·18	0·05
6		0·55	4·90	8·22	12·79	9·00	10·93	4·55	1·85	0·69	0·38	0·23	0·21	1·60
7		0·21	0·39	0·42	0·76	0·60	1·14	2·36	8·34	8·29	2·88	0·73	0·45	0·08
8§														
9		0·47	0·29	0·22	0·17	0·14	0·14	0·23	1·81	6·14	3·86	1·27	0·64	−2·96
10		1·15	0·61	0·37	0·29	0·25	0·49	1·54	5·82	8·89	4·01	1·68	1·20	−1·34
11		0·97	0·76	1·46	3·49	2·60	3·20	2·79	1·28	1·51	3·31	2·88	2·07	0·72
12		0·37	0·43	1·09	2·42	2·24	3·16	1·81	1·14	0·38	0·40	0·57	0·25	−0·37
13		2·51	3·41	4·54	6·08	5·27	7·58	6·48	5·63	3·57	2·75	2·92	2·27	2·99
14§														
15		0·25	0·30	0·95	1·29	28	2·85	3·21	2·90	17	0·54	0·31	0·27	0·41
16		0·00	0·00	0·00	0·04	0·03	0·16	0·05	0·02	0·01	0·00	0·00	0·00	−1·31
17		0·39	1·42	2·16	2·04	2·14	3·06	2·06	1·30	0·66	0·75	0·53	0·51	0·22
18		0·38	0·37	0·41	0·54	0·70	1·46	1·71	0·90	0·62	0·14	0·15	1·11	1·09
19		0·77	0·80	1·68	2·85	2·17	2·96	1·81	2·02	0·79	0·64	0·59	0·72	0·16
20		2·84	2·46	2·62	1·94	1·27	4·10	8·05	8·29	2·67	1·44	0·91	0·82	1·24
21		0·81	1·10	0·64	0·36	0·24	0·77	5·49	3·55	1·09	0·51	0·24	0·93	1·18
22		0·82	0·98	0·69	0·43	0·28	0·25	1·04	2·85	1·59	0·82	0·50	0·84	0·13
23		0·41	0·42	0·37	0·41	0·36	1·23	0·79	0·61	0·91	0·93	0·48	0·47	−0·74
24		0·97	1·72	3·05	4·21	3·16	4·98	4·83	3·25	0·89	1·06	1·04	1·74	2·94
25§														
26		1·93	1·91	1·23	1·03	0·70	1·01	3·17	13·77	18·50	10·88	5·23	3·51	0·75
27		0·23	0·23	0·22	0·22	0·21	0·24	0·24	0·24	0·22	0·22	0·22	0·22	−1·16

	0·12	0·14		0·13		0·22	0·44	1·39	1·09	0·29	0·15	0·13	-0·94
	0·49	0·44		0·37		0·38	0·54	1·33	1·69	1·12	0·74	0·56	-1·00
	0·89	1·08		1·55		1·69	1·62	1·59	1·33	1·05	0·94	0·88	-0·24
	0·60	0·44	0·88	0·36	0·83	1·11	0·92	0·48	0·06	0·06	0·12	0·34	0·95
32	0·26	0·20	0·15	0·11	0·11	0·20	0·65	2·56	1·94	0·50	0·51	0·38	0·39
33	2·49	2·99	4·24	3·75	2·45	6·07	6·08	4·58	2·47	1·38	0·58	1·07	1·07
34	1·42	1·94	3·29	4·75	3·58	5·58	4·34	2·93	2·13	1·69	1·64	1·36	1·21
35	0·02	0·00	0·00	0·00	0·12	0·85	0·65	0·07	0·05	0·01	0·00	0·02	0·98
36	0·01	0·00	0·00	0·00	0·00	0·13	0·47	0·10	0·03	0·01	0·00	0·00	1·31
37	0·41	0·77	2·57	2·21	2·33	2·99	2·64	1·56	0·93	0·60	0·69	0·71	0·10
38	0·21	0·24	0·16	0·35	0·33	0·86	0·86	1·63	0·73	0·07	0·14	0·22	0·30
39	1·53	2·15	3·42	1·88	2·18	5·19	3·27	3·06	1·64	0·28	0·27	0·68	1·08
40§													
41	0·45	0·72	1·09	1·02	0·92	1·41	2·24	6·25	8·00	3·63	0·82	0·48	−1·29
42	1·46	2·30	2·63	2·11	2·02	4·54	3·99	2·52	2·09	0·99	0·50	1·03	1·19
43	0·78	1·17	1·57	2·07	1·93	2·25	1·73	1·15	1·11	0·93	0·77	0·85	−0·14
44	1·37	1·43	1·55	1·64	1·49	1·72	1·53	1·54	1·50	1·45	1·46	1·43	0·15
45	0·15	0·13	0·13	0·13	0·12	0·16	0·22	0·24	0·18	0·16	0·15	0·14	−1·23
46	0·00	0·00	0·00	0·00	0·00	0·33	0·08	0·05	0·02	0·00	0·00	0·00	−1·21
47	1·22	2·42	2·79	4·34	2·63	5·52	3·36	2·80	1·50	1·13	0·89	1·08	1·91
48	1·74	2·30	4·14	5·58	4·03	6·37	4·33	3·18	2·61	2·93	2·06	1·40	0·48
49	0·10	0·01	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·08	0·11	0·52	−0·54
50	0·29	0·28	0·20	0·22	0·46	0·37	0·56	1·00	0·55	0·35	0·22	0·25	−0·94
51	0·35	0·34	0·33	0·34	0·35	0·78	1·59	2·18	1·08	0·56	0·36	0·31	−0·42
52	1·41	1·16	1·49	2·01	1·79	2·10	1·90	1·94	1·83	0·87	0·88	1·22	0·04
53	0·38	0·30	0·23	0·18	0·16	0·18	0·56	5·65	9·43	2·85	0·79	0·59	−1·46
54	8·77	15·66	23·10	14·78	12·17	2·36	9·32	15·94	7·34	14·20	7·26	6·33	1·23
55	1·00	0·96	0·56	0·40	0·35	0·86	2·94	1·91	1·00	0·57	0·66	1·08	0·53
56	0·74	0·58	0·55	0·47	0·38	0·41	0·59	2·83	5·72	2·88	1·41	0·92	−1·62
57	0·43	0·35	0·35	0·31	0·26	0·30	0·52	4·17	10·44	3·78	0·74	0·44	−3·06

† Source: U.S. Geological Survey.
‡ 1 = Humid temperate, 2 = dry.
§ Not included in analysis.

TABLE 3. Frequencies of humid temperate and dry stations for various levels of discriminant scores

Class limits for discriminant score	Frequency of humid	Frequency of dry	Total
−3·15 to −2·80		2	2
−2·79 to −2·10			
−2·09 to −1·40			2
−1·39 to −0·70	5	9	14
−0·69 to 0·00	4	3	7
0·01 to 0·70	12		12
0·71 to 1·40	10		10
1·41 to 2·10	4		4
2·11 to 2·80			
2·81 to 3·50	2		2
Total	38	15	53

TABLE 4. Classification results for ecodomains based on a linear discriminant function utilizing average monthly runoff data

Actual group	No. of stations	Predicted group membership 1	2
Group 1	38	32	6
Humid temperate		84·2%	15·8%
Group 2	15	1	14
Dry		6·7%	93·3%

Percentage of grouped stations correctly classified: 86·79%

percentage of grouped stations correctly classified was 87%.

The high percentage of correctly classified stations indicates a high degree of discrimination between the two ecodomains. Thus, the regional ecosystems tested in this study exhibit a high degree of ability to circumscribe stations with similar hydrologic productivity. Although classification results can theoretically achieve a level of 100%, inherent natural variation or inadequacy of the variables is such that this level can probably never be reached. With this in mind, 87% is good discriminating power, considering the smallness of the sample. Lachenbruch and Mickey (1968) indicated that using a classification function to classify the same cases that were used to compute it is biased in favor of better discrimination. Even allowing for this bias, the discrimination between groups is impressive.

The misclassified stations provide a clue to the validity of the map units. For example, most of the misclassified stations are relatively near the dry/humid temperate boundary. This result can be interpreted to mean that the cores of the regional units are valid but the boundaries, in terms of hydrologic productivity, may need some adjustment. This interpretation would not be possible if the misclassified stations had been scattered throughout the groups.

The misclassified stations also serve to confirm the existence of finer subdivisions. For example, Bailey's (1976) map shows the dry western side of the humid temperate

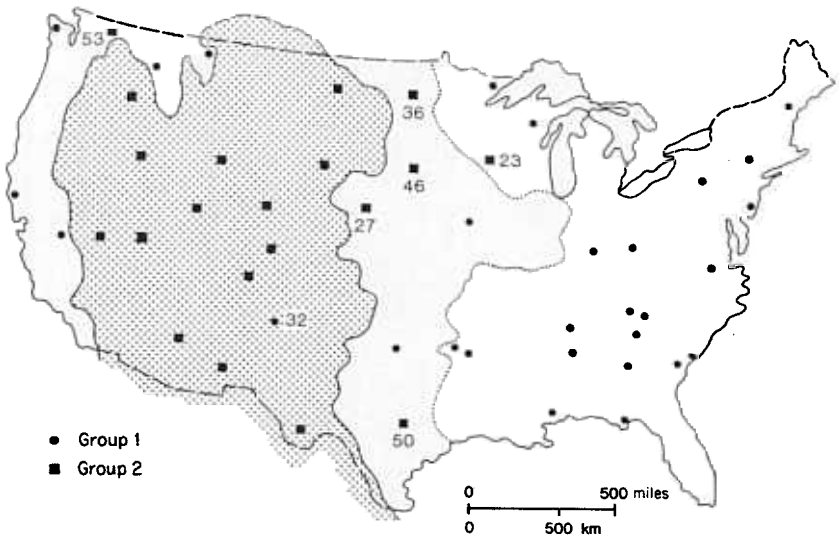

Figure 2. Predicted group membership from discriminant analysis, hydrologic bench-mark stations. ....., eastern boundary of the subhumid prairie.

ecodomain in central USA distinguished as subhumid prairie (Figure 2). Four of the seven misclassified stations (Nos 27, 36, 46, and 50) are located in this region.

Discriminant analysis seems to be a particularly appropriate method for testing the validity of land units at all scales of interest. In this study, the method was applied to the broadest level of ecological generalization. The next level of testing suggested as worthwhile is at more detailed levels of the hierarchy than was possible with the low resolution data available for this study. Through multi-level application of this method, a complete analysis of the ecoregion map may be done. Other measures of productivity, such as net primary productivity, need to be used for testing.

The method differs from previous use of multivariate approaches with land units (Radloff and Betters, 1978; Laut and Paine, 1982; Briggs and France, 1983) which use cluster analysis of grid units to provide the initial map units. The approach taken in this study uses multivariate discriminant analysis to test and validate map units initially recognized and delineated by theoretical considerations.

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References

Bailey, R. G. (1976). *Ecoregions of the United States*. Miscellaneous Publication 1391. Washington, D.C.: USDA.

Bailey, R. G. (1983). Delineation of ecosystem regions. *Environ. Mgmt* 7, 365–373.

Briggs, D. J. and France, J. (1983). Classifying landscapes and habitats for regional environmental planning. *J. environ. Mgmt* 17, 249–261.

Casetti, E. (1964). *Multiple discriminant functions*. Technical Report No. 11, Computer Applications in the Earth Sciences Project. Evanston, Illinois: Northwestern University, Department of Geography.

Cobb, E. D. and Biesecker, J. E. (1971). *The national hydrologic bench-mark network. Circular 460-D*. Washington, D.C.: U.S. Geological Survey.

Crowley, J. M. (1967). Biogeography. *Can. Geogr.* 11, 312–326.

Davis, L. S. (1980). Strategy for building a location-specific, multipurpose information system for wildland management. *J. For.* **78**, 402–408.

Dixon, W. J. (ed.) (1981). *BMDP Statistical Software 1981*. Berkeley: University of California Press.

Hutchison, N. E. (1975). *WATSTORE, National Water Data Storage and Retrieval System. Open File Report 75-426*. Washington, D.C.: U.S. Geological Survey.

Inkley, D. B. and Anderson, S. H. (1982). Wildlife communities and land classification systems. In *Transactions 47th North American Wildlife and Natural Resource Conference* (K. Sabol, ed.), pp. 73–81. Washington, D.C.: Wildlife Management Institute.

Lachenbruch, P. A. (1975). *Discriminant Analysis*. New York: Hafner Press.

Lachenbruch, P. A. and Mickey, M. R. (1968). Estimation of error rates in discriminant analysis. *Technometrics* **10**, 1–10.

Laut, P. and Paine, T. A. (1982). A step towards an objective procedure for land classification and mapping. *Appl. Geogr.* **2**, 109–126.

Olson, R. J., Kumar, K. D. and Burgess, R. L. (1982). Analysis of ecoregions utilizing the geoecology data base. In *Proceedings In-Place Resource Inventories* (T. Brann, ed.), pp. 149–156, 9–14 August 1981, Orono, Maine. Washington, D.C.: Society of American Foresters.

Omernik, J. M., Shirazi, M. A. and Hughes, R. M. (1982). A synoptic approach for regionalizing aquatic ecosystems. In *Proceedings In-Place Resource Inventories* (T. Brann, ed.), pp. 199–218, 9–14 August 1981, Orono, Maine. Washington, D.C.: Society of American Foresters.

Omi, P. N., Wensel, L. C. and Murphy, J. L. (1979). An application of multivariate statistics to land-use planning: classifying land units into homogeneous zones. *Forest Sci.* **25**, 399–414.

Pavlik, H. F. and Hole, F. D. (1977). Soilscape analysis of slightly contrasting terrain in southwestern Wisconsin. *Soil Sci. Soc. Am. J.* **41**, 407–413.

Radloff, D. L. and Betters, D. R. (1978). Multivariate analysis of physical site data for wildland classification. *Forest Sci.* **24**, 2–10.

Rowe, J. S. (1962). Soil, site and land classification. *Forestry Chron.* **38**, 420–432.

Rowe, J. S. and Sheard, J. W. (1981). Ecological land classification: a survey approach. *Environ. Mgmt* **5**, 451–464.

Sharpe, D. M. (1975). Methods of assessing the primary production of regions. In *Primary Productivity of the Biosphere* (H. Lieth and R. Whittaker, eds), pp. 147–166. New York: Springer-Verlag.

Steiner, D. (1965). A multivariate statistical approach to climatic regionalization and classification. *Tijdschr. K. ned. aardrijksk. Genoot.* **82**, 329–347.

Zobler, L. (1957). Statistical testing of regional boundaries. *Ann. Assoc. Am. Geogr.* **47**, 83–95.