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ESTIMATING CONSERVATION NEEDS FOR RANGELANDS USING USDA NATIONAL RESOURCES INVENTORY ASSESSMENTS

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ABSTRACT. *This study presents (1) the overall concept of assessing non-federal western rangeland soil loss rates at a national scale for determining areas of vulnerability for accelerated soil loss using USDA Natural Resources Conservation Service (NRCS) National Resources Inventory (NRI) data and the Rangeland Hydrology and Erosion Model (RHEM) and (2) the evaluation of a risk-based vulnerability approach as an alternative to the conventional average annual soil loss tolerance (T) for assessment of rangeland sustainability. RHEM was used to estimate runoff and soil loss at the hillslope scale for over 10,000 NRCS NRI sample points in 17 western states on non-federal rangelands. The national average annual soil loss rate on non-federal rangeland is estimated to be 1.4 ton ha^{-1} year^{-1}. Nationally, 20% of non-federal rangelands generate more than 50% of the average annual soil loss. Over 29.2 $\times 10^6$ ha (18%) of the non-federal rangelands might benefit from treatment to reduce 1559-1570soil loss to below 2.2 ton ha^{-1} year^{-1}. National average annual soil loss rates combine areas with low and accelerated soil loss. Evaluating data in this manner can misrepresent the magnitude of the soil loss problem on rangelands. Between 23% and 29% of U.S. non-federal rangelands are vulnerable to accelerated soil loss ($\geq$2.2 ton ha^{-1} event^{-1}) if assessed as a function of vulnerability to a runoff event with a return period of $\geq$25 years. The NRCS has not evaluated potential soil loss risk in national reports in the past, and adaptation of this technique will allow the USDA and its partners to be proactive in preventing accelerated soil loss on rangelands.*

Keywords. *Conservation Effects Assessment Project, National resources inventory, Non-federal rangelands, Rangeland Hydrology and Erosion Model, Soil and water conservation, Soil erosion, Soil loss tolerance.*

Soil erosion is a general term describing the degradation of the landscape by wind and water processes. By 1935, soil erosion was considered a national issue for more than 50% of the country (Weaver and Noll, 1935; Helms, 1990). Concern over soil erosion on rangelands led, in part, to the passing of the Taylor Grazing Act of 1934 and the establishment of the Grazing Service (later to become the Bureau of Land Management) to manage federal lands. The USDA Soil Conservation Service (later to become the Natural Resources Conservation Service) was created in 1935 to provide, in part, technical range management assistance to private landowners for reducing soil erosion from wind and water. In 1992, the NRCS National Resources Inventory (NRI) estimated that approximately 46 $\times$ 10^6 ha (30.5%) of non-federal rangelands were eroding by wind and water forces at greater than sustainable levels (Spaeth et al., 2003a). The estimated annual costs of damage caused by soil erosion and excessive sediment in surface waters within the U.S. is approximately \$6 billion to \$16 billion annually (Osterkamp et al., 1989; Lal, 1994).

Soil erosion is a natural process, and the erosion potential of a site is the result of complex interactions among soil, vegetation, topographic position, land use and management, and climate. Soil erosion occurs when climatic processes (wind, rainfall, and runoff) exceed the soil's inherent resistance to these forces. Splash and sheetflow erosion are important erosion processes to measure and predict because they are the dominant types of soil erosion occurring in arid and semi-arid rangelands on sites that are undisturbed or in natural/reference conditions (Nearing et al., 2011).

Rangeland soils are generally consolidated, uncultivated, and often contain lower organic matter content than cropland soils. Tolerable soil loss rates for arid and semi-arid rangeland soils are often lower than those for cultivated Midwestern U.S. soils (11.2 ton ha^{-1} year^{-1}) due to shallower soil depth and slower rates of soil formation (DeBano and Wood, 1990). On croplands, erosion tends to be dominated by a combination of rill and interrill erosion,

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with rills capable of generating a substantial amount of soil loss (Meyer et al., 1975). Rangeland surfaces are more complex than croplands with uniformly arranged crops and tilled soil. Rangelands surfaces are usually covered by gravel pavements, rocks, plant litter, woody debris, and biological soil crusts. Rangeland vegetation is irregularly distributed in a naturally "patchy" arrangement and in most cases has varied plant heights and hydraulic resistance due to a mixture of plant life forms (Weltz et al., 1992; Ludwig et al., 2005, 2007). Thus, concentrated flow erosion (accelerated soil loss) does not occur readily on most undisturbed rangelands (Simanton et al., 1991). However, disturbed and degraded rangelands have accelerated soil loss rates, induced by concentrated flow, that can be very significant (Pierson et al., 2008, 2011). Runoff and soil loss per unit area from concentrated flow processes can be ten-fold greater than splash and sheetflow erosion combined (Pierson et al., 2008). In the southwest desert, soil loss rates can exceed 10 ton ha^{-1} $year^{-1}$ on rangeland watersheds (Lane and Kidwell, 2003; Nearing et al., 2007).

Numerous authors have discussed the importance of hydrologic connectivity in controlling runoff and sediment movement (Reid et al., 1999; Cammeraat, 2002, 2004; Bracken and Croke, 2007; Mueller et al., 2007; Reaney et al., 2007) and stated that vegetation patterns and connectivity are significant controlling factors (Dunkerley and Brown, 1999; Valentin et al., 1999; Imeson and Prinsen, 2004) on rangelands. Tongway and Ludwig (1997) found that overland flow on degraded tussock grasslands was concentrated in long straight paths between the grasses. In good-condition grassland, overland flow was tortuous, uniformly distributed, and produced less soil loss. In shortgrass prairie plant communities, formation of concentrated flow channels significantly increased runoff, although sediment yield was not increased (Koler et al., 2008).

Dominant erosion processes vary with rangeland conditions, the type of plants present, the gap between plant basal areas, and the connectivity of the bare interspaces (Okin et al., 2009). Plant basal areas, rocks, plant litter, woody debris, and biological soil crusts prevent soil loss from occurring from raindrop splashes by protecting the soil surface from impacts (Belnap, 2006). These obstructions cause water to flow around them, resulting in concentrated soil loss in the interspace areas (Puigdefabregas, 2005; Ludwig et al., 2005, 2007). This process results in an island effect in which excessive soil loss occurs in the interspace areas where runoff is concentrated (Ravi et al., 2010). The soil loss process can be accelerated in these situations and result in loss of biotic integrity, desertification, and sustainability of the site (Schlesinger et al., 1990, 1996; Schlesinger and Pilmanis, 1998; Chartier and Rostagno, 2006; Ridolfi et al., 2008). Examples of this are often seen in shrub-dominated landscapes that have formed coppice dunes (e.g., sagebrush, creosote bush, and mesquite) and in woodlands where juniper and piñon pine have expanded into sagebrush steppe communities in arid and semi-arid rangelands (Pierson et al., 1994, 2011; Spaeth et al., 1994; Davenport et al., 1998).

In rangelands, rare or unexpected runoff events can trigger a nick point along a hillslope that compromises the ecological site's stability and hydrologic function by allowing water to concentrate and accelerate soil loss. Small disturbances on a hillslope may create small patches of exposed soil that are prone to splash erosion. High-intensity rainfall on these bare nick points can generate substantial soil loss from raindrop impacts. Vegetated surfaces between nick points are protected, resulting in minor runoff and low sediment yield (Davenport et al., 1998; Wilcox et al., 2003; Puigdefabregas, 2005; Urgeghe et al., 2010). The same landscape with uniform disturbance may experience more runoff and soil loss from a similar runoff event due to the increased connectivity of bare soil areas and the existence of previously formed concentrated flow paths. These organized flow paths increase the runoff velocity and the ability of water to continually erode and transport sediment downslope (Wilcox et al., 1996; Davenport et al., 1998; Urgeghe et al., 2010).

More than 20 years ago, the Society of Range Management proposed that a site conservation rating be developed to assess the degree of protection from soil loss (SRM, 1991). The SRM recommendation was: "The effectiveness of present vegetation in protecting the site against accelerated erosion by water and/or wind should be assessed independently of the actual or proposed use of the site. This assessment should be called a Site Conservation Rating. The Site Conservation Rating at which accelerated erosion begins should be called the Site Conservation Threshold. Any site rated below the Site Conservation Threshold would be considered in unsatisfactory condition and those above it, satisfactory."

The most widely used soil conservation standard in the U.S. is the soil loss tolerance (*T*) value. The *T* value is generally interpreted as an estimate of the maximum rate of soil loss that can occur on a specific soil type and still sustain a high level of crop productivity (Cox, 2008). However, soil loss tolerance does not address the full range of ecosystem services provided by soils. There is a growing concern that *T* values may be too high for many soils (Johnson, 1987; Alexander, 1988; Cox, 2008). This is especially true for many fragile arid and semi-arid rangelands. There is very limited understanding of the rate of rangeland soil formation and minimal knowledge about the effect of soil loss on the sustained productivity of different rangeland and forest soils (Klock, 1982; DeBano and Wood, 1990). No direct cause-and-effect studies have been published for rangelands that have directly measured a soil loss tolerance rate. Attempts to extend the concept of soil loss tolerance from cropland to rangelands are questionable because of the fragility of rangeland ecosystems, the irreversibility of soil loss, and the large errors associated with measuring soil loss on rangelands (Wight and Siddoway, 1982). Therefore, *T* values for rangelands will probably remain subjective within the general conceptual framework of site productivity, soil loss, and soil formation (DeBano and Wood, 1990).

Hillslope soil loss processes on rangelands are distributed in space and time. Comparing soil loss resulting from distributed processes with a spatially averaged annual value, such as soil loss tolerance, presents a logical inconsistency (Lane et al., 1999). As a result, the standard method of using average annual soil loss on rangelands cannot address the multiple environmental challenges that now confront producers, managers, and policymakers, and new approaches and guidelines are warranted that address current and future needs.

Existing soil erosion prediction tools, such as the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) and the Water Erosion Prediction Project (WEPP; Tiscareno-Lopez et al., 1993; Flanagan and Nearing, 1995), have not been widely adopted for use on rangelands. One reason for WEPP not being widely used on rangelands is that the plant growth subroutine cannot capture the complexity of the diverse plant assemblages on rangelands and how they differentially respond to climate and management. A second reason is the lack of a lookup database to fully parameterize the more than 10,000 ecological sites that have been defined on rangelands.

The Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) and RUSLE were developed for cropland and failed as useful predictors of erosion on rangelands (Trieste and Gifford, 1980; Mitchell, 2010). RUSLE was found to consistently underpredict soil loss on rangeland hillslopes when compared to observed data from large rainfall simulation experiments across the western U.S. (Spaeth et al., 2003a). Elliot (2000) reported that RUSLE overpredicted sediment yield by three-fold, and WEPP rangeland predictions were approximately 17% of observed soil loss on small rangeland watersheds in Colorado. Wilcox et al. (1992) found poor correlation between observed and predicted runoff on rangelands using WEPP. Moffet et al. (2007) reported that WEPP significantly underpredicted soil loss because it could not account for fire effects on soil properties on steep slopes.

By the time rangeland landscape deterioration is detected using available tools or models, the rangeland ecosystem functions may already have been compromised (Heede, 1979; NRC, 1994; De Soyza et al., 2000a, 2000b). The challenge for rangeland erosion modeling is to aid land managers in defining thresholds of accelerated soil loss and assessing the risk of crossing those thresholds to avert land degradation. This requires more than comparing a predicted long-term average annual soil loss value to the soil loss tolerance value. It requires the ability to identify an ecosystem's vulnerability to extreme runoff events before changes in resources occur (Pierson, 2000).

The objective of this study is to propose a risk-based approach for national soil loss vulnerability assessment on non-federal rangelands. This article presents (1) the overall concept of assessing non-federal western rangeland soil loss rates at a national scale for determining areas of vulnerability for accelerated soil loss using on-site NRCS NRI rangeland data and the Rangeland Hydrology and Erosion Model (RHEM) and (2) the evaluation of a risk-based vulnerability approach as an alternative to the conventional average annual soil loss tolerance (*T*) for assessment of rangeland sustainability.

METHODS

A new physically based model has been developed by the USDA Agricultural Research Service (ARS) and NRCS for assessing soil loss rates on rangelands that specifically assesses the risk of soil loss at national, regional, and local scales (Weltz et al., 2008). RHEM was developed exclusively on data collected from a large number of geographically distributed rangeland erosion experiments (Simanton et al., 1991; Pierson et al., 2002; Nearing et al., 2011; Wei et al., 2007, 2009). The unit scale for raindrop splash and sheetflow erosion used to develop RHEM is a rangeland rainfall simulator plot with a minimum size of 2 m × 6 m (long axis pointed downslope). This was done in order to incorporate the scale of rangeland heterogeneity and variability associated with the complex vegetation patterns on rangeland sites. Source terms for RHEM are based on rangeland data, which model splash and sheetflow effects as the dominant processes on undisturbed natural rangelands. Research has indicated that infiltration, runoff, and erosion dynamics are correlated with the presence/absence and composition of specific plant taxa and growth attributes (Spaeth et al., 1996; Andreu et al., 1998; Bochet et al., 1998). An important aspect of the model relative to application by rangeland managers is that RHEM is parameterized based on plant growth form classification using data that are typically collected for rangeland management purposes (e.g., rangeland health assessments).

RHEM was designed to require minimal inputs that are readily available for most rangeland ecological sites. Model inputs are surface soil texture; slope length (≤100 m), steepness (≤100%), and shape (linear, concave, or convex); dominant plant life (e.g., shrub, shortgrass, annual grass, etc.); percent canopy cover; percent ground cover by component (rocks, plant litter, plant basal area, and biological soil crusts); and precipitation. Precipitation can be estimated by the model by selecting the nearest weather station in the model interface. RHEM estimates runoff, soil loss, and sediment delivery rates and volumes at the hillslope spatial scale and the temporal scale of a single rainfall event. The model is a single-event prediction tool and therefore does not predict daily changes in plant growth and associated changes in standing biomass, canopy, or ground cover. To evaluate the impacts of plant growth and management on soil loss, the user can run a baseline scenario and then run an alternative scenario (e.g., change canopy and ground cover). The user can then compare differences in soil loss as a result of changes in vegetation attributes across sites, from management, or from climate change (Belnap et al., 2013; Hernandez et al., 2013; Zhang et al., 2012; Weltz and Spaeth, 2012; Weltz et al., 2014).

RHEM does not update soil moisture on a daily time step. Instead, the user inputs initial soil moisture, and this value is used in every estimate of soil loss. This is similar to RHEM's approach to evaluating the impact of plant canopy and ground cover. This provides consistent evaluation of the site for various precipitation events but not for the interactions of soil moisture, plant cover, and precipitation. To evaluate seasonal impacts, the user can alter the initial soil moisture and vegetation to reflect the site conditions at a specific time in relation to the initial precipitation and then compare the scenarios. The USDA has long used runoff as a function of return period to design conservation practices. We have chosen to follow this approach by estimating runoff for events with 2, 10, 25, and 50 year return periods to predict soil loss on rangelands. RHEM does not predict stream channel erosion, but the model does have the capability to estimate soil loss induced by concentrated flow. The infiltration equations in RHEM are taken directly from WEPP. Infiltration is computed using the Green-Ampt Mein-Larson model (Mein and Larson, 1973) for unsteady intermittent rainfall, as modified by Chu (1978). The rainfall excess rate is calculated only when the rainfall rate is greater than the infiltration rate.

Measured field data from the WEPP effort for 49 ecological sites in 15 states collected using a large rotating-boom rainfall simulator were used to develop the RHEM erosion equations (Simanton et al., 1991; Pierson et al., 2002; Nearing et al., 2011). These new explicit erosion equations and parameters were developed from only western rangeland soils and are described by Wei et al. (2007, 2009) and Nearing et al. (2011):

$$D_{ss} = K_{ss} \cdot I^{1.052} \cdot q^{0.592} \tag{1}$$

where D_{ss} is the rate of splash and sheetflow erosion for the area (kg m^{-2} s^{-1}), K_{ss} is the splash and sheetflow erodibility coefficient, I is the rainfall intensity (m s^{-1}), and q is the runoff rate (m s^{-1}). Concentrated flow erosion in RHEM is calculated using the excess shear stress equation developed by Foster (1982). Transport capacity is calculated using the Yalin equation as implemented in WEPP (Finkner et al., 1989). Validation studies of the ability of RHEM to predict runoff (r^2 = 0.87) and sediment yield (r^2 = 0.50) indicated that the model is overall acceptable in predicting soil loss on rangelands (Nearing et al., 2011).

A linear slope shape was utilized for all hillslopes, resulting in no deposition predicted along the hillslope. Therefore, soil loss and sediment yield are equal under these conditions, and the results in this article are reported as soil loss. Climate (precipitation intensity, duration, and frequency) was estimated for each NRCS NRI primary sample point with the CLIGEN weather generator using data from the nearest available NOAA weather station (Nicks et al., 1995; Zhang and Garbrecht, 2003). CLIGEN was run to provide 300 years of daily precipitation records for input into RHEM. If runoff occurred, then soil loss at the end of the evaluated hillslope was estimated for that day and used in the estimation of the average annual soil loss over the 300-year time span. In addition, the data were analyzed to provide estimates of the 2, 10, 25, and 50 year return period runoff events to provide estimates of the vulnerability of the site to accelerated soil loss. The return period runoff events (e.g., 25 or 50 year) were determined from the 300-year climate sequence. This approach provided an estimate of soil loss (average annual and on a return period runoff event basis) for the NRCS NRI sample point based on the data collected on the particular sample day.

For many arid and semi-arid western rangeland soils, the sustainable soil loss rate is estimated to be ≤2.2 ton ha^{-1} year^{-1} due to their shallow depth, low organic matter content, and the slow rate of soil formation in erratic and dry climates (DeBano and Wood, 1990). We propose that soil loss rates of 2.2 to 4.5 ton ha^{-1} year^{-1} put the long-term sustainability of these rangelands at risk and that soil loss rates of >4.5 ton ha^{-1} year^{-1} be considered unsustainable (table 1).

Since 2003, NRCS NRI data, with updated field protocols for rangelands, has been collected annually at field segments in 17 western states (Spaeth et al., 2003b; Herrick et al., 2010). The NRCS NRI rangeland data set (2003-2006) is based on a spatially unbiased sample population of plots using a national sampling frame (Nusser and Goebel, 1997; Nusser et al., 1998). Qualitative assessment and quantitative measurement data were collected with handheld computers on more than 10,000 plots (0.16 ha each) over a four-year period starting in 2003 (NRCS, 2010a). The spatially unbiased sample population of rangeland points was selected using a national sampling strategy together with GIS-based analysis of land cover and ownership. Field crews were provided with extensive annual training prior to data collection each year following recently established protocols (NRCS, 2010a) to ensure consistent and repeatable data.

The NRCS NRI data collected between 2003 and 2006 at over 10,000 sites across the western U.S. were used to parameterize RHEM to estimate hillslope-scale soil loss. Each NRCS NRI segment was correlated to an ecological site with an associated soil component name and was sampled on a single day. When the soil component name was not identified (e.g., areas not yet mapped), the Soil Survey Geographic (SSURGO) database (NRCS, 2010b) was used to identify the soil texture by horizons to a depth of 50 mm. The sample protocols were designed to provide the relevant soil, topography, and vegetation inputs. Quantitative measurements of vegetation cover and composition were based on a line-point intercept method to estimate soil loss (Bonham, 1989).

Soil loss reporting regions were defined by using a combination of common resource areas (CRAs), major land resource areas (MLRAs), and land resource regions (LRRs) to form a unique geographic region. Interpretation of quantitative estimates of soil loss was based on statistically weighted aggregations of NRCS NRI sample points aggregated into polygons through the use of CRA measurements. Sample numbers per CRA varied from a minimum of 49 to a maximum of 329 NRCS NRI sample points per polygon. Sample area of the CRA varied from a minimum 535,200 ha to a maximum of 12,517,900 ha. The spatially unbiased design of the NRCS NRI facilitates scaling and aggregation within GIS for national assessments (Herrick et al., 2010). The option of using Omernick level III ecoregions (USEPA, 2010) as a template for reporting regions was evaluated, but these areas were too large and had too much diversity to reflect soil loss rates at a local scale. The level IV ecoregions, which are at a smaller scale than the level III ecoregions, were not complete for the entire western U.S. at the time of model analysis. Therefore, we chose a geography based on CRAs as it has an additional benefit of being more consistent with previous NRCS reports on soil loss by major land resource regions.

Table 1. Proposed soil loss classes to define accelerated soil loss rates indicating unhealthy conditions and leading to site degradation, loss of ecosystem services, and loss of sustainability if not addressed.

Soil Loss Class	Runoff Event Based Soil Loss Rate
Sustainable	≤2.2 ton ha^{-1}
At risk	2.2 to 4.5 ton ha^{-1}
Unsustainable	≥4.5 ton ha^{-1}

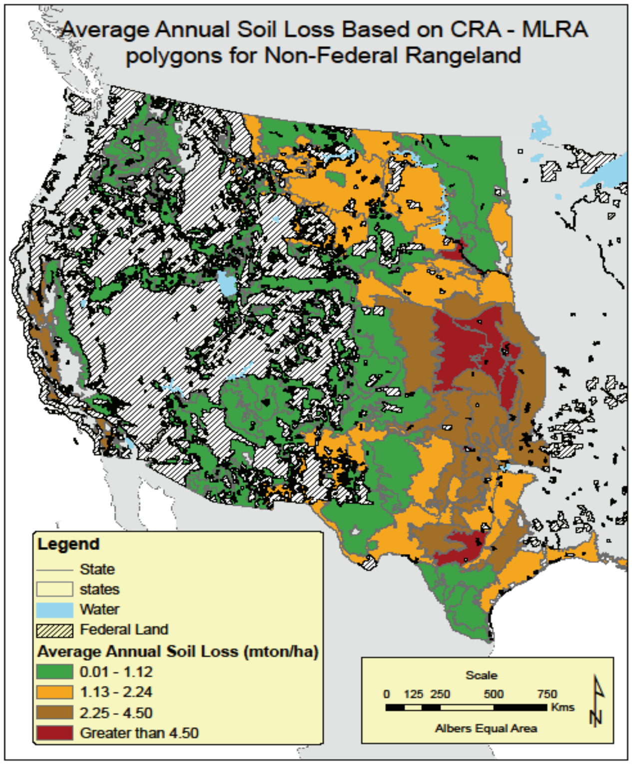

Figure 1. Geographic representation of average annual raindrop splash and sheetflow soil loss (ton ha^{-1} year^{-1}) for hillslopes on non-federal rangelands of the western U.S.

Table 2. National estimated average annual soil loss as a percentage of area and by proposed soil loss class on non-federal rangelands.

Region	Soil Loss (%) by Soil Loss Class[a]		
	Sustainable	At Risk	Unsustainable
National	82	10	8
Arizona	95	4	1
California	66	10	24
Colorado	92	5	3
Idaho	99	1	0
Kansas	52	20	28
Montana	81	12	7
North Dakota	71	14	15
Nebraska	61	20	19
New Mexico	95	3	2
Nevada	100	0	0
Oklahoma	66	17	17
Oregon	98	2	0
South Dakota	77	9	8
Texas	78	13	10
Utah	98	2	0
Washington	98	2	0
Wyoming	90	7	3

[a] Sustainable = soil loss of ≤2.2 ton ha^{-1} year^{-1}.
At risk = soil loss of 2.2 to 4.5 ton ha^{-1} year^{-1}.
Unsustainable = soil loss of ≥4.5 ton ha^{-1} year^{-1}.

Results and Discussion

Average Annual Soil Loss

Soil loss on non-federal rangelands is not uniformly distributed across the U.S. (fig. 1 and table 2). RHEM estimated that the national average annual soil loss rate on non-federal rangeland in the 17 western states was 1.4 ton ha^{-1} year^{-1} (SD = 3.3 ton ha^{-1} year^{-1}) and varied from 0.0 to 85.0 ton ha^{-1} year^{-1}. The highest estimated average annual soil loss rates at individual NRCS NRI sample segments were in Oklahoma and Nebraska (71.0 to 85.0 ton ha^{-1} year^{-1}), followed by Kansas and Texas (35.0 to 40.0 ton ha^{-1} year^{-1}). More than 29.2 × 10^6 ha (18%) of non-federal rangelands might benefit from conservation practices that could reduce average annual soil loss to less than 2.2 ton ha^{-1} year^{-1} (1.0 ton acre^{-1} year^{-1}), which is the historical soil loss tolerance rate for much of the U.S. western rangelands.

On non-federal rangeland, 20% of the area produces more than 50% of the average annual soil loss (fig. 2). This indicates that approximately 32.5 × 10^6 ha of non-federal rangelands might benefit from conservation practices to reduce the soil loss and increase the environmental sustainability of these landscapes. Approximately 8% (13 × 10^6 ha) of rangelands have estimated average annual soil loss

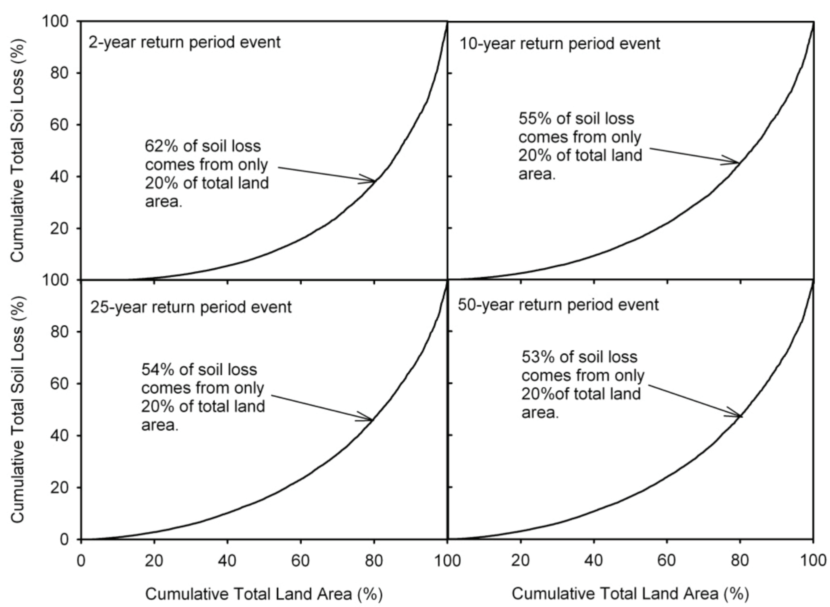

Figure 2. National estimates of cumulative soil loss by percent area for four return period runoff events (2, 10, 25, and 50 year).

rates of >4.5 ton ha^{-1} year^{-1}, which is considered unsustainable and should be targeted for conservation treatments.

EVENT-BASED SOIL LOSS

If soil loss occurred uniformly, then the average annual soil loss rate would be 2.2 ton ha^{-1}. In addition, if the soil formation rate was 2.2 ton ha^{-1}, then it could be argued that the site is sustainable. However, soil loss on many rangelands is not uniformly distributed, spatially or temporally, across the landscape (fig. 3). Average annual soil loss rates cannot explain all soil loss in arid and semi-arid rangelands because most soil loss occurs during high-intensity rainfall events that generate large amounts of runoff and that may occur only a few times in a decade.

We propose that soil loss, in relation to sustainability, be assessed based on vulnerability or risk in relation to runoff events of varying return periods. This will account for the natural variation in vegetation due to climate (e.g., drought or wet periods) and for the influence of management on vegetation (e.g., shifts in plant species, changes in spatial orientation of vegetation, plant density, and changes in canopy and ground cover). National average soil loss rates for non-federal rangelands for 2, 10, 25, and 50 year return period runoff events are 0.4, 2.4, 3.3, and 4.1 ton ha^{-1}, respectively. If soil loss is estimated based on runoff event return period (e.g., 2, 10, 25, or 50 years), then more non-federal rangelands areas are vulnerable to exceeding the sustainable soil loss rate than when using long-term average annual soil loss estimates (table 3). Rangelands are not plowed or planted like croplands. Therefore, concentrated flow paths (such as rills or ephemeral gullies on croplands) are not removed once formed. On rangelands, these concentrated flow paths facilitate water accumulation and accelerated soil loss in subsequent runoff events, resulting in the site crossing a hydrologic threshold and becoming permanently degraded (Davenport et al., 1998; Reid et al., 1999; Wilcox et al., 2003; Urgeghe et al., 2010; Pierson et al., 2011).

Rangelands are fragile and vulnerable to accelerated soil loss. Approximately 5% (8.1×10^6 ha) of non-federal rangelands are estimated to have soil loss rates that would classify them as at risk or unsustainable for a 2-year runoff event (table 3). Approximately 17% (27.6×10^6 ha) of non-federal rangelands are estimated to have soil loss rates that would classify them as at risk or unsustainable for a 10-year runoff event. As the runoff return period increases, the percentage of rangelands that are vulnerable to at risk and unsustainable soil loss increases. It is estimated that approximately 29% (47.2×10^6 ha) of the U.S. non-federal rangelands have soil loss rates that would classify the site as at risk or unsustainable for an extreme (50 year) runoff event.

In Nevada, the average annual soil loss predicted by RHEM is estimated to be below 2.2 ton ha^{-1} year^{-1}. The primary reasons are the low average annual rainfall (193 mm) and that the non-federal rangelands are disproportionally located along river bottoms with minimal slopes (<8%). When soil loss is assessed for a 50-year return period runoff event, approximately 8% of non-federal rangelands are at risk due to high soil loss rates, and 3% of non-federal rangelands are estimated to be unsustainable (table 4). Weltz et al. (2014) used RHEM to estimate the impact of changing from one vegetation plant community (ecological state) to another for a Wyoming sagebrush dominated ecological site near Austin, Nevada. Weltz et al. (2014) reported that soil loss was 2.4 to 3 times lower for the Wyoming sagebrush plant community than it was on a burned site previously dominated by a cheatgrass plant community. In addition to greater soil loss, the burned cheatgrass plant community had 1.2 to 1.6 times more runoff during intense summer thunderstorms, putting the site in the at risk class for sustainability due to accelerated soil loss. This same pattern was found in Utah, where 12% of non-federal rangelands are estimated to be at risk of high soil loss rates and 8% of non-federal rangelands are estimated to be unsustainable for a 50-year return period runoff event (table 4).

The Colorado Plateau and Great Basin regions of the U.S. have prevailing climatological, geological, and ecological conditions that limit the development of soil and plant communities. In these landscapes, abiotic processes are dominant, and soil loss is inherently high (e.g., the Mancos shale region of the Colorado Plateau). Simanton et al. (1991) reported that soil loss rates on a Mancos shale rangeland site near Meeker, Colorado, were twice as high as at other western rangelands sites evaluated. They ascribed the high soil loss rates to rill processes on these fragile soils, which were not visible at the other rangeland sites evaluated. This region has an arid to semi-arid climate, and much of the exposed geological parent material is weakly cemented and high in dispersible salts. The soils are shallow, poorly developed, and highly erodible. The region is prone to high-intensity convective precipitation events. As a result of these constraints, the region has minimal vegetation, and the vegetation tends to be clumped and scattered across the landscape, making the region vulnerable to rilling and high soil loss rates. As soil loss is related to rainfall intensity, most of the soil loss occurs during rare storm events. Consequently, rill and arroyo formation is pronounced, and the average sediment yield on the Colorado Plateau frequently exceeds 3 ton ha^{-1} year^{-1} (Langbein and Schumm, 1958; West, 1983).

By using the NRCS NRI data displayed in GIS, it was simple and efficient to define areas with moderate to high potential soil loss rates that should be targeted to control soil loss. Vulnerability to accelerated soil loss on non-federal rangelands is concentrated in two broad areas of the U.S. (i.e., California and the Central Plains), although nearly every geographic region or state has areas that are eroding at an accelerated and unsustainable rate. In Kansas, the areas vulnerable to soil loss today are the same areas that were impacted during the Dust Bowl era of the 1930s and the droughts of the 1950s and 1970s. By targeting the areas that are most vulnerable to soil loss, we can more effectively reduce soil loss. This requires that landscapes are assessed at a scale at which targeting is plausible by using geographic regions with similar climate, soils, topography, vegetation, and management. Actual soil loss in each

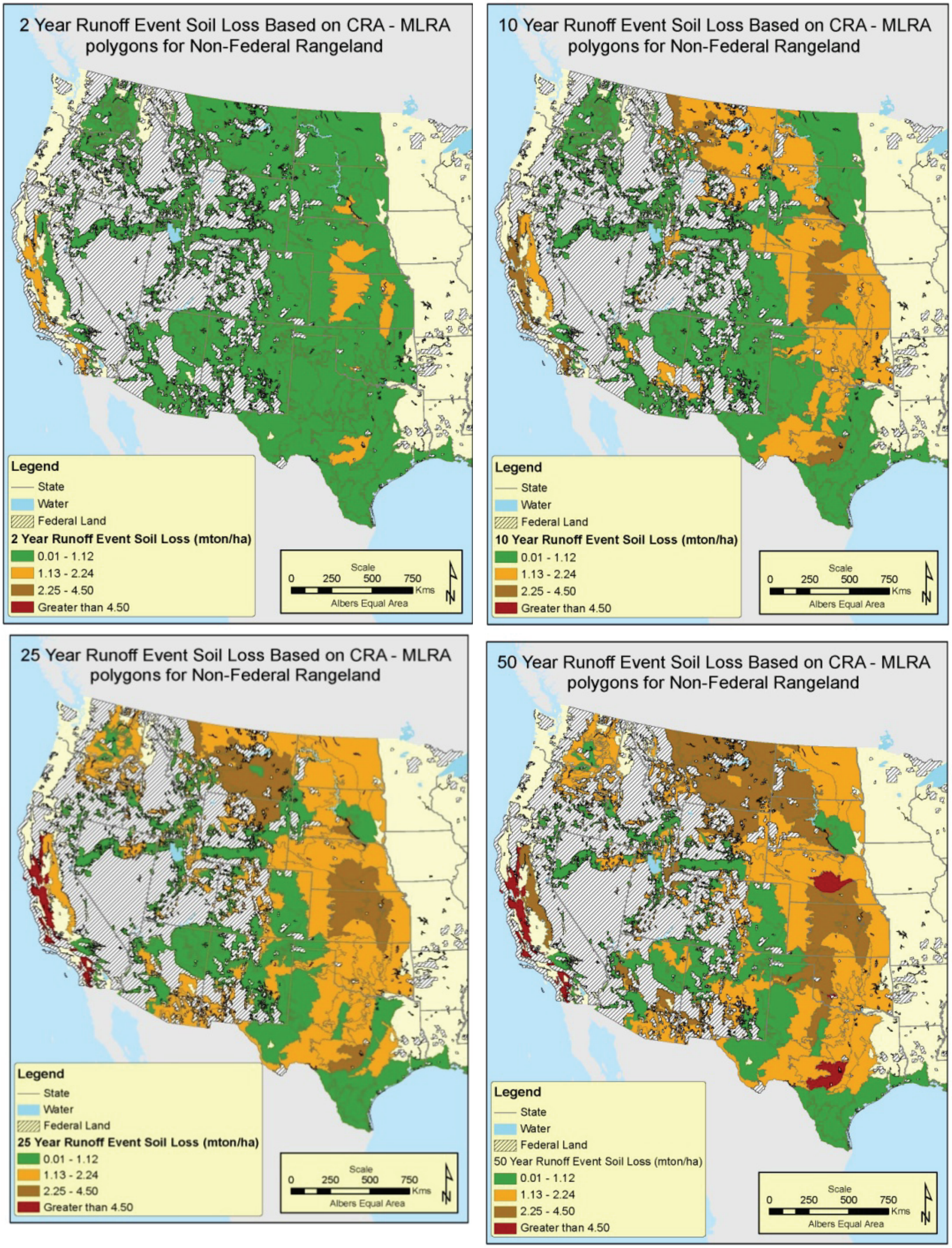

Figure 3. Geographic representation of soil loss (ton ha^{-1}) for hillslopes showing areas of non-federal rangelands of the western U.S. most vulnerable to accelerated soil loss for different return period runoff events.

Table 3. National estimated percent of soil loss (%) and area that may benefit from conservation (ha) by soil loss class on non-federal rangelands for four return period runoff events (2, 10, 25, and 50 year).[a]

Runoff Event	Sustainable Area (%)	At Risk Area (%)	At Risk Area (ha)	Unsustainable Area (%)	Unsustainable Area (ha)
2 year	95	4	6,504,300	1	1,626,075
10 year	83	12	19,513,305	5	8,130,780
25 year	77	15	24,391,530	8	13,009,005
50 year	71	17	27,643,680	12	19,513,305

[a] Sustainable = soil loss of ≤2.2 ton ha^{-1} year^{-1}; at risk = soil loss of 2.2 to 4.5 ton ha^{-1} year^{-1}; unsustainable = soil loss of ≥4.5 ton ha^{-1} year^{-1}.

Table 4. Estimated percent soil loss (%) and area that may benefit from conservation (ha) in Nevada and Utah by soil loss class on non-federal rangelands for four return period runoff events (2, 10, 25, and 50 year).[a]

State	Runoff Event	Sustainable Area (%)	At Risk Area (%)	At Risk Area (ha)	Unsustainable Area (%)	Unsustainable Area (ha)
Nevada	2 year	100	0	0	0	0
	10 year	95	5	167,387	0	0
	25 year	91	9	301,239	0	0
	50 year	89	8	267,786	3	100,400
Utah	2 year	100	0	0	0	0
	10 year	99	1	4,293	0	0
	25 year	86	11	47,507	3	12,900
	50 year	80	12	51,800	8	34,546

[a] Sustainable = soil loss of ≤2.2 ton ha^{-1} year^{-1}; at risk = soil loss of 2.2 to 4.5 ton ha^{-1} year^{-1}; unsustainable = soil loss of ≥4.5 ton ha^{-1} year^{-1}.

NRCS NRI field segment depends on how the vegetation at the site is managed in relation to the season of the year and when the chance of precipitation is greatest (e.g., site vulnerability).

By using the NRCS NRI data displayed in GIS, it was easy to identify that the Edwards Plateau region of Texas has the state's highest potential soil loss rates for a 50-year return period runoff event (>4.5 ton ha^{-1}) (fig. 4). Weltz and Spaeth (2012) used RHEM to assess ecological sites invaded by ash juniper on the Edwards Plateau near Johnson City, Texas. They determined that applying conservation to return the invaded sites to reference conditions could reduce soil loss by up to six-fold depending on the runoff return period evaluated. In contrast, the flat Central Panhandle region of Texas has the least amount of potential soil loss from a 50-year return period runoff event (0.65 ton ha^{-1}). The Panhandle region is associated with low relief, shortgrass prairie vegetation, and high vegetative cover. The difference in soil loss rates is due primarily to inherent landscape position, with greater than average slopes in the Edwards Plateau (9%) vs. the central Panhandle (2%) and higher annual precipitation in the Edwards Plateau (747 mm year^{-1}) than in the central Panhandle (437 mm year^{-1}).

RHEM is an improvement over USLE and RUSLE as it can be applied as a decision support tool with limited inputs to evaluate the impact of alternate management or conservation practices and determine the amount of change in vegetation and ground cover that is required to reduce vulnerability to potentially accelerated soil loss from given runoff events. RHEM provides a means of evaluating alternative conservation practices to determine which are most effective at lowering the vulnerability to accelerated and unsustainable soil loss (Weltz and Spaeth, 2012; Weltz et al., 2014). The model interface allows the user to modify the vegetation community, make changes in the canopy and ground cover that would be derived from implementing a conservation practice (e.g., brush management, prescribed grazing, or rangeland seeding), and evaluate the amount of soil conserved as a result of the proposed conservation activity. Hernandez et al. (2013) reported that RHEM could effectively assess the influence of canopy and ground cover, plant life, soils, and topography on current soil loss rates on rangelands in southern Arizona. RHEM also allows the user to evaluate slope length and steepness to assist in designing conservation practices (e.g., terraces or water harvesting) that would be required to achieve a targeted soil loss rate. Belnap et al. (2013) evaluated RHEM for its effectiveness in estimating runoff and soil loss on biological soil crust dominated sites in Utah. They reported that RHEM, once calibrated, predicted that sites with the lowest amount of biological soil crusts had the highest amount of soil loss and that soil loss potential increased by a factor of 10 as slope gradients increased from 0% to 10%.

CONCLUSION

National averages of annual soil loss are valuable for developing policy and quantifying the impact of these policy decisions, as exemplified by the implementation of the 1985 Farm Bill and the Conservation Reserve Program (CRP). However, national and state averages of annual soil loss are not effective for targeting where and what conservation practices should be deployed to cost-effectively reduce soil loss. To achieve this goal, explicit geospatial data must be used to target the most vulnerable areas to reduce soil loss on rangelands.

This study proposes an alternative to the current standard of using average annual soil loss and soil loss tolerance (*T*) for assessing sustainability on arid and semi-arid rangelands. The use of a risk-based vulnerability assessment has proven useful for identifying rangeland sites under threat of accelerated soil loss, even when traditional assessment based on soil loss tolerance suggests acceptable rangeland soil loss conditions. We propose that soil loss, in relation to sustainability, be assessed on the basis of vulnerability or risk in relation to runoff event return period (≥2 year return period). Our approach inherently accounts for natural varia-

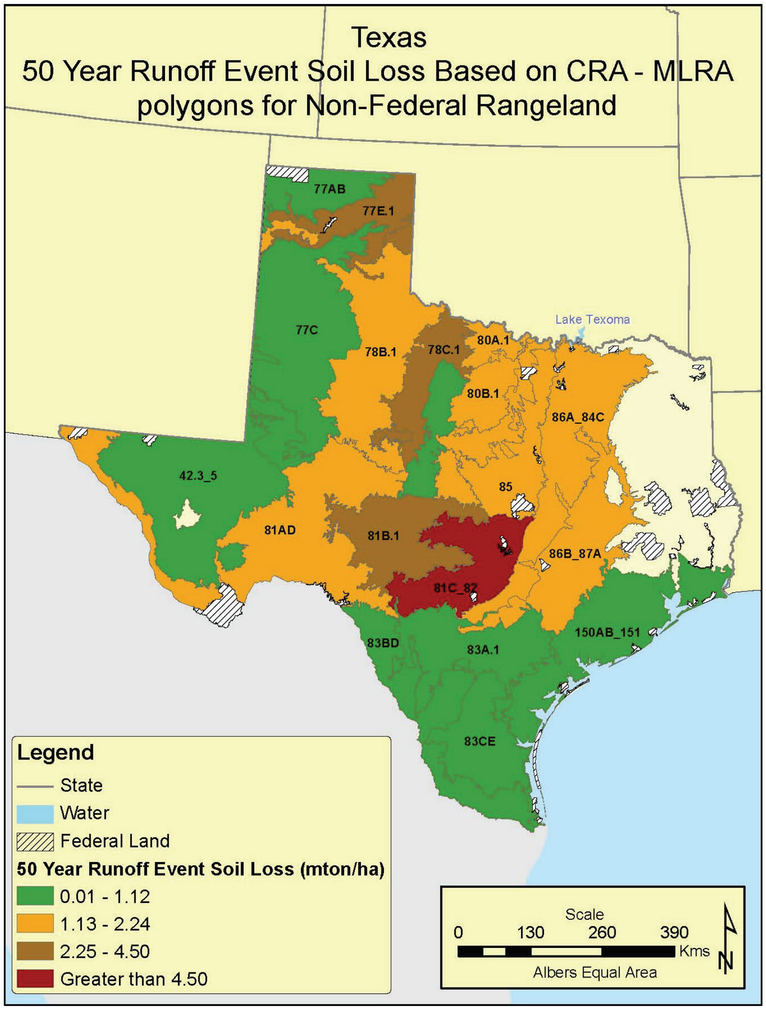

Figure 4. Geographic representation of Texas hillslope areas that are vulnerable to accelerated soil loss on non-federal rangelands from a 50-year return period runoff event (ton ha^{-1}).

tions in vegetative due to climate and management influence. Differentiation between geologic and anthropogenic induced or accelerated soil loss is also possible with this approach. This will allow rangelands to be classified as being at risk or unsustainable due to soil loss as a function of topography, plant community, precipitation intensity, and storm duration. RHEM was designed to evaluate risk and vulnerability of soil loss in response to runoff criteria. RHEM was designed to allow land managers to evaluate alternative conservation practices and determine which management action has the largest impact on reducing soil loss. Using RHEM in this manner allows land managers to improve the probability of achieving sustainability of rangelands by implementing appropriate conservation practices before accelerated soil loss occurs.

The results from this study and that of Hernandez et al. (2013) suggest that RHEM could be further improved with additional experimental data on infiltration, runoff, and soil loss within key ecological sites. Studies that focus on contrasting alternative plant communities within an ecological site are needed to parameterize the model to reflect changes in plant communities that result from management actions (e.g., changes in plant species, species distribution and abundance, or spatial arrangement) and that impact hydrologic processes. In addition to canopy and ground cover, RHEM must consider the total coverage of biological soil crusts and the level of development of the biological soil crust in order to be effective in predicting runoff and soil loss on rangelands (Belnap et al., 2013). New field techniques must be designed to quantify the influence of the spatial distribution of vegetation (e.g., canopy gap, plant density, species assemblage, and plant spatial orientation) to effectively measure and model concentrated flow processes that initiate rills and accelerated soil loss on arid and semi-arid rangelands.

RHEM provides a means to develop a risk index that can describe which rangeland sites are vulnerable and when these sites are most vulnerable (e.g., time of year and type of runoff event) to soil loss. This concept is a sharp departure from the USDA's traditional evaluation of soil loss, which has used average annual soil loss and usually treated accelerated soil loss after it has occurred. RHEM provides a means of evaluating alternative conservation practices to determine which practices are most effective at lowering the risk of accelerated soil loss in a cost-effective manner. This new technology will allow the USDA and its conservation partners to be proactive in preventing accelerated soil loss, rather than concentrating on repairing degraded lands, which may not be possible if the site has eroded to the point that it has crossed an ecological and environmental threshold.

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