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Authors: Williams, C. Jason, Pierson, Frederick B., Spaeth, Kenneth E., Brown, Joel R., Al-Hamdan, Osama Z., et al.

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Case Study

Application of Ecological Site Information to Transformative Changes on Great Basin Sagebrush Rangelands

By C. Jason Williams, Frederick B. Pierson, Kenneth E. Spaeth, Joel R. Brown, Osama Z. Al-Hamdan, Mark A. Weltz, Mark A. Nearing, Jeffrey E. Herrick, Jan Boll, Peter R. Robichaud, David C. Goodrich, Philip Heilman, D. Phillip Guertin, Mariano Hernandez, Haiyan Wei, Viktor O. Polyakov, Gerardo Armendariz, Sayjro K. Nouwakpo, Stuart P. Hardegree, Patrick E. Clark, Eva K. Strand, Jonathan D. Bates, Loretta J. Metz, and Mary H. Nichols

On The Ground

- The utility of ecological site descriptions (ESD) in the management of rangelands hinges on their ability to characterize and predict plant community change, the associated ecological consequences, and ecosystem responsiveness to management.
- We demonstrate how enhancement of ESDs with key ecohydrologic information can aid predictions of ecosystem response and targeting of conservation practices for sagebrush rangelands that are strongly regulated by ecohydrologic or ecogeomorphic feedbacks.
- The primary point of this work is that ESD concepts are flexible and can be creatively augmented for improved assessment and management of rangelands.

Keywords: adaptive management, ecological site, erosion, Rangeland Hydrology and Erosion Model, resilience, runoff.

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Major Land Resource Area 23, the Malheur High Plateau, is representative of the northern Great Basin (Fig. 1), both in terms of the defining biophysical factors and the management challenges. Land managers across the Great Basin Region are challenged with addressing broad-scale existing and looming transformative ecological changes caused by plant community transitions and altered fire regimes. In particular, the sagebrush (***Artemisia*** spp.) ecosystem occupying much (~40%) of the Great Basin (~380,000 km^2) is considered one of the most imperiled ecosystems in the United States due to native woody and introduced annual weeds.[1,2] At mid-elevations (300-400 mm annual precipitation), grazing practices, climate conditions, and associated periods of reduced fire activity have promoted range expansion of pinyon (***Pinus*** spp.) and juniper (***Juniperus*** spp.) conifers. Encroachment of sagebrush rangelands by these species has formed extensive wooded shrublands and woodlands throughout much of the Great Basin. In recent decades, dense woody fuel loading in wooded shrublands has increased the occurrence of high severity fires. Burned woodland sites are also subject to invasion by cheatgrass (***Bromus tectorum*** L.) and a subsequent increase in fire frequency. At lower elevations (<300 mm annual precipitation), extensive cheatgrass invasion has converted sagebrush–bunchgrass communities to annual grasslands with a 10-fold increase in fire frequency. Collectively, these plant community transitions and altered fire regimes reduce biological diversity, wildlife habitat, and livestock forage; amplify runoff and soil loss; limit potential ecosystem goods and services; and increase the likelihood of permanent site degradation.

The utility of ecological site descriptions (ESDs) in the management of these systems hinges on their ability to

Figure 1. Geographic location of the Great Basin (bold black outline) and Major Land Resource Area 23 (MLRA 23, red outline) Malheur High Plateau, which contains the South Slopes 12-16 PZ (R023XY302OR)[11] Ecological Site. MLRA and Great Basin spatial data obtained from SAGEMAP (http://sagemap.wr.usgs.gov). Basemap of United States obtained from National Geographic and ESRI (http://www.arcgis.com/home).

characterize and predict plant community change, the associated ecohydrologic consequences, and ecosystem responsiveness to management. Plant community transitions commonly induce changes in vegetation structure that alter hydrology and erosion processes that, in turn, perpetuate a new stable state.[3,4] Plant community transitions that increase vegetation and ground cover promote infiltration and soil stability and an increase in soil water recharge and nutrients that further enhance vegetation productivity. In contrast, transitions that increase bare ground can facilitate runoff and erosion that further reduce soil water availability, remove critical soil nutrients, and limit vegetation productivity. Encroaching pinyon and juniper on sagebrush rangelands commonly outcompete shrubs and grasses for limited soil water, resulting in decreased understory vegetation and increased bare ground, runoff, and soil loss.[3,5,6] Increased fire frequency following cheatgrass invasion may also perpetuate a degraded, annual-dominated stable state. Burning increases erosion, and frequent occurrences of burned conditions may amplify soil loss over time.[7,8] Plant community dynamics are generally well documented for Great Basin sagebrush rangelands following woodland encroachment, cheatgrass invasion, and various management practices.[9] Likewise, the general hydrologic trends and erosion effects of these disturbances and management actions are documented in the literature.[8,10]

New technologies for quantifying ecohydrologic responses to disturbances and conservation practices are now available for integration of vegetation and hydrology interactions into ESDs.[4] This integration potentially increases the applicability of ESDs for assessing Great Basin sagebrush rangelands and for targeting of conservation efforts and expenditures. In this ecosystem, surface hydrology and erosion processes are affected by vegetation transitions and are important drivers of change. This tightly coupled feedback loop suggests that a more thorough understanding of hydrologic and erosion processes could be a powerful predictive tool. We employ the RHEM tool to characterize surface hydrology and erosion in context with community dynamics as a basis for improving rangeland management decision-making.

Ecological Site Concepts and State and Transition Model

The "South Slopes 12-16 Precipitation Zone (PZ)" (ID: R023XY302OR[11]) Ecological Site was selected for demonstration in this study. Conifer encroachment, cheatgrass invasion, and ecohydrologic feedbacks are primary drivers of state transitions on the site. The site is therefore representative of plant community structural and ecosystem functional dynamics common to sloping sagebrush rangelands throughout the Great Basin. The site is located in Major Land Resource Area (MLRA) 23 – Malheur High Plateau (Fig. 1). A full description of the site biologic and physical attributes is available online in the published ESD from the Natural Resource Conservation Service (NRCS).[11] A generalized state-and-transition model (STM) is shown in Figure 2.

The NRCS-approved ESD[11] describes five ecological states for the study site. The Reference State (State 1) contains two community phases: (1.1) a reference plant community phase with an understory of bluebunch wheatgrass (***Pseudor–*** [Pursh] Á. Löve ssp. ***spicata***), Idaho fescue (***Festuca idahoensis*** Elmer), Sandberg bluegrass (***Poa secunda*** J. Presl), Thurber's needlegrass (***Achnatherum thurberianum*** [Piper] Barkworth), and other perennial grasses and a shrub component of mountain big sagebrush (***A. tridentata*** Nutt. ssp. ***vaseyana*** [Rydb.] Beetle), basin big sagebrush (***A. tridentata*** Nutt. ssp. ***tridentata***), and antelope bitterbush (***Purshia tridentata*** [Pursh] DC.); and (1.2) a second phase, promoted by burning, that is dominated by bluebunch wheatgrass, Idaho fescue, Thurber's needlegrass, and other perennial grasses and forbs.

Invasion of the Reference State by annual forbs and grasses facilitates transition to State 2. State 2 includes three community phases: (2.1) one with sagebrush-steppe vegetation and trace cover of cheatgrass and annual weeds; (2.2) a second phase, facilitated by mismanaged grazing or reduced fire, with increased coverage of sagebrush and Sandberg bluegrass and trace cover of cheatgrass and annual weeds; and (2.3) a fire-limited phase with early-succession western juniper (***J. occidentalis*** Hook.) encroachment, sagebrush, Sandberg bluegrass, and trace cover of cheatgrass and annual weeds. Drought, improper grazing, or fire-exclusion in State 2 promotes transition to State 3. As juniper cover increases, sagebrush, grasses, and forbs decline. In State 3, juniper dominates site resources (biotic threshold), sagebrush and other shrubs decline, and extensive bare ground develops in the intercanopy. Sandberg bluegrass becomes the dominant grass species in State 3 and other perennial bunchgrasses are reduced in abundance and productivity. Juniper woodland development is complete in State 3 and soil erosion increases, ultimately driving the site beyond an abiotic threshold to State 4. In State 4, the site is dominated by juniper, soil loss is evident, and all ecological processes have been significantly altered. Catastrophic wildfire in State 4 promotes transition to State 5. In State 5, cheatgrass dominates the site, the shrub or perennial bunchgrass component has dropped out, and the hydrologic and nutrient cycles are negatively affected through changes in dynamic soil properties and soil loss. Transition to State 5 promotes more frequent burning (grass–fire cycle) than preinvasion, and the grass–fire cycle perpetuates cheatgrass dominance.

We applied the Rangeland Hydrology and Erosion Model (RHEM) tool (Version 2.3[i]) to estimate annual and event runoff and erosion and probability of occurrence of soil loss for ecological states of the study site and for dynamic vegetation conditions induced by disturbance and management.[4] The RHEM tool was created specifically for predicting runoff and erosion responses on rangelands and recently was applied to national rangeland assessments.[12,13] The tool was developed based on a suite of vegetation, hydrology, and erosion experiments conducted on grasslands, shrublands, and woodlands across the western United States.[13] The model produces graphical and tabulated output for annual and event precipitation, runoff, and erosion. The RHEM includes an optional [RHEM] Risk tool component that calculates probability of occurrence of soil loss, soil loss risk, for any year to fall into Low, Medium, High, or Very High soil loss categories.[14] The respective category thresholds are based on the 50^{th}, 80^{th}, and 95^{th} percentiles for probability of occurrence of soil loss for a user-defined baseline condition (e.g., reference condition).

For this study, we formulated RHEM scenarios for one community phase from each state and conditions representing wildfire and tree removal by prescribed fire and cutting. For brevity, we did not model each plant community phase in each state or all possible management situations. RHEM model scenarios were configured to represent selected ecological state conditions using respective state vegetation and ground cover attributes[4] and a climate station (Sheaville, Oregon, USA, Station ID: 357769, 1396 m elevation, ~315 mm annual precipitation [Fig. 3]), loam surface soil texture, 50-m hillslope length, uniform slope topography, and 35% slope gradient representative of the climate, soil, and topographic characteristics for the study site.[11] The Reference State (State 1, Phase 1.1) was selected as the baseline condition for application of the RHEM Risk tool. Relative comparisons of

[i] For more on the Rangeland Hydrology and Erosion Model (RHEM) see http://apps.tucson.ars.ag.gov/rhem/.

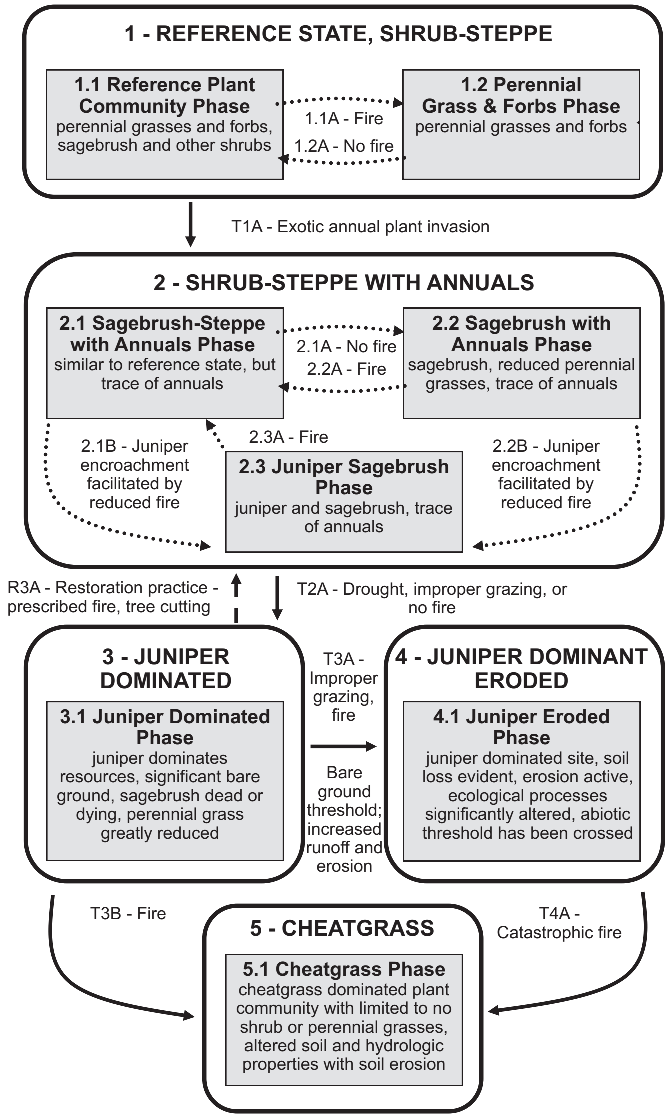

Figure 2. Generalized STM showing fundamental components for the South Slopes 12-16 PZ (R023XY302OR)[11] Ecological Site located in Major Land Resource Area 23, Malheur High Plateau. Individual ecological states are delineated by bold black rectangles, each with one or more within-state plant community phases (shaded rectangles). State transitions are indicated by solid black arrows. Within-state community pathways are indicated by dotted black arrows. Restoration pathways are indicated by dashed black arrows.

RHEM outputs (Figs. 4-6) by ecological state and for disturbances and management provide a baseline for assessing current ecohydrological function and potential ecosystem responses to plant community transitions and management. The RHEM results are summarized within Table 1 as an abbreviated site narrative within the context of the site STM (Fig. 2).

Implications for Conservation Decisions

RHEM-predicted runoff and erosion are minimal for the Reference State except for extreme events (≥ 25-year return interval; Fig. 4). Dense vegetation and ground cover under Reference State conditions dissipate raindrop impact, trap and store water, increase time available for infiltration, and limit runoff and erosion.[10] Erosion for the reference condition occurs mainly in isolated bare patches, but downslope sediment delivery is limited due to deposition in and around plants, plant litter, and other ground cover elements. RHEM results suggest the Reference State is indicative of good soil retention, with an 80% probability that soil loss will not exceed 0.645 t ha^{-1} in any given year (Low to Medium risk; Fig. 6A). Annual soil loss in excess of 1.0 t ha^{-1} is generally considered high for Great Basin rangelands. RHEM predicted runoff and erosion for State 2 is similar to that for the Reference State, although both runoff and soil loss slightly increase for 5- to 100-year events. State 2 is generally considered less ecologically desirable than the Reference State due to trace cover of juniper and/or cheatgrass, but vegetation and ground cover amounts in each phase of State 2 act to limit soil and water losses. Burning of the Reference State and State 2 increases runoff and erosion at the annual and event scales by

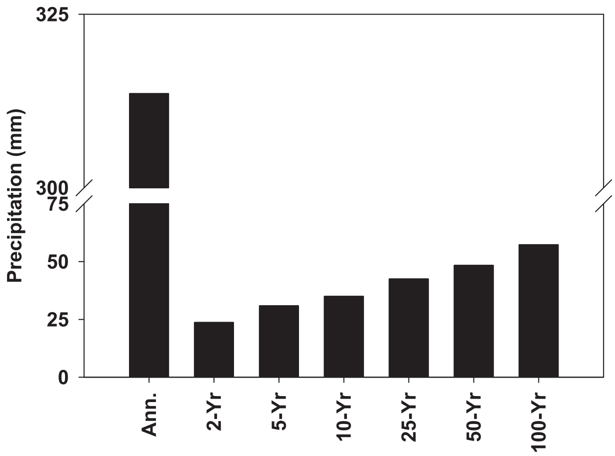

Figure 3. Precipitation at the annual time scale (Ann.) and for 2-, 5-, 10-, 25-, 50-, and 100-year return-interval runoff events in RHEM runoff and erosion modeling for the South Slopes 12-16 PZ Ecological Site. Values derived by RHEM based on climate data for the Sheaville, Oregon, USA, Climate Station, ID: 357769.

two- to five-fold and 30- to 70-fold, respectively (Fig. 4), but the increases are likely short-lived (1-3 years) due to the resilience of both states. Periodic fires are necessary to sustain the Reference State and State 2 (Fig. 2).

States 3 and 4 represent initial and potentially irreversible degraded state trajectories, respectively (Fig. 2). Increased western juniper cover associated with fire exclusion enhances connectivity of bare ground and runoff sources and promotes formation of high velocity concentrated flow through bare intercanopy areas.[3,15] Concentrated flow has greater sediment transport and detachment capacity than rainsplash and sheetflow and results in greater soil loss relative to conditions representative of the Reference State. Increased runoff and soil loss results in reduced retention of water and nutrients. Increased intercanopy bare ground following juniper dominance increases soil water loss to evapotranspiration without beneficial intercanopy plant productivity, effectively isolating soil water and soil nutrients to tree islands.[5] Juniper encroachment may also affect the spatial patterns of snow distribution and melt, and the timing and amount of soil water recharge and streamflow generation.[16] These changes in water availability influence vegetation productivity and thereby negatively affect habitat for sagebrush obligate species.

RHEM-predicted runoff and soil loss are greater for States 3 and 4 relative to the Reference State for nearly all return interval runoff events (Fig. 5); however, only erosion amounts are substantially greater for most return-interval events. High erosion rates associated with transition from State 3 to State 4

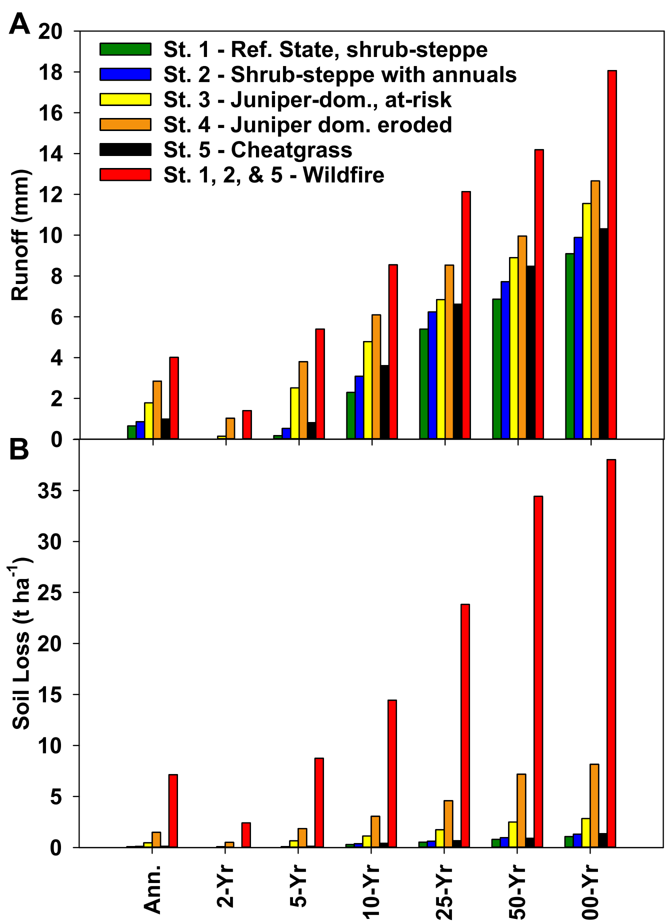

Figure 4. A, RHEM predicted runoff and **B,** erosion at annual time scale (Ann.) and for 2-, 5-, 10-, 25-, 50-, and 100-year return interval runoff events for each of the five ecological states and for burned conditions in States 1, 2, and 5 (St. 1,2, & 5 Wildfire).

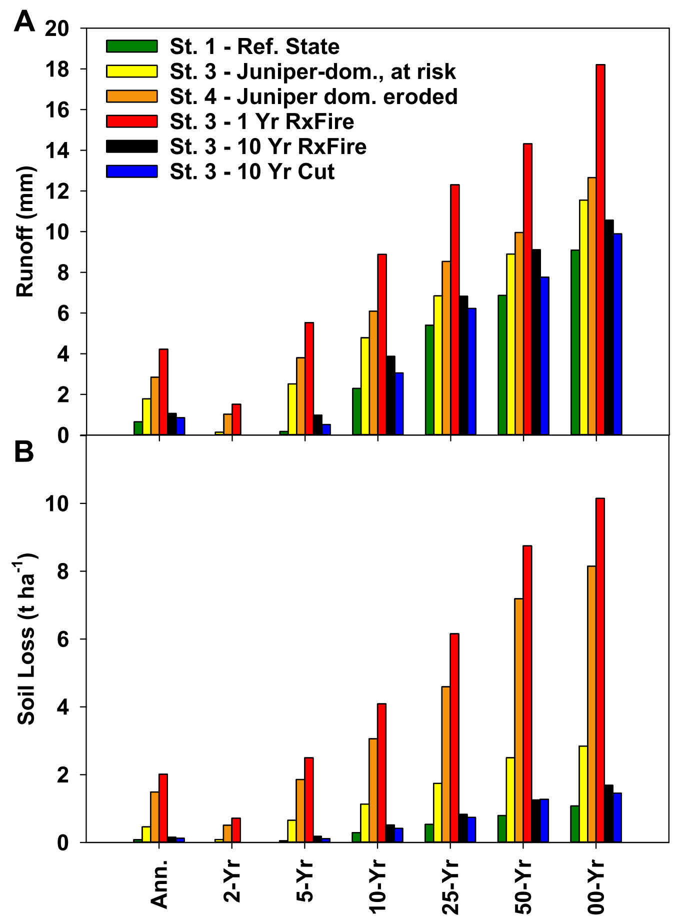

Figure 5. A, RHEM predicted runoff and **B,** erosion at annual time scale (Ann.) and for 2-, 5-, 10-, 25-, 50-, and 100-year return interval runoff events for State 1 (St. 1 Ref. State), State 3 (St. 3 Juniper-dom. at risk), State 4 (Juniper dom. eroded), and State 3 1 year following prescribed fire (St. 3 1 Yr RxFire), and 10 years following prescribed fire (St. 3 10 Yr RxFire) and tree cutting (St. 3 10 Yr Cut).

demark a likely shift beyond a soil conservation threshold to an irreversible degraded stable state. The likelihood of soil loss to exceed 1.195 t ha^{-1} (Very High category) is 34% for State 3 and more than 50% for State 4 (Fig. 6B) in any given year. Juniper removal by prescribed burning in State 3 may increase runoff and soil loss (Fig. 5) in the first few years post-fire, but likely results in reduced soil loss risk as vegetation and ground cover return in the years post-treatment.[9,10] RHEM simulations of State 3 indicate that the likelihood of Very High levels of soil loss decreases from 34% without treatment to 11% within 10 year after treatment, while the likelihood of Low to Medium soil loss increases from approximately 40% to nearly 70% after treatment for any given year (Fig. 6B). Similar results can be achieved through tree cutting without the initial erosion risk associated with the immediate post-fire period (Fig. 6B). Either treatment in State 3, assuming favorable vegetation response, dramatically reduces long-term erosion risk relative to State 4 (Fig. 6B). Burning initially increases erosion risk, and sagebrush recovery following burning may take decades.[9,10] Tree cutting without fire will retain the shrub and key perennial bunchgrass components,[9] but may increase the severity of a subsequent wildfire due to increased amounts of downed woody fuels. Vegetation recruitment after tree removal by burning or cutting may require seeding in later stages of State 3. Prescribed burning and tree cutting are not commonly applied in State 4.

Assessing the ecohydrologic ramifications of cheatgrass (transition to State 5) requires consideration of effects associated with repeated burning. The effects of cheatgrass on infiltration, runoff, and soils for unburned conditions are not well known.[17] Fire removal of cover for any state increases the connectivity of runoff and erosion generating bare ground, and facilitates a temporary shift from rainsplash and sheetflow to concentrated flow as the dominant erosion process across the site.[7,8,10] Post-fire vegetation and hydrologic recovery is generally more rapid for the Reference State and State 2 due to the presence of perennial bunchgrasses. Increased fire frequency in the cheatgrass-dominated State 5 increases the frequency of bare ground exposure to erosion processes and likely results in long-term loss of nutrient rich surface soil through repeated erosion by water and wind.[8,17] The probability of Very High soil loss (>1.195 t ha^{-1}) is more than 80% for burned conditions in the Reference State and State 5 in any given year (Fig. 6A). This condition will occur more often in State 5 (fire frequency is ~10-fold higher) relative to the Reference State, potentially increasing long-term soil loss and pushing the site

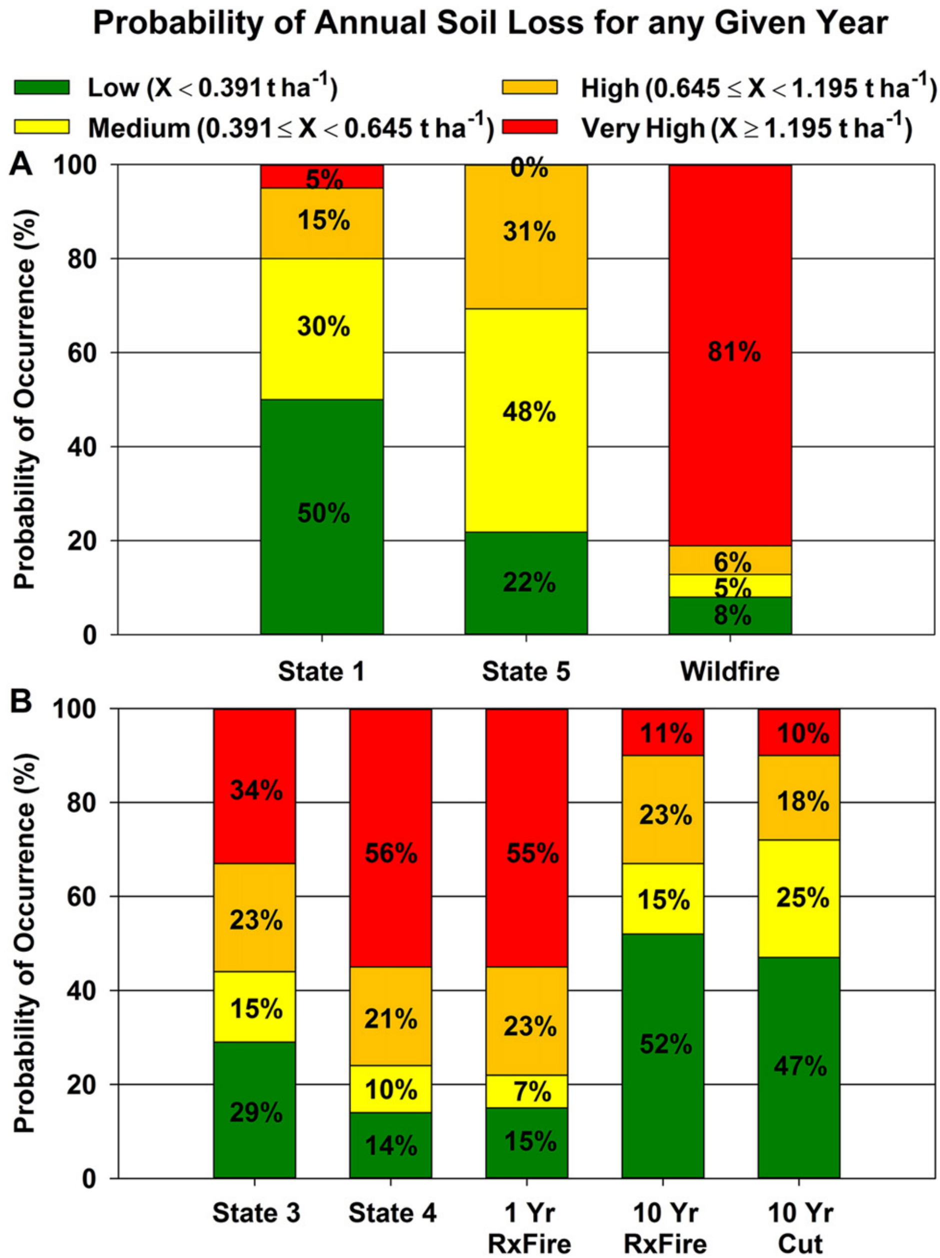

Figure 6. RHEM predicted probability (expressed as percent) of occurrence of soil loss for any year for sagebrush and cheatgrass states (**A**, State 1 shrub-steppe, State 5 cheatgrass, and States 1, 2, and 5 after wildfire [Wildfire]); and for juniper-encroached states and tree removal practices (**B**, State 3 juniper-dominated, State 4 juniper dominant eroded, and State 3 1 year following prescribed fire [1 Yr RxFire], and 10 years following prescribed fire [10 Yr RxFire] and tree cutting [10 Yr Cut]).

beyond a soil conservation threshold. RHEM predicted erosion for burned conditions of State 5 exceed that of unburned conditions in the Reference State by 30- to more than 70-fold across the annual to 100-year return interval runoff events, ranging from 2 to nearly 40 t ha^{-1} for the simulated return interval events, and 7 t ha^{-1} at the annual time scale (Fig. 4B).

Conclusions and Management Implications

Ecological Site Description concepts are broadly applicable and provide a framework to inform and guide rangeland management decisions. In this paper, we demonstrate how knowledge and quantification of key vegetation, hydrology, and soil relationships in the ESD context can improve rangeland assessments and targeting of management practices in Great Basin sagebrush steppe.

For the example presented here, integration of vegetation and relative estimates of runoff and erosion into the STM or ESD context identifies the ecohydrologic ramifications of each state transition and allows for more informed understanding of short- and long-term site responses to various management alternatives. We did not consider other factors important to a land management decision process, such as land use designations or goals, cost and practicality of treatment alternatives, resource

Table 1. Ecohydrologic-based narrative for the ecological site dynamics and generalized STM components of the South Slopes 12-16 PZ (R023XY302OR) Ecological Site

State	Community pathways/Transitions and resilience
1. Reference state shrub-steppe	Plant community phase change is controlled by fire. Ample cover favors infiltration and retention of water and soil resources (high resilience). Runoff and erosion are low (except for 50-yr to 100-yr runoff events) and are biotically regulated by cover amount and structure. Fire promotes shift to Phase 1.2. Burning alters surface susceptibility to runoff and erosion and dramatically increases annual and event responses (2- to more than 70-fold, see Figure 4). Runoff and erosion rates post-fire generally return to near pre-fire levels within 1 to 3 years with successful ground cover recovery (bare < 50%). Cheatgrass invasion promotes transition to State 2.
2. Shrub-steppe with annuals	Phase is promoted by invasion of cheatgrass into State 1. Hydrologic vulnerability is generally low, as with State 1. Burning results in similar community as Phase 1.1, but with cheatgrass. High severity fire may favor State 5 transition. As in State 1, burning increases risk of runoff and erosion. Runoff and erosion rates post-fire generally return to near pre-fire levels within 1 to 3 years with ground cover recovery (bare < 50%; threshold). Reduced fire with drought or heavy grazing facilitates increased shrub cover, a shift to Phase 2.2, and slightly increased runoff and erosion rates for the 25- to 100-year runoff events. Western juniper encroachment with reduced fire is pathway to Phase 2.3, increased bare ground connectivity, and amplified runoff and soil loss for the 10- to 100-year runoff events.
3. Juniper-dominated - at risk state	Extensive bare intercanopy area (bare > 40%) develops and becomes source of high runoff and sediment detachment by rainsplash and overland flow. Concentrated flow develops during intense rainfall, resulting in increases in runoff and erosion (onset of abiotically controlled soil loss; structural/functional threshold). Severe wildfire creates uniform bare ground, and water repellent soils under burned trees promote rapid runoff. Post-fire runoff and erosion rates can be 2- to more than 10-fold higher than for unburned conditions. Severe fire and cheatgrass re-establishment foster transition to State 5. Prescribed burning may create a restoration pathway to State 2 by decreasing understory competition with trees, but restoration may require seeding. Long-term runoff and erosion are potentially reduced by tree removal where vegetation and ground cover return to levels of State 2. Erosion risk is likely elevated immediately after prescribed fire for tree removal, but is likely reduced to near State 1 levels within 10 years after burning. Tree cutting is an alternative treatment to reduce long-term erosion risk without the short-term fire-induced erosion pulse. A lack of fire associated with drought and/or improper grazing promotes woodland succession and extensive intercanopy bare ground. Intercanopy bare ground > 50% to 60% is warning of likely transition to State 4 and persistence of abiotic-driven soil loss.
4. Juniper dominant eroded	Lack of fire sustains juniper dominance, decreased shrub/understory cover, and extensive intercanopy bare ground, commonly 60+% (structural/functional threshold for persistence of abiotic control). Concentrated flow is dominant erosion mechanism. Runoff and erosion extensive (can be 2- to more than 10-fold higher than reference state) and potential exists for long-term loss of critical soil resources. RHEM predicted probability of soil loss occurrence in excess of 1.195 t ha^{-1} is more than 50% in any given year. Intercanopy (usually 70% of area) aggregate stability is low and water flow paths and terracettes are often evident. This state is considered very difficult to reverse. Burning with cheatgrass re-establishment advances State 5.
5. Cheatgrass	Results from frequent burning (3-15 yr) or drought. Runoff and erosion similar to States 1 and 2 in unburned condition, but may increase by 2- to more than 70-fold relative to reference state in immediate post-fire years. RHEM predicted probability of soil loss occurrence in excess of 1.195 t ha^{-1} is more than 80% for any given year immediately post-fire. Wind erosion may be a concern on large burned expanses. Sustained grass-fire cycle represents an abiotic threshold, as restoration to State 2 is very difficult without adequate seeding and post-treatment precipitation. Long-term loss of critical soil resources is likely with frequent-recurring burning. Transition is difficult to reverse.

availability, and broader area management objectives. However, such information is easily accommodated into an ESD-based decision-making framework.

Although we present a single site-specific application, the same approach can be applied at the landscape scale. RHEM model scenarios and ecohydrologic interpretations can be developed for selected states across multiple ecological sites at the landscape-scale. RHEM is also the hillslope hydrology and erosion engine for the KINEROS2/AGWA model, which enables simultaneous RHEM simulations across all hillslopes in one or more watersheds.[18] Model results supplementing current ESD information could be used to target and optimize conservation efforts across multiple sites for maximum ecological and economic benefit. For example, tree removal may be more effective at locations with vegetation early in the juniper encroachment gradient and that have highly erodible soils. An integrated ESD-RHEM approach across multiple sites would equip a decision maker to predict potential site responses and most effectively implement resources across a landscape.

The general approach presented here is not limited to sagebrush rangelands or to hydrologic and erosion processes. We demonstrate how enhancement of ESDs with key ecohydrologic information can aid predictions of ecosystem response and targeting of conservation practices for sloping sagebrush rangelands that are strongly regulated by ecohydrologic or ecogeomorphic feedbacks. Similar approaches could be applied to other rangeland ecosystems with other self-regulating processes, disturbances, and factors (e.g., wind erosion and evaporation on bare soils in flat terrain).[19] We acknowledge that application of our approach may be difficult for sites with limited local knowledge and available data. Building and assessing ecological models and predicting plant community and ecohydrologic responses to disturbances and management are inherently more difficult in cases with limited information. A primary point of this work is that ESD concepts are flexible and can be creatively augmented for improved assessment and management of rangelands.

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Authors are Research Hydrologist, Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ 85719, USA, jason.williams@ars.usda.gov (Williams); Research Leader and Supervisory Research Hydrologist, Northwest Watershed Research

Center, USDA Agricultural Research Service, Boise, ID 83712, USA (Pierson); Rangeland Management Specialist, Central National Technology Support Center, USDA Natural Resources Conservation Service, Fort Worth, TX 76115, USA (Spaeth); Rangeland Ecologist, Jornada Experimental Range, USDA Natural Resources Conservation Service, Las Cruces, NM 88003, USA (Brown); Assistant Professor, Department of Civil and Architectural Engineering, Texas A&M-Kingsville, Kingsville, TX 78363, USA (Al-Hamdan); Research Leader, Great Basin Rangelands Research Unit, USDA Agricultural Research Service, Reno, NV 89512, USA (Weltz); Research Agricultural Engineer, Southwest Watershed Research Center, USDA Agricultural Research Service, AZ 85719, USA (Nearing); Research Soil Scientist, Jornada Experimental Range, USDA Agricultural Research Service, Las Cruces, NM 88003, USA (Herrick); Professor, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA 99164, USA (Boll); Research Engineer, Rocky Mountain Research Station, USDA Forest Service, Moscow, ID 83843, USA (Robichaud); Research Hydraulic Engineer, Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ 85719, USA (Goodrich); Research Leader, Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ 85719, USA (Heilman); Professor, School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721, USA (Guertin); Hydrologist, Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ 85719, USA (Hernandez); Research Associate, School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721, USA (Wei); Soil Scientist, Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ 85719, USA (Polyakov); Information Technology Specialist, Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ 85719, USA (Armendariz); Research Assistant Professor, Natural Resources and Environmental Science, University of Nevada-Reno, Reno, NV 89557, USA (Nouwakpo); Research Plant Physiologist, Northwest Watershed Research Center, USDA Agricultural Research Service, Boise, ID 83712, USA (Hardegree); Rangeland Scientist, Northwest Watershed Research Center, USDA Agricultural Research Service, Boise, ID 83712, USA (Clark); Assistant Professor, Department of Forest, Rangeland, and Fire Sciences, University of Idaho, Moscow, ID 83844, USA (Strand); Rangeland Ecologist, Range and Meadow Forage Management Research, USDA Agricultural Research Service, Burns, OR 97720, USA (Bates); Rangeland Management Specialist, Blackland Research and Extension Center, USDA Natural Resources Conservation Service, Temple, TX 76502, USA (Metz); and Research Hydraulic Engineer, Southwest Watershed Research Center, USDA Agricultural Research Service, Tucson, AZ 85719, USA (Nichols).