USDA United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Note
PNW-RN-524
April 1998

Lithosequence of Soils and Associated Vegetation on Subalpine Range of the Wasatch Plateau, Utah

James O. Klemmedson and Arthur R. Tiedemann

Abstract

Phosphorus (P) and sulfur (S) in soil and parent material are important in the accumulation of nitrogen (N) and organic carbon (C_{org}) in soils. In an observational study, the role of P and S in soil development was explored on a small knoll in the Wasatch subalpine summer range of central Utah that had been severely eroded during uncontrolled grazing in the late 1800s. Vegetation, litter, soil, and parent material were sampled along a transect across six strata forming highly visible narrow, concentric rings around the knoll. Even-numbered strata were characterized by large amounts of surface rock and sparse vegetative cover. Odd-numbered strata had less surface rock and visibly greater vegetative cover. Data for vegetation, litter, and soil surface properties displayed highly consistent peak and valley patterns for odd- and even-numbered strata with significant differences for 9 of 10 of these properties between the two strata groups. Organic C, potassium (K), and S of the parent material, and available N (N_{av}), P (P_{av}), and S (S_{av}) and exchangeable K (K_{ex}) of the 0- to 15-cm soil layer also displayed peak and valley patterns. Multiple regression of herbage yield on C_{org} and S of soil parent material, and P_{av} and (K_{ex}) of the solum gave high R^2s of 0.94 and 0.93. Multiple regression of grass yield on C_{org} and K_{ex} of the 0- to 15-cm soil layer had $R^2 = 0.95$. Based on results, the hypothesis that P of the parent material has influenced soil and plant development of these strata was rejected. The data subtly suggest that sulfur may play a key role in the development of these soil-plant systems. *Stipa lettermanii* Vasey and *Cymopterus lemmonii* Welch were strongly, but oppositely, correlated with most attributes studied, thereby suggesting these species may play important indicator roles of soil-vegetation development.

Keywords: Parent material, soil nutrients, pattern, phosphorus, sulfur, *Stipa lettermanii*, *Cymopterus lemmonii,* overgrazing, erosion, productivity.

JAMES O. KLEMMEDSON is professor emeritus, School of Renewable Natural Resources, 325 Biological Sciences East Building, University of Arizona, Tucson, AZ 85721; and ARTHUR R. TIEDEMANN is scientist emeritus, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry and Range Sciences Laboratory, 1401 Gekeler Lane, La Grande, OR 97850.

This research was supported by Grants 85-CRSR-2-2717 and 91-38300-6156, Range Research Grant Program, U.S. Department of Agriculture, Cooperative State Research Service, Washington, DC.

Introduction

In the subalpine zone of the Wasatch Plateau, central Utah, the human part of the biotic factor (Jenny 1980) seems to have been the overriding influence in the present condition and successional status of this summer range. After 35 years of destructive overgrazing by cattle and sheep in the late 1800s, these ranges were left in extremely poor condition (Reynolds 1911, Sampson and Weyl 1918). Erosion became so severe over much of the plateau that most of the soil A horizon was lost, and the vegetation had reverted to an early successional stage (Sampson 1919). Ninety years after grazing was first controlled, the range, though much improved, is not yet stable. Disturbance, though greatly lessened, is still present. The extent of degradation was not uniform over the entire summer range (Sampson and Weyl 1918), and recovery has not been uniform. Other state factors (Jenny 1980), especially topography and soil parent material, seem to have strongly influenced not only the extent of degradation in soils and vegetation but also the extent of subsequent recovery. Topography and soil parent material have differentially influenced successional status and productivity of specific soil-plant systems.

This study of soil-vegetal-parent material relations may explain strongly developed soil surface and vegetal patterns observed on a small knoll on this summer range. The hypothesis was that phosphorus (P) and sulfur (S) contents of contrasting parent materials, and their derived soils have been major factors controlling soil and vegetation development on this knoll (Walker 1956, Walker and Adams 1958). In turn, contrasting soil-plant systems that developed on those parent materials have responded differently to degradation caused by sheep grazing from 1870 until 1905 and the pathways of secondary successional that began thereafter with the regulation of grazing. These relations may have important implications for managing the summer range, especially if contrasting systems are distinctly different in site potential.

Description of Study Area

The study area was a small knoll on the Wasatch Plateau east of Ephraim, Utah, near the head of Manti canyon and just southwest of Snow Lake (39°14'N., 111°27' W.). The Wasatch Plateau is long, narrow, and oriented approximately north to south along the crest of the Wasatch Range with riblike ridges extending east and west. The plateau is about 3150 m elevation, gently rolling to nearly level, and dotted with knolls and small mountains. Slope gradient varies from nearly flat to about 35 percent for herbaceous communities and up to 65 percent for timbered sites on north-facing slopes.

Soil parent materials are of the Flagstaff limestone (Stanley and Collinson 1979) that crops out over about 7200 km^2 in central Utah.[1] The dominant lithology is freshwater lacustrine limestone and calcareous shales with minor interbeds of sandstone, oil shale, conglomerate, gypsum, and volcanic ash (Weber 1964, see footnote 1). Soils are mostly fine, mixed Argic Cryoborolls, but lithic, pachic, and vertic Cryoborolls also are locally present.

---

[1] Personal communication. 1988. J.F. Schreiber, Jr., Final report on the Flagstaff Limestone (Paleocene-Early Eocene) in the Manti-LaSal National Forest, east of Manti-Ephraim, Sanpete County, Utah. Department of Geosciences, University of Arizona, Tucson, AZ 85721.

Figure 1—Contrasting parallel strata of soils and vegetation are clearly apparent on the southwest aspect of Snow Lake knoll.

Average annual precipitation is about 840 mm; two-thirds of this occurs as snowfall between November and April. Precipitation averages only 173 mm during summer (June through September), but it ranges considerably. Mean annual temperature is about 0 °C (Ellison 1954).

Vegetation is chiefly herbaceous, but small patches of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) (plant nomenclature follows Holmgren and Reveal 1966) dot the landscape, especially on steep northerly exposures of east-west ridges and knolls. Because there are no apparent remnants of the original vegetation, opinions differ regarding successional status of present vegetation and character of the pristine vegetation. Ellison (1954) describes the original plant community as mixed-upland herb dominated by tall forbs, whereas Sampson (1919) considers wheatgrasses to be the primary species of the herbaceous climax (that is, what he merely refers to as summer range). Our recent research (Klemmedson and Tiedemann 1994) tends to support Sampson's thesis.

The small knoll at Snow Lake is typical of many knolls on the plateau. It occupies about 18 ha at the base and rises about 20 m to a nearly flat crest of 5 to 10 ha. On the sloping south and west exposures, narrow bands or strata forming concentric rings around the knoll are clearly evident below the crest of the knoll (fig. 1). The narrow bands or strata are an obvious expression of degraded communities (midseral at best) occupying highly eroded soils associated with contrasting layers of sedimentary rock. The dip of the sediment layers across this part of the plateau is very slight, as readily observed on steep cut and eroded surfaces nearby, hence the sedimentary layers or strata at the study site appear as nearly horizontal concentric rings around the knoll.[2]

---

[2] Personal communication. 1986. C.F. Lohrengel, geologist, Snow College, Ephraim, UT 84627.

Methods

Six strata were sampled to investigate soil-vegetation-parent material relations associated with the observed pattern. The first five strata were adjacent to each other; the stratum between strata 5 and 6 was omitted because of extreme heterogeneity within. The lateral distance across each stratum averaged 10.4 m. Slope gradient ranged from 12 to 16 percent, for strata 1-5, whereas that for stratum 6 near the top of the slope was 7 percent. Single soil pits were excavated midway between the upper and lower visual boundaries of each stratum along a transect that extended perpendicular to the contour on the southeast aspect (S. 30° E.) of the knoll. Soil profiles were described by standard terminology, and samples of known volume were collected of each horizon (three to five per pit). Grab samples of parent rock (either the C or R horizon) also were collected from each pit.

Herbage and litter in each stratum were sampled in four 0.5-m^2 plots randomly located each of 2 years. Foliar cover was visually estimated by species; mass of grasses, forbs, and litter were determined by harvesting each component separately, followed by ovendrying (70 °C) and weighing. For chemical analyses, soils were air-dried, sieved to remove coarse fragments (> 2-mm diameter), then ground to pass a 0.15-mm sieve. Parent material samples were pulverized, ground to pass the 0.15-mm sieve, then analyzed in the same manner as soils. Samples were analyzed for total carbon (C) by dry combustion (Nelson and Sommers 1982) in a LECO high-frequency induction furnace (Leco Corp., St. Joseph, Missouri).[3] Organic C (C_{org}) of soils was determined by difference after determining carbonate with a gasometric method (Dreimanis 1962). Total nitrogen (N) was determined with semimicro-Kjeldahl (Bremner and Mulvaney 1982) and total S by dry combustion in the LECO high-frequency induction furnace (Tiedemann and Anderson 1971). Soil total P (P_{tot}) was determined by using ascorbic acid color development (Olson and Sommers 1982) after hydrofluoric acid digestion (Bowman 1988). Inorganic P also was determined with the ascorbic acid color development on samples ignited at 550 °C for 2 hours (Olsen and Sommers 1982), and organic P (P_{org}) was determined by difference between P_{tot} and inorganic P. Cations were determined by inductively coupled plasma emission spectroscopy (Barnes 1977) after extraction with perchloric acid digestion for total cations (Johnson and Ulrich 1959) and ammonium acetate for exchangeable cations (Thomas 1982). Available nutrients were determined as follows: P by ascorbic acid color development following 0.5 m sodium bicarbonate extraction (Olsen and Sommers 1982), N by steam distillation of 2 N KCl extracts (Keeney and Nelson 1982), S with 1:1 water extracts, followed by ion chromatography (Dick and Tabatabai 1979).

---

[3] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1—Descriptive surface and soil profile characteristics for the 6 strata on Snow Lake knoll

Stratum	Depth of A horizon	Depth to C or R horizon	Slope gradient	Surface rock cover	Texture of A horizon	Description of parent rock
	– – Centimeters – –		*– – Percent – –*			
1	7.5	58	16	15.6	Gravelly loam	Slightly clayey micrite
2	2.5	43	16	84.6	Silty clay loam	Clayey micrite
3	2.5	56	14	15.2	Gravelly, silty clay loam	Clayey micrite
4	5.0	56	15	76.4	Silty clay loam	Clayey micrite
5	5.0	61	12	12.9	Gravelly loam	Clayey micrite
6	4.0	71	7	72.3	Silty clay loam	Very clayey micrite

Data were analyzed with graphic analysis, t-tests, linear regression, and correlation. Arcsin transformations were used for percentage data. Limited scope and lack of opportunity for replication in this observational study severely restricted more sophisticated analyses. To facilitate comparison among strata and simplicity of analysis, data for individual soil horizons of each soil pit were pooled and expressed for the 0- to 15-cm soil layer and for the entire solum. Because most profiles were only 20 to 30 cm deep and stony in the subsoil, these two values usually did not differ greatly. Most results for soils are expressed in terms of the surface 15 cm of soil.

Results and Discussion

Profiles for the six strata were similar, differing chiefly in depth of the A horizon, number and soil structure of horizons within the B, and amount and kind of coarse fragments (table 1). The following brief description for profile 3 was typical:

A—0 to 3 cm; very dark grayish-brown gravelly, silty clay loam; weak, fine granular structure; 15 percent gravel, 2 percent cobbles.

Bt1—3 to 13 cm; dark brown gravelly, silty clay loam; strong, medium subangular blocky structure; 20 percent gravel, 5 percent cobbles.

Bt2—13 to 38 cm; dark brown gravelly, silty clay loam; moderate, medium prismatic to strong, medium subangular blocky structure; 20 percent gravel, 5 percent cobbles.

Bk—38 to 56 cm; dark yellowish-brown, very gravelly, silty clay loam; moderate, fine angular blocky structure; 20 percent gravel.

R—Limestone bedrock.

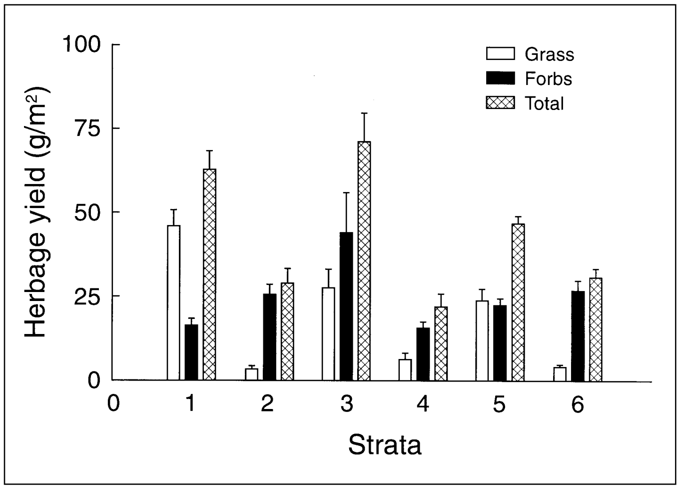

Figure 2—Herbage yield distribution across six strata on Snow Lake knoll. Bar values are means and standard errors of four samples.

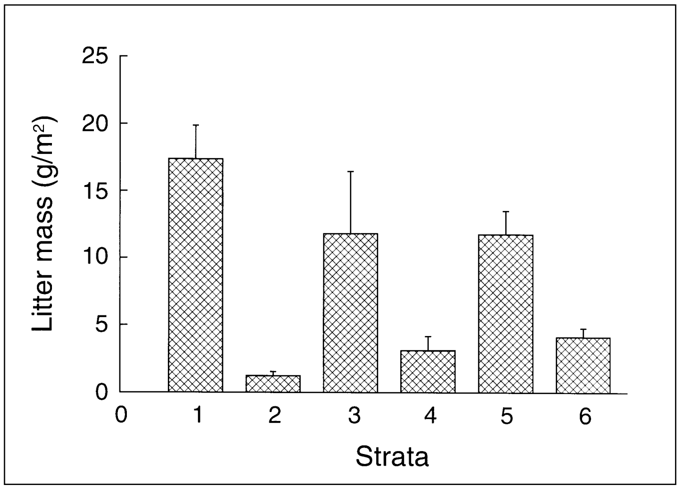

Figure 3—Pattern of accumulated surface litter for six strata on Snow Lake knoll. Bar values are means and standard errors of four samples.

Cyclic Pattern in Vegetation and Soil Surface

The cyclic pattern of horizontal strata on the hill slope of the Snow Lake knoll that was so readily observed from a distance (fig. 1) is just as apparent in graphic display of vegetal and soil surface characteristics portrayed in figures 2-5. Of the nine attributes displayed in these bar graphs, all but one (yield of forbs, fig. 2) show a consistent alternating peak and valley pattern proceeding up the slope. Using t-tests, we can reject the hypothesis that odd- and even-numbered strata were equivalent for these eight attributes (P-values ranged from 0.05 to 0.001). Based on herbage yields, litter mass, cover of litter, bare ground, and rock (figs. 2-4), it is

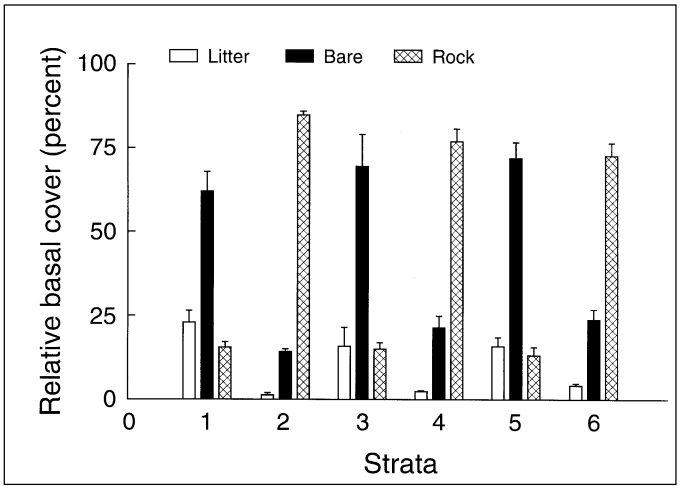

Figure 4—Pattern of litter, bare ground, and rock distribution on six strata on Snow Lake knoll. Bar values are means and standard errors of four samples.

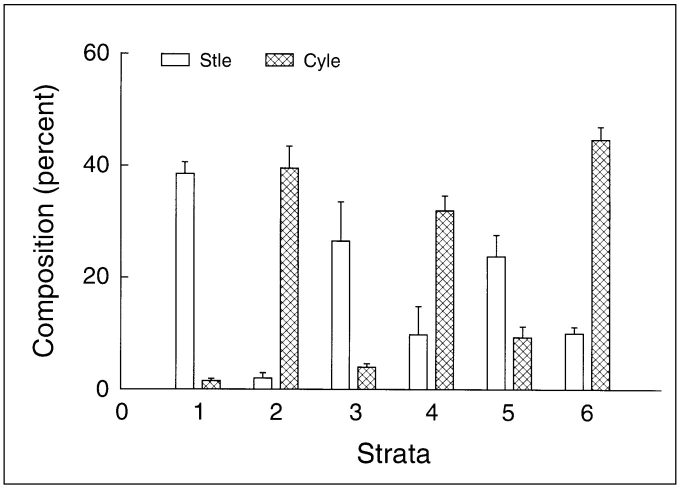

Figure 5—Pattern of *Stipa lettermanii* (Stle) and *Cymopterus lemmonii* (Cyle) distribution on six strata on Snow Lake knoll. Bar values are means and standard errors of four samples.

apparent that odd-numbered strata have far greater productivity than even-numbered strata (fig. 6). Large amounts of surface rock (> 60 percent) in even-numbered strata portrayed relative rockiness of the underlying soil profile as well, and strongly hinted of the extent of soil lost through erosion. Estimates of 50 to 85 percent loss of the A horizon from a nearby area of flat topography (Klemmedson and Tiedemann 1994) are probably conservative for this hill slope. For these strata, soil A horizons ranged from 1 to 5 cm thickness.

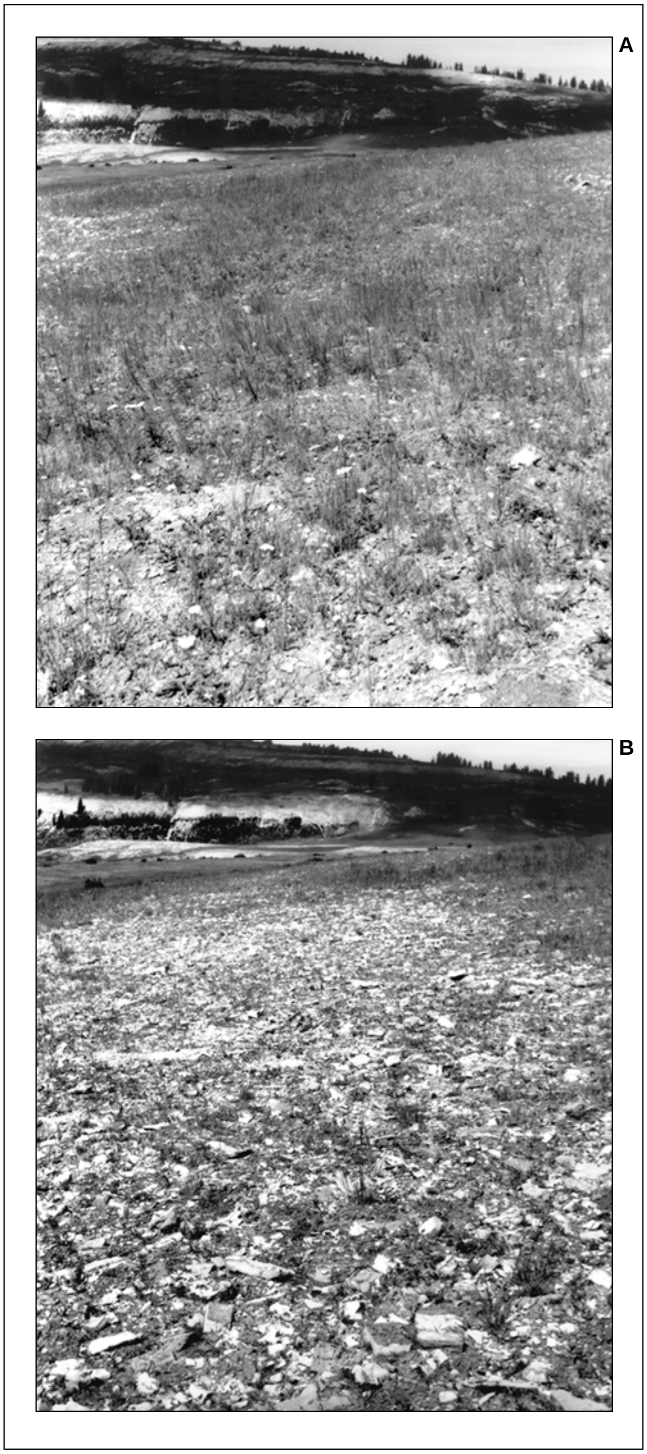

Figure 6—Representative odd- (**A**) and even-numbered (**B**) strata showing differences in soil surface conditions (that is, bare ground and rock) and vegetation.

Table 2—Percentage composition of species present on 6 strata on Snow Lake Knoll

	Stratum						
Vegetal component	1	2	3	4	5	6	Average
				Percent			
Grasses and sedges:							
Agropyron trachycaulum (Link) Malts	14.4	11.9	2.8	8.9	42.8	13.9	15.8
Festuca ovina v. *brachypylla* (Schult.) Piper	1.0	3.0	3.2	3.0			1.7
Poa fendleriana (Steud.) Vasey				19.8	.9		3.5
Stipa lettermanii Vasey	38.5	2.0	26.5	9.9	23.7	10.0	18.4
Total	53.9	16.9	32.5	41.6	67.4	23.9	39.4
Forbs and shrubs:							
Achillea millefolium ssp. *lanulosa* (Nutt.) Piper	16.4	27.7	16.1	7.9	14.9	15.4	16.4
Artemisia ludoviciana v. *incompta* (Nutt.) Cronq.	8.2		12.5	2.0		1.5	4.0
Aster foliaceus v. *canbyi* Gray			24.1				4.0
Astragalus miser v. *oblongifolius* (Rydb.) Cronq.	6.1	1.0		3.9		5.4	2.7
Chenopodium album L.					.5		.1
Cymopterus lemmonii Welch	1.5	39.6	4.0	31.7	9.3	44.6	21.8
Erysimum inconspicuum (S. Wats.) MacMill.				1.0			.2
Lesquerella utahensis Rydb.	6.2	14.8	6.4	7.9	4.6	9.2	8.2
Potentilla glandulosa Lindl.					1.9		.3
Taraxacum officinale Weber					1.4		.2
Thlaspi montanum L.				1.0			.2
Vicia americana v. *americana* Muhl.	7.2		4.4	3.0			2.4
Viola nuttallii v. *nuttallii* Pursh	.5						.1
Total	46.1	83.1	67.5	58.4	32.6	76.1	60.6

The extremely rocky even-numbered strata had higher percentages of coarse fragments (channers, flagstones, and cobbles) than adjacent odd-numbered strata (mostly gravel) and were described as clayey-skeletal and lithic in their classifications. Interestingly, odd-numbered strata with lower amounts of surface rock (< 25 percent) had high percentages of bare ground (62 to 72 percent). Thus, the absolute amount of bare ground plus rock exceeded 56 percent for all strata.

Of the 17 plant species found in the six strata (table 2), 4 were grasses and 13 were forbs. Grasses dominated the odd-numbered, high-yielding strata, whereas forbs dominated even-numbered, low-yielding strata. Only five species, two grasses (*Agropyron trachycaulum* (Link) Malte. and *Stipa lettermanii* Vasey) and three forbs (*Achillea millefolium* L. ssp. *lanulosa* (Nutt.) Piper, *Cymopterus lemmonii* Welch, and *Lesquerella utahensis* Rydb.), were present in all strata. Of these, *S. lettermanii* and *C. lemmonii* were negatively associated (fig. 5) and highly correlated (positively or negatively) with several variables discussed in figures 2-4. The other 15 species showed little or no relation to these variables.

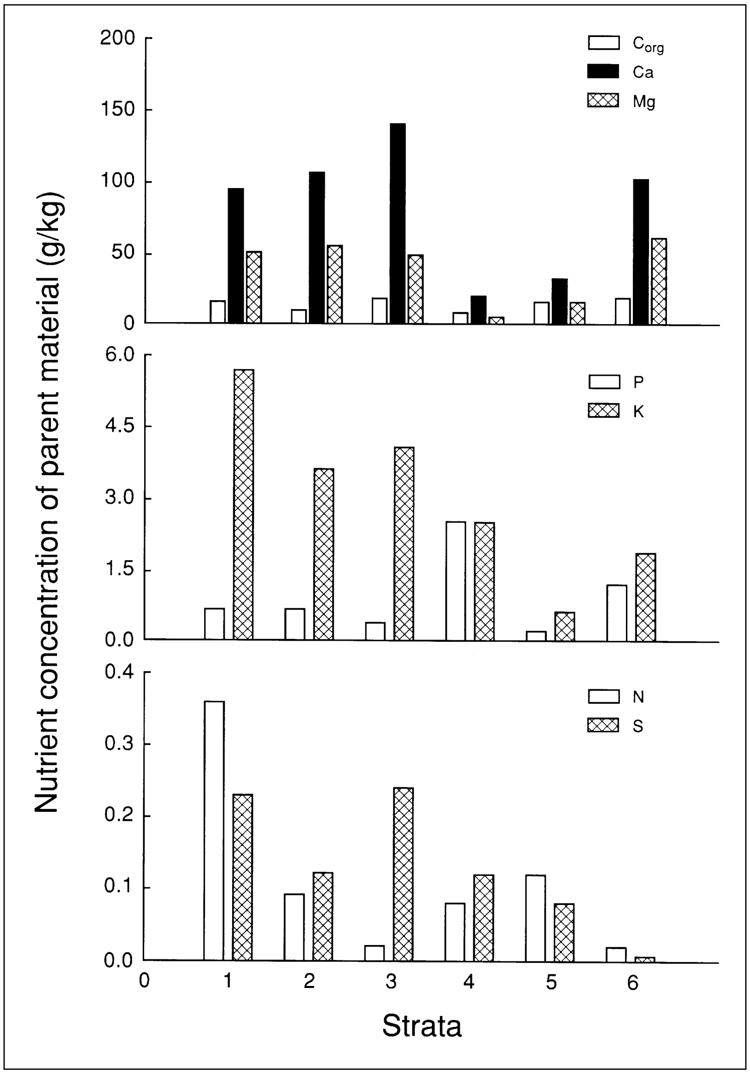

Figure 7—Pattern of nutrient concentration in single parent material samples for six strata on Snow Lake knoll.

Parent Material-Vegetation Relations

To investigate the hypothesis, we graphed concentrations of several parent material elements for each of the six strata (fig. 7). Only potassium (K), S, and C_{org} followed the peak and valley pattern shown in figures 2-5 for vegetal and soil surface properties. Pursuing this route, vegetal attributes of the strata were related with these and other chemical properties of the parent material by correlation analysis (table 3). Herbage yield was significantly ($P < 0.10$) correlated only with concentration of S, and yield of grasses was correlated ($P < 0.10$) with N and S. The multiple-regression equation relating herbage yield with C_{org} and S was highly significant ($P < 0.014$, regression coefficient [R^2] = 0.94). Standard partial regression coefficients indicated that S (0.68) was a slightly more important estimator of herbage yield than C_{org} (0.61). Multiple regressions relating grass yields with N and S, or other variables of the parent material, were not significant.

Table 3—Pearson's correlation coefficients (r) expressing relation between key vegetal attributes and element concentration of the soil parent material

Element	Dry matter yield: Herbage	Dry matter yield: Grass	Species composition: *Stipa lettermanii*	Species composition: *Cymopterus lemmonii*
	Grams per square meter		– – – – *Percent* – – – –	
Organic carbon (C_{org})	0.70	0.49	0.57	-0.40
Total nitrogen (N_{tot})	.36	.75[a]	.67	-.52
Total phosphorus (P_{tot})	-.67	-.48	-.43	-.51
Total sulphur (S_{tot})	.76[a]	.72[a]	.65	-.76[a]
Total calcium (Ca_{tot})	.52	.17	.13	-.08
Total magnesium (Mg_{tot})	.28	.06	.01	-.16
Total potassium (K_{tot})	.51	.56	.45	-.38

[a] Significant at $p < 0.10$.

Based on correlation analysis, concentration of parent material nutrients had little influence on composition of the two key plants, *S. lettermanii* and *C. lemmonii* (table 3). Correlation coefficients (r) between composition of *C. lemmonii* and parent material nutrients were all negative; only that for S was significant ($P < 0.10$).

Soil-Vegetation Relations

Four nutrients (available N [N_{av}], available P [P_{av}], exchangeable K [K_{ex}], and available S [S_{av}]) of the 0- to 15-cm soil layer generally displayed the same cyclic pattern (fig. 8) portrayed earlier for attributes of the vegetation and soil surface (figs. 2-5). Similar patterns as distinct as these (fig. 8) were found for the same nutrients in the entire solum (data not shown), and for other nutrients; for example, C_{org}, S, and P. When grouped, however, odd- and even-numbered strata did not differ significantly for soil properties. Relating plant attributes with surface soil (0 to 15 cm) nutrients across the six strata by simple correlation produced interesting results. Yield of total herbage and grasses, and *S. lettermanii* composition were highly correlated (correlation coefficients > 0.79) with P_{av}, S_{av} and K_{ex}, and C_{org} concentration of the surface soil (table 4). Similarity of r values among these nutrients is expected because of high multicollinearity ($r > 0.98$). By contrast, yield of forbs and composition of *C. lemmonii* were not significantly correlated with any of the nutrients (table 4). Yield of grasses and composition of *S. lettermanii* also were highly correlated ($r = 0.98$), hence the similarity of r values for a given nutrient with these two vegetal attributes.

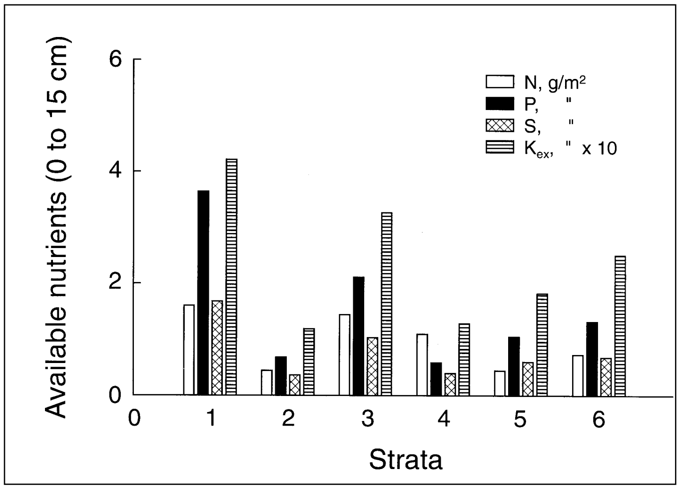

Figure 8—Pattern of distribution of solum nutrients for the six strata sampled on Snow Lake knoll. Bar values are weighted means for three to five horizons of single soil pits.

Regression analysis showed that nutrients of the solum explained more variance for total herbage yield, whereas nutrients of the 0- to 15-cm soil layer accounted for more variance for yield of grasses. Linear regression relating herbage yield with P_{av} and K_{ex} of the soil profile was significant at $P < 0.02$ and $R^2 = 0.93$. Standard partial regression coefficients showed K_{ex} was the more important of these two variables. Yield of grass was significantly predicted ($P < 0.012$ and $R^2 = 0.95$) by C_{org} and K_{ex} of the 0- to 15-cm soil layer. Based on standard partial regression coefficients, C_{org} was the more important variable here. We are cautious in attributing significance to any one nutrient because of multicollinearity among nutrients. Available S (S_{av}), however, may be an exception. Although it did not appear in the above regressions, because of high correlation ($r > 0.99$) with C_{org} in surface soils and K_{ex} in the solum, we suspect it may play an important role in development of these soil-plant systems. Like P, S plays a key role in soil C and N accumulation (Walker and Adams 1958, Williams and others 1960). The nutrient, S_{av}, was usually significant when included in regressions, especially for yield of grasses.

The most striking finding of this study was the strong negative association between *S. lettermanii* and *C. lemmonii* and the high, but opposite, correlation between composition of these two species and so many soil and site attributes of the study site (table 5). This negative association between the two species also was shown earlier for nutrients of the parent material (table 3), with the exception of P_{tot}. These results suggest high indicator value for both species. *Stipa lettermanii* clearly occupied strata with greater productive capacity, whereas *C. lemmonii* was found on rocky strata with shallow soils low in nutrients. The two strata groups (odd- and even-numbered) seem to have different plant production potentials and to be on different seral paths. The negative relations between available soil nutrients and percentage composition of *C. lemmonii* suggests that this plant is well adapted to nutrient-limited soils that may occur in secondary succession on infertile soils (Gleeson and Tilman 1990, Redente and others 1992), but more characteristic of early primary succession (Crocker and Major 1955, Olsen 1958).

Table 4—Pearson's correlation coefficients (r) expressing the relation between key attributes of the vegetation and amounts (g/m²) of selected nutrients in the 0- to 15-cm soil layer

	Dry matter yield			Species composition	
Nutrient	Total herbage	Grass	Forbs	*Stipa lettermanii*	*Cymopterus lemmonii*
	– Grams per square meter –			*– – – Percent – – –*	
Organic carbon (C_{org})	0.83[a]	0.91[a]	0.09	0.92[c]	-0.37
Available nitrogen (N_{av})	.63	.67	.12	.69	-.15
Available phosphorus (P_{av})	.79[b]	.90[a]	.04	.88[a]	-.31
Available sulphur (S_{av})	.80[b]	.91[a]	.05	.90[a]	-.35
Exchangeable potassium (K_{ex})	.82[a]	.84[a]	.21	.86[a]	-.24

[a] Significant at $p < 0.05$ level.
[b] Significant at $p < 0.10$ level.
[c] Significant at $p < 0.01$ level.

Table 5—Contrasting relations of *Stipa lettermanii* and *Cymopterus lemmonii* with various soil and site variables as portrayed by the correlation coefficient (r)

	Species composition	
Variable	*Stipa lettermanii*	*Cymopterus lemmonii*
	Percent	
Herbage	0.86[a]	-0.89[a]
Litter mass	.99[a]	-.93[a]
Bare ground	.76[b]	-.94[a]
Rock cover	-.84[a]	.95[a]
Bare ground + rock	-.96[a]	.94[a]
Soil, 0 to 15 cm layer:		
Organic carbon, (C_{org})	.92[a]	-.74[b]
Available nitrogen, (N_{av})	.69	-.59
Available phosphorus, (P_{av})	.88[a]	-.70[b]
Available sulphur, (S_{av})	.90[a]	-.72[b]
Exchangeable potassium, (K_{ex})	.86[a]	-.66

[a] Significant at $p < 0.05$ level.
[b] Significant at $p < 0.10$ level.

In contrast, *S. lettermanii* seems more sensitive to nutrient availability as indicated by its positive relation to C_{org}, P_{av}, S_{av}, and K_{ex}. This species seems indicative of a higher seral stage than *C. lemmonii*, but this is conjecture and needs to be supported by further study.

Results of this study demonstrated highly consistent cyclic patterns of vegetation, soil, and parent material properties across six horizontal strata, thereby suggesting a strong impact of parent material on soils and vegetation. The results, however, do not support the hypothesis that P of the parent material has influenced soil and plant development. The data do subtly suggest that S may play a role in soil and plant community development, and this hypothesis should be examined more closely. Large amounts of surface rock and bare ground, even on strata with highest pro-ductivity, reveals much about the history of degradation before control of grazing and the productive potential of this hill. It suggests the hill site was subjected to extensive erosion during the period of unregulated grazing, that restoration has been extremely slow, and site stability has not been reestablished after nearly 90 years of regulated grazing.

Conclusions

The soil-vegetal-cover relations of these sites, especially even-numbered strata of low productivity, suggest the need to regulate grazing on this and similar sites to assure that recovery is not impeded and that no further degradation occurs.

Two prominent species, *S. lettermanii* and *C. lemmonii*, were strongly, but oppositely, correlated with most attributes studied, thereby suggesting important indicator roles of soil-vegetation succession. Positive relations between *S. lettermanii* and P_{av} and S_{av} of the soil indicate that amendment with these elements may favor succession toward dominance of grasses. Previous research (Klemmedson and Tiedemann 1994) tends to support this speculation. Although fertilization is probably not an economically feasible option, further study may be warranted, particularly for sites that are severely deteriorated and actively eroding.

Acknowledgments

The authors gratefully acknowledge the Shrub Improvement and Revegetation Project, Intermountain Research Station (now the Rocky Mountain Research Station), Provo, Utah, for providing facilities for this research. We thank H.K. Swenson and V.L. Parslow, Natural Resources Conservation Service, for describing the soil profiles; Dr. J.F. Schreiber, professor of geosciences, University of Arizona, for assistance with descriptions of the geology of the area; Gary Jorgensen, range technician, Intermountain Research Station and Dr. Clyde Blauer, professor, Snow College, Ephraim, Utah, for plant identification and field sampling; and Justine McNeil, University of Arizona, for laboratory analyses and manuscript preparation. We thank Bernard Bormann and Richard Aguilar for critical review of the manuscript.

English Equivalents

1 centimeter (cm) = 0.394 inch
1 meter (m) = 39.37 inches or 3.281 feet
1 square meter (m^2) = 10.764 square feet
1 gram (g) = 0.035 ounce (avoirdupois)
1 kilogram (kg) = 2.205 pounds
1 hectare (ha) = 2.471 acres
°C = (°F - 32)/1.8
1 square kilometer = 0.386 square miles

Literature Cited

Barnes, R.M. 1977. Review of the applications of the inductively coupled plasma. In: Barnes, R.M., ed. Applications of inductively coupled plasmas to emission spectroscopy. Philadelphia, PA: The Franklin Institute Press: 3-49.

Bowman, R.A. 1988. A rapid method to determine total phosphorus in soils. Soil Science Society of America Journal. 52: 1301-1304.

Bremner, J.M.; Mulvaney, C.S. 1982. Nitrogen-total. In: Page, A.L., ed. Methods of soil analysis. Part 2. 2d ed. Agron. Monogr. 9. Madison, WI: American Society of Agronomy and Soil Science Society of America: 595-624.

Crocker, R.L.; Major, J. 1955. Soil development in relation to vegetation and surface age at Glacier Bay, Alaska. Journal of Ecology. 43: 427-448.

Dick, W.A.; Tabatabai, M.A. 1979. Ion chromatographic determination of sulfate and nitrate in soils. Soil Science Society of America Journal. 43: 899-904.

Dreimanis, A. 1962. Quantitative gasometric determination of calcite and dolomite by using Chittick apparatus. Journal of Sedimentary Petrology. 32: 520-529.

Ellison, L. 1954. Subalpine vegetation of the Wasatch Plateau, Utah. Ecological Monographs. 24: 89-124.

Gleeson, S.K.; Tilman, D. 1990. Allocation and the transient dynamics of succession on poor soils. Ecology. 71: 1144-1155.

Holmgren, A.H.; Reveal, J.L. 1966. Checklist of the vascular plants of the Intermountain region. Res. Pap. INT-32. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 160 p.

Jenny, H. 1980. The soil resource: origin and behavior. New York: Springer-Verlag. 377 p.

Johnson, C.M.; Ulrich, A. 1959. Analytical methods for use in plant analysis. Bull. 766. Berkeley, CA: California Agricultural Experiment Station: 26-77.

Keeney, D.R.; Nelson, D.W. 1982. Nitrogen—inorganic forms. In: Page, A.L., ed. Methods of soil analysis. Part 2. 2d ed. Agron. Monogr. 9. Madison, WI: American Society of Agronomy and Soil Science Society of America: 643-698.

Klemmedson, J.O.; Tiedemann, A.R. 1994. Soil and vegetation development in an abandoned sheep corral on degraded subalpine rangeland. Great Basin Naturalist. 54: 301-312.

Nelson, D.W.; Sommers, L.E. 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., ed. Methods of soil analysis. Part 2. 2d ed. Agron. Monogr. 9. Madison, WI: American Society of Agronomy and Soil Science Society of America: 539-580.

Olson, J.S. 1958. Rates of succession and soil changes on southern Lake Michigan sand dunes. Botanical Gazette. 119: 125-170.

Olson, S.R.; Sommers, L.E. 1982. Phosphorus. In: Page, A.L., ed. Methods of soil analysis. Part 2. 2d ed. Agron. Monogr. 9. Madison, WI: American Society of Agronomy and Soil Science Society of America: 404-430.

Redente, E.; Friedlander, J.E.; McLendon, T. 1992. Response of early and late semiarid seral species to nitrogen and phosphorus gradients. Plant and Soil. 140: 127-135.

Reynolds, R.V.R. 1911. Grazing and floods: a study of conditions in the Manti National Forest, Utah. Bull. 91. Washington, DC: U.S. Department of Agriculture, Forest Service. 16 p.

Sampson, A.W. 1919. Plant succession in relation to range management. Bull. 791. Washington, DC: U.S. Department of Agriculture. 76 p.

Sampson, A.W.; Weyl, L.H. 1918. Range preservation and its relation to erosion control on western grazing lands. Bull. 675. Washington, DC: U.S. Department of Agriculture. 35 p.

Stanley, K.O.; Collinson, J.W. 1979. Depositional history of Paleocene-Lower Eocene Flagstaff Limestone and coeval rocks, central Utah. American Association of Petroleum Geology Bulletin. 63: 311-323.

Thomas, G.W. 1982. Exchangeable cations. In: Page, A.L., ed. Methods of soil analysis. Part 2. 2d ed. Agron. Monogr. 9. Madison, WI: American Society of Agronomy and Soil Science Society of America: 159-165.

Tiedemann, A.R.; Anderson, T.D. 1971. Rapid analysis of total sulphur in soils and plant materials. Plant and Soil. 35: 197-200.

Walker, T.W. 1956. The accumulation of organic matter in grassland soils. Paris: Transactions of the International Congress of Soil Science, 6th Congress: 409-416.

Walker, T.W.; Adams, A.F.R. 1958. Studies on soil organic matter: I. Influence of phosphorus content of parent materials on accumulation of carbon, nitrogen, sulphur, and organic phosphorus in grassland soils. Soil Science. 85: 307-318.

Weber, J.N. 1964. Carbon-oxygen isotopic composition of Flagstaff carbonate rocks and its bearing on the history of Paleocene-Eocene Lake Flagstaff of central Utah. Geochimica et Cosmochimica Acta. 28: 1219-1242.

Williams, C.H.; Williams, E.G.; Scott, N.M. 1960. Carbon, nitrogen, sulphur, and phosphorus in some Scottish soils. Journal of Soil Science. 11: 334-346.

Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, Oregon 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, OR 97208