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Landscape and Watershed Processes

Quantitative Soil Descriptions for Ecoregions of the United States

Mostafa A. Shirazi,* Colleen Burch Johnson, James M. Omernik, Denis White, Patricia K. Haggerty,
and Glenn E. Griffith

ABSTRACT

Researchers have defined and mapped ecological regions of the United States based on similar patterns of ecosystems such as deserts, forests, and croplands. These studies are useful in regional research, monitoring, and environmental management because data can be more readily extrapolated within the same ecoregion and to regions with similar characteristics. The description of ecoregions is largely holistic and qualitative. Conversely, quantitative information for soil are abundant and soil is an important ecosystem component related to many ecoregion properties. We used the nationwide State Soil Geographic database (STATSGO) to describe the soils of 84 Level III ecoregions in the United States. Among the 24 soil characteristics studied were texture, rock fragments, available water capacity, bulk density, and organic matter content. For each ecoregion we developed ranks to describe (i) its similarity to the U.S. average soil characteristics, (ii) the accuracy of predicting those characteristics, (iii) how well the soil map unit boundaries fit within ecoregion boundaries, (iv) the spatial relationship of soils across neighboring ecoregion boundaries, and (v) the homogeneity of texture–rock patterns. We present a national map of soil texture and rock fragments and five soil ranks for each ecoregion, and examine relationships between soils and other ecological components for selected ecoregions. Because soils relate to other ecosystem components such as vegetation, geology, and land use, the soil ranks complement and enrich the qualitative ecoregion descriptions. Similar analyses of physical or biological components of ecoregions will expand the understanding of the ecosystem patterns.

Wise management and policy decisions regarding the environment require assessments of complex ecosystems and translations of theoretical constructs into applications (Hoag et al., 1998). The environment consists of the physical, chemical, and biological factors that interact with each other. At a biological community level, these relationships define an inseparable entity called an ecosystem (Odum, 1959; Warren, 1971). Ecosystems, such as forests, deserts, and agricultural land are considered natural units for studying the environment. Ecoregions are composed of ecosystems that are relatively homogeneous, or exhibit a particular pattern, within a defined boundary, that is different from the neighboring regions (Bailey et al., 1985; Rowe and Sheard, 1981; Omernik and Bailey, 1997; Omernik et al., 2000). Ecoregions represent geographic units for regional studies (Commission for Environmental Cooperation, 1997) and as with ecosystems, no single component of an ecoregion can completely describe it. However, investigations of components begin the process of translation between theoretical and applied knowledge.

Decisions regarding environmental monitoring or assessment are often made at the spatial scale of ecoregions. Karlen et al. (1997) discussed the use of soil data at the regional scale but very few quantitative data have been developed for ecoregions. This type of data is needed because resource utilization often targets particular features, such as minerals, water, or lands productive for agriculture or forests. Further, lessons learned within an ecoregion are more readily transferable in the same ecoregion and to other similar ecoregions.

Soils are an important ecoregion component that has been used in environmental assessments with ecological, social, and economic contexts (Hoag et al., 1998). Others have used soil characteristics and models to describe the influence of soil on water quality (Shirazi et al., 2001b,c; Johnson et al., 1991; Larson and Pierce, 1994). In a discussion of environmental assessment using soil data (e.g., the State Soil Geographic database [STATSGO]; Soil Survey Staff, 1991), Lammers and Johnson (1991, p 154) noted that "soil map units can be linked to soil properties needed to support process models." These authors emphasized that "a geographic framework is needed . . . to ensure spatial congruence of data" and cited Omernik (1987) as a suitable framework for the United States. Our study combines soil data from STATSGO with a national framework (e.g., ecoregion maps) to facilitate regional environmental assessments in the United States.

Omernik and others defined ecoregions at the continental scale (Level I), national and regional scales (Levels II and III), and for 32 of the 48 conterminous United States (USEPA, 2000) at a subregional scale (Level IV). Level III ecoregions are widely used in environmental management and they incorporate many components such as geology, vegetation, soils, and land use to describe them (USEPA, 2000). Ecoregions are periodically updated with new information and 84 Level III ecoregions are currently defined for the conterminous United States. They range in size from 15 000 to 365 000 km^2 and may be discontinuous.

The scale of STATSGO is suitable for this study because it is designed to be "useful for understanding the soil resources and for planning broad use in a state or region" (Soil Survey Staff, 1991). In STATSGO, map units define geographic land areas by the characteristics of similar soil series. There are 10 483 soil map units in

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the United States with an average area of 750 km^2. Each map unit may include many dispersed polygons (mean number of polygons = 7.5, standard deviation = 17.7, minimum = 1, maximum = 405), and because soil characteristics of separate polygons are not distinguished from those of the entire map unit at the STATSGO scale, the map unit is the minimum spatial entity.

Shirazi et al. (2001c) aggregated soil characteristics of all soil layers above bedrock for each map unit in the STATSGO database and developed five models. The models were based on relationships among the map units in the texture classes (USDA5): cr = coarse, mocr = moderately coarse, mecr = medium coarse, mofn = moderately fine, and fn = fine. They partitioned the map units according to similar ranges of rock fragments in each texture class and used the appropriate model to predict the mean soil characteristics. Because the map units for all 48 conterminous U.S. states were used, we refer to these models collectively as the *U.S. model*. The authors presented a detailed list of soil characteristics and later applied the models to water quality prediction (Shirazi et al., 2001b,c).

The goal of our study is to quantify soil properties of Level III ecoregions of the United States. Specifically, our objectives are to (i) produce a map of 20 texture–rock classes along with the Level III ecoregions for the United States; (ii) use the U.S. model and 24 selected STATSGO variables to estimate the mean soil characteristics of the United States and each ecoregion; (iii) describe the agreement between soil and ecoregion boundaries, spatial separation across ecoregion borders, and the diversity of textures in each ecoregion; and (iv) summarize the above soil information as quantitative ranks to examine them in relation to other ecoregion characteristics.

MATERIALS AND METHODS

We followed the methods of Shirazi et al. (2001a) to classify all soil map units in the United States by texture. Each USDA5 texture class was also divided into four sets based on percent rock fragments, thus forming 20 classes of soil map units. The data were stored in a geographic information system (GIS) to create a map of the 20 texture–rock classes, and GIS techniques were used to intersect the soil map units with each ecoregion and determine the percent of map unit area inside the ecoregion border.

We determined the mean value for each of the 24 selected soil characteristics (see Table 1 for names and abbreviations) from all map units in a texture–rock class. Thus, there were 24 × 20 = 480 "observed" means derived from the soil characteristics of STATSGO map units nationwide. The means were also estimated using the U.S. models and standard errors were calculated by regression with the observed means. These values were needed for subsequent comparisons with ecoregion soil characteristic means, which were estimated by the same procedure.

Ecoregion Ranks

For each ecoregion we calculated two ranks from the means and standard errors. The first was based on the sums of quadratic products, that is, the squared distance (Johnson and Wichern, 1982) of the means for the 24 soil characteristics. The resultant values (or statistics) were sorted from the smallest to the largest and assigned a rank (R_{sc}). This rank is used to compare mean characteristics to the national average. A second rank was calculated by summing the error of the 24 soil characteristics and sorting the results from the smallest to the largest. This rank is designated as R_{er} and indicates the error of prediction relative to the U.S. models.

Table 1. Abbreviations and symbols used throughout the paper.

Term	Definition
	Soil texture
USDA5	Summarization of 12 USDA texture classes into 5: cr (coarse), mocr (moderately coarse), mecr (medium coarse), mofn (moderately fine), and fn (fine) textured soils
	Soil characteristics
awch	high available water capacity (cm/cm)
awcl	low available water capacity (cm/cm)
blkh	high bulk density (g/cm^3)
blkl	low bulk density (g/cm^3)
cath	high cation exchange capacity (cmol/kg)
catl	low cation exchange capacity (cmol/kg)
clay	clay (%)
pdep	depth (m)
kfch	erodibility factor without rock
liqh	high liquid limit (%)
liql	low liquid limit (%)
ormh	high organic matter (%)
orml	low organic matter (%)
perh	high permeability (cm/h)
perl	low permeability (cm/h)
pHh	high pH
pHl	low pH
rkwh	high rock (% wt.)
rkwl	low rock (% wt.)
sand	sand (%)
slph	high slope (%)
slpl	low slope (%)
wtdh	high depth to water table (m)
wtdl	low depth to water table (m)
	Soil map unit–ecoregion boundary agreement
A_e	ecoregion area (km^2)
α	dimensionless area
α_m^t	total intersected map unit area
α_i^t	total inclusion zone area
$\alpha_m^t - \alpha_i^t$	total exclusion zone area
α_m^s	map unit area at switch point
α_i^s	inclusion zone area at switch point
$\alpha_m^s - \alpha_i^s$	exclusion zone area at switch point
α_m^1	first map unit area in sorted list
α_i^1	first/largest inclusion zone map unit area
	Soil ranks for ecoregions
R_{er}	Standard error of prediction (soils similar/dissimilar to USA)
R_{mu}	map unit–ecoregion boundary agreement (good/poor)
R_{nh}	neighbor–host soil overlap (segregated/shared)
R_{sc}	soil characteristics mean
R_{tx}	texture class diversity (homogeneous/heterogeneous)

The conceptual and mathematical definitions for the "agreement" or "fit" between ecoregion and soil map unit boundaries are based on their intersection areas. Level III ecoregions intersect an average of 196 map units (standard deviation = 150, minimum = 22, maximum = 738). The boundaries of the map units frequently extend beyond an ecoregion boundary, producing what we call an *exclusion zone*. This zone is made up of parts of the intersecting map units that are outside the ecoregion and in contrast to the *inclusion area* inside the boundary. When the soil exclusion area is large relative to the ecoregion and its circumscribed inclusion area, the "fit" to the ecoregion boundary is considered poor. Conversely, a small exclusion area, with an inclusion area nearly equal to the ecoregion area, indicates a high level of spatial coincidence. Ranks describing the soil–ecoregion boundary agreements based on intersection areas are derived below.

We used A_e, A_m, and A_i to denote, respectively, the areas of an ecoregion, a map unit, and the part of an intersecting map unit inside the ecoregion boundary. These three areas were combined into two types of dimensionless areas $\alpha_m = A_m/A_e$ and $\alpha_i = A_i/A_e$ and we referred to them as *map unit* and *inclusion areas*. Next, we sorted the inclusion areas from the largest to the smallest such that:

$$\alpha_{i1} > \alpha_{i2} > \ldots > \alpha_{is-1} > \alpha_{is} > \alpha_{is+1} > \ldots > \alpha_{it-1} > \alpha_{it} \qquad [1]$$

where t is the total number of intersections and $1 < s < t$. The number, s, is a derived property that defines the area of "fit" (Eq. [4], below). We calculated sorted cumulative areas from Eq. [1] and used superscripts for summation as follows:

$$\alpha_i^1 < \alpha_i^2 < \ldots < \alpha_i^{s-1} < \alpha_i^s < \alpha_i^{s+1} < \ldots < \alpha_i^{t-1} < \alpha_i^t \qquad [2]$$

The quantity α_i^t is the total soil area within an ecoregion covered by t map units. Theoretically, $\alpha_i^t = 1$ for ecoregions containing no surface waters. However, α_i^t is generally less than 1 and is used as the limit for cumulative inclusion area. These statistics range from 0.3178 to 0.9341 and, for the USA as a whole, $\alpha_i^t = 0.9830$.

Like the inclusion areas, we summed the entire area of intersected map units into:

$$\alpha_m^1 < \alpha_m^2 < \ldots < \alpha_m^{s-1} < \alpha_m^s < \alpha_m^{s+1} < \ldots < \alpha_m^{t-1} < \alpha_m^t \qquad [3]$$

where α_m^t is the total of map unit areas. A unique exclusion area can be calculated for any sequential map unit number based on the difference between Eq. [2] and [3]. For example, $\alpha_m^1 - \alpha_i^1$ is the exclusion area for the first map unit, and the exclusion zone for all map units is $\alpha_m^t - \alpha_i^t$.

The cumulative areas in Eq. [2] and [3] each form a line in a coordinate system with the number of map units as the horizontal axis and α as the vertical axis. The two lines never intersect, but the inclusion versus exclusion area relationships are optimized at map unit number s, such that:

$$\alpha_m^s \leq \alpha_i^t \text{ and } \alpha_m^{s+1} > \alpha_i^t \qquad [4]$$

In other words, the solution for s is obtained when the direction of the inequality changes from $<$ to $>$ between map unit s and $s + 1$. Equation [4] delimits this point of "switching" or "crossover" beyond which the cumulative map unit area exceeds the inclusion area limit. The resulting α_i^s value mathematically defines the "fit." We sorted the 84 ecoregion α_i^s values from the largest to the smallest to create a rank (R_{mu}) that reflects its place along a good-to-poor agreement sequence.

To determine how much of the soils in an ecoregion, referred to as the *host*, are shared with their neighbors, we used map units 1 through s of the host (i.e., up to and including the switch point). Recall that parts of these map units may exist in neighboring ecoregions, which are not necessarily directly adjacent to the host ecoregion. The host inclusion area was divided by the sum of corresponding map unit areas in the neighboring ecoregions to produce a ratio. Then, the reciprocals of the ratios for the 84 ecoregions were sorted from the smallest to largest to form a neighbor–host rank called R_{nh}. Low ranks indicate more separation of soils between the host and neighboring ecoregions and high values denote more overlap.

We used the 20 texture–rock classes to describe soil homogeneity within ecoregions. Theoretically, an ecoregion's soil texture can be completely heterogeneous if covered uniformly by all 20 classes or completely homogeneous if covered by a single class. That is, homogeneity or heterogeneity = (maximum area of any class)/(mean area of all possible classes). The values are obtained by separating α_i^t into areas for each class and determining the class with the greatest total area:

$$\alpha_i^t = \Sigma\, \beta_k^{tk}, \quad k = 1, 2, \ldots, 20 \qquad [5]$$

where β_k is the total area in class k and the superscript tk denotes summation over the number of map units in the class. The two theoretical limits for any ecoregion are:

$$\beta_1^{t1} = \beta_2^{t2} = \ldots = \beta_{20}^{t20} = \alpha_i^t/20 \qquad [6]$$

$$\beta_j^{tj} = \alpha_i^t, \quad j = 1, 2, \ldots, 20 \qquad [7]$$

Equation [6] defines the uniform distribution of all 20 classes and Eq. [7] indicates that only class j covers the entire soil area of the ecoregion. For the first limit, $\alpha_i^t/20 = 0.05$, and the maximum to mean ratio is $\beta/0.05 = 1$ in Eq. [6]. For $\alpha_i^t = 1$ in Eq. [7], the ratio is $\beta_j/0.05 = 20$. We calculated the texture–rock class areas for each of the 84 ecoregions, divided the maximum by the real $\alpha_i^t/20$ (i.e., mean area of all possible texture classes) for the ecoregion, sorted the 84 ratios from the largest to the smallest, and assigned a rank (R_{tx}). Thus, low R_{tx} ranks indicate homogeneous texture and higher ranks reflect greater heterogeneity. For example, for the whole USA, $\alpha_i^t = 0.9830$, $\beta_{17} = 0.1205$, $0.9830/20 = 0.0492$, and $0.1205/0.0492 = 2.45$, which indicates a high rank and a heterogeneous texture.

Ecoregions can be compared using the appropriate individual ranks. However, a multivariate analysis is needed to determine relationships among the ranks. We used a minimal spanning tree analysis (Becker et al., 1988) based on the original five soil statistics, for the 84 ecoregions and the United States, to classify ecoregions relative to the U.S. values.

RESULTS AND DISCUSSION

Figure 1 displays the spatial relationship of texture and rock fragment classes for the conterminous United States overlaid with Level III ecoregion boundaries. The texture–rock fragment classes and ecoregion lines were produced independently but are shown together to facilitate visual comparison.

The first two columns in Table 2 identify the ecoregion number and name. For the remainder of the paper we often refer to the number only. The ecoregion's average USDA5 texture class is listed in the third column of Table 2. The last five columns contain ranks ranging from 1 to 84. For all but the soil texture ranks, the statistics derived for the USA were the limits to the values calculated for the regions. The estimated values for the U.S. squared distance, total error, switch point area, neighbor-to-host area ratio, and texture–area ratio are, respectively: 0.78, 128%, 0.9830, 0.0, and 2.45. The texture–area ratios closest to the USA were for Ecoregions 22 and 6 (2.24 and 3.23, respectively).

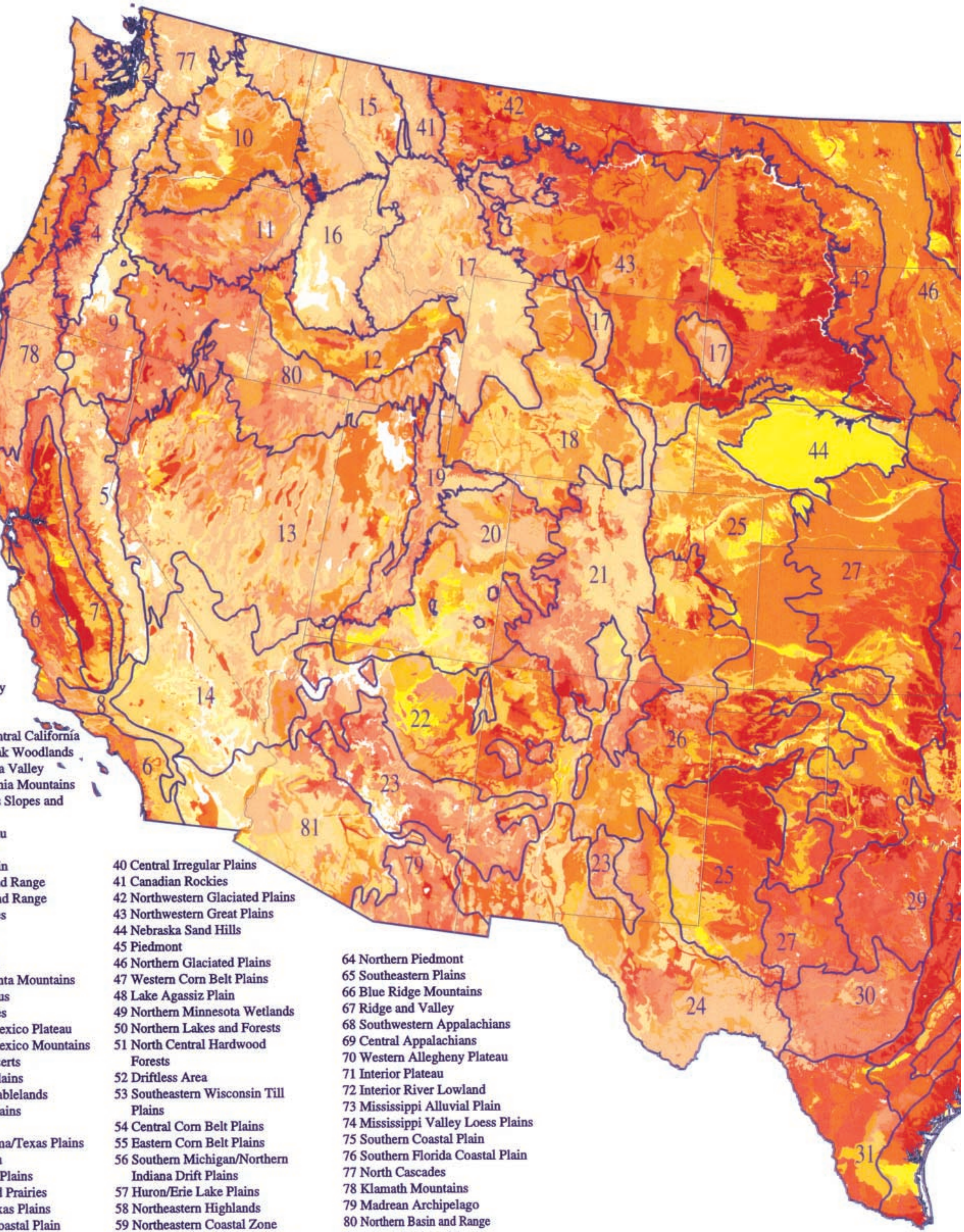
The mean soil texture for the United States is medium coarse (mecr), as well as for 45% ($n = 38$) of the ecoregions. Coarse (cr) soils dominate only three ecoregions (44, 75, 76) and the mean texture is fine (fn) for seven (28, 29, 30, 32, 34, 45, 73).

Ecoregion Ranks and Soil Map Unit Data

Although data are available for all ecoregions, we explain soil characteristics and the ranks using the cen-

Table 2. Level III Omernik Ecoregions by number, name, average USDA5 texture class, and five ranks: soil characteristics (R_{sc}) and their standard errors of prediction (R_{er}) relative to the USA (1 = most similar, 84 = least similar); soil–ecoregion boundary agreement (R_{mu}) (1 = good fit, 84 = mismatched); neighbor–host soil relationship (R_{nh}) (1 = least in common, 84 = most in common); and soil map unit texture diversity (R_{tx}) (1 = most homogeneous, 84 = most heterogeneous).

Ecoregion	Name	USDA5	R_{sc}	R_{er}	R_{mu}	R_{nh}	R_{tx}
1	Coast Range	mecr	70	77	9	11	61
2	Puget Lowland	mecr	59	74	63	58	27
3	Willamette Valley	mofn	75	51	49	48	64
4	Cascades	mecr	38	58	54	59	47
5	Sierra Nevada	mocr	17	70	5	12	37
6	Southern and Central California Chaparral and Oak Woodlands	mecr	52	11	53	61	83
7	Central California Valley	mofn	56	5	11	6	58
8	Southern California Mountains	mocr	65	30	71	73	39
9	Eastern Cascades Slopes and Foothills	mocr	76	43	33	38	72
10	Columbia Plateau	mecr	26	34	7	16	69
11	Blue Mountains	mofn	23	66	57	63	63
12	Snake River Basin	mecr	7	78	37	47	79
13	Central Basin and Range	mecr	53	60	25	30	60
14	Mojave Basin and Range	mocr	35	72	61	68	29
15	Northern Rockies	mecr	8	73	43	51	19
16	Idaho Batholith	mocr	67	63	52	57	17
17	Middle Rockies	mecr	10	50	32	36	35
18	Wyoming Basin	mocr	13	71	17	22	68
19	Wasatch and Uinta Mountains	mecr	46	28	35	39	30
20	Colorado Plateaus	mocr	3	40	31	37	82
21	Southern Rockies	mecr	69	36	19	21	44
22	Arizona–New Mexico Plateau	mocr	1	3	36	41	84
23	Arizona–New Mexico Mountains	mofn	57	39	75	77	73
24	Chihuahuan Deserts	mecr	18	24	10	15	59
25	Western High Plains	mecr	12	53	41	50	78
26	Southwestern Tablelands	mecr	2	21	50	55	81
27	Central Great Plains	mecr	16	67	62	69	42
28	Flint Hills	fn	58	26	55	53	21
29	Central Oklahoma–Texas Plains	fn	19	32	64	70	57
30	Edwards Plateau	fn	63	4	79	81	23
31	Southern Texas Plains	mofn	54	45	4	9	43
32	Texas Blackland Prairies	fn	74	29	47	54	26
33	East Central Texas Plains	mofn	42	37	82	78	51
34	Western Gulf Coastal Plain	fn	55	23	39	43	28
35	South Central Plains	mecr	28	17	45	45	74
36	Ouachita Mountains	mofn	48	44	14	10	7
37	Arkansas Valley	mecr	5	27	76	42	49
38	Boston Mountains	mofn	49	65	24	26	5
39	Ozark Mountains	mofn	72	8	1	2	22
40	Central Irregular Plains	mofn	51	16	20	25	71
41	Canadian Rockies	mecr	43	62	48	46	16
42	Northwestern Glaciated Plains	mofn	39	1	58	64	41
43	Northwestern Great Plains	mofn	34	14	12	17	80
44	Nebraska Sand Hills	cr	83	69	3	5	3
45	Piedmont	fn	62	38	2	3	14
46	Northern Glaciated Plains	mecr	45	12	46	52	13
47	Western Corn Belt Plains	mecr	73	19	13	14	54
48	Lake Agassiz Plain	mecr	81	56	59	67	66
49	Northern Minnesota Wetlands	mocr	84	84	80	82	38
50	Northern Lakes and Forests	mocr	24	80	21	28	77
51	North Central Hardwood Forests	mocr	31	46	69	72	67
52	Driftless Area	mecr	36	18	42	20	55
53	Southeastern Wisconsin Till Plains	mecr	25	41	16	8	36
54	Central Corn Belt Plains	mecr	6	25	28	34	32
55	Eastern Corn Belt Plains	mofn	14	9	18	18	40
56	Southern Michigan–Northern Indiana Drift Plains	mocr	41	42	30	35	76
57	Huron–Erie Lake Plains	mofn	78	64	60	65	65
58	Northeastern Highlands	mocr	29	75	66	44	25
59	Northeastern Coastal Zone	mocr	33	57	56	62	10
60	Northern Appalachian Plateau and Uplands	mecr	64	48	74	74	1
61	Erie Drift Plains	mecr	50	13	83	1	31
62	North Central Appalachians	mecr	68	52	84	84	2
63	Middle Atlantic Coastal Plain	mocr	32	76	70	71	50
64	Northern Piedmont	mecr	44	61	73	76	20
65	Southeastern Plains	mofn	30	20	15	19	70
66	Blue Ridge	mecr	40	31	51	56	24
67	Ridge and Valley	mofn	15	10	65	66	34
68	Southwestern Appalachians	mecr	9	33	26	23	9
69	Central Appalachians	mecr	47	55	78	80	4
70	Western Allegheny Plateau	mecr	11	22	67	60	45
71	Interior Plateau	mofn	22	2	6	13	56
72	Interior River Lowland	mecr	27	7	72	75	33
73	Mississippi Alluvial Plain	fn	79	15	23	27	18
74	Mississippi Valley Loess Plains	mecr	71	6	34	40	6
75	Southern Coastal Plain	cr	61	81	8	4	8
76	Southern Florida Coastal Plain	cr	82	83	44	7	12
77	North Cascades	mocr	66	82	40	33	11
78	Klamath Mountains	mecr	21	35	29	32	15
79	Madrean Archipelago	mofn	20	49	68	31	75
80	Northern Basin and Range	mecr	4	68	22	29	52
81	Sonoran Basin and Range	mocr	60	47	38	49	53
82	Laurentian Plains and Hills	mecr	77	54	77	79	46
83	Eastern Great Lakes and Hudson Lowlands	mecr	37	59	81	83	48
84	Atlantic Coastal Pine Barrens	mocr	80	79	27	24	62



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11 Blue Mountains
12 Snake River Plain
13 Central Basin and Range
14 Mojave Basin and Range
15 Northern Rockies
16 Idaho Batholith
17 Middle Rockies
18 Wyoming Basin
19 Wasatch and Uinta Mountains
20 Colorado Plateaus
21 Southern Rockies
22 Arizona/New Mexico Plateau
23 Arizona/New Mexico Mountains
24 Chihuahuan Deserts
25 Western High Plains
26 Southwestern Tablelands
27 Central Great Plains
28 Flint Hills
29 Central Oklahoma/Texas Plains
30 Edwards Plateau
31 Southern Texas Plains
32 Texas Blackland Prairies
33 East Central Texas Plains
34 Western Gulf Coastal Plain
35 South Central Plains
36 Ouachita Mountains
37 Arkansas Valley
38 Boston Mountains
39 Ozark Highlands
40 Central Irregular Plains
41 Canadian Rockies
42 Northwestern Glaciated Plains
43 Northwestern Great Plains
44 Nebraska Sand Hills
45 Piedmont
46 Northern Glaciated Plains
47 Western Corn Belt Plains
48 Lake Agassiz Plain
49 Northern Minnesota Wetlands
50 Northern Lakes and Forests
51 North Central Hardwood Forests
52 Driftless Area
53 Southeastern Wisconsin Till Plains
54 Central Corn Belt Plains
55 Eastern Corn Belt Plains
56 Southern Michigan/Northern Indiana Drift Plains
57 Huron/Erie Lake Plains
58 Northeastern Highlands
59 Northeastern Coastal Zone
60 Northern Appalachian Plateau and Uplands
61 Erie Drift Plain
62 North Central Appalachians
63 Middle Atlantic Coastal Plain
64 Northern Piedmont
65 Southeastern Plains
66 Blue Ridge Mountains
67 Ridge and Valley
68 Southwestern Appalachians
69 Central Appalachians
70 Western Allegheny Plateau
71 Interior Plateau
72 Interior River Lowland
73 Mississippi Alluvial Plain
74 Mississippi Valley Loess Plains
75 Southern Coastal Plain
76 Southern Florida Coastal Plain
77 North Cascades
78 Klamath Mountains
79 Madrean Archipelago
80 Northern Basin and Range
81 Sonoran Basin and Range
82 Laurentian Plains and Hills
83 Eastern Great Lakes and Hudson Lowlands
84 Atlantic Coastal Pine Barrens

Fig. 1. (Continued).

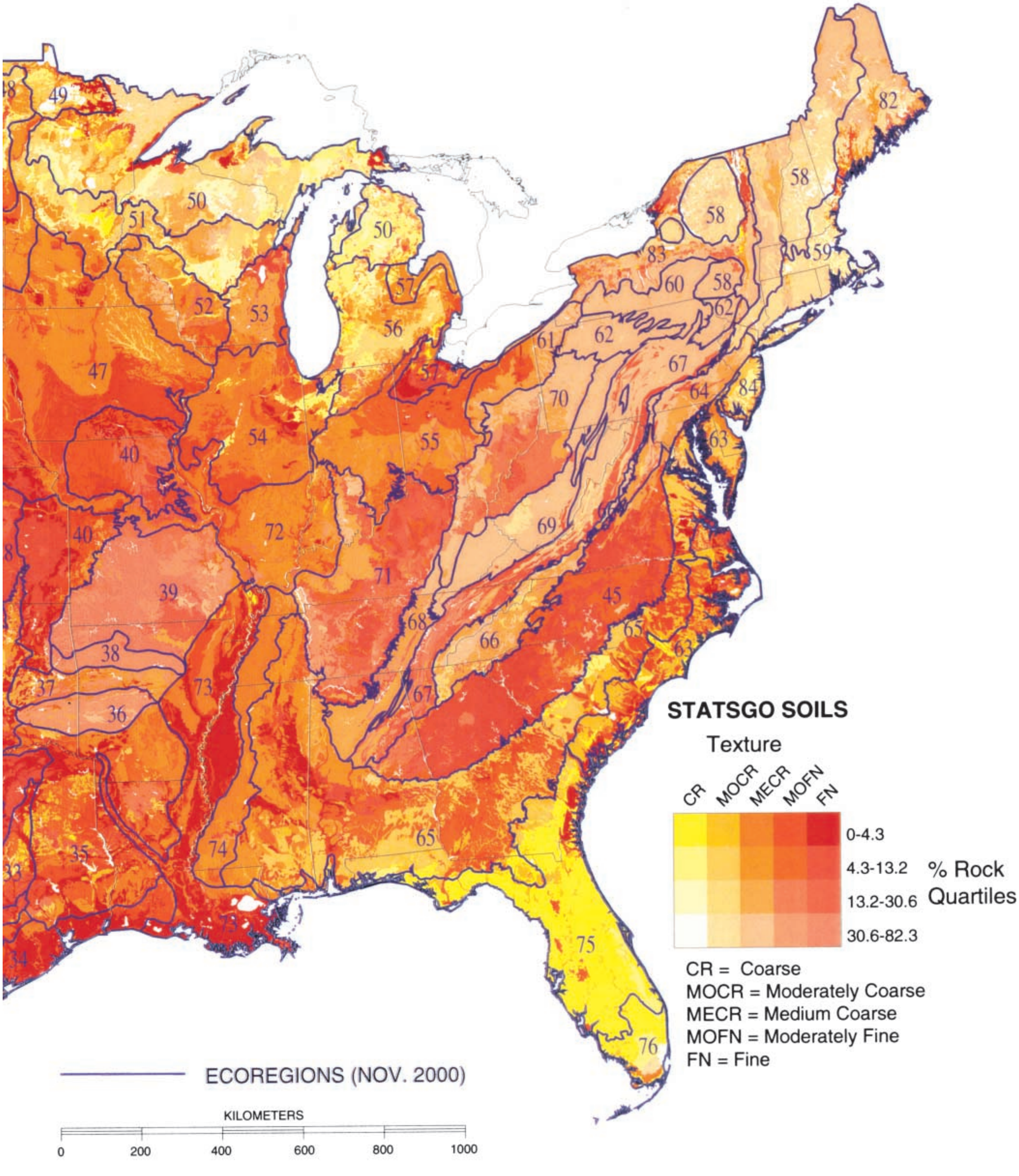

Fig. 1. Soil texture (USDA5) and rock contents of State Soil Geographic database (STATSGO) soil map units of the conterminous United States and the boundaries of 84 Level III Omernik ecoregions. The yellow color represents coarse (cr) soils with colors darkening through moderately coarse (mocr), medium coarse (mecr), moderately fine (mofn), and fine (fn) soils in the reddest shade. A higher percentage of rocks adds coarseness to a soil and is depicted as decreasing color intensity within the texture class.

trally located Ecoregion 39 (the Ozark Highlands). This ecoregion is intersected by 79 soil map units and has a moderately fine (mofn) mean texture (Table 2). The soil characteristics are unlike the U.S. mean values as indicated by $R_{sc} = 72$ and the detailed comparison in Fig. 2a. Their errors are shown in Fig. 2b, and together provide a good predictability rank of $R_{er} = 8$.

Recall that R_{sc} is a rank of the sorted squared distances of ecoregion soil characteristics relative to the USA as the central reference point. A high rank could result from two factors: (i) a large difference in the mean soil characteristics of the ecoregion versus the U.S. mean and (ii) negligible correlations between the ecoregion and the U.S. soil characteristics. The predictability rank R_{er} determines the nature of the relationship in the second factor. For example, when the difference between the mean soil characteristics for the ecoregion and USA is small and their correlations are strong, both R_{sc} and

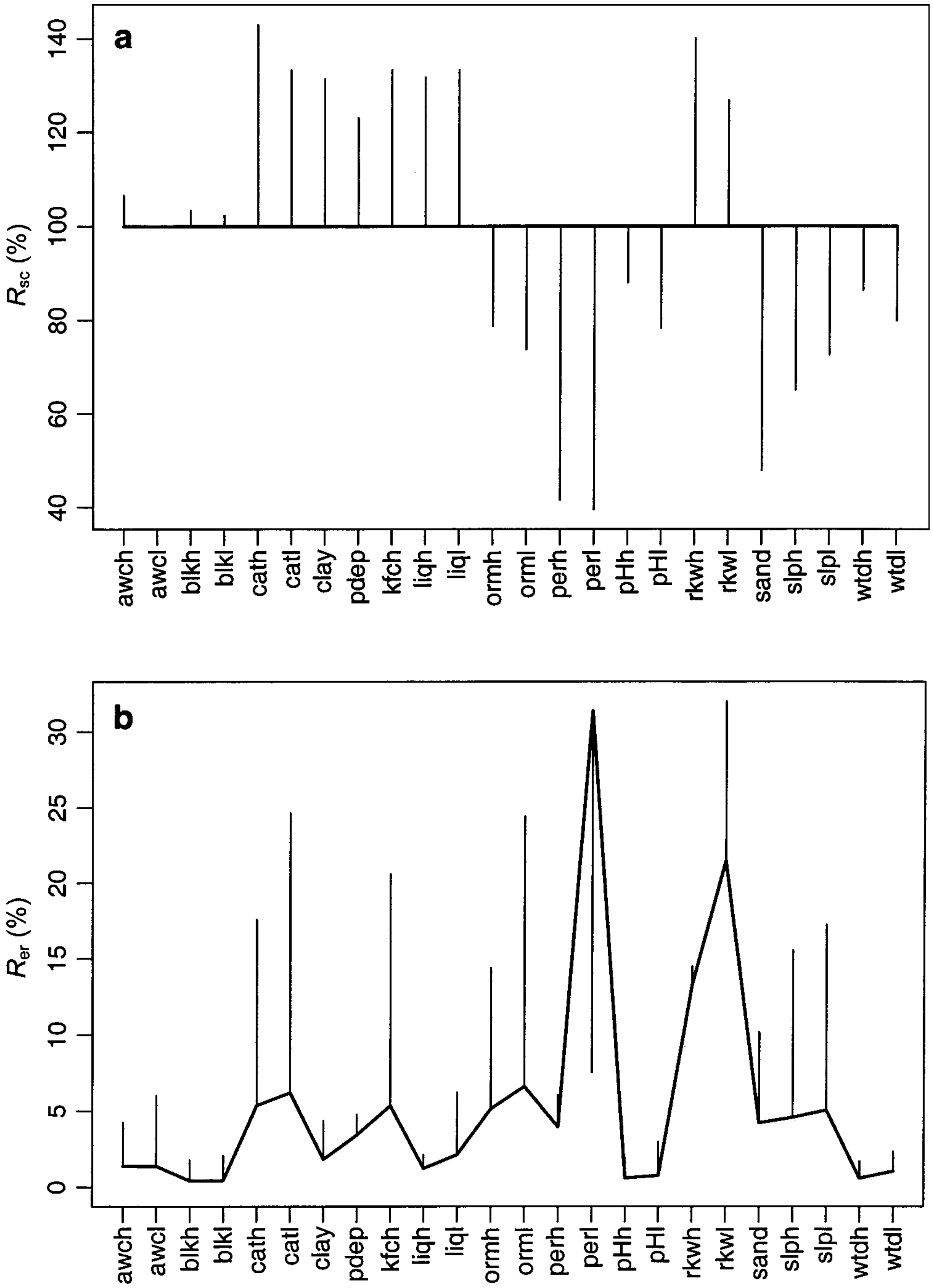

Fig. 2. Comparison of U.S. and Ecoregion 39 soil characteristics. (*a*) The baseline represents each mean soil characteristic for the USA and the bars above and below represent the amount of difference for Ecoregion 39. For example, the cation exchange capacities (cath, catl), percent clay, and liquid limits (liqh, liql) are greater than the national averages whereas soil permeability (perh, perl) and percent sand are less. (*b*) The bars indicate error differences between the U.S. model and the standard errors of prediction for the Ozark Highlands. Values for percent clay and percent rocks are above the U.S. average in this ecoregion, and perl is below average. R_{sc}, compares mean characteristics to the national average; R_{er}, error of prediction relative to the U.S. models.

R_{er} will be low ranks. Alternatively, a high R_{sc} coupled with a low R_{er}, such as for Ecoregion 39, indicates that the mean soil characteristics are very different from the USA but the ecoregion's soil characteristics are strongly and predictably related to each other.

For the Ozark Highlands, 36 of the 79 intersected map units cover 93.4% of its total area (Fig. 3a), which produces the best boundary agreement among the 84 ecoregions and the rank of $R_{mu} = 1$. Figure 3a illustrates the increase in inclusion area and total map unit area with increasing numbers of intersected map units. Figure 3b shows the spatial distribution of the cumulative areas inside and outside Ecoregion 39 at the switch point.

In this example, Ecoregion 39 is the host region and the rank $R_{nh} = 83$ indicates that soils change abruptly at ecoregion boundaries. Only 5.3% of the inclusion zone soils are within neighboring Ecoregions 38, 40, 72, and 73. Therefore, the soil map units are largely segregated within the host ecoregion borders. Of the neighbors, the smallest proportion of map unit area (0.13%) is

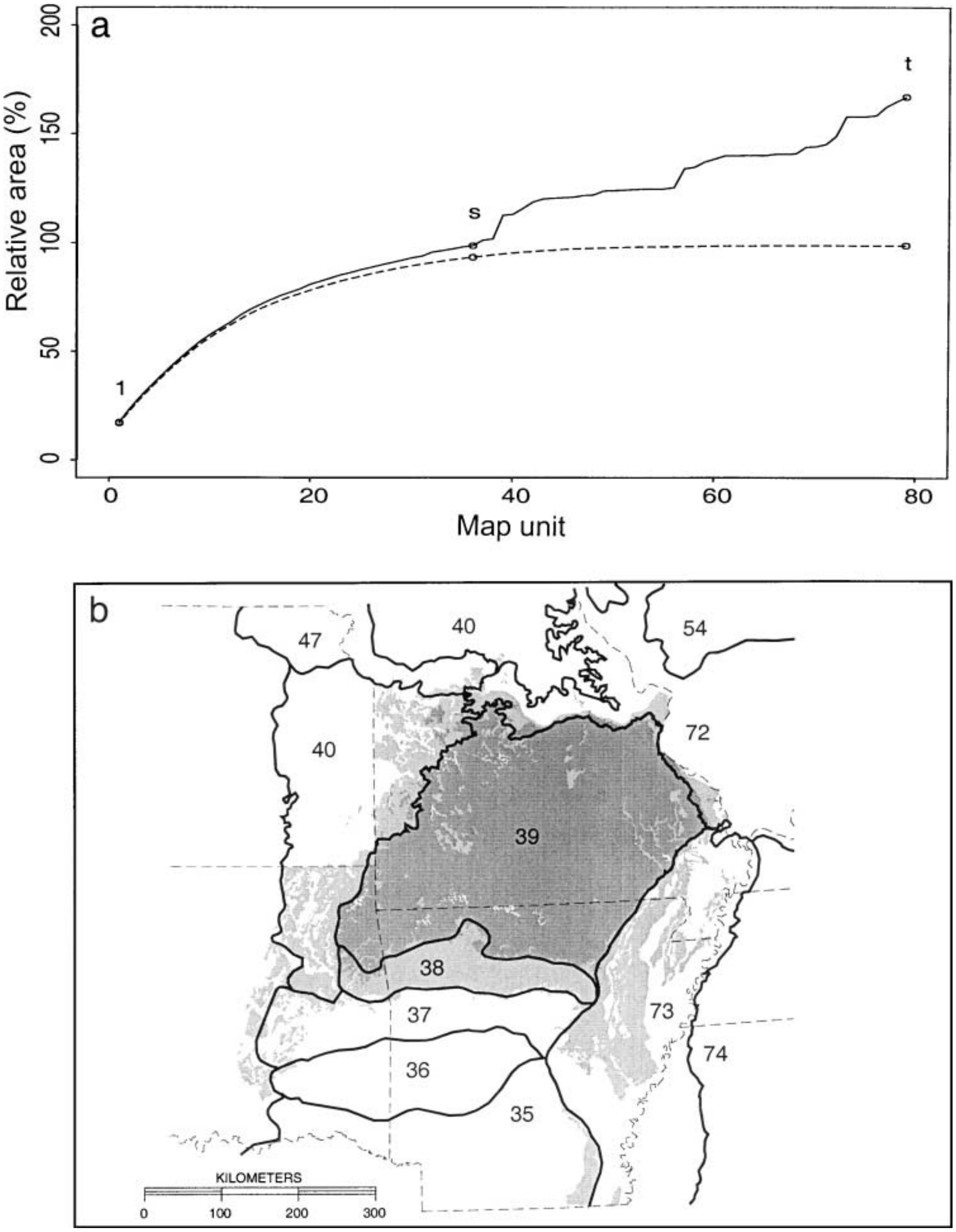

Fig. 3. **Analysis of Ecoregion 39. (*a*) The relationships between map unit areas (solid lines, Eq. [3]) and inclusion areas (dashed lines, Eq. [2]) for Ecoregion 39. The vertical axis represents dimensionless areas, α. From left to right, the circular markers locate map unit areas α_m^1, α_m^s, and α_m^t on the solid lines, and α_i^1, α_i^s, and α_i^t on the dashed lines. The 1 denotes the largest single contributor of area, *s* is the "switch point" from inside to outside the ecoregion, *t* is the total number of map units, and the subscript i refers to the inclusion zone. The vertical difference between the solid and dashed lines represents the size of the exclusion zone for the ecoregion. At 1, the exclusion zone ($\alpha_m^1 - \alpha_i^1$) is minimal whereas the inclusion area, α_i^1, is the largest for a single map unit. (*b*) The spatial relationships of intersecting map units of Ecoregion 39 demonstrate the "switch point" between the inclusion and exclusion zones. Map unit areas < *s* are dark gray, parts of which are outside the ecoregion boundary. Although the light gray areas extend far beyond the ecoregion boundary, only those within the ecoregion boundary and the dark gray areas outside the boundary determine the boundary agreement and the neighbor–host ranks (R_{mu} and R_{nh}).**

within the Mississippi Alluvial Plain (73) to the southeast. Here, the soils and contrasting landforms manifest the most abrupt boundary change. Soil textures in Ecoregion 39 are moderately homogeneous, as indicated by R_{tx} = 22 (Table 2).

Ecoregion Ranks and Geographic Characteristics

Level III ecoregions represent the distribution of distinct patterns of ecosystems in the United States. The patterns naturally differ because of relationships between many ecological characteristics. For example, the mutual occurrence of cool and moist soils in a mountainous terrain, wet or moist forest vegetation, and forestry land use, may be used to define a homogeneous region. If these correlated geographic phenomena are spatially extensive and produce sharp boundaries with the neighboring ecoregions, the region is "distinct" as well. The relationships between ecological components in a heterogeneous ecoregion are variable or form a spatially fragmented pattern (mosaic). When the characteristics gradually merge with the neighboring regions, it is a transitional ecoregion. An understanding of these patterns helps determine the extent to which data may be extrapolated within an ecoregion or between similar regions and is aided by quantitative assessments of one or more components. The reliability of data extrapolation is improved when components of the ecoregion are concordant.

Soils vary considerably in different ecoregions and the five soil ranks define distinctiveness, texture homogeneity, and transitional characteristics of ecoregions with respect to their soils. The relationships among ranks form patterns similar in concept to concordant ecoregion components, except that the ranks are quantitative and relative to the entire United States. The numerical statistics derived for all but the soil texture rank are bounded by the U.S. values as the upper limits.

To facilitate the discussion of ecoregions spanning a diverse array of soils, the ecoregions were sorted based on the relationships among all five soil rank statistics with respect to the U.S. values. The sorted list was then divided into three equal groups. We used the groups to illustrate the predictability of soil characteristics as shown in Fig. 4, plotting the smallest total errors on the left and progressively larger errors to the right. As the distance from the U.S. error baseline increases from

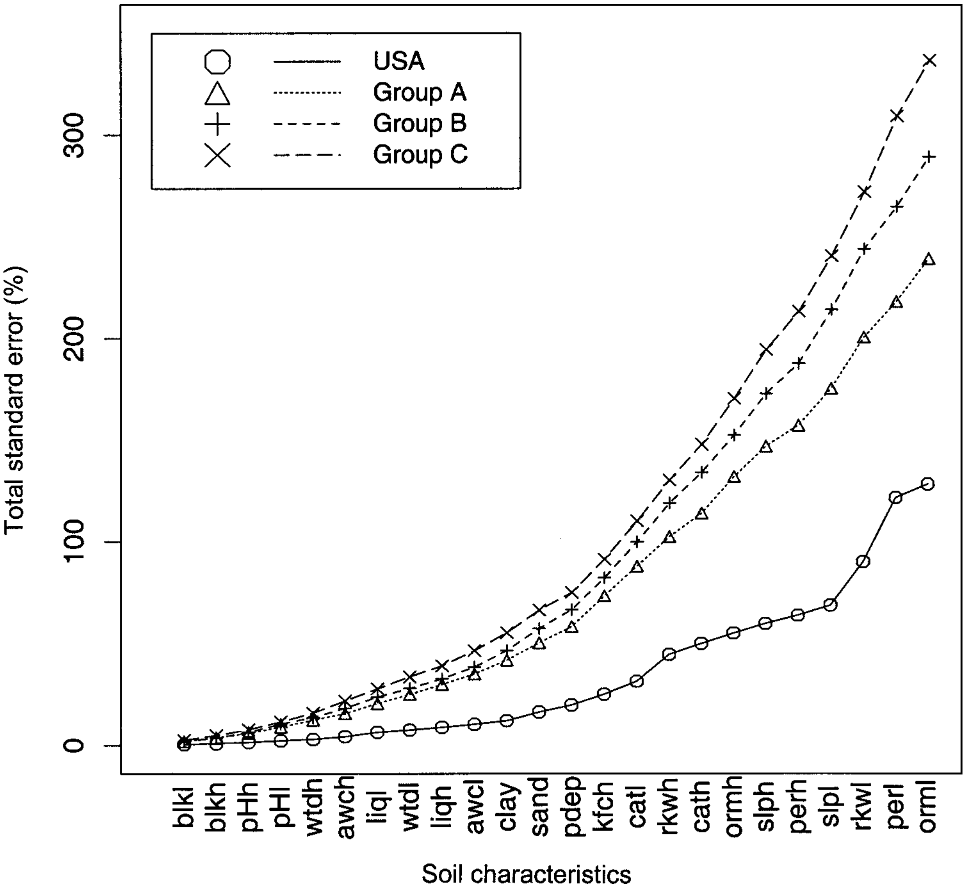

Fig. 4. A summary of the standard errors of predicting soil characteristics of the State Soil Geographic database (STATSGO) map units of the United States and three groups of Level III ecoregions. The groups were based on the relationships among the five soil ranks compared with the U.S. values. Group A has the highest predictability (lowest total error) and Group C has the lowest predictability (highest errors). Group A = Ecoregions 8, 32, 37, 54, 24, 34, 65, 70, 26, 52, 35, 40, 47, 73, 43, 46, 6, 72, 67, 55, 7, 30, 42, 71, *22*, 74, *39*, and 61. Group B = Ecoregions 17, 79, 59, 69, *62*, 82, 3, 48, *60*, 81, 31, 36, 53, 20, 56, 51, 33, 23, 21, 9, 45, 10, 29, 66, 78, 68, 19, and 28. Group C = Ecoregions *49*, 76, 77, 75, 84, 50, 12, 63, 58, 2, 1, 15, 14, 18, 5, 27, 80, 11, 64, 41, 38, 13, 16, 57, *44*, 83, 4, and 25. Soil characteristics and standard errors of ecoregions in italic type are listed in Table 3.

the left to the right and from Group A to Group C, the predictability of the ecoregion soil characteristics decreases.

Table 3 summarizes mean soil characteristics for the United States and for two Level III ecoregions from each group. The high and low ranges of State Soil Geographic database (STATSGO) soil characteristics were retained as separate quantities to preserve variability. Prediction error, reflecting the variability of soil characteristics, was expressed as a percentage of the mean. For the USA, the error is largest for permeability and rock, intermediate for organic matter and clay, and small for bulk density and pH.

The ecoregions in Table 3 (also marked in italic type in the Fig. 4 caption) represent the entire range of our soil ranks and were used to examine relationships between soils and other ecological components. This simple classification could be improved with quantitative information for other ecoregion components, and ultimately determine the ability to extrapolate data within the same ecoregion or between ecoregions in the group. However, discussions of associations between the soil ranks and other ecoregion components will remain qualitative until methods are developed to quantify those components.

Ecoregions Most Distant from the USA

Northern Minnesota Wetlands (49)

With ranks $R_{sc} = 84$, $R_{er} = 84$, $R_{mu} = 80$, $R_{nh} = 82$, and $R_{tx} = 38$, the soils in this ecoregion are the least similar to the U.S. mean soils, the least predictable, and have indistinct borders and moderately uniform textures. The high organic content of this ecoregion is a distinguishing soil characteristic. Ecologically, it is a transitional region. The central portion of Ecoregion 49 is dominated by swamps with boreal forest vegetation, sparse human population, and wildlife habitat as a major land use. On the east, the ecoregion gradually merges into the Northern Lakes and Forests (50) with its mix of spruce fir, pine, and hardwood vegetation and the land uses of forestry, recreation, and some mining. On the west, agriculture becomes more common, as is typical in the adjacent Lake Agassiz Plain (48) ecoregion.

The Nebraska Sand Hills (44)

With very prominent ranks $R_{sc} = 83$, $R_{er} = 69$, $R_{mu} = 3$, $R_{nh} = 4$, and $R_{tx} = 3$, this ecoregion stands out noticeably because of its soils. It is one of the most distinctive and ecologically homogenous ecoregions in North America as well as one of the largest areas of grass-stabilized sand dunes in the world. Coarse soils predominate and it generally lacks cropland agriculture and trees, except for some riparian trees in the north and east. Grazing is the main land use, but the density of cattle is less than in adjacent Ecoregions 47, 27, and 25. The latter regions are arable with irrigation and 47 is a productive cropland.

Ecoregions of Intermediate Distance to the USA

North Central Appalachians (62)

The ranks $R_{sc} = 68$, $R_{er} = 52$, $R_{mu} = 84$, $R_{nh} = 84$, and $R_{tx} = 2$ indicate highly diffuse soil boundaries and a very homogeneous texture. Most overlaps of the soil map units are with Ecoregions 67, 69, and 70 to the south and east. Ecoregions 60 and 62 to the north and west were affected by glaciation whereas most of this ecoregion was not, therefore a geomorphically distinct boundary separates these ecoregions. Ecoregion 62 is generally more heavily forested than its neighboring

Table 3. A comparison of mean soil characteristics and their standard errors for selected ecoregions and the United States. Soil characteristic names and units are listed in Table 1.

	Mean							Standard error						
Characteristic	**22**	**39**	**44**	**49**	**60**	**62**	**USA**	**22**	**39**	**44**	**49**	**60**	**62**	**USA**
								%						
awch	**0.14**	**0.13**	**0.11**	**0.16**	**0.10**	**0.12**	**0.15**	**2.97**	**4.28**	**6.62**	**3.97**	**7.92**	**4.19**	**1.40**
awcl	**0.11**	**0.08**	**0.06**	**0.10**	**0.06**	**0.08**	**0.11**	**3.93**	**6.04**	**7.91**	**8.54**	**8.15**	**2.68**	**1.39**
blkh	**1.31**	**1.48**	**1.81**	**1.66**	**1.70**	**1.59**	**1.49**	**1.66**	**1.80**	**2.70**	**4.60**	**2.62**	**1.47**	**0.43**
blkl	**1.21**	**1.28**	**1.63**	**1.42**	**1.41**	**1.32**	**1.29**	**1.92**	**2.09**	**2.75**	**8.12**	**2.50**	**1.63**	**0.44**
cath	**4.41**	**14.59**	**2.43**	**18.15**	**5.88**	**3.13**	**10.35**	**6.96**	**17.60**	**15.21**	**46.50**	**13.00**	**6.97**	**5.36**
catl	**2.03**	**6.36**	**0.45**	**6.32**	**2.17**	**1.15**	**5.40**	**9.97**	**24.66**	**13.49**	**33.66**	**16.20**	**2.91**	**6.21**
clay	**19.64**	**34.51**	**3.67**	**17.41**	**15.65**	**15.34**	**23.10**	**4.26**	**4.39**	**4.44**	**6.76**	**13.35**	**12.92**	**1.84**
pdep	**1.20**	**1.63**	**1.49**	**1.48**	**1.37**	**1.37**	**1.44**	**6.32**	**4.80**	**5.97**	**18.67**	**10.49**	**5.25**	**3.43**
kfch	**0.29**	**0.35**	**0.16**	**0.19**	**0.00**	**0.00**	**0.27**	**12.02**	**20.60**	**16.84**	**26.94**	**10.49**	**5.25**	**5.35**
liqh	**29.81**	**52.48**	**2.87**	**34.07**	**30.82**	**31.25**	**38.23**	**3.76**	**2.13**	**3.38**	**14.84**	**4.82**	**6.37**	**1.24**
liql	**21.29**	**35.25**	**1.79**	**19.52**	**19.07**	**17.24**	**24.23**	**3.76**	**6.24**	**3.60**	**9.94**	**4.11**	**6.74**	**2.14**
ormh	**0.36**	**0.73**	**0.38**	**4.38**	**1.18**	**0.54**	**1.06**	**18.22**	**14.38**	**14.20**	**36.89**	**36.45**	**11.32**	**5.14**
orml	**0.13**	**0.21**	**0.11**	**0.38**	**0.30**	**0.17**	**0.37**	**21.45**	**24.43**	**19.23**	**732.40**	**18.55**	**7.70**	**6.62**
perh	**11.82**	**4.59**	**47.29**	**14.53**	**3.76**	**10.63**	**8.67**	**9.78**	**6.08**	**49.63**	**21.92**	**11.24**	**44.59**	**3.97**
perl	**3.88**	**1.37**	**14.24**	**3.95**	**0.59**	**1.64**	**2.65**	**18.83**	**7.53**	**104.30**	**26.89**	**10.81**	**88.65**	**31.38**
pHh	**8.43**	**6.12**	**7.48**	**8.05**	**6.78**	**5.90**	**7.38**	**1.60**	**1.97**	**2.53**	**3.40**	**1.76**	**1.16**	**0.60**
pHl	**7.46**	**4.33**	**5.76**	**6.37**	**4.65**	**4.11**	**5.90**	**2.19**	**2.99**	**4.08**	**3.41**	**3.00**	**1.60**	**0.77**
rkwh	**19.84**	**55.99**	**1.56**	**16.25**	**55.46**	**55.34**	**22.31**	**17.13**	**14.52**	**14.94**	**16.74**	**34.95**	**25.74**	**13.28**
rkwl	**12.68**	**33.62**	**0.07**	**3.90**	**34.42**	**38.05**	**13.28**	**20.86**	**32.03**	**36.00**	**35.21**	**44.42**	**40.64**	**21.48**
sand	**53.38**	**17.69**	**88.43**	**57.07**	**31.91**	**39.83**	**42.00**	**6.93**	**10.17**	**13.10**	**16.61**	**7.03**	**10.80**	**4.23**
slph	**12.57**	**17.67**	**20.93**	**2.86**	**15.40**	**19.59**	**14.51**	**15.99**	**15.56**	**22.07**	**21.81**	**39.14**	**27.33**	**4.59**
slpl	**2.44**	**7.23**	**7.72**	**0.32**	**6.33**	**8.04**	**5.27**	**26.93**	**17.25**	**27.33**	**17.50**	**19.62**	**13.92**	**5.06**
wtdh	**1.81**	**1.56**	**1.64**	**0.77**	**0.93**	**1.23**	**1.50**	**1.50**	**1.71**	**1.70**	**10.18**	**5.83**	**6.09**	**0.59**
wtdl	**1.80**	**1.47**	**1.53**	**0.41**	**0.69**	**0.92**	**1.37**	**2.41**	**2.36**	**2.20**	**12.06**	**9.07**	**8.51**	**1.06**

ecoregions and has very little agriculture. The neighboring ecoregions have dairy agriculture (61 and 70), a mosaic of forest and croplands (60 and 67), or are similarly densely forested (69). Ecoregion 62 is ecologically distinct, but the soil ranks indicate a poor fit of soil map units in the ecoregion and considerable overlap with adjacent regions.

Northern Appalachian Plateau and Uplands (60)

Ranks $R_{sc} = 64$, $R_{er} = 48$, $R_{mu} = 74$, $R_{nh} = 74$, and $R_{tx} = 1$ indicate that soils in this ecoregion are mainly distinctive in their texture homogeneity, which is similar to the neighboring North Central Appalachians (62), with $R_{tx} = 2$. Ecologically, Ecoregion 60 is transitional between the less hilly, more agricultural and urban terrain of the Eastern Great Lakes and Hudson Lowlands ecoregion (83) and the more mountainous, forested, and less populated Ecoregions 62 and 58. Although many areas of Ecoregion 60 contain dairy farms with pastures, hay, and grain fields, there are also large areas of oak and northern hardwood forests. Surrounding Ecoregions 83, 62, and 58 tend to have more homogeneous land cover and are more distinguishable in their combination of geographic characteristics.

Ecoregions Closest to the USA

Arizona–New Mexico Plateau (22)

The ranks $R_{sc} = 1$, $R_{er} = 3$, $R_{mu} = 36$, $R_{nh} = 41$, and $R_{tx} = 84$ indicate that soil characteristics are similar to the U.S. mean and highly predictable, with moderate agreement of soil–ecoregion boundaries and overlaps, and very heterogeneous textures. A substantial portion of the shared soils are in Ecoregion 23. Ecologically, Ecoregion 22 is transitional between semiarid grasslands in 26 to the east, the higher relief tablelands in 20 to the north, and the lower, hotter, and less vegetated deserts in the south (24) and west (14, 81). The mountainous regions around 22 are more moist and vegetated while the surrounding deserts are hotter and drier. The diversity of climate and terrain in this region is reflected in very heterogeneous patterns of soil characteristics and texture ($R_{sc} = 1$ and $R_{tx} = 84$).

Ozark Highlands (39)

The ranks $R_{sc} = 72$, $R_{er} = 8$, $R_{mu} = 1$, $R_{nh} = 2$ and $R_{tx} = 22$ define soils that are distinct in characteristics and with respect to segregation from neighboring ecoregions. It is also ecologically distinct because all bordering ecoregions, with the exception of the Boston Mountains (38), belong to separate Level II ecoregions. In particular, Ecoregion 39 differs in physiography, vegetation, and land use from adjacent Ecoregions 38, 40, 72, and 73. The majority of Ecoregion 39 is a dissected limestone plateau covered by oak or oak–pine forests. Less than one-fourth of its core has been cleared for pasture and cropland, but agriculture increases to about one-half or more at the periphery. However, the bordering Ecoregions 40, 72, and 73 are even more agricultural.

CONCLUSIONS

Conventional mapped soil texture information describes 12 USDA classifications separately for different clay, silt, sand, and rock contents. By contrast, the texture–rock map (Fig. 1) in this study was developed by combining these soil properties vertically and over the space of soil map unit groups (Shirazi et al., 2001a,c). Despite some discrepancies across state lines in STATSGO data, the overall patterns in the soil information help explain and identify Level III ecoregions. Shirazi et al. (2001b) demonstrated a link between soils and water quality predictions. This study found associations between ecoregion boundaries and soil information, thus confirming the importance of soils as an ecological property. In addition, it is another step in quantifying ecoregion characteristics. For a more complete analysis of ecoregions and to enhance the reliability of data extrapolations, similar assessments should be conducted on other components such as climate, geology, physiography, and flora and fauna.

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