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Case Study

Generalizing Ecological Site Concepts of the Colorado Plateau for Landscape-Level Applications

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On the Ground

- Numerous ecological site descriptions in the southern Utah portion of the Colorado Plateau can be difficult to navigate, so we held a workshop aimed at adding value and functionality to the current ecological site system.
- We created new groups of ecological sites and drafted state-and-transition models for these new groups.
- We were able to distill the current large number of ecological sites in the study area (ca. 150) into eight ecological site groups that capture important variability in ecosystem dynamics.
- Several inventory and monitoring programs and landscape scale planning actions will likely benefit from more generalized ecological site group concepts.

Keywords: drylands, land classification, MLRA 35, grazing, biological soil crusts, erosion.

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The Colorado Plateau is an iconic landscape of the American West—containing dozens of national parks, monuments, historic sites, and several UNESCO World Heritage Sites—including some of the Nation's most recognizable landmarks, such as the Grand Canyon and the Arches National Park. The concentration of outdoor destinations has led to a rapid increase in recreational tourism on the Plateau—visitation to the Arches National Park has nearly doubled over the last 15 years.[1] Energy development (mostly oil and gas) has also accelerated in recent years, with a threefold increase in drilling rates in Utah between 2000 and 2008.[2] Agriculture has been an important activity in the region from the prehistoric ages to modern times, with irrigated agriculture carried out in locations with suitable soils and water and domestic livestock grazing (primarily cattle) occurring across the majority of the region.[3] Management of these co-occurring land uses are complicated by forecasts of a more arid and variable climate in the southwestern United States.[4]

Because of the variety of land-use pressures, extensive lands managed by federal and tribal entities, and concentration of areas of recreation and conservation concern (e.g., national parks and monuments), the Plateau has a large and diverse set of stakeholder groups—often with conflicting values and differing perspectives. Discussions among stakeholder groups regarding managing land uses and mitigating climate change impacts are often complicated by the large imprint of past land uses, droughts, highly heterogeneous landscapes, and disagreements about reference conditions and management objectives. Tools that clearly specify ecological potential and possible state changes should facilitate these discussions. These tools are made available to managers via the Natural Resources Conservation Service (NRCS) Ecological Site Descriptions (ESDs). As described earlier in this special issue by Bestelmeyer et al., the utility of ESDs could be improved by simplifying them for stakeholder groups interested in broader-scale interpretation of ecological information. One approach to ESD simplification is to group ecological sites into broader units and then construct state-and-transition models (STMs) and related interpretations for individual groups.

With the hope of improving ESD information to support stakeholder discussions, a group of scientists and managers with knowledge of existing ESDs (U.S. Geological Survey, Bureau of Land Management [BLM], National Park Service [NPS], Agricultural Research Service, the NRCS, and university and private consultants) met in April 2016 to develop Ecological Site Groups (ESGs) and to draft associated STMs for the Colorado Plateau. The focus of the spatial scope of the workshop was on the Major Land Resource Area (MLRA) 35 within Utah (because of the existing data and experience), but allowed our work to extend beyond the MLRA 35 boundaries, where appropriate (Fig. 1). We limited our work to rangeland ecosystem types, including Woodlands but excluding Riparian and True Forestland types. Here, we report some of the outcomes of the workshop and follow-up analyses.

Landscape Attributes: Soils, Climate, Plant Communities, and Drivers of Change

The soil and geomorphic properties of the Plateau are strongly influenced by underlying geologic parent material, tectonic faulting, aeolian processes, and the relatively recent down-cutting by the Colorado River and associated drainages.[5] Geologic parent materials are predominantly sedimentary and include sandstones, silt/mudstones, limestones, and shales. Although well-known features of the Colorado Plateau are the exposed cliffs, rock outcrops, and thin soil deposits, landscape settings with deeper soil deposits tend to support plant communities that provide critical wildlife and livestock habitat (Grasslands and Shrublands). Key factors that appear to exert a strong influence on the distribution and resilience of Plateau plant communities include parent material salinity, mineralogy, and texture; landform; sand deposition; and soil depth.[6]

The Plateau is characterized as a cold desert ecosystem, with plant species assemblages adapted to low and variable precipitation, warm summers, and cold winters.[7] A strong gradient in summer (monsoonal)–winter (frontal) precipitation occurs, going from the southeast (~ 40% monsoonal) to the northwest (~ 20% monsoonal). Annual precipitation totals and average temperatures vary greatly across the region, mostly as a result of elevation, and both summer and winter precipitation are highly variable year to year.[7] This climate regime has resulted in a diverse plant community that is responsive to both cool season precipitation (often winter moisture stored in the soil profile) and summer monsoon events.[8] Plant communities comprise cool-season (C_3), warm-season (C_4), and succulent (CAM) functional types. Common Grassland species include Needle and Thread (*Hesperostipa comata* [C_3]), Indian Rice Grass (*Achnatherum hymenoides* [C_3]), James' Galleta (*Pleuraphis jamesii* [C_4]), Alkali Sacaton (*Sporobolus airoides* [C_4]), and Blue Gramma (*Bouteloua gracilis* [C_4]). Dominant shrub species include Big Sagebrush (*Artemisia tridentata* [C_3]), Blackbrush (*Coleogyne ramosissima* [C_3]), *Ephedra* species [C_3]), Shadscale Saltbrush

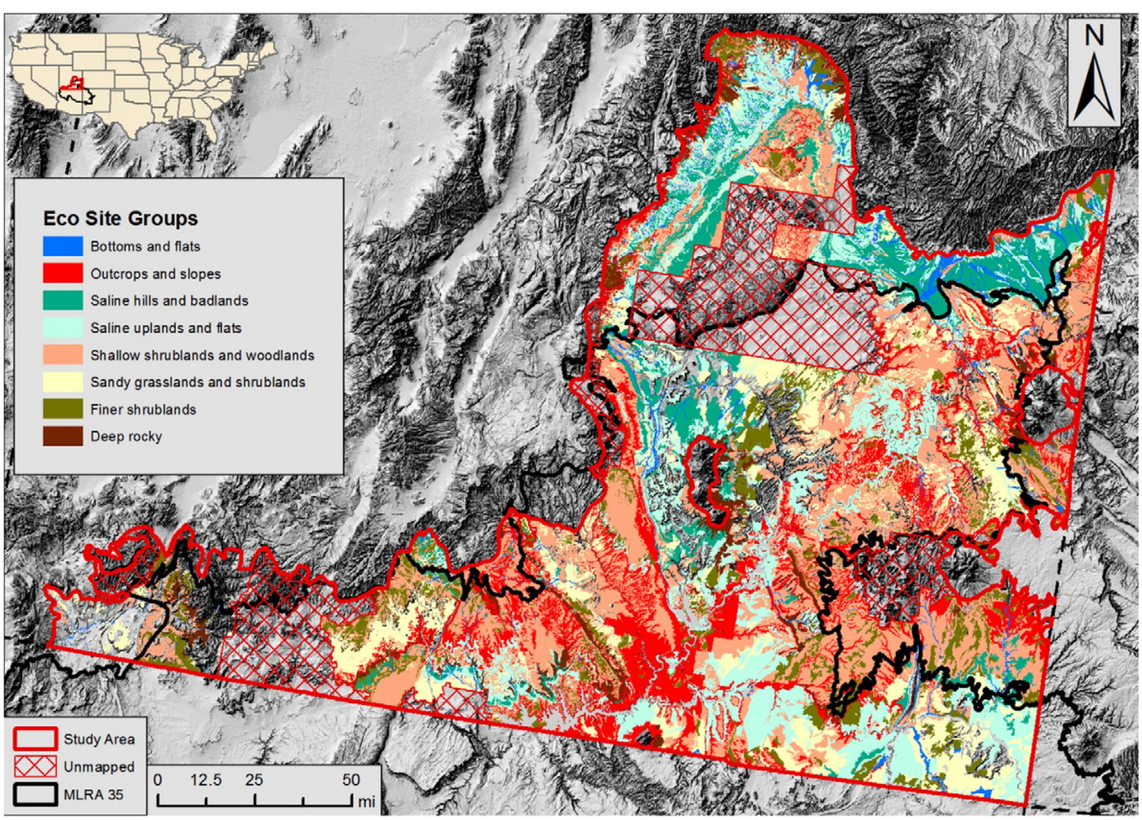

Figure 1. Map showing the study area used to query US soil survey geographic database (SSURGO) soil components *(thick red outline)*, and spatial correspondence to Major Land Resource Area (MLRA) 35 *(thick black outline)*. The study area was created by selecting Environmental Protection Agency (EPA) level 4 ecoregions, overlaying MLRA 35 within Utah, eliminating alpine and subalpine units, and then selecting SSURGO map units that overlapped highlighted ecoregions. Also shown are portions of study area where SSURGO has not been completed *(red crosshatch)*.

(*Atriplex confertifolia* [C_4]), and Mat Saltbrush (*Atriplex corrugata* C_4]). Tree species are primarily Utah Juniper (*Juniperus osteosperma* [C_3]) and Pinyon Pine (*Pinus edulis* [C_3]).

Common nonnative invasive species include such species as Cheatgrass (*Bromus tectorum* [C_3]) and *Salsola* (C_4); however, the extent and relative dominance of these invasive species is not as great as in the neighboring Great Basin province. Fires are smaller and infrequent on the Plateau because of large areas of broken topography, discontinuous fine fuels, and the prevalence of warm-season native species that grow actively during the monsoon season. The continued spread of invasive species into native plant communities is of great concern because of the resulting increase in the risk, extent, and frequency of fires.

Forecasts for a warmer climate with greater probability of severe and prolonged droughts,[4] current trends in recreational uses and energy development,[1,2] and demonstrated sensitivity of Plateau soils and plant communities to climate and land use are all of great concern to land managers in the region. Experiments and modeling results suggest that Plateau perennial grass species (particularly cool-season species) are highly sensitive to moderate prolonged drying.[8,9] Warming experiments (+2 and +4°C) documented a reduction in growth and performance of both cool-season and warm-season grasses.[10] Finally, biological soil crusts are an important component of the Colorado Plateau ecosystems and are highly sensitive to surface disturbance, warming, and altered precipitation.[11]

As is characteristic of the arid West, the current ecological conditions on the Plateau are greatly influenced by past land uses and droughts. The arrival of the transcontinental railroad to the region in the late 1800s led to overgrazing across the Plateau (both by sheep and cattle), and this, combined with the regional drought of the 1890s, resulted in widespread soil erosion and ecological state changes.[12,13] Many of these changes in ecological condition have persisted despite the improvements in grazing management following the Taylor Grazing Act and the return of years of normal to above-average precipitation. The current distribution of ecological states in the region is mediated by both current and historical land uses as well as soil and climate variations.[14,15]

Ecological Site Group Concepts

The goal of the ESG exercise was to define groups as generally as possible (resulting in the lowest number possible) while still being able to represent important ecological dynamics and critical management information with a single STM. Given the strong influence of geology and landform on the spatial structure, potential composition, and temporal dynamics of the Plateau plant communities, we began defining our proposed ESGs by subdividing the landscape on the basis of easily recognized topographic and geologic breaks. This process resulted in four general soil groups representing well-recognized constraints on plant community composition and dynamics: 1) bottoms and flats receiving run-on moisture; 2) outcrops and slopes that shed water and/or have very limited soil rooting volume; 3) soils derived from shales and other high-salt geologic parent materials; and 4) a broad group of upland soils derived from nonsaline limestones, sandstones, and siltstones (Table 1). We then examined the existing mapped soils and associated ESDs that fell within these four groups and further subdivided them until our goal of producing useful groups was met, and this resulted in eight ESGs (Fig. 2; see Table 1).

To describe these eight ESGs, we summarized the distribution of soil classes and properties ascribed to them in the US soil survey geographic (SSURGO) database within our study area (see Fig. 1). Soil components with ESD designations were put into the ESGs to query soil characteristics hypothesized to distinguish the groups. We used 1630 linked soil components and about 150 correlated ESDs. In summaries of property and class distributions, the ESGs were clearly distinguished by soil depth, slope, particle size, soil suborder, and general soil parent material (Fig. S1). Soil depth, slope, and particle size in the control section had the strongest relationship to the ESGs, whereas soil suborder, parent material, and landform had a moderate relationship. Investigation of nested relationships by using classification trees[16] showed that soil depth was most effective in the initial grouping of the ESGs. Particle size and slope tended to separate soils at the next level in the tree, whereas landform and soil suborder were mostly associated with finer-level groupings.

The ESGs contain important within-group variations in climate that affect plant community productivity and composition, as well as the characteristic states and probability of transitions. Thus, climate ranges will need to be explicitly accounted for in the final STMs (Fig. 3). Most of the ESGs span the full range of MLRA 35 elevations and climates that correspond to a wide range in expected plant production. For example, ESDs associated with the Shallow Shrublands and Woodlands group report production from 225 kg/ha in low-elevation Shrublands to upward of 1000 kg/ha in high-elevation Woodlands. Across most of the ESGs, there is a range in expected functional group composition along the elevation gradient, with more drought-/desert-adapted species at the lower end (e.g., greater composition contribution of warm-season grasses, Blackbrush, and Juniper) to species better suited for cooler and wetter conditions at the higher end (e.g., cool-season grasses, Wyoming and Mountain Big Sagebrush, and Pinyon Pine). There is also variation in the likelihood of specific transitions along these elevation gradients (as identified in the ESD STMs). For example, loss of Pinyon Pine is of concern across many ESDs, but only at the lower-elevation range for this species (primarily Ustic Aridic sites, approximately 1400 to 2000 m in elevation). Similarly, we expect the risk of transitioning to an eroding or bare ground state is much greater at the drier end than at the wetter end of the climate gradients (e.g., Fig. 3).

The ESGs also span important soil-geomorphic variability that will affect both expected plant community composition, production, and transition likelihoods[17] (Tables 1 and 2). For

Table 1. Ecological Site Group soil-landform setting and dominant plant communities

Ecological Site Group	Soil-landform setting	Dominant plant communities
Bottoms and Flats	This group occurs in flat, low-lying areas. Most have ephemeral washes and streams (not perennial). Soil texture, depth, and chemistry vary widely.	Dominated by shrubs associated with run-in landscape settings (higher surface or ground water available) and mixture of perennial cool-season and warm-season grasses.
Outcrops and Slopes	Bedrock controlled landforms with vegetation relegated to pockets, very shallow soil, or fissures. Often steep.	Pinyon-Juniper Woodlands, with various shrubs interspersed. Mostly exposed bedrock.
Saline Hills and Badlands	Highly salt limited (approaching sodic in some), erosion features common, often sloping.	Ephedra and Mat Saltbush dominated, with associated salt-tolerant species.
Saline Uplands and Flats	Salt limitations are less apparent than in hills and badlands because of mixing of non-saline/nongypsic parent material (often sandstone).	Shadscale and Galleta communities.
Shallow Shrublands and Woodlands	These are soils shallow to bedrock (~ < 50 cm) and often have high coarse fragment content (~ very gravelly and coarser).	Blackbrush Shrublands and Pinyon-Juniper Woodlands.
Sandy Grasslands and Shrublands	Deep aeolian and alluvial generally sandy deposits with varying levels of soil development.	Grasslands with some scattered shrubs (primarily Fourwing Saltbrush, but with some Sand Sage, Blackbrush, and Ephedra on sandier sites).
Finer Shrublands	Deep aeolian and alluvial deposits ranging from sandy loams to clay loams, with varying levels of soil development.	Mixed Shrub-Grasslands, with Blackbrush at the lower elevations transitioning to mostly Sagebrush at upper elevations.
Deep Rocky	These are loamy soils that are > 50 cm deep and have > 35% rock fragments by volume.	Exhibit a wide variety of dominant shrubs and trees, including Blackbrush, Big Sagebrush, and Juniper. All sites support higher grass cover than the nonrocky correlates.

instance, variation in slope affects water capture and susceptibility to erosion, which would induce corresponding variation in production and resilience to disturbances (see Supplemental Fig. 1). Most groups span a range of soil textures, which will affect susceptibility to invasion by exotic annuals,[18] erodibility, and drought resilience.[17] For ESGs that include shallow and/or rocky soils, the amount of exposed bedrock, the kind and depth of restriction, and the coarse fragment content and size will all affect plant community composition, productivity, and response to disturbance. It will be important to communicate within-group variability imposed by climate and soil factors to users, in descriptions, in tabular data, and/or in probability of transitions (*see Bestelmeyer et al., this issue*).

Generalized State-and-Transition Models

We examined published STMs for ESDs within each group as a first step toward developing general STMs (see Table 2). Based on existing STMs, some transition types are common across several ESGs: invasion by nonnative annual grasses and forbs, loss of perennial grasses, loss of soil and site stability (as a result of decreased ground cover, including biological soil crusts), tree encroachment, and shrub encroachment. Several ESGs have very few or no transitions of concern documented in the existing STMs (Outcrops and Slopes, Saline Hills and Badlands, and Deep Rocky). There are also transitions that are unique to individual ESGs: Tamarisk invasion only occurs in the Bottom and Flats and a range-seeding state is only included in Finer Shrublands (although we have also observed this state in the Shallow Shrublands and Woodlands ESGs). The remaining groups exhibit some combination of the common transitions described above (see Table 2). In the April 2016 workshop, we developed a draft of generalized STMs for four ESGs, one of which is described in Figure 3.

Challenges for Conservation Land Management

Several national and regional terrestrial ecosystem inventory and monitoring programs on the Plateau will benefit from well-defined ESGs and associated STMs. Data from these programs can also be used for quantifying the impact of environmental variation on state transition probabilities. Past and ongoing programs within the Plateau that use ESDs in their design and/or data interpretation include the NPS-

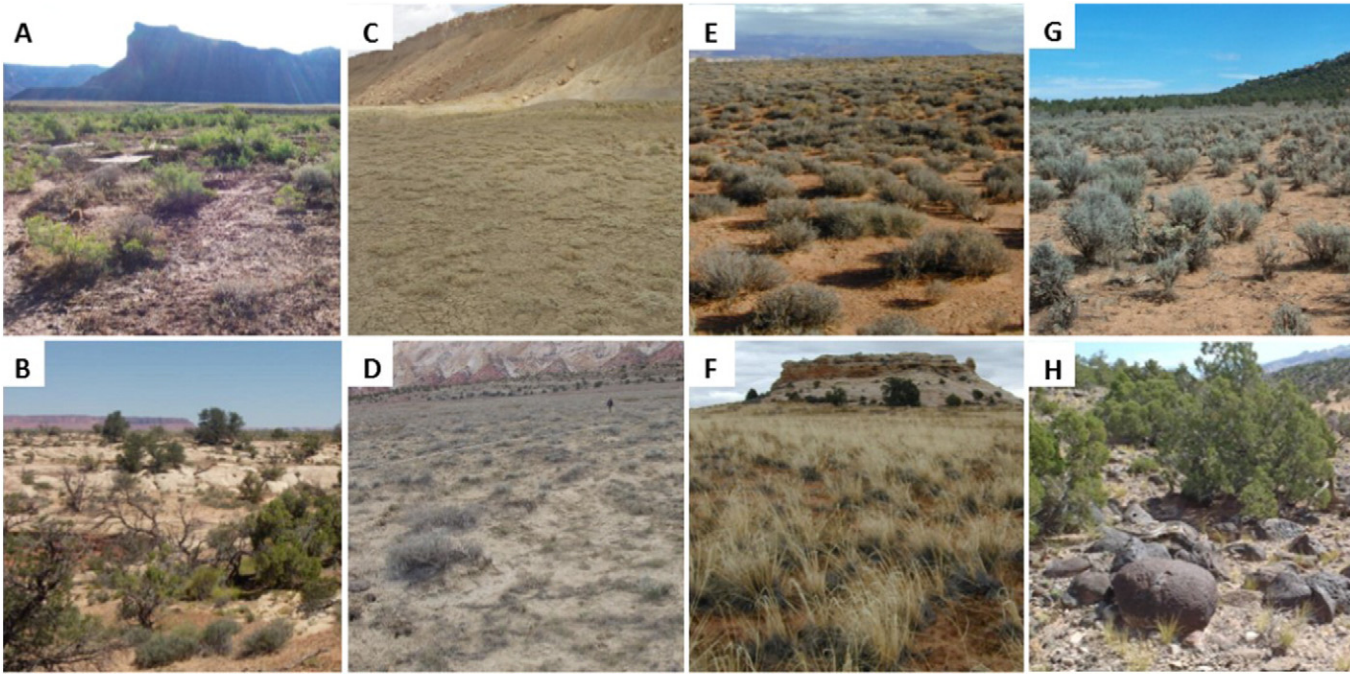

Figure 2. Photos illustrating Ecological Site Group (ESG) concepts *(ecological site description [ESD] depicted in parentheses)*. **A,** Bottoms and Flats (Alkali Flat [Greasewood]). **B,** Outcrop and Slopes (Rock Pocket). **C,** Saline Hills and Badlands (Desert Clay [Saltbrush]). **D,** Saline Uplands and Flats (Desert Loam [Shadscale]). **E,** Shallow Shrublands and Woodlands (Semidesert Shallow Sandy Loam [Utah Juniper, Blackbrush]). **F,** Sandy Grasslands and Shrublands (Semidesert Sandy Loam [Fourwing Saltbush]). **G,** Finer Shrublands (Semidesert Loam [Wyoming Big Sage]); **H,** Deep Rocky (Semidesert Stony Loam [Utah Juniper-Pinyon]).

Inventory and Monitoring Program[19]; Utah Division of Wildlife trend studies[20]; the BLM Assessment, Inventory, and Monitoring Strategy[21]; the NRCS National Resource Inventory[22]; monitoring and research studies at the level of individual management units (e.g., BLM range trend studies, monitoring programs within individual NPS units); and inventory or monitoring work done for research.[14] However, effective decision making based on these data sets is limited

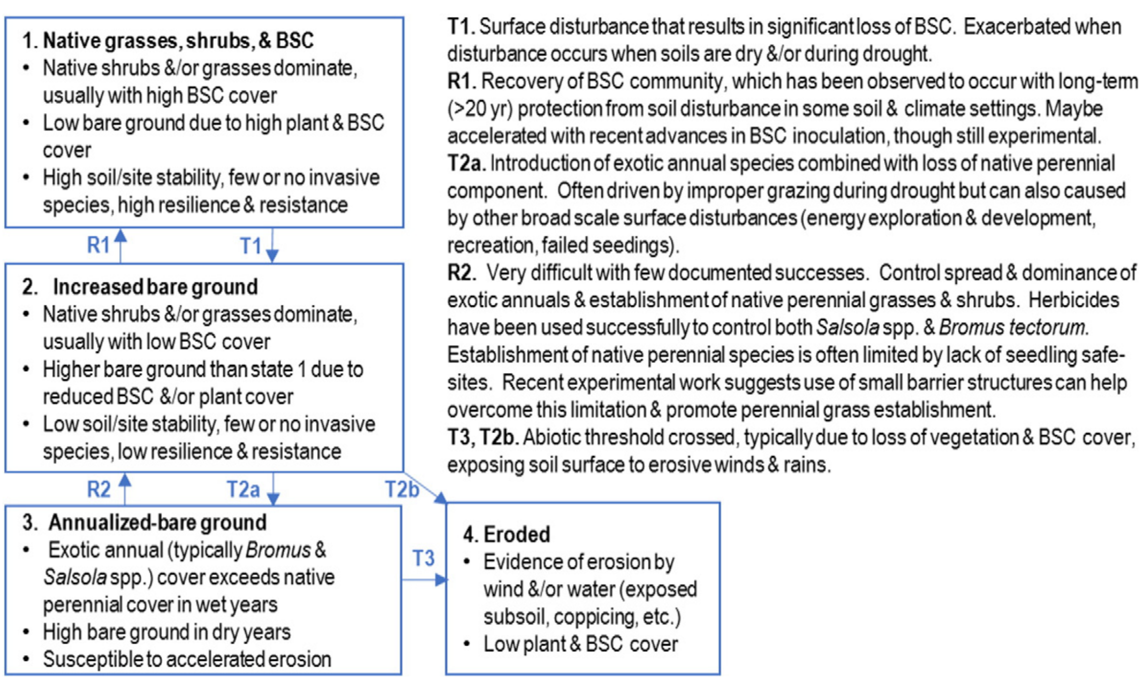

Figure 3. A draft state-and-transition model for Sandy Grasslands and Shrublands ecological Site Group (ESG) developed during the workshop and modeled on Miller et al.[14] Includes state concepts and descriptions of transitions and restoration pathways. BSC, biological soil crusts (a mix of cyanobacteria, lichens and mosses).[11]

Table 2. Within Ecological Site Group gradients and known types of transitions

Ecological Site Groups	Important soil and topographic gradients	Types of transitions
Bottoms and Flats	Texture (wide range), alkalinity, and depth to ground water.	Loss of perennial grasses, Tamarisk dominance, Cheatgrass dominance, accelerated erosion.
Outcrops and Slopes	Slope, extent of soil pockets, bedrock kind (hardness, weathering, degree of fractures).	Very few; Pinyon Pine mortality during drought, Cheatgrass invasion (not dominance).
Saline Hills and Badlands	Depth (shallow to deep), soil texture (clay to loam), mineralogy (shales, gypsiferous), salinity/alkalinity/sodicity.	Very few; fluctuating perennial grass, Cheatgrass invasion (not dominance).
Saline Uplands and Flats	Depth (shallow to deep), texture (loam to sandy loam), mineralogy (shales, gypsiferous), salinity/alkalinity/sodicity, rock fragment content.	Invasion and dominance by Cheatgrass, loss of perennial grasses, accelerated erosion.
Shallow Shrublands and Woodlands	Slope, soil depth (shallow to very shallow), soil texture (loamy sand to loam, primarily), restriction kind (bedrock, petrocalcic, degree of rock fracturing).	Loss of perennial grasses, Cheatgrass invasion (not dominance), accelerated erosion, tree/shrub encroachment, pinyon pine mortality during drought.
Sandy Grasslands and Shrublands	Soil texture (sands to coarser sandy loams), calcic development.	Loss of perennial grasses, Cheatgrass, and *Salsola* invasion and dominance, accelerated erosion, tree/shrub encroachment.
Finer Shrublands	Soil texture (sandy loam to sandy clay loam), argillic and calcic horizon development and depth.	Loss of perennial grasses, Cheatgrass, and *Salsola* invasion and dominance, accelerated erosion, tree/shrub encroachment, range seedings of non-native species.
Deep Rocky	Slope, soil texture (sands to loams), coarse fragment amount and size.	Very few; tree encroachment and dominances, fluctuating perennial grass cover.

by deficiencies of the current ecological site system (some of which are described by *Bestelmeyer et al., this issue*). On the Plateau, the very high number of ESDs has led to a mismatch between the degree of specificity in ESD-based land classification and the sampling density afforded by most inventory and monitoring programs. Funding levels for these programs, combined with the large amount of land they are tasked with evaluating, have resulted in low sampling intensity and lumping of ecological sites in analyses (e.g., Munson et al.[15]). Such ad hoc treatment of ecological site information could create confusion among different stakeholders.

There are several broad-scale planning and management actions occurring in the region that could also benefit from the development of ESG concepts and associated STMs. The BLM is currently implementing a new landscape-level approach to planning future mineral developments nationally (Master Leasing Plans [MLPs]), and several Master Leasing Plans have been initiated or will be underway soon on the Plateau.[23] Management planning and environmental analyses for other common land uses, such as livestock grazing and recreation, could also benefit from generalized ecological site concepts and STMs that facilitate broad-scale analyses and communication with diverse audiences and stakeholder groups. A well-described and mapped system of ESGs and associated STMs (made accessible via an online database; see *Bestelmeyer et al., this issue*) would have the potential to inform management decisions about siting requirements and best management practices for particular land-use types and could lead to data-driven prescriptions for site reclamation or restoration.

Recommendations for Improvements and Future Applications

We are optimistic that the added value and functionality of the ESGs proposed here (see Figs. 1 and 2) and future quantification of within-ESG edaphic gradients (see Table 1 and Fig. S1) will facilitate interpretation of monitoring data for decision support and inform broad-scale planning and management actions on the Plateau. These efforts can be further enhanced with regional ecological state mapping and spatial representations of important soil gradients within ESGs. ESGs and associated gradients can be represented by established gridded climate data (e.g., Parameter-elevation Regressions on Independent Slopes Model), SSURGO soil maps, and new approaches for mapping landforms, topographic setting, and soil properties based on terrain derivatives, and satellite lithology indices.[6] However, there are still some unresolved questions with regard to ESG definitions, and considerable work needs to be done before the general STMs outlined at our workshop can be employed.

Several ESGs include ESDs with a wide range in functional group composition within the reference state (e.g., perennial grass to woody dominated; see Table 1). The role of soils or the climate in these variations is not understood—some ESDs did not explain the presence of certain plants on particular soils. For example, Blackbrush is mostly associated with ecological sites that are characterized as shallow and/or rocky but can also be found in the reference state for ESDs within both the Sandy Grasslands and Shrublands and Finer Shrublands ESGs. It is possible that some ESDs that have reference states dominated by Blackbrush and other woody species are either alternative stable states of related ecological sites (with no explanation for the underlying soil); alternatively, the occurrence of these shrub states could be determined by some environmental variable that is, as of yet, unexplained (e.g., limiting nutrients).[17]

Finally, several issues with STMs on the Plateau will need to be resolved, either by exploring current data or by conducting new research. First, biological soil crusts (BSCs) occur in most ESGs and loss of BSCs potentially could be used as one of the defining indicators that a transition has occurred[14] (see Fig. 3). However, BSC integrity is not currently a key characteristic in published STMs in the study area, and more work is needed to assess when and how BSCs should be used in STMs. Second, invasion and dominance by the Cheatgrass (*Bromus tectorum*) and *Salsola* species is of great concern to many Plateau land managers. For some ESGs, dominance by these invasive species is not depicted in the majority of published STMs (see Table 2), which suggests that some ESGs may be resistant to dominance by invasive species. This notion should be confirmed through examination of available data. Last, identification of restoration pathways (and lack thereof) is a critical component of STMs, including restoration from highly disturbed or developed land. Developing STMs with sufficient details about restoration pathways, transition drivers, and other STM components to satisfy diverse stakeholders is costly and time intensive. By grouping ESDs into just eight ESGs (compared with the existing 150 ESDs), STM development efforts can be concentrated on fewer classes, which would result in fewer, more accessible models for informing landscape scale planning, communication, and decision making.

Lasting impacts of overgrazing (historical or current), oil and gas development, and/or recreation activities are expected in all ESGs (now and in the future). Given the current intensification of land uses on the Plateau, coupled with forecasts for a warmer and drier future in the Southwest,[4] mitigation of the deleterious impacts of land use and climate change on Plateau ecosystems will be a primary focus of land managers and stakeholders in the years to come.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rala.2016.10.010.

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