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Soil depth assessment of sagebrush grazing treatments using electromagnetic induction

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Abstract

Depth to a root restricting layer affects both soil moisture and nutrient availability, resources strongly correlated to plant cover and production. We evaluated the potential of 2 electromagnetic induction meters (EM38 and EM31) for non-destructively assessing soil depth to bedrock in 2 long-term seasonal sagebrush steppe sheep grazing treatments with different vegetational compositions. Apparent conductivity readings, measured with the EM38 and EM31 in both the horizontal (H) and vertical (V) dipole orientations, were positively related to soil depth. Apparent conductivity measured with the EM31H (r^2 = 0.78) and EM38V (r^2 = 0.75) were the best predictors of depth. Soil depth distributions were similar between grazing treatments based on Kolmogorov-Smirnov (K-S) tests of the EM38H apparent conductivity (P = 0.47) and EM38V apparent conductivity (P = 0.56). In contrast, K-S tests for the EM31H apparent conductivity (P = 0.09) and EM31V apparent conductivity (P < 0.01) indicated the fall-grazed treatment had a larger area in which soil depth exceeded 150 cm. Because less than 2% of each grazing treatment was predicted to have soils deeper than 150 cm, however, overall site differences between the 2 treatments appeared to be minor. Therefore, the vegetational differences between the treatments have probably resulted more from differences in the seasonality of grazing rather than ecological site characteristics as reflected in soil depth. Maps of soil depth indicated both treatments consisted of intermittent shallow and deep soils, created by several parallel basalt pressure ridges. Results suggest electromagnetic induction can effectively assess the spatial variability of soil depth and could aid in selecting sites for rangeland monitoring or manipulation.

Key Words: apparent conductivity, bedrock, kriging, site heterogeneity

Resumen

La profundidad de las capas duras en el suelo que impiden el desarrollo radical, afectan tanto el contenido de humedad de un suelo así como la disponibilidad de nutrimentos, recursos que están fuertemente correlacionados con la producción y la cobertura de las plantas. En este trabajo, evaluamos el potencial de dos medidores de inducción electromagnética (EM38 y EM31) que permiten realizar una evaluación no destructiva de la profundidad del suelo desde la superficie hasta el lecho rocoso rocoso. Esto se realizó durante muchos años en una pradera de Artemisa, bajo dos tratamientos con diferente composición de plantas y con pastoreo en primavera y otoño de ganado ovino . La mediciones de conductividad aparente (AC), realizadas con el EM38 y EM31 en orientaciones bipolares horizontal (H) y vertical (V), fueron relacionadas positivamente con la profundidad del suelo. Las mediciones de AC realizadas con el EM31H (r^2 = 0.78) y EM38V (r^2 = 0.75) fueron las mejores para la predicción de profundidad. La distribución de profundidad del suelo fue similar para ambos tratamientos de pastoreo. El análisis fue basado en las pruebas de Kolmogorov-Smirnov (K-S) para la AC en las mediciones EM38H (P = 0.47) y EM31V (P = 0.56). En contraste, las pruebas K-S de AC para lass mediciones de EM31H (P = 0.09) y EM31V (P < 0.01) indican que los tratamientos de pastoreo en otoño presentan una superficie mayor en la cual la profundidad del suelo excede de los 150 cm. Solamente en menos del 2% de cada tratamiento de pastoreo se hicieron predicciones de profundidades de suelo mayores de 150 cm, sin embargo, las diferencias generales del sitio entre los dos tratamientos son aparentemente menores. A pesar de esto, las diferencias de vegetación presentadas entre los dos tratamientos probablemente resultó mas de diferencias en la estacionalidad del pastoreo que de las características ecológicas del sitio reflejadas como profundidad del suelo. Los mapas de profundidad de suelo elaborados indican que ambos tratamientos presentan intermitencia en suelos profundos y someros, causados por la existencia de crestas paralelas de basalto. Los resultados obtenidos nos indican que la inducción electromagnética puede efectivamente evaluar la variabilidad espacial del suelo y puede ayudar en la selección de sitos para el monitoreo y manipulación de los pastizales.

Variability in the amount and type of vegetational cover on rangeland landscapes reflects both ecological site heterogeneity and disturbance history (Miller et al. 1994) occurring at various spatial scales (Brown and Smith 1993). This variability is particularly accentuated in arid and semiarid rangelands because of the

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limited water and nutrients available for plant growth (Tueller 1987). To successfully evaluate the relative influence of perturbations (e.g., grazing) on rangeland vegetation, the variability in ecological site conditions must be detected and quantified.

Monitoring the impact of livestock grazing has traditionally involved a comparison of grazed areas to ungrazed benchmarks (National Research Council 1994). Numerous problems, however, have been identified with the reliability of using benchmarks for rangeland condition assessment, one of which is their environmental uniqueness (West 1991, Tausch 1996). As a result, livestock grazing impacts can only be assessed in those situations where the rangelands under comparison are similar with respect to important ecological site characteristics, including soil properties such as depth, fertility, and texture (National Research Council 1994). Soil depth is a particularly important consideration across the western U.S. because many rangelands are dominated by shallow and spatially heterogeneous soils.

Rather than assuming that ecological sites are similar, it may be more practical to determine the relative areas of shallow, moderately-deep, and deep soils within each of the areas being compared. Furthermore, knowing the location and distribution of the various soil depths could be important for subsequently establishing benchmarks or other monitoring stations that can then be used to reliably evaluate vegetation change due to livestock grazing. In some situations, unconfounded comparisons may not be possible, averting the waste of time and resources. Detailed, objective information on soil depth could also provide more effective stratification for localized rangeland inventory sampling procedures. Unfortunately, conventional means of examining soil characteristics (i.e., from soil coring or pits) are destructive, time consuming, and expensive, especially for monitoring features deep within the soil profile (e.g., depth to bedrock).

Electromagnetic induction (EM) technology may enable rangeland scientists and managers to quickly and non-destructively evaluate the soil depth component of ecological site heterogeneity. Electromagnetic induction has been used to map natural subsurface features such as geologic strata (Zalasiewicz et al. 1985, Brus et al. 1992), permafrost layers (Kawasaki and Osterkamp 1988), sand deposits (Kitchen et al. 1996), soil salinity (Cannon et al. 1994, Hendrickx et al. 1992), groundwater (Cook et al. 1989, McNeill 1991), clay deposits (Palacky 1987), claypans (Doolittle et al. 1994), petrocalcic layers or caliche (Boettinger et al. 1997), as well as soil electrical conductivity profiles (Cook and Walker 1992).

In this study, EM techniques were used to map and quantify soil depth to bedrock on 2 grazing treatments within a semiarid sagebrush steppe rangeland. These treatments have pronounced differences in vegetation that have been directly attributed to differences in the seasonality of sheep grazing (fall vs spring) since 1924 (Mueggler 1950, Laycock 1967, Bork et al. 1998). The study area has high ecological site heterogeneity, however, primarily because it consists of soils formed in variable depths of unconsolidated loess and alluvium overlying basalt bedrock. The EM investigations facilitated an evaluation of the extent to which soil depth rather than grazing, may have influenced the previously documented differences in vegetation between the treatments. The objectives of this study were to, (1) establish calibrated empirical relationships between soil depth and the EM data, (2) evaluate the use of EM for mapping soil depth at the landscape scale, and (3) determine whether the long-term fall-grazed and spring-grazed treatments had similar soil depth distributions.

Methods

Study Site

Research was conducted within the long-term seasonal fall and spring grazing treatments at the U.S. Sheep Experiment Station headquarters near Dubois, Ida. (44°14'44" N. Lat; 112°12'47" W. Long.). The headquarters are situated at 1,650 m elevation (5,449 ft.), in the northeastern portion of the intermountain sagebrush steppe (West 1983). This vegetation type is the largest ecosystem type within the temperate semi-desert region of North America, and has been heavily altered by the cumulative impact of disturbances such as wildfire, insect irruptions, and the introduction of livestock and cultivation practices (Miller et al. 1994). The climate is semiarid with cold winters and warm summers, averaging 325 mm of precipitation annually (NOAA 1993).

Vegetation in the study area is dominated by three-tip sagebrush (*Artemisia tripartita* Rydb.), bluebunch wheatgrass (*Pseudoroegnaria spicata* [Pursh.] A. Löve), and arrowleaf balsamroot (*Balsamorhiza saggitata* [Pursh.]) (Laycock 1963; with current names following Kartesz [1994]). The 2 treatments were established in 1924 to differentiate between the impact of annual sheep grazing in fall versus spring. Since then, the spring-grazed paddock has changed from vegetation co-dominated by native, perennial herbs, to domination by perennial shrubs and annual (mostly non-native) herbs (Craddock and Forsling 1938, Mueggler 1950, Laycock 1967, Bork et al. 1998). In contrast, regular fall grazing decreased shrubs, resulting in a mixed, semi-open plant community with a diverse understory of perennial herbs. More detailed species compositional information within the 2 grazing treatments can be found in Mueggler (1950), Laycock (1967), and Bork et al. (1998).

Geologically, the parent material in the area consists of loess, mostly 0.5 to 2 m thick, but occasionally to 3 m, overlying mid- to late-Pleistocene age basalt rock (Scott 1982). Soils are formed primarily in loess with lesser amounts of residuum and alluvium on 0–12% slopes, and are dominated by fine-loamy, mixed, frigid Calcic Argixerolls (Natural Resources Conservation Service 1995). In addition, there is considerable variation across the landscape of soil properties, including the degree of argillic and calcic horizon expression and the thickness of a subsurface cobble line. Soil depths within the study area range from very shallow (< 25 cm) to very deep (> 150 cm), making it difficult to stratify the study area for vegetation sampling and interpretation. Soil depth was the focus of this investigation because it determines nutrient and water-holding capacity, and thus, influences plant cover and productivity.

Data Collection

Electromagnetic induction measures the apparent conductivity of earthen materials. Apparent conductivity is a weighted average measurement of electrical conductivity within a column of earthen materials to a specified observation depth (Greenhouse and Slaine 1983), and is expressed in milliSiemens per meter (mS/m). Apparent conductivity (AC) depends on at least 4 factors: soil water content, type and concentration of ions in solution, amount and type of clay minerals, and temperature of the substrate (McNeill 1980). Increases in soil water content, cation exchange capacity, and clay content tend to increase AC (Rhoades et al. 1976, Kachanoski et al. 1988), as does depth to a less-conductive restrictive layer (e.g., bedrock or a cemented horizon).

Electromagnetic induction techniques are most effective when only 1 of the aforementioned factors varies across the landscape while the others remain relatively constant (Cook et al. 1989).

Long-term fall- and spring-grazed paddocks, each 12.5 ha in size, were sampled during the third week of July, 1995, using EM techniques. The spring-grazed paddock was situated north of the fall-grazed paddock. A 30-m systematic sampling grid imposed across both treatments produced 156 sampling points per treatment. Apparent conductivity was measured at each gridpoint using EM38 and EM31 meters (both made by Geonics Limited), in both the vertical (V) and horizontal (H) dipole orientations. Most measurements were made within 0.5 m of each gridpoint however, some were made up to 4 m from the gridpoint to avoid interference from fences and other unmovable metal objects, which greatly increase AC. Both meters were calibrated prior to and during sampling (McNeill 1986, Geonics Limited 1992).

The depth of observation for each meter depends on intercoil spacing (unique to each meter), the transmission frequency, and the dipole orientation. The theoretical observation depths for the EM38 meter were approximately 1.5 and 0.75 m in the vertical and horizontal dipole orientations, respectively, when measurements were made at the soil surface. The EM31, which was held at waist height (about 1 m) above the ground while sampling, resulted in theoretical observation depths of about 5 and 2 m in the vertical and horizontal dipole orientations, respectively.

To determine the quantitative relationships between soil depth and AC, soil depth was measured at 64 points from 3 gridlines in the spring treatment and 2 gridlines in the fall treatment. Gridlines were selected to cover the range of measured AC. Of the 64 points, 2 were eliminated because they were located within a solitary vernal pool. The unusually high salt content of the vernal pool could have distorted the soil depth-AC relationship. Three other points were discarded because they occurred in soils heavily disturbed by animals (e.g., marmots or badgers).

At the remaining 59 gridpoints, soil pits were dug and the maximum soil depth measured. For deeper soils, where pits were impractical, depth to bedrock was measured using an auger; several holes were bored to ensure bedrock had been found rather than just an isolated stone. Although the maximum depth measureable using this technique was about 160 cm, bedrock was reached on all but 2 points.

For mapping purposes, a [1]Rockwell Precision Lightweight GPS Receiver (PLGR)™ with 1 meter precision was used to determine the geographic location of each treatment paddock corner and the sampling grid. Elevations for all gridpoints were measured with a laser transit level.

Analysis

Initially, the apparent conductivity (AC) data from the fall- (N = 24) and spring-grazed (N = 35) treatments were tested for homogeneity using the Proc GLM procedure (SAS Institute Inc. 1988) because data were collected from each paddock on separate days. Differential weather conditions may have altered AC readings between days, creating potential for a grazing treatment by AC interaction. Once the possibility of an interaction was ruled out, the data from both paddocks were combined (N = 59) for soil depth-AC calibration. Simple linear regressions established 4 predictive relationships between soil depth and AC (i.e., measured with the EM38 and EM31, in both the horizontal [H] and vertical dipole orientations [V]).

A Kolmogorov-Smirnov (K-S) chi-square test (Steel and Torrie 1980) was used on paired frequency histograms of AC (in 0.5 mS/m intervals) to determine if the distributions were similar between the 2 grazing treatments. Cubic convolution kriging within a geo-mapping software program, [2]SURFER™, was used to draw isodepth lines of soil depth based on AC.Complete maps were used to calculate the relative area of each treatment within consecutive depth classes (37.5 cm intervals). A 3-dimensional map of soil depth was overlaid on the elevational data, enabling interpretation of the pattern of soil depths across the landscape of both treatments.

Results and Discussion

Soil Depth - AC Relationships

Apparent conductivity data from each grazing treatment was found to be homogeneous (i.e., no treatment interaction) for both the EM38 and EM31, in the horizontal (P = 0.98 and P =0.58, respectively) and vertical orientations (P =0.38 and P = 0.70, respectively). As a result, soil depth-AC calibration was done with data from both treatments. Apparent conductivity was positively correlated with soil depth (r^2 = 0.62 to 0.78, depending on the EM meter and dipole orientation; Fig. 1).

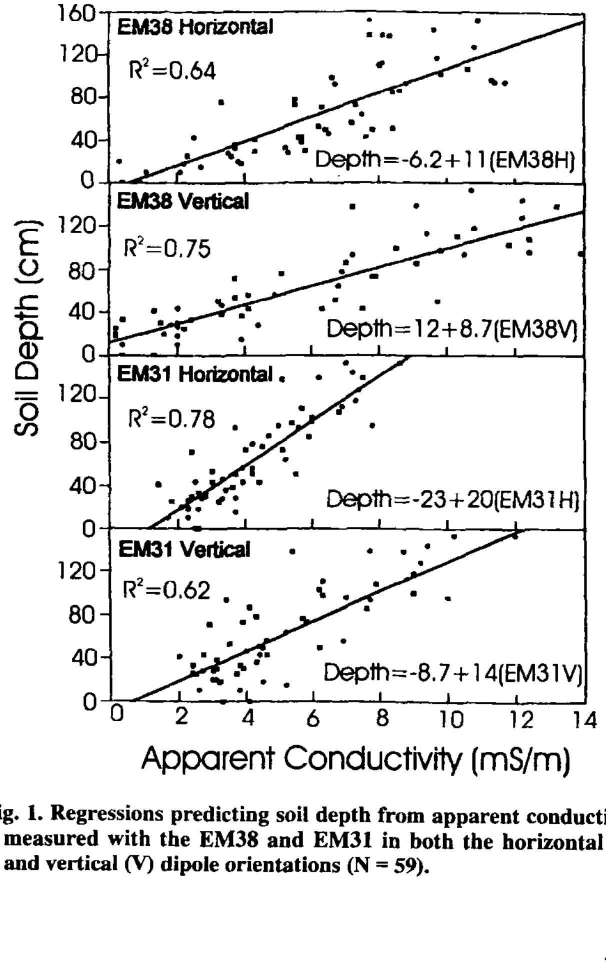

Fig. 1. Regressions predicting soil depth from apparent conductivity measured with the EM38 and EM31 in both the horizontal (H) and vertical (V) dipole orientations (N = 59).

[1]Rockwell International Corp. Collins Avionics Communication Division 350 Collins Road NE Cedar Rapids, Ia 52498.

[2]Golden Software Inc., 809-14th St., Golden, Colo 80401.

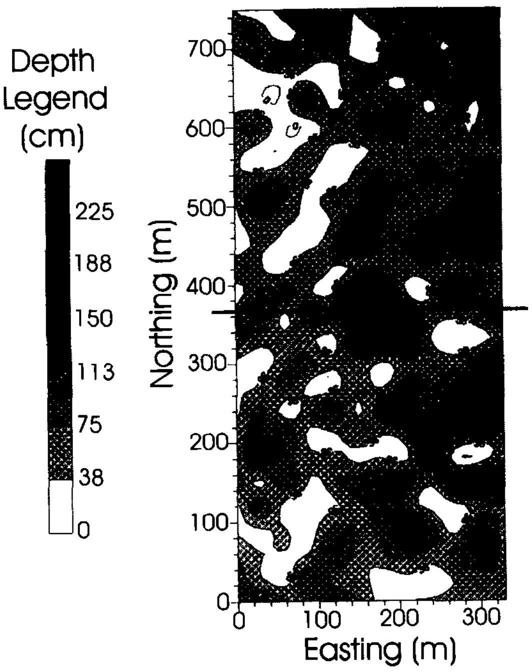

Fig. 2. Map of predicted soil depth within the fall-grazed (bottom) and spring-grazed (top) treatments based on apparent conductivity measured with the EM31H.

Apparent conductivities (AC) measured all 4 ways were highly correlated with one another ($r = 0.898$ to 0.964). As a result, the regressions for soil depth and AC measured with the EM31H and EM38V, which had the greatest coefficients of determination (r^2 of 0.78 and 0.75, respectively), were used for mapping soil depth. Only the map derived from the EM31H will be discussed here (Fig. 2). Isodepth lines were drawn at 37.5 cm intervals beginning at 0 cm, with the 75, 150, and 225 cm depths representing the approximate observation depths of the EM38H, EM38V, and EM31H, respectively. Three-dimensional contour maps of the treatments depicting soil depth across the landscape were similar for the EM31H and EM38V, with the EM31H map provided here (Fig. 3).

Despite the number of variables capable of influencing AC (e.g., moisture, salt, clay, and depth to a restrictive layer), AC was a good predictor of soil depth in this semiarid sagebrush steppe rangeland. Overall, the effectiveness of the regressions may have been limited by several factors, including the difficulty in accurately measuring soil depth (i.e., due to the irregular depth of contact between soil and rock or the variable cobble layer). Spatial variability in the thickness and degree of development of the argillic and calcic horizons in soils of the study area may also have limited the fit of the regressions, because the clay and carbonate accumulations associated with these horizons directly affect AC.

The EM31H and EM38V data had the strongest association between AC and depth, suggesting the type of electromagnetic induction (EM) meter and orientation used also influenced the potential utility and interpretability of the predictive relationships. The similiar r^2 between the EM38V and EM31H soil depth-AC regressions was not unexpected because each has a similar theoretical observation depth (150 and 200 cm, respectively). These observation depths approximately coincided with the maximum depth to bedrock in this landscape (Scott 1982), and likely account for why only a small proportion of the study area was mapped at depths greater than 150 cm (Fig. 2). The poorer predictability of the EM38H soil depth-AC regression may be attributed to the limited theoretic observation depth of this sampling procedure, which would fail to properly measure AC in areas with soils deeper than 75 cm (i.e., > 1/3 of the study area). Conversely, the effectiveness of the EM31V, measuring AC to 5 m depth, was probably limited by the common occurrence of basalt below 150 cm. Basalt bedrock is a poor conductor of electromagnetic energy and would restrict AC regardless of soil depth. The use of EM technology could help range scientists and managers by allowing spatial variability in soil depth to be assessed. The practical applications of this information on rangelands are numerous. For example, where variability is high the stratification of grazing treatments for vegetation sampling is critical during rangeland inventory, particularly if limited sample sizes are employed across the landscape. Stratification based only on visible aboveground characters (i.e., elevation, slope, exposure, vegetation, surface soil texture) is unlikely to be as reliable and objective as with the use of a subsurface mapping tool such as EM.

Another important application of this technology is for conducting rangeland condition assessments. When establishing benchmarks for monitoring range condition, EM could be used to map and subsequently screen prospective sites by determining whether rooting opportunities are uniform among the sites from which comparisons will be made (or inferred). Electromagnetic induction (EM) therefore has the potential to ameliorate the fundamental problem of off-site to benchmark comparisons (West 1991, Tausch 1996). Electromagnetic induction could be used on any rangeland with relatively thin loess, till, or alluvial deposits over bedrock, to verify that surficial vegetational changes are due to surface-based environmental disturbances (e.g., livestock, fire, insects, weather, etc.) rather than soil variability. Detailed subsurface mapping of rangelands could also allow investigators to quantitatively compensate for non-uniform site conditions by using apparent conductivity (AC) data as a covariate. This information can be tied into a GIS system to directly interpret vegetation patterns occurring over larger spatial scales (e.g., Stroh et al. 1993).

One of the major disadvantages of using EM techniques is that this process does require intensive ground-truthing, which must be repeated on any new area examined. In addition, AC data for quantitative site assessment are most effective when only a single response parameter varies across a site. Anomalies such as vernal pools, or other conditions where salts, clays, or excessive moisture may be present, can confound the soil depth-AC relationships obtained as well as the resulting maps of soil depth. An example of this was evident with the vernal pool at the north end of the spring-grazed paddock, which was measured at less than 85 cm depth but was incorrectly mapped up to a maximum of 225 cm. Both the EM38 and EM31 meters seem practical for investigating small to medium sized areas (such as done here), because individual readings take a minimal amount of time to complete (15 to 30 seconds). Although the equipment costs of these instruments are not excessive, particularly for the EM38 (e.g., purchase costs are about $6,850 and $16,695 for the EM38 and EM31-MK2 [a comparable model to the EM31 used here], respectively), labor costs may prevent their routine use on very large areas. Automated procedures are being developed, however, to improve the efficiency with which these data are collected (e.g., Kitchen et al. 1996).

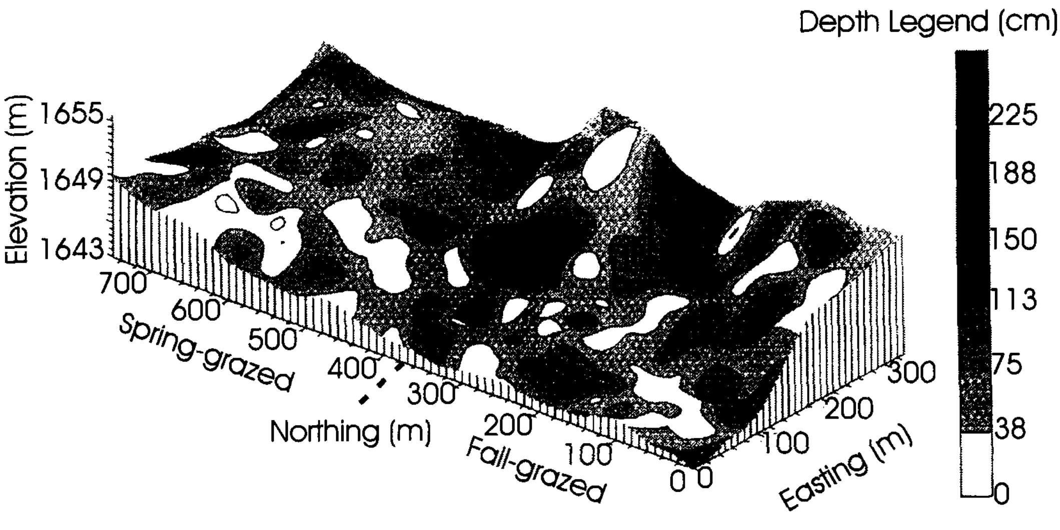

Fig. 3. Three-dimensional contour map depicting the distribution of predicted soil depth within the spring-grazed (left) and fall-grazed (right) treatments based on apparent conductivity measured with the EM31H.

Despite the potential drawbacks, EM could represent a significant cost-benefit to users in the long-term, relative to both the costs of manual soil sampling and the risks associated with incorrect interpretation of other (e.g., vegetational) data because of confounding soil depth conditions. Perhaps the most notable limitation at this point has been the lack of testing for common applications in rangeland environments.

Comparison Between Grazing Treatments

Results of the K-S tests for symmetry in the frequency distribution of the apparent conductivity (AC) data between grazing treatments varied, depending on the meter and dipole orientation used (Table 1). For example, the EM38H and EM38V readings indicated AC distributions were comparable between grazing treatments. In contrast, the EM31H and EM31V data indicated AC distributions differred significantly ($P < 0.10$) between the same treatments.

Despite the above differences, the area mapped within each predicted soil depth class was relatively similar between the fall-grazed and spring-grazed treatments (Table 2). In particular, the areas mapped by the EM31-H and EM38-V data were very similar within each treatment and depth class (Table 2). For all 4 data types, the most abundant soil depth class was that from 37.5 to 75 cm. About 90% of the total study area had predicted soil depths < 113 cm. Only about 2% of the area had predicted soil depths > 150 cm (Table 2, Fig. 2).

Table 1. Results of the Kolmogorov-Smirnov equivalence tests of the apparent conductivity frequency distribution data from the fall and spring-grazed treatments, by meter and dipole orientation.

Meter & Dipole Orientation	Theoretical Depth of Observation	K-S Test Reults: D-Statistics	P-Value
	(cm)		
EM38H	75	0.0962	0.47
EM38H	150	0.0897	0.56
EM38H	225	0.1410	0.09
EM38H	500	0.2051	P<0.01

This study appears to be the first direct comparison of a quantifiable subsurface rangeland characteristic, soil depth, between 2 grazing paddocks with unique management histories. Soil depth maps based on the EM31-H and EM38-V AC data (Fig. 2) showed that both the long-term fall- and spring-grazed treatments contained considerable heterogeneity, with pockets of deeper (> 75 cm) soils interspersed among numerous shallower (< 75 cm) ones. In addition, a pattern of alternating strips of deep and shallow soils (oriented SW to NE) was evident throughout the combined length of both treatments (Fig. 2). This pattern was likely produced by underlying parallel basaltic pressure ridges, separated by depressions with deeper soils. Although the shallowest soils (< 38 cm) were often found on topographic highs, this was not always the case (see Fig. 3), indicating that topographic position alone is not a good indicator of soil depth.

The relative areas of each of the 4 most common depth classes (< 150 cm) were similar between the 2 grazing treatments (Table 2). Because these depth classes make up about 98% of the area within each treatment, the relative abundances of plant species within each treatment were probably determined by factors other than soil depth. These results therefore support the proposition that the vegetational differences between the treatments are the result of differences in long-term seasonal grazing (Mueggler

Table 2. Proportion of the fall- and spring-grazed treatments mapped in various depth categories, as predicted by the EM31H and EM38V AC measurements.

Depth Interval	EM31H Fall	EM31H Spring	EM38V Fall	EM38V Spring
(cm):	(% of area)		(% of area)	
0–38	20.44	19.69	17.97	17.18
38–75	41.97	50.70	44.30	52.55
75–113	25.63	22.62	29.14	26.55
113–150	8.43	5.42	6.76	3.07
150–188	2.17	1.39	1.83	0.30
188–225	1.36	0.18	0.0	0.18
225+[1]	0.0	0.0	0.0	0.17

[1]The area within the spring treatment is partly attributable to an isolated vernal pool.

1950, Laycock 1967, Bork et al. 1998) rather than a difference in soil depth. Unlike the soils shallower than 150 cm, the deepest soils (> 150 cm) were distributed non-uniformly between the grazing treatments. This pattern was particularly apparent at the greatest AC observation depth (i.e., the EM31V data), with the fall-grazed treatment having a greater area of these soils (Fig. 2). Although the deepest soils make up only a very small proportion of the entire study area, this information remains important because localized vegetation sampling strategies falling within them may distort data intended for inference to the entire grazing treatment.

Conclusion

Most remote sensing tools have addressed the synoptic assessment of visible rangeland characters such as vegetation or soil surface properties (Tueller 1989). This study indicates that EM offers a rapid, non-invasive, and efficient tool for quantifying and mapping soil depth and thus, rangeland site quality, particularly in areas where the depth to bedrock is less than 2 m. In the process, this technology has shown the potential to affect future rangeland management by influencing mapping, sampling, and monitoring procedures.

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