Using Science to Bridge Management and Policy: Terracette Hydrologic Function and Water Quality Best Management Practices in Idaho

By Mark V. Corrao, Barbara E. Cosens, Robert Heinse, Jan U.H. Eitel, and Timothy E. Link

On The Ground

- Nonpoint source (NPS) pollution is a leading cause of water quality degradation on 40% of the semiarid lands within the western United States, with sediment from runoff on agricultural lands making up 15%.
- Managing NPS pollution through best management practices (BMPs) relies on site-specific knowledge and voluntary application.
- The dominant hydrologic processes in semiarid environments are a product of local climate, vegetation, and soil conditions; therefore, land use and ecosystem resilience invariably hinge on a balance of shifting, and often competing, social and environmental drivers.
- Our measurements of terracette hydrologic function and existence on more than 159,000 hectares within Idaho enabled an estimate of potential NPS erosion and sediment generation, emphasizing the value of site-specific scientific research for land managers.
- Our study provides an example of how microtopographic landforms, such as terracettes, are connected with state and federal clean water policy as one example of how interdisciplinary research can have far-reaching application.

Keywords: rangelands, terracettes, erosion, water, policy, best management practices.

Rangelands 37(5):191–199

doi 10.1016/j.rala.2015.08.003

© 2015 The Society for Range Management

Nonpoint source (NPS) pollution, as defined within the U.S. Clean Water Act (CWA) amendments of 1972, is described as nutrient, temperature, or sediment inputs by nondiscrete sources to public water ways and is currently the leading cause of water resource degradation within the United States.¹ Degraded waters within the United States

are identified by the states and listed under section §303(d) of the CWA. The U.S. Environmental Protection Agency (EPA) has stated that nearly 40% of NPS pollution in the country is attributed to agricultural activities, with sediment comprising approximately 15% of that total.¹ Within Idaho, there are 27,481 stream kilometers listed as impaired by NPS pollution according to the Idaho Department of Environmental Quality.²

The mitigation of NPS pollution is currently through the application of “preferred actions,” promulgated by the EPA and defined by the CWA as best management practices (BMPs).¹ BMPs have been extensively developed with the agricultural community through problem assessment, examination of alternative practices, and public participation to help mitigate the human impacts of land use on water quality.³ All BMPs are applied in a process of give-and-take negotiation by local conservation districts and landowners on a strictly voluntary basis,^{3,4} supported by an array of management guidance documents and funding available through many federal, state, and local sources. Therefore, application of BMPs to reduce NPS pollution, such as runoff-derived nutrients or sediment, remains at the sole discretion of local interests and private landowners unaided by a regulatory framework. The successful application of BMPs hinges on site-specific knowledge and the adoption of recommended practices by landowners,⁵ conservation districts, and local interest groups.

Nearly 40% of the semiarid land in the western United States is managed as rangelands,^{6,7} with grazing representing the single largest land type designation.⁸ Since the 1940s, the number of cattle in the western United States has expanded by more than 60%, whereas the private acreage of rangelands (not counting public leases) has decreased by more than 15%.⁹ Within Idaho, 6 million hectares (ha) (approximately 28%) of public lands are managed as grazing allotments, and nearly all

¹ For more on BMPs in the CWA, see section 319(b) of the Federal Water Pollution Control Act (aka Clean Water Act).

are semiarid. On pasture lands such as these, animal stocking rates and erosion are of primary concern, often leading to management efforts focused on vegetation composition and biomass production.¹⁰ Management of grazing land production often coincides with managing NPS pollution facilitated by the application of BMPs. Managers in semiarid lands also understand the continual challenges they face, resulting, in part, from the complexity of site-specific conditions and variable local climate.

Hydrologic research in semiarid ecosystems has been extensive, given the importance of water, vegetation, and topography on land use. At the hillslope scale, interactions of microtopography, soil properties, and soil water play a significant role in runoff, erosion, and vegetative growth.^{11,12} Understanding these complex hydrologic interactions at the pasture scale is critical to the successful application of BMPs, given the influence they have on water quality through the suppression or amplification of NPS pollution. The role of water in land use, as well as a key variable in ecosystem function,¹³ was the driving motivation behind our research aimed at improving our understanding of the effects of terracettes on vadose zone hydrologic processes. Our work represents a baseline mechanistic understanding of terracette hydrology and, coupled with a statewide survey of terracette occurrence, led to (1) a discussion of terracette-influenced soil water on semiarid rangelands, (2), an estimate of potential NPS pollution (soil loss) as a result of terracettes, and (3) potential implications for rangeland management.

Terracettes and Semiarid Rangelands

Microtopographic features referred to as “terraces”¹⁴ are repetitious “bench” (path-like) and “riser,” (slope-like) features common in semiarid environments such as those throughout the western United States¹⁵ (Fig. 1). The soil conditions of terracette benches and risers in active pasturelands are often impacted by animal use, resulting in altered vegetative cover and soil compaction.¹⁶ For example, high cattle stocking densities

Figure 1. Semiarid rangeland terracettes near Clarkston, Washington, on the north bank of the Snake River, March, 2014 (Photograph by Mark Corrao).

on terracette sites primarily increase soil compaction on bench surfaces, with the degree of compaction being influenced by soil texture and water conditions.^{16–18} Consequently, highly compacted soil conditions decrease the root growth ability of many plants, thereby reducing overall site vegetation,¹⁹ which can lead to increased soil water at field capacity as a result of less plant transpiration and altered soil pore structure.^{18,20} Vegetation is vital to rangeland use as feed for grazing animals¹⁰ and, in the presence of semiarid terracettes, for reducing hillslope runoff by increasing infiltration at the outer edge of benches.¹¹ The hydrologic interactions of terracette features may be significant in reducing erosion²¹ and increasing the amount of soil water on hillslopes²² in semiarid rangelands within the western United States through the ability of these microtopographic features to impede surface runoff.¹¹ The significance of this may be that microtopographic landforms are capable of reducing NPS pollution when managed under human-ascribed BMPs.

Assessing the Hydrologic Function of Terracettes in Idaho

Mean (30-year average) annual precipitation and temperature for our study area were 312.7 mm and 11.7°C, respectively. We measured field conditions (e.g., soil water content, soil texture, compaction, infiltration, and vegetation cover) at two terracette (east aspect, moderate/low cattle stocking density – EMD; and west aspect, high cattle stocking density – WHD) and two non-terracette sites (grazed and ungrazed) from 2013 to 2015¹⁷ (Fig. 2 and Tables 1 and 2),¹⁷ with the goal of capturing changes in transitional-period soil moisture by using soil core, soil probe, and penetrometer sampling methods. We also surveyed vegetative cover, bare earth, and rock and litter percentages during June 2013 at all sites. The two terracette field sites exhibited differing aspects, bench and riser dimensions, cattle stocking densities, and site characteristics (see Table 1).¹⁷

Subsequent field assessments provided detailed topographic surveys of both terracette sites through multiple scans from a Leica ScanStation II terrestrial laser scanner (TLS), merged into one layer to minimize terrain shadowing, for the creation of digital terrain models (DTMs) to characterize bench and riser morphology.¹⁷ Laser scanning results were cross-referenced with manual measurements of terracette feature profiles from three transects across each site. Based on the TLS-derived DTMs, we calculated the relative area of benches and risers within each site. We used multivariate analysis of variance (ANOVA) to test for differences in soil water and compaction between features within each site and between sites. Two-sample, equal-variance Student’s *t* testsⁱⁱ were used to assess the statistical significance of differences in soil water and compaction among more than 100 benches and risers under differing site conditions. Based on *t* test results comparing benches and risers,^{iii,17} we hypothesized that

ⁱⁱ $\alpha < 0.05$.

ⁱⁱⁱ $P < 0.000$.

Figure 2. Study area map and sample site locations near Clarkston, Washington, on the north bank of the Snake River. Images are of the West site terracettes with high-density cattle stocking; East site terracettes with moderate-low density cattle stocking; Grazed Control non-terracerette site with high-density cattle stocking; and Ungrazed Control non-terracerette site with grazing excluded.

differences in soil water and compaction between terracette benches and risers may exist on most actively grazed rangelands in semiarid areas.

The Rangeland Hydrology and Erosion Model (RHEM), specifically designed for rangeland erosion predictions,²³ was used to estimate soil erosion/loss for the terracette and non-terracerette sites in our study based on previous research

showing RHEM to be a reasonable predictor of disturbed²⁴ and undisturbed²³ rangeland erosion. In order to simulate a terracette site with differing conditions for benches and risers, separate simulations were completed for each feature as an “independent uniform hillslope” by using measured site characteristics and an assumed representative slope length of 2 m, based on the average slope length of a single bench/riser

Table 1. Data collected at all field sites presented as averages within a site¹⁷

Site	Grazed control	EMD	WHD	Ungrazed control
Elevation (m)	356	354	370	362
Annual precipitation (mm)	313	313	313	313
Aspect (azimuth)	268	95	286	290
Slope (degrees)	28	49	26	22
Soil class	Silt loam	Silt loam	Silt loam	Silt loam
Vegetation cover (%)	4.2	65	36.5	95
Cattle density (AU ha ⁻¹)	10	0.05	10	
Grazing period	Sept-March	April-June	Sept-March	
Grazing intensity	High	ModerateLow	High	
Terracettes (y/n)	No	Yes	Yes	No
Bench width (m)		0.45	0.58	
Riser length (m)		1.59	1.29	
Site area (m ²)	972	2090	1806	2176

Table 2. Mean soil characteristic values across all field sites

	Grazed control	EMD		WHD		Ungrazed control
		Bench	Riser	Bench	Riser	
Sand (kg kg ⁻¹)	0.24	0.30	0.30	0.24	0.24	0.29
Silt (kg kg ⁻¹)	0.60	0.55	0.54	0.59	0.59	0.56
Clay (kg kg ⁻¹)	0.16	0.15	0.15	0.17	0.17	0.15
Organic carbon (kg kg ⁻¹)	0.027	0.023	0.024	0.028	0.031	0.028
Compaction (kPa)	3652	2359	1252	3833	2471	1113
Bulk density (kg m ⁻³)	1503	1456	1306	1628	1374	1289
Infiltration (cm day ⁻¹)		1.64	1.86	1.42	1.65	
$\theta_{v-wetseason}$ (m ³ m ⁻³)	0.34	0.35	0.30	0.35	0.34	0.31
$\theta_{v-dryseason}$ (m ³ m ⁻³)	0.14	0.12	0.10	0.16	0.11	0.12

Volumetric soil water content (θ_v) is separated by spring-winter “wet” and summer-fall “dry” season to illustrate annual variations.¹⁷

Figure 3. An assessment of 1000 random sample locations generated in ArcMap 10.2 of 20.3 ha each within Idaho was completed to quantify terracette aerial extent and categorize occurrence by dominant slope, aspect, vegetation type, and ownership. Aerial extent of terracettes was used to estimate potential erosion generated from terracette sites as opposed to non-terracette sites.

feature profile. The results of these simulations were then combined into a “composite terracette” site by adding the predicted soil loss rates for bench and riser features together given the percent-area of each feature calculated from the TLS DSM results.

To conceptualize terracette influences at a regional scale, we quantified the extent of terracettes within Idaho through a 1000-plot survey (20.3 ha plot size) using publicly available remotely sensed “Natural Color” digital ortho-imagery and geographic information system (GIS) data from the Inside Idaho database²⁵ (Fig. 3). Survey data included manual digitization of visible terracettes within each plot, average plot slope (degrees), dominant aspect of terracette area (N, S, E, W), plot-center elevation, ownership class (federal, state, private, other), and vegetation type (grass, shrubs/brush, mature timber). Survey results were used to estimate statewide terracette occurrence and model maximum, minimum, and average estimates of erosion for the EMD and WHD sites using RHEM. We used modeling estimates to provide a conceptual demonstration of terracette influenced sediment and erosion and to draw attention to BMPs specifically targeting these conditions in semiarid rangelands.

What We Found

Cattle densities for the EMD and WHD terracette sites were representative of moderate/low-density (0.05 AU per ha) and high-density (10 AU per ha), respectively. Through analysis of field data collected for terracette and non-terracette sites, we observed a significant trend^{iv} of increased soil compaction with increased cattle stocking (Fig. 4). This trend persisted throughout the data as shown by the greater compaction on terracette benches as opposed to risers, as well as greater overall mean site compaction for sites with higher animal stocking densities compared with those with less or no cattle influence. Similarly, a positive correlation

^{iv} Coefficient of determination, $R^2 = 0.86$.

Figure 4. An inverse relationship ($R^2 = 0.86$) between vegetative cover and compaction across all sampling locations was observed.¹⁷ Compaction values are represented as the mean in the upper 10 cm of each penetrometer profile ($n = 60+$) collected at a 1-cm measurement frequency using a Cone Penetrometer (Model CP401 by Rimik, Toowoomba, Australia). Vegetation survey data was gathered following the protocol described by Herrick et al.³⁵ The images above each column depict the vegetative conditions at each site as compaction increased from high to low (left to right).

between compaction and soil water content was demonstrated through our analysis of soil core samples and represented by an increase in soil water on terracette benches ($> 6\%$) as opposed to risers as well as between the more compact WHD site ($> 2\%$) and all other sites, including the Ungrazed control. There are many hydraulic processes that can influence subsurface soil moisture (e.g., redistribution, lateral flow, or groundwater through-flow) within the vadose zone. However, variable soil depth and

physical characteristics coupled with rainfall-dominated climates represent the conditions for much of the semiarid west, leading to an inherent variety of soil moisture conditions. The notable hydrologic processes observed in this study are depicted in the conceptual model of terracette function shown in Fig. 5.

Vegetative cover differed greatly at all sites (see Table 1), further supporting the trend between compaction and soil water we observed during sample analysis. Terracette and

Figure 5. Increased soil compaction led to greater soil water storage in the upper 10 cm of terracette benches compared with the less compact risers. Overall compaction values > 2500 kPa resulted in unvegetated benches and reduced vegetative cover on risers partly due to the ability of highly compacted soils to reduce plant root growth. Increased compaction can result in decreased infiltration and increased surface runoff and erosion; however, vegetation on terracette risers has the potential to reduce runoff from benches by slowing overland flow velocities and increasing soil infiltration.¹¹

Table 3. Supervised classification software (ENVI 5.0) used to analyze terrestrial laser scanning data for the East and West terracette sites to identify percent-area of benches and risers at differing slope gradients (all values presented are means)

	EMD		WHD	
	Bench	Riser	Bench	Riser
Terracette site area (m ²)	314	1776	704	1102
Terracette site slope (°)	49	49	26	26
Feature percent-area (%)	15	85	39	61
Feature slope (°)	8	56	5	39
Feature dimension (cm)	45*	159*	58*	129†
Vegetation cover (%)	56	74	30	43
Runoff‡ (mm yr ⁻¹)	2.7	1.3	6.9	4.4
Soil loss‡ (ton ha ⁻¹ yr ⁻¹)	0.03	0.19	0.26	0.44
Grazed control site soil loss‡ (ton ha ⁻¹ yr ⁻¹)				8.72
Ungrazed control site soil loss‡ (ton ha ⁻¹ yr ⁻¹)				0.01

* Coefficient of determination for bench width to site slope, $R^2 = 0.93$.

† Coefficient of determination for riser length to site slope, $R^2 = 0.82$.

‡ Rangeland Hydrology and Erosion Model Web Tool simulation results (30-year average).

non-terracette sites both exhibited reduced vegetative cover with increasing compaction (see Fig. 4).¹⁷ For samples with penetration resistance values greater than 2500 kPa (approximately 363 pounds per square inch), soil surfaces were predominantly devoid of vegetation and surface organic matter. These highly compacted areas also had the greatest soil water content in the upper 10 cm compared with sites with penetration resistance lower than 2500 kPa. Additionally, plots with the lowest compaction exhibited the greatest vegetation density and the lowest soil moisture, corroborating the suggested mechanism by which plants reduce soil water through transpiration, as well as the influence soil characteristics have on moisture exchange.

Transect measurements of bench and riser morphology yielded a positive trend of decreasing bench width^v and increasing riser length^{vi} as the slope gradient increased. These measures compared well with percent benches and riser area for the EMD^{vii} and WHD sites,^{viii} respectively. Additional supervised classification analysis of bench and riser percent-area from the TLS scan DTMs yielded similar results showing that a slope of 15 degrees comprised nearly equal (approximately 50%) bench and riser percent-area; however, at an average site slope of 65 degrees, risers comprised nearly 100% of plot conditions, that is, terracettes were no longer a dominant, or present, feature. Terracette morphology was input into RHEM for simulation of annual runoff and soil loss for bench and riser features independently. Per-feature simulations were then coupled

with DTM bench and riser percent-area calculations (Table 3) to estimate average soil loss for the EMD (0.11 ton ha⁻¹ yr⁻¹) and WHD (0.35 ton ha⁻¹ yr⁻¹) sites as a whole.

Completion of the 1000 plot statewide survey indicated more than 159,000 ha of terracettes exist within Idaho. RHEM simulation results applied to the EMD and WHD statewide terracette-area survey results showed the potential for 17,500 and 55,600 tons of sediment annually, respectively. For comparison purposes, applying the ungrazed (0.01 ton ha⁻¹ yr⁻¹) and Grazed Control (8.72 ton ha⁻¹ yr⁻¹) site conditions to the 159,000 ha identified in the statewide survey, showed an estimated soil loss of 1500 and 1.38 million tons per year, respectively. The model results presented in this paper for soil loss/erosion per unit area are similar to those presented in other studies for disturbed and undisturbed rangeland conditions,^{23,26,27} further supporting the importance of BMPs targeting rangeland erosion and the mitigation of potential impacts to stream water quality. The influence of local climate, site conditions, and erosional potential varies greatly, and although the results of this study are likely reasonable relative predictions, additional site-specific information would increase the accuracy runoff and soil loss estimates for terracette hillslopes.

Nonpoint Source Pollution, Terracettes, and Rangeland Management

Cattle use of terracette sites can increase soil compaction and soil water.⁸ This is most noticeable in well-developed soils, such as loams and clays, which are more easily compacted as a result of a higher percentage of smaller soil particles. Compacted soils commonly have reduced pore sizes,

^v $R^2 = 0.93$.

^{vi} $R^2 = 0.82$.

^{vii} $R^2 = 0.60$ and 0.97 .

^{viii} $R^2 = 0.82$ and 0.86 .

which can lead to increased soil moisture below field capacity due to alterations in soil characteristics.²⁰ In compacted soils, a greater soil moisture at or below field capacity equates to an increased antecedent moisture condition at the onset of precipitation and decreased total storage volume at saturation, both of which are known to play a significant role in watershed hydrology and the timing of runoff.^{28,29} Additionally, our results suggest that compaction and soil characteristics are influencing plant growth on terracette benches, which is in agreement with previous studies demonstrating the influence of compaction on plant root-growth,¹⁹ infiltration rates, and overland flow.^{9,16,30}

Vegetation, soil water, and microtopography are all key variables in semiarid rangeland runoff and erosion processes, influencing rainfall infiltration and altering the velocity and pathways of overland flow.¹¹ Understanding the interactions of terracette hydrology and vegetation can improve hydrologic modeling efforts and BMPs targeting NPS pollution for semiarid rangelands, similar to the process-based modeling approach presented for agricultural land BMPs for improved selection, location, and effectiveness by Brooks et al.³¹ Describing the mechanistic and hydrologic functions of terracettes can aid in the reduction of runoff and erosion for some rangeland sites through improving the effectiveness of BMPs, such as cattle stocking density and rotational grazing duration to minimize soil compaction and maintain adequate vegetative cover. Knowledge of the specific physical characteristics for any site helps define the challenges managers face to maintain sustainable use and the effectiveness of BMPs selected to mitigate potential negative impacts.³²

Rangeland BMPs can be improved through the scientific assessment of terracette hydrology. This, in turn, helps in the justification of management decisions and emphasizes the importance of communication between land managers and scientists,³³ in the development and application of BMPs.^{3,5} Balancing land use and NPS pollution policy brings science and management together at many levels,³³ providing an example of the value in understanding site-specific conditions to guide management decisions within the framework of established natural resource policy.

The significance of the use of site-specific science to inform NPS pollution policy stems, in part, from our knowledge that 40% of the impacts to streams in the United States are derived from agricultural lands¹ and from the role that policy has in guiding the management of these lands. Within the goal of rangeland sustainability, management faces the challenge of addressing NPS pollution and maintaining a balance among land use, economic viability, competing uses such as recreation, and ecosystem resilience, further complicated by variable site conditions. Currently, there have been more than 30 BMPs published by the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) (see Supplemental Table in Online Supplemental Materials at <http://dx.doi.org/10.1016/j.rala.2015.08.003>), for use in the management of NPS pollution (runoff and erosion) on rangelands.³⁴ There are, however, many more management practices being tested and applied on lands throughout the

western United States that may provide similar or improved results for specific areas, emphasizing the importance of continued collaboration and communication among scientists, managers, and policymakers.

The most effective BMPs^{3,4} are selected on the basis of site-specific knowledge commonly derived from a landowner or manager's understanding of an area they oversee and the animals they raise. The results of our research are limited in scope; however, we believe the framework we used to provide this example of how a microtopographic landform, such as a terracette, is connected with state and federal clean water concerns and the sustainability of rangelands is of value and provides a vivid illustration, with far-reaching application.

Conclusions

This as well as previous terracette research¹⁷ emphasizes the importance of vegetation and the significant role it can have in reducing soil runoff and erosion. Soil loss estimates and the site conditions in the study demonstrate the importance of tailoring rangeland management decisions, such as animal stocking rates, to site-specific conditions in consideration of the influence soil use may have on soil characteristics. Specifically, the results from this work showed terracettes on steeper slopes trend toward less bench area and increased potential for soil loss, with the opposite observed as the slope decreases. We speculate this may be due, in part, to changes in travel-path (bench) width as slope steepness varies, leading to increases in soil disturbance and compaction on steeper sites. Our observations are similar to previous research findings, noting that the influences of cattle hoof action on soils are most pronounced under wet-season conditions when soils are vulnerable to compression and deformation.^{18,20}

Best management practices applied as a result of site-specific information are likely to mitigate or curtail NPS pollution better than a more indiscriminate application based on regional hydrologic or climatic conditions.⁵ Additionally, the value of site-specific data and localized BMP success has the potential to extend beyond specific application sites and inform practices at the regional scale where similar conditions may exist. The presence of more than 6 million ha of rangelands in Idaho alone and the importance of understanding terracette hydrology, the occurrence of this feature at a state-scale, and the relationship of these features to land use will all provide value to the managers and policymakers working in semiarid rangelands.

Connecting science and land management often involves building relationships and communication, which help guide the development of new information and tools useful in the pursuit of sustainably managing NPS pollution. Communication of management knowledge based on personal experience can be valuable and plays a vital role in the application of BMPs,⁵ the development of balanced natural resource policy, and the maintenance or achievement of a sustainable level of ecosystem services desired from the natural environment. At the time this paper was prepared, we were not aware of a

quantification of NPS-impacted Idaho streams associated specifically with rangelands; however, increasing our understanding of the hydrologic function on lands inevitably helps mitigate potential impacts and secure the use of these lands for future generations.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.rala.2015.08.003>.

Acknowledgments

We would like to gratefully acknowledge the Wilma Ranch for providing us with access to their working rangelands and the overwhelming support and patience from ranch staff, particularly Eric Turley, during field sampling. We would like to express our thanks to Anita Fallen for her exceptional assistance in laboratory analysis and to Tiffany Corrao, Mary Engels, John MacPhearson, Suyog Gyawali, and Kevin Erixson for their assistance in field sampling. We would also like to thank Dr. Erin Brooks and two anonymous reviewers for their constructive comments during the development of this manuscript.

We greatly acknowledge the financial support provided by Northwest Management Inc., for field research and laboratory analysis throughout this research through grant No. 9992.

References

- USEPA. 2009. National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle. Washington, DC: USEPA. 43 p.
- IDEQ. 2011. Idaho's 2010 Integrated Report—final. Boise, ID: IDEQ. 102 p.
- ICE, G. 2004. History of innovative best management practice development and its role in addressing water quality limited waterbodies. *Journal of Environmental Engineering* 130(6):684-689.
- D'ARCY, B., AND A. FROST. 2001. The role of best management practices in alleviating water quality problems associated with diffuse pollution. *Science of the Total Environment* 265:359-367.
- PANNELL, D., G. MARSHALL, N. BARR, A. CURTIS, F. VANCLAY, AND R. WILKINSON. 2006. Understanding and promoting adoption of conservation practices by rural landholders. *Australian Journal of Experimental Agriculture* 46(11):1407. Available at: <http://www.publish.csiro.au/?paper=EA05037> Accessed 6 February 2014.
- EMMERICH, W. 2007. Ecosystem water use efficiency in a semiarid shrubland and grassland community. *Rangeland Ecology & Management* 60:464-470.
- SACO, P.M., G.R. WILLGOOSE, AND G.R. HANCOCK. 2007. Eco-geomorphology of banded vegetation patterns in arid and semiarid regions. *Hydrology and Earth System Sciences* 11(6):1717-1730.
- KRUEGER, W., M. SANDERSON, J.B. CROPPER, M. MILLER-GOODMAN, C.E. KELLEY, R.D. PIEPER, P.L. SHAVER, AND M.J. TRILICA. 2002. Environmental impacts of livestock on US grazing lands. *Council for Agricultural Science and Technology* 22:1-16.
- TRIMBLE, S., AND A. MENDEL. 1995. The cow as a geomorphic agent—a critical review. *Geomorphology* 13:233-253.
- HOLECHEK, J.L. 1988. An Approach for Setting the Stocking Rate. 10:10-14.
- BERGKAMP, G. 1998. A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. *Catena* 33(3-4):201-220.
- ROBINSON, D.A. 2008. Soil moisture measurement for ecological and hydrological watershed-scale observatories: a review. *Vadose Zone Journal* 7(1):358.
- PRINGLE, C. 2000. Threats to US public lands from cumulative hydrologic alterations outside of their boundaries. *Ecological Applications* 10(4):971-989.
- ØDUM, H. 1922. Om "Faarestiernes" natur. In: Reitzel CA, editor. København, Denmark: I kommission hos. 29 p.
- RAHM, D. 1962. The Terracette problem. *Northwest Science* 36(3):65-80.
- GIFFORD, G., AND R. HAWKINS. 1978. Hydrologic impact of grazing on infiltration: a critical review. *Water Resources Research* 14(2):305-313.
- CORRAO, M.V., R. HEINSE, J.U.H. EITEL, B. COSENS, AND T.E. LINK. 2015. Terracette soil moisture patterns in semiarid rangelands as a tool to inform sustainable best management practices and bridge water resource science, management, and policy: Chapter 1: Terracette influenced soil moisture patterns on semiarid rangelands. [Ph.D. Dissertation]. Moscow, ID: University of Idaho. 1-15 p.
- SCHMALZ, H.J., R.V. TAYLOR, T.N. JOHNSON, P.L. KENNEDY, S.J. DEBANO, B.A. NEWINGHAM, AND P.A. MCDANIEL. 2013. Soil Morphologic properties and cattle stocking rate affect dynamic soil properties. *Rangeland Ecology & Management* 66(4):445-453.
- GERARD, C., P. SEXTON, AND G. SHAW. 1982. Physical factors influencing soil strength and root growth. *Agronomy Journal* 74(5):875-879.
- VILLAMIL, M.B., N.M. AMIOTTI, AND N. PEINEMANN. 2001. Soil Degradation related to overgrazing in the semi-arid southern caldenal area of Argentina. *Soil Science* 166(7):441-452.
- GALLART, F., J. PUIGDEFABREGAS, AND G. DEL BARRIO. 1993. Computer simulation of high mountain terraces as interaction between vegetation growth and sediment movement. *Catena* 20:529-542.
- GREENWOOD, P., S. KUONEN, W. FISTER, AND N.J. KUHN. 2015. The influence of terraces on the surface hydrology of steep-sloping and subalpine environments: some preliminary findings. *Geographica Helvetica* 70(1):63-73.
- NEARING, M.A., H. WEI, J.J. STONE, F.B. PIERSON, K.E. SPAETH, M.A. WELTZ, D.C. FLANAGAN, AND M. HERNANDEZ. 2011. A rangeland hydrology and erosion model. *The American Society of Agricultural and Biological Engineers* 54(3):1-9.
- AL-HAMDAN, O.Z., M. HERNANDEZ, F.B. PIERSON, M.A. NEARING, C.J. WILLIAMS, J.J. STONE, J. BOLL, AND M.A. WELTZ. 2014. Rangeland hydrology and erosion model (RHEM) enhancements for applications on disturbed rangelands. *Hydrological Processes* 29(3):445-457.
- STATE OFFICE, IDAHO 2012. Interactive Numeric and Spatial Information Data Engine (INSIDE) Idaho. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.
- WEI, H., M.A. NEARING, J.J. STONE, D.P. GUERTIN, K.E. SPAETH, F.B. PIERSON, M.H. NICHOLS, AND C.A. MOFFET. 2010. A New splash and sheet erosion equation for rangelands. *Soil Science Society of America Journal* 73(4):1386-1392.
- AL-HAMDAN, O., AND F. PIERSON. 2013. Risk assessment of erosion from concentrated flow on rangelands using overland flow distribution and shear stress partitioning. *Transactions of the ASABE* 6(2):539-548.
- CHAUVIN, G.M., G.N. FLERCHINGER, T.E. LINK, D. MARKS, A.H. WINSTRAL, AND M.S. SEYFRIED. 2011. Long-term water balance and conceptual model of a semi-arid mountainous catchment. *Journal of Hydrology* 400(1-2):133-143.

29. CASTILLO, V.M., A. GÓMEZ-PLAZA, AND M. MARTÍNEZ-MENA. 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. *Journal of Hydrology* 284(1-4):114-130.
30. DUNNE, T., W. ZHANG, AND B.F. AUBRY. 1991. Effects of rainfall, vegetation, and microtopography on infiltration and runoff. *Water Resources Research* 27(9):2271-2285.
31. BROOKS, E.S., S.M. SAIA, J. BOLL, L. WETZEL, Z.M. EASTON, AND T.S. STEENHUIS. 2015. Assessing BMP effectiveness and guiding bmp planning using process-based modeling. *Journal of the American Water Resources Association* 51(2):343-358.
32. RITTENBURG, R.A., A.L. SQUIRES, J. BOLL, E.S. BROOKS, Z.M. EASTON, AND T.S. STEENHUIS. 2015. Agricultural BMP effectiveness and dominant hydrological flow paths: concepts and a review. *Journal of the American Water Resources Association* 51(2):305-329.
33. LIKENS, G.E. 2010. The role of science in decision making: does evidence-based science drive environmental policy? *Frontiers in Ecology and the Environment* 8(6):1-9.
34. NRCS, 2013. Conservation practices. National Conservation Practice Standards. Washington, DC: NRCS.
35. HERRICK, J., J. VAN ZEE, AND K.M. HAVSTAD. 2005. Monitoring manual for grassland, shrubland and savanna ecosystems. Volume I: Quick Start. Volume II: Design, supplementary methods and interpretation. Washington, DC: U.S. Department of Agriculture. 206 p.

Authors are Hydrologist, University of Idaho., Moscow, Idaho, 83844 (Corrao, mcorrao@nmi2.com); Professor of Law, University of Idaho, Moscow, Idaho, 83844 (Cosens); Associate Professor of Soil Physics, University of Idaho, Moscow, Idaho, 83844 (Heinse); Research Assistant Professor, University of Idaho - McCall Field Campus, Moscow, Idaho, 83844 (Eitel) and Professor of Forest Hydrology, University of Idaho, Moscow, Idaho, 83844 (Link). We greatly acknowledge the finical support provided by Northwest Management Inc., for field research and laboratory analysis throughout this research through grant No. 9992.