Terracette Soil Moisture Patterns in Semiarid Rangelands as a Tool to Inform Sustainable Best Management Practices and Bridge Water Resource Science, Management, and Policy

A Dissertation

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by

Mark V. Corrao

Major Professor: Robert Heinse, Ph.D.

Committee Members: Barbara Cosens, J.D.; Timothy Link, Ph.D.; Jan Eitel, Ph.D.

Department Administrator: Jan Boll, Ph.D.

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Authorization to Submit Dissertation

This dissertation of Mark V. Corrao, submitted for the degree of Doctorate of Philosophy with a Major in Water Resources and titled “Terracette Soil Moisture Patterns in Semiarid Rangelands as a Tool to Inform Sustainable Best Management Practices and Bridge Water Resource Science, Management, and Policy,” has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ________________________________ Date: ________
Robert Heinse, Ph.D.

Committee Members: ________________________________ Date: ________
Barbara Cosens, J.D.

________________________________ Date: ________
Timothy Link, Ph.D.

________________________________ Date: ________
Jan Eitel, Ph.D.

Department Administrator: ________________________________ Date: ________
Jan Boll, Ph.D.

Abstract

There are 17,076 stream miles listed for Category 5 nonpoint source (NPS) water quality impairment on Idaho’s 303(d) list. Nearly 40% of NPS impairment in the U.S. is attributed to agricultural activities, with sediment comprising ~15% of this water quality pollution. Best management practices (BMPs) have developed to mitigate NPS pollution; however the need for site-specific research and an improved understanding of hydrologic processes persists in order to continue development and application of these practices. In the semiarid western U.S. water plays a defining role in public land use, with soil moisture, vegetation, and microtopography being key variables in the hydrologic function of ecosystems. Within the State of Idaho alone, 6 million hectares (~28%) of public lands are managed directly as grazing allotments, the majority of which are in semiarid areas. The most prominent microtopographic features in semiarid systems are ‘cat steps’ or ‘terracettes’, described as soil surface variations of <1 m consisting of repetitious ‘benches’, path-like, and ‘riser’, slope-like, features on hill sides of greater than ~15% slope. Due to limitations in the spatial resolution of topographic data and computational resource demands, hydrologic models have not accounted for terracettes despite a general recognition that influences of microtopography on soil moisture patterns in semiarid ecosystems can increase the accuracy of variables used in the modeling of processes such as surface runoff and sediment transport. The importance of sustainable rangeland management and the need to address water, erosion, and sedimentation challenges in semiarid ecosystems exemplifies the need to contextualize the hydrologic response of terracettes at a plot-scale and quantify their extent at a regional scale to inform sustainable BMPs and bridge water resource science, management, and policy.

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Dedication

I would like to thank my Mother and Father for their never-ending encouragement and support for without them I would not be as accomplished as I am; and to my wife, for without her care and patience I would not have been able to pursue this achievement.

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Chapter 1. Terracette Influenced Soil Moisture Patterns on Semiarid Rangelands

Corrao, M.V., R. Heinse, J.U.H. Eitel, and T.E. Link

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Abstract

Microtopographic features known as terracettes are found throughout many semiarid rangelands. Their soil properties and hydrologic function, however, are virtually unknown. This research is presented as a case study identifying the differences in soil properties between terracette bench and riser features, and their effect on soil moisture at two terracette sites and two non-terracette control sites (grazed and ungrazed) in Eastern Washington State. The objectives of this research where to: 1) assess differences in soil moisture between terracette bench and riser features; 2) identify soil cover and cattle stocking density effects on soil moisture patterns, and; 3) quantify differences in retained soil moisture between these terracette and non-terracette sites. Measurements of volumetric water content (θ_v), bulk density, soil texture, saturated hydraulic conductivity, pH, and ECe were collected throughout the 2013 and 2014 field seasons and combined with measures of compaction, vegetative cover and cattle density for each site. Our results show significant volumetric water content differences between terracette benches and risers, with benches exhibiting higher mean θ_v than risers across all sites during both ‘wet’ (+6.14%) and ‘dry’ (+6.63%) periods. Comparison of terracette and non-terracette sites showed greater θ_v on terracette sites influenced by higher animal stocking rates and differences in mean θ_v to a depth of up to 20 cm. The greatest differences in θ_v, bulk density, and compaction for all sites occurred in the upper 10 cm. Greater water content on terracette benches is partially attributed to shifts in pore size distribution with compaction, and a reduction in transpiration resulting from lower vegetative cover resulting from plant-root impedance. We conclude that soil compression and deformation resulting from hoof impacts on terracette benches can inhibit root-water uptake and simultaneously enhance soil water retention in smaller pores. The results of this work provide a baseline mechanistic understanding of terracettes valuable to semiarid rangeland management.

Introduction

Understanding soil moisture patterns at the hillslope scale is a critically-important part of modeling watershed ecological and hydrological processes (Porporato et al., 2002; Rodríguez-Iturbe and Porporato, 2005). At local scales soil moisture can be spatially highly variable (Western et al., 2002) playing a critical role in the rainfall-runoff response of catchments (Bergkamp, 1998) and serving as an ecological driver controlling plant transpiration, and particularly in semiarid lands, acting as the dominant control affecting the structure, function and diversity of an ecosystem (Robinson, 2008). Antecedent moisture conditions in hydrologic models often include some parameterization of topography (Gerke et al., 2010; Harpold et al., 2010). However, because of limitations in the spatial resolution of topographic data and computational resource demands (Tesfa et al., 2011), hydrologic models have not accounted for microtopography (soil surface variations of < 1m vertical relief as described by Moser et al., 2007) despite a general recognition that influences of microtopography on soil moisture patterns in semiarid ecosystems can increase the precision of variables used in modeling processes such as surface runoff and sediment transport (Savabi 2001; Mapfumo et al. 2004; Easton et al. 2008; Jones et al. 1996). A greater knowledge of microtopographic influences on soil moisture is also critical for land managers tasked with predicting forage production and animal stocking densities (Naeth et al., 1990; Holechek et al., 1999; Krueger et al., 2002; Bilotta et al., 2007) in water-limited and hydrologically sensitive ecosystems.

Microtopography is commonly included in the broader framework of topographic heterogeneity describing patterns of vertical relief at many spatial scales formed by geologic, hydrologic, physical, and biological processes (Larkin et al., 2006). Microtopographic features referred to as ‘cat steps’ (Buckhouse and Krueger, 1981) or ‘terracettes’ (Ødum, 1922) (Fig. 1) are repetitious ‘bench’, path-like, and ‘riser’, slope-like, features that exist on hill sides of greater than 15° in semiarid environments of the Western U.S. (Rahm, 1962), as well as throughout the world (Radcliffe, 1968; Gallart et al., 1993; Kück and Lewis, 2002; Wilson et al., 2004; Henck et al., 2010). The majority of terracette research has focused on formational processes encompassing either geomorphic processes (Rahm, 1962; Bielecki and Mueller, 2002; Kück and Lewis, 2002) or grazing animals (Buckhouse and Krueger, 1981; Watanabe, 1994), with attempts at modeling formation (Gallart et al., 1993), relating formation to anthropogenic history (Henck et al., 2010) and classification (Anderson, 1972) on the periphery. Measurements of terracettes in semiarid environments have been shown to exhibit bench widths of 15-76 cm and riser heights of 5 to >120 cm on slope gradients between 9 – 60° with lengths of 3 to >300 m (Rahm, 1962; Anderson, 1972; Bergkamp, 1998; Weihs and Shroder, 2011).

Past research has not directly focused on terracettes and their influence on soil moisture, with the majority of references to soil moisture being a secondary result of rainfall, runoff, and/or erosion experiments (Emmett, 1970; Watanabe, 1994; Bergkamp et al., 1996; Bergkamp, 1998) including measures of compaction, bulk density, soil texture, and/or vegetation (Western et al., 2002; Robinson, 2008; Robinson et al., 2008). Radcliffe (1968) reported higher soil moisture on bench as opposed to riser features for a temperate climate (annual precipitation 1194 mm) in New Zealand during analysis of total carbon and major cations related to pastureland health. Field observations in semiarid Mediterranean environments have shown increased infiltration at the outer edge of terracette benches during episodic rain events as a result of vegetation on risers (Bergkamp 1998). Soil moisture contents measured by the same authors during rainfall experiments further supported these infiltration results through observance of a uniform wetting front in the soil profile to a depth of 15 cm over 50 min on terracette benches, and conversely rapid non-uniform infiltration on risers, where saturation was reached to a depth of 25 cm in <10 min (Bergkamp et al., 1996). Overland flow simulations have also demonstrated microtopography, similar to terracettes, can reduce the net runoff and erosion in semiarid systems during rainfall events by buffering velocity through reduced slope-length, and depression storage (Liu and Singh, 2004; Mayor et al., 2008).

Studies of semiarid rangeland environments, terracettes, and the impacts of grazing emphasize the importance of sustainable rangeland management (Alderfer and Robinson, 1947; Dormaar et al., 1989; Holechek et al., 1999) and the need to address water, erosion and sedimentation challenges in these ecosystems (Laycock and Conrad, 1967; Bilotta et al., 2007; Schmalz et al., 2013). Previous research encompassing both terracettes and soil moisture has occurred in temperate environments, or as a byproduct of surface hydrological investigations which have not addressed critical gaps in our mechanistic understanding of how and why soil moisture varies spatially on terracette hillslopes in semiarid environments.

The specific focus of this paper is on semiarid hillslopes with active cattle grazing. Our research was driven by the hypothesis that terracette sites exhibit greater soil moisture than non-terracette sites due to increased retention of water on terracette benches as compared to risers, resulting from altered soil characteristics. The specific objectives of this research were to 1) assess differences in soil moisture between bench and riser features of terracettes; 2) identify soil cover and cattle stocking density effects on soil moisture, and; 3) assess retained soil moisture between terracette and non-terracette sites.

Methods

Site Description – This study was conducted from 2013 to 2014 on an active cattle ranch near Clarkston, WA (46°26' N, 117°08' W), in Whitman County north of the Snake River (Fig. 2). Long-term precipitation and air temperature data was provided by the Nez Perce County Regional Airfield at Lewiston, ID, located 12.5 km SE of the site at 437 m elevation. Mean (30-year average) annual precipitation and temperature for the area were 312.7 mm and 11.7°C, respectively. The 30-year average 'wet' period typically spans from December to June receiving an average of 207 mm or 66.1%, of annual precipitation. The 'dry' period typically begins in June and continues through November averaging 106 mm (33.9% of average annual precipitation). The 2013 and 2014 wet season precipitation was 166 mm (68.8% of annual) and 191 mm (69.1% of annual), respectively and the dry season precipitation measured 75.18 mm (31.2%) and 85.60 mm (30.9%) for 2013 and 2014, respectively. Study site soils are predominately silt loam textured Kuhl-Alpowa complex per the Whitman County, Washington Soil Survey (Soil Survey Staff, 1980). These soils are shallow and moderately well-drained with as average saturated hydraulic conductivity (K_s) of 15.06 mm/hr, and an average mineral horizon depth of 15 to 30 cm.

Data Collection – Two terracette sites with differing aspect, an Eastern ("East") and Western ("West"), and two non-terracette control sites ("Grazed Control" and "Ungrazed Control"), were established for this study. Site description data is presented in Table 1. Soil data were collected following the methods described by Radcliffe (1968) who found a sampling intensity of four cores per terracette feature was sufficient, following an initial sampling study using 10 cores. We chose a sampling density of 20 cores on terracette sites during each field visit, 10 samples on benches and 10 on risers, respectively, due to spatial heterogeneity in terracette feature characteristics (bench width and riser height). At each sample location, two soil cores, one soil probe and five penetrometer measures were gathered. For the Grazed and Ungrazed Control sites a total of 10 core samples were collected during each field visit and 20 penetrometer measures were gathered on two separate occurrences in April and December, 2014. A minidisk infiltrometer (Decagon Devices, Inc., Pullman, WA, U.S.A.) was used to measure saturated hydraulic conductivity at 20 locations (10 bench and 10 riser) for each of the terracette sites in June, 2014 following the methods described by Zhang, (1997). Field sampling occurred on October 15, 2013, March 11-14, 2014, April 21, 2014, May 29, 2014, June 5, 2014, June 17, 2014, November 6, 2014, and December 8, 2014 with the goal of capturing temporal changes in soil moisture.

Soil core samples were collected using a soil probe (2 cm diameter by 1 m long) and an ICT International model No. 0200 soil bulk density sampler (5.7 cm diameter and 10 cm long). Sampling commenced following snowmelt when field sites were near field capacity and continued into the dry season until soil moisture was observed to no longer vary or sampling was inhibited by soil strength. Soil cores were collected by first removing any surface cover then driving the sampler into the soil with a slide-hammer or small mallet. At each sample location three soil cores were obtained with the ICT sampler. Two cores were immediately sealed in plastic bags for particle size analysis (PSA), organic carbon (OC) and electrical conductivity (ECe) analysis for the upper 10 cm of the soil profile. The third core was kept intact by securing it in a metal canister for analysis of ρ_b and volumetric water content (θ_v) following the methods presented by Blake (1965) and Cassel & Nielsen (1986). Additionally, soil probe samples were collected simultaneously alongside ρ_b samples with an offset of 10 to 15 cm parallel to the bench or riser being sampled in a northerly direction. Soil probe samples were collected to a depth of 1 m or instrument refusal, and were partitioned by 20 cm depth increments into storage containers for laboratory analysis of PSA, OC and ECe. All samples were immediately stored on ice in a cooler for laboratory analysis. Laboratory PSA was performed using sieving, flocculation and suspension procedures (Gee and Bauder, 1986), with clay and silt measured through suspension using the pipette method (Kilmer and Alexander, 1949) and soil organic carbon was determined by rapid dichromate oxidation

(Nelson and Sommers, 1982). Throughout the 2013 and 2014 field seasons 725 soil cores and 354 compaction measures were collected between all sites.

Soil penetration resistance (as a surrogate for compaction) was measured on all four sites using a Cone Penetrometer (Model CP401 by Rimik, Toowoomba, Australia). Compaction measures were recorded to a depth of 70 cm or instrument-refusal, via the method of random core sampling as presented by Radcliffe (1968) with the same modification as described above for soil core sampling. Compaction measurement frequency ranged from 45 and 90 samples per bench and riser feature at both terracette sites in order to capture ≥30 profiles beyond 35 cm of depth. Penetrometer sampling was completed with the objective of comparing bench and riser features intra-site and to the non-terracette control site conditions.

During June 2013, percent vegetative cover, bare earth, rock and litter were estimated occularly at locations identified in the same manner as described for in situ core sampling following the rangeland density and cover-type methods presented in Herrick et al. (2005). Cattle density for each pasture was obtained from the ranch staff. Cattle densities for the West and Grazed Control sites were considered to be ‘high-density’ while that of the East site was considered ‘moderate to low-density’ as described in the literature (Dormaar et al., 1989; Naeth et al., 1990; Holechek et al., 1999; Pietola et al., 2005). Terracette feature morphology (bench width / riser length) was measured perpendicular to the slope at three transects across each terracette site (East and West) during the 2014 field season (Table 1) following the methods presented by Rumball, (1966).

Statistical Analysis – Statistical analysis was completed using the open source statistical software package, R version 3.1.2 (R. Core Team, 2015). For soil samples collected on terracette sites bench and riser data were regressed against each other as well as against the control sites data. Throughout this study a significance level of $\alpha = 0.05$ was considered for all comparisons. Pearson correlation coefficients were determined for relationships between θ_v, ρ_b, PSA, OC, vegetative cover % and compaction within a site and between sites. Stepwise multiple regression, both forward and backward, were also used to determine the most suitable property to best describe variations in θ_v within and between sites. Moran’s I statistics were calculated for θ_v and ρ_b to evaluate the presence of spatial autocorrelation and to inform further analysis.

Pearson correlations were also used to identify relationships between θ_v, ρ_b, and OC for ‘dry’ and ‘wet’ season measurements and to further identify spatiotemporal variation in θ_v with respect to terracette morphology or the lack thereof. Welch two-sample t-test assuming normal distribution and the Wilcoxon nonparametric rank-sum test with continuity correction were completed to test for normality and further assess the structure of each dataset. Two-sample t-test results were also used to gauge the significance of seasonal differences in θ_v within a site and between sites. Contingency plots of quartile values were performed to further assess normality and visualize 95% confidence limits to determine if a *log* transform was valuable (results not shown). In addition; linear regression, Analysis of Variance (ANOVA), biplot, and Principle Components Analysis (PCA) were completed in R, when appropriate, to further explore variation and trends between variables (results not shown).

Results

Soil Texture, Hydraulic Conductivity and Vegetative Cover – Mean soil characteristics between terracette and non-terracette sites are presented in Table 2. Averaged particle size across all sites (0 to 30 cm depth) yielded sand, silt and clay percentages of 27, 57 and 16 respectively with a mean soil organic carbon content of 2.7%. Hydraulic conductivity was observed to be 10.90 and 18.62 mm hr^{-1} for East site benches and risers and 14.23 and 16.49 mm hr^{-1} for West site benches and risers, respectively. Percent vegetative cover varied from 4 to 96% across all sites with terracette site averages of 65 and 31% for East and West, respectively. Percent-bare-ground at the East and West sites were 29 and 60%, respectively. A significant inverse relationship ($R^2 = 0.86$) between compaction and percent-vegetative-cover was also observed across all sites.

Compaction and Bulk Density – A significant positive trend ($R^2 = 0.78$) between compaction and ρ_b was observed across all sites. Compaction on benches varied from 622 to 5220 kPa on the East site and from 1200 to 6280 kPa on the West site. Compaction on risers ranged from 118 to 2590 kPa and 1480 to 3580 kPa for the East and West sites, respectively, with the Grazed Control and Ungrazed Control sites averaging 4180 and 1110 kPa. Mean ρ_b on terracette benches was significantly higher (+14.6%) than on risers for all terracettes sites (Fig. 3) with maximum values of 1776 and 1858 kg m^{-3}, on East and West sites, respectively.

Soil Moisture – Volumetric water content was significantly different between benches and risers, with benches exhibiting higher mean θ_v than risers across terracette sites during both dry and wet periods (Table 3). Mean and standard deviation of θ_v varied from a low of 0.1m^3 m^{-3} (± 0.02) on East risers to a high of 0.353 m^3 m^{-3} (± 0.026) on West benches (Table 4). Within terracette and non-terracette sites there were no statistically distinguishable spatial patterns in θ_v (Moran's I test, p-values from 0.16 – 0.92, $\alpha = 0.05$) with the exception of the West site during the wet season in 2014 (Moran's I test, p-value = 0.017, $\alpha = 0.05$) (Fig. 4). Spatial autocorrelation of ρ_b was not significant for any site during the 2013 or 2014 field seasons (Moran's I test, p-values from 0.17 – 0.81, $\alpha = 0.05$).

Comparison of θ_v between the East (benches 0.10 m^3 m^{-3} and risers 0.123 m^3 m^{-3}) and Grazed Control site (0.142 m^3 m^{-3}) showed a significantly greater θ_v (p-value < 0.001) at the Grazed Control site during the 'dry' season (Table 3).The West site as a whole (dry 0.137 m^3 m^{-3} and wet 0.348 m^3 m^{-3}) exhibited a greater mean θ_v than the East site as a whole (dry 0.112 m^3 m^{-3} and wet 0.325 m^3 m^{-3}). Mean θ_v was significantly greater on the West site than on the Ungrazed Control site (p-value < 0.041) regardless of season, however, mean θ_v at the East site was not significantly different (p-value >0.179) than that of the Ungrazed Control site under any conditions.

Discussion

Soil Moisture – Significantly greater θ_v (+6.63% 'dry' and +6.14% 'wet') were observed on terracette benches as opposed to risers under nearly all conditions, with the exception of the statistically insignificant +1.11% θ_v at the West terracette site when near saturation during the wet season. The differences between bench and riser water contents were distinguishable from within-site and between-site variance around the mean θ_v for the sites ($CV_{West} = 0.51$, $CV_{East} = 0.52$, $CV_{Grazed\text{-}Control} = 0.47$, $CV_{Ungrazed\text{-}Control} = 0.47$). The West site influenced by a high density of cattle (10 AU ha^{-1}) showed significantly greater θ_v than that of the Ungrazed

Control site and the East terracette site with a low density of cattle (0.05 AU ha^{-1}). Conversely, mean bench θ_v on the East site showed no significant difference from the Ungrazed Control site and significantly less θ_v than the West terracette site (Table 4).

Water content showed a positive corollary relationship ($R^2 = 0.61$) to increasing ρ_b between benches and risers within sites as well as between terracette sites as a whole (Fig. 5). Our results of increased θ_v with increased compaction could be related to soil structural changes from grazing and cattle stocking density following the conclusions of Villamil et al. (2001) who showed that water stored in the smaller pores of compacted soils, lead to greater water retention at field capacity and potentially greater plant available water in compacted top soils for a grazed non-terracette site of similar soil texture in Argentina.

Compaction and Bulk Density – Compaction profiles by depth show a positive relationship between increased cattle stocking density and compaction, with the greatest impacts occurring in the upper 10 cm of the soil profile and no significant differences between bench and risers below depths of 15 cm. These findings are supported by Dec et al., (2012) who noted the effect of hoof impact on compaction decreased rapidly with depth. Mean compaction across all sites ranged from 1110 to 4180 kPa with a maximum value of 6280 kPa observed on benches of the West site (Fig. 3). This range of compaction is in agreement with reports in the literature by Benjamin et al. (2003) of 1100 to 3100 kPa for a silt loam in Chile under active grazing, and the results of Bachmann et al. (2006) who reported a 5000 kPa maximum for an actively grazed silt loam.

Bulk density in the soil profiles showed a positive corollary relationship ($R^2 = 0.61$) to θ_v, with the greatest impacts occurring in the upper 10 cm of the soil profile and patterns of θ_v on terracette sites being identified as higher soil moisture on benches as opposed to risers. These results agree with the findings of Chanasyk & Naeth (1995) showing a similarly positive corollary trend of increasing θ_v with increasing compaction ($R^2 = 0.78$). In addition, more than half (>55%) of the variability in soil moisture content on the East and West terracette sites were attributed to compaction and volumetric water content according to particle size analysis. The influence of ρ_b in our results aligns with those presented for non-terracette sites by Donkor et al. (2002) showing increased θ_v with increased ρ_b under grazing during periods of reduced precipitation for the upper 10 cm of a soil profile. These results are further supported by the work of Villamil et al. (2001) who showed bulk densities on grazed sites can be as much as 27% higher than on ungrazed sites in the upper 5 cm.

Our results align well with those describing the relationship of cattle density to soil deformation, increases in ρ_b, and compaction in semiarid environments for non-terracette rangelands (Dormaar et al., 1989; Naeth et al., 1990; Dec et al., 2012) and the potential of grazing animals to substantially alter soil characteristics, pore size and pore continuity (Alaoui et al., 2011; Dec et al., 2012). Cattle hoof-action is known to be a driving factor in alteration of soil pore structure leading to an overall reduction of soil pore size distribution (Villamil et al., 2001; Pietola et al., 2005; Krümmelbein et al., 2009). The significant greater θ_v observed in this study on the West site as compared to the Grazed Control site (+1.55% 'dry' and +3.75% 'wet') may indicate increased plant available moisture on terracettes as compared to non-terracettes under similar conditions, however additional research is needed, as greater θ_v is likely due to soil structural alterations from the influence of cattle hoof impacts (Pietola et al., 2005; Reszkowska et al., 2010) and may not be plant available dependent on soil texture (Unger and Kaspar, 1994; Tokunaga, 2006).

Vegetative Cover – We observed low vegetative cover on benches compared to risers which supports the negative correlation between θ_v and vegetative cover (Fig. 5). It is likely that partial plant-root penetration impedance due to increased compaction is a factor in the reduced vegetative cover observed on benches as compared to risers. Significant reductions in plant rooting ability above compaction values of 2500 kPa and ρ_b values of 1700 kg m^{-3} have been shown for fine-textured soils similar to the silt loam of our sites (Gerard et al., 1982). Percent-vegetative cover on the East and West sites was highly variable and similar to the findings of Rahm (1962) for terracettes in Whitman County, WA, under the influence of cattle on slopes of 15 – 30% and >30%. We speculate that the relatively low vegetative cover on terracette benches increases θ_v due to a reduction in soil water loss resulting from reduced plant transpiration as suggested by Unger and Kaspar (1994) and others (e.g., Dec et al., 2012).

Additional considerations potentially influencing measures of θ_v in this study could result from site variations in slope and aspect as exemplified by the 286° and 290° azimuths of the West and Ungrazed Control sites compared to the 95° azimuth of the East site. In the

Inland Northwest north-facing aspects are exposed to seasonally less direct sunlight durations than southern aspects, potentially resulting in energy balance / evaporative flux differences. The slight northward facing ‘west’ aspect of the West and Ungrazed Control sites could influence the magnitude of their relationship (Western et al., 1999) with that of the East site, which exhibited a slightly southward facing ‘east’ aspect. We further speculate different relationships observed in θ_v between sites is attributed to the combined influence of cattle stocking rates coupled with variations in vegetation and site aspect.

Characterization of soil moisture plays a vital role in accurately assessing the soil moisture conditions for semiarid land management (Vereecken and Huisman, 2008). Our results suggest there may be value in the inclusion of terracette influenced soil moisture patterns for semiarid rangeland management, where increased compaction can lead to increased θ_v. The inclusion of only two terracette sites of opposing aspect in this study limits the scope of our findings; however a generalization of our results showing increased θ_v on terracettes may be applicable to other sites of similar conditions, or valuable to future terracette research at differing scales. For example; at the plot scale, soil moisture is known to have a dominant influence on runoff (Merz and Plate, 1997) therefore, increased antecedent moisture conditions (Harpold et al., 2010) on terracette sites as opposed to non-terracettes sites may lead to increases in runoff or erosion, at least partially, from plant root impedance and soil structural alterations resulting from compaction (Schmalz et al., 2013). At the hillslope scale the identification of soil moisture patterns on terracettes can offer insight into processes driven by soil moisture conditions such as nutrient cycles, biogeochemical processes, and microbial activity (Robinson, 2008). At the regional scale soil moisture is a fundamental ecosystem resource and in semiarid lands controls the structure, function, and species composition of an ecosystem (Porporato et al., 2002; Rodríguez-Iturbe and Porporato, 2005) therefore, an improved understanding of soil moisture patterns on terracette hillslopes may improve rangeland use and sustainability efforts in semiarid environments.

Conclusions

The results of this research showed the existence of greater θ_v on terracette benches as compared to risers at the plot scale (<1 m^2) for the sampling conditions observed, and an overall greater soil moisture for terracette sites as compared to non-terracette sites under similar conditions. Furthermore, our results showed significant differences in ρ_b and compaction between terracette benches and risers as well as between terracette and non-terracette sites given the land use, soil and climatic conditions of this study area. These results show support for our hypothesis regarding soil moisture patterns with respect to terracette features in that; significant seasonal differences in soil moisture can exist between terracette benches and risers (> +6%); there can be significant differences in ρ_b and soil penetration/compaction between bench and riser features under differing cattle stocking rates; and increased soil moisture conditions can exist on terracette sites as compared to non-terracette sites.

The findings of this research further suggest differences in soil moisture across grazed-terracette sites may not be limited to the topographic effects that morphologically increase soil water (i.e., ponding or infiltration on benches), but rather, are the result of combined morphologic function and dynamic soil properties such as compaction, organic matter, and soil surface cover (Schmalz et al., 2013). Additionally, these results suggest grazing can increase soil moisture for some soils, but increased soil moisture does not necessarily contribute to forage production as it may be in part not accessible to plant roots due to compaction. Therefore, studies that conclude grazing is a preferred management practice because it increases soil-water may be drawing the wrong conclusion if site-specific soil texture and vegetative conditions are not considered.

To further this research and define the application and importance of spatiotemporal patterns of soil moisture on terracette slopes in semiarid ecosystems, studies are needed that evaluate terracette hydrology over a wider range of site variability (i.e., multiple slope gradients, vegetative conditions, soil textures and climatic conditions), and assess the relationship of terracettes to rangeland erosion and forage management at a hillslope or watershed scale.

Literature Cited

Alaoui, A., J. Lipiec, and H.H. Gerke. 2011. A review of the changes in the soil pore system due to soil deformation: A hydrodynamic perspective. Soil Tillage Res. 115-116: 1–15.

Alderfer, R., and R. Robinson. 1947. Runoff from pastures in relation to grazing intensity and soil compaction. J. Am. Soc. Agron. 39(11): 948–958.

Anderson, E.W. 1972. Terracettes: A suggested classification. R. Geogr. Soc. 4(1): 17–20.

Bachmann, J., K. Contreras, K.H. Hartge, and R. MacDonald. 2006. Comparison of soil strength data obtained in situ with penetrometer and with vane shear test. Soil Tillage Res. 87(1): 112–118.

Benjamin, J.G., D.C. Nielsen, and M.F. Vigil. 2003. Quantifying effects of soil conditions on plant growth and crop production. Geoderma 116(1-2): 137–148.

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.

Bergkamp, G., L.H. Cammeraat, and J. Martinez-Fernandez. 1996. Water movement and vegetation patterns on shrubland and an abandoned field in two desertification-threatened areas in Spain. Earth Surf. Process. Landforms 21: 1073–1090.

Bielecki, A., and K. Mueller. 2002. Origin of terraced hillslopes on active folds in the southern San Joaquin Valley, California. Geomorphology 42(1-2): 131–152.

Bilotta, G.S., R.E. Brazier, and P.M. Haygarth. 2007. The impacts of grazing animals on the quality of soils, vegetation, and surface waters in intensively managed grasslands. Adv. Agron. 94: 237–280.

Blake, G. 1965. Bulk density. In C.A. Black (ed.) Methods of soil analysis, Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. Am. Soc. Agron.: 374–390.

Buckhouse, J., and W. Krueger. 1981. What Caused Those Terracettes?. Rangelands Arch. 3(2): 72–73.

Cassel, D., and D. Nielsen. 1986. Field Capacity and Available Water Capacity. In A Klute (ed.) Methods of soil analysis, Part 1. 2nd. edition. Agronomy Monograph. Soil Sci. Soc. Am.: 901–926.

Chanasyk, D., and M. Naeth. 1995. Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada. Can. J. Soil Sci.: 551–557.

Dec, D., J. Dörner, O. Balocchi, and I. López. 2012. Temporal dynamics of hydraulic and mechanical properties of an Andosol under grazing. Soil Tillage Res. 125: 44–51.

Donkor, N.T., J. V. Gedir, R.J. Hudson, E.W. Bork, D.S. Chanasyk, and M. a. Naeth. 2002. Impacts of grazing systems on soil compaction and pasture production in Alberta. Can. J. Soil Sci. 82(1): 1–8.

Dormaar, J.F., S. Smoliak, and W.D. Willms. 1989. Vegetation and soil responses to short-duration grazing on fescue grasslands. J. Range Manag. 42(3): 252–256.

Emmett, W. 1970. The hydraulics of overland flow on hillslopes. United States Department of the Interior - Geological Survey Professional Paper 662-A.

Gallart, F., J. Puigdefabregas, and G. del Barrio. 1993. Computer simulation of high mountain terracettes as interaction between vegetation growth and sediment movement. Catena 20: 529–542.

Gee, G.W., and J.W. Bauder. 1986. Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods (EA Klute, Ed.). American Society of Agronomy-Soil Science Society of America.

Gerard, C., P. Sexton, and G. Shaw. 1982. Physical factors influencing soil strength and root growth. Agron. J.: 875–879.

Gerke, H., P. Germann, and J. Nieber. 2010. Preferential and unstable flow: From the pore to the catchment scale. Vadose Zo. J. 9(2): 207.

Harpold, A., S. Lyon, P. Troch, and T. Steenhuis. 2010. The hydrological effects of lateral preferential flow paths in a glaciated watershed in the northeastern USA. Vadose Zo. J. 9(2): 397.

Henck, A., J. Taylor, H. Lu, Y. Li, Q. Yang, B. Grub, S.J. Breslow, A. Robbins, A. Elliott, T. Hinckley, J. Combs, L. Urgenson, S. Widder, X. Hu, Z. Ma, Y. Yuan, D. Jian, X. Liao, and Y. Tang. 2010. Anthropogenic hillslope terraces and swidden agriculture in Jiuzhaigou National Park, northern Sichuan, China. Quat. Res. 73(2): 201–207.

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.

Holechek, J., H. Gomez, F. Molinar, and D. Galt. 1999. Grazing studies: what we've learned. Rangelands 21(2): 12–16.

Kilmer, V.J., and L.T. Alexander. 1949. Methods of making mechanical analyses of soils. Soil Sci. 68(1): 15–24.

Krueger, W., M. Sanderson, J.B. Cropper, M. Miller-Goodman, C.E. Kelley, R.D. Pieper, P.L. Shaver, and M.J. Trlica. 2002. Environmental impacts of livestock on US grazing lands. Counc. Agric. Sci. Technol. 22: 1–16.

Krümmelbein, J., S. Peth, Y. Zhao, and R. Horn. 2009. Grazing-induced alterations of soil hydraulic properties and functions in inner Mongolia, PR China. J. Plant Nutr. Soil Sci. 172: 769–776.

Kück, K., and C. Lewis. 2002. Terracettes and active gelifluction terraces in the Drakensberg of the Province of the Eastern Cape, South Africa: a process study. South African Geogr. J.: 1–23.

Larkin, D., G. Vivian-Smith, and J.B. Zedler. 2006. Topographic heterogeneity theory and ecological restoration. p. 142–164. *In* Falk, D.A., Palmer, M.A., Zedler, J.B. (eds.), Foundations of Restoration Ecology. Island Press, Washington, DC, USA.

Laycock, W., and P. Conrad. 1967. Effect of grazing on soil compaction as measured by bulk density on a high elevation cattle range. J. Range Manag.: 136–140.

Liu, Q., and V. Singh. 2004. Effect of microtopography, slope length and gradient, and vegetative cover on overland flow through simulation. J. Hydrol. Eng. 9(5): 375–382.

Mayor, Á.G., S. Bautista, E.E. Small, M. Dixon, and J. Bellot. 2008. Measurement of the connectivity of runoff source areas as determined by vegetation pattern and topography: A tool for assessing potential water and soil losses in. Water Resour. Res. 44(10): 1–13.

Merz, B., and E.J. Plate. 1997. An analysis of the effects of spatial variability of soil and. Water Resour. Res. 33(12): 2909–2922.

Naeth, M.A., D.J. Pluth, and D.S. Chanasyk. 1990. Soil compacting impacts of grazing in mixed prairie and fescue grassland ecosystems of Alberta. Can. J. Soil Sci. 70: 157–167.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter, In: Methods of soil analysis, Part 2, 2nd ed. Agron. J. 9: 961–1010.

Ødum, H. 1922. Om“ Faarestiernes” natur (CA Reitzel, Ed.). København, I kommission hos.

Pietola, L., R. Horn, and M. Yli-Halla. 2005. Effects of trampling by cattle on the hydraulic and mechanical properties of soil. Soil Tillage Res. 82(1): 99–108.

Porporato, A., P. D’Odorico, F. Laio, L. Ridolfi, and I. Rodriguez-Iturbe. 2002. Ecohydrology of water-controlled ecosystems. Adv. Water Resour. 25: 1335–1348.

R. Core Team. 2015. R: A language and environment for statistical computing. Available at www.R-project.org.

Radcliffe, J. 1968. Soil conditions on tracked hillside pastures. New Zeal. J. Agric. Res.: 37–41.

Rahm, D. 1962. The Terracette Problem. Northwest Sci. 36(3): 65–80.

Reszkowska, A., J. Krümmelbein, S. Peth, R. Horn, Y. Zhao, and L. Gan. 2010. Influence of grazing on hydraulic and mechanical properties of semiarid steppe soils under different vegetation type in Inner Mongolia, China. Plant Soil 340(1-2): 59–72.

Robinson, D.A. 2008. Soil moisture measurement for ecological and hydrological watershed-scale observatories: A review. Vadose Zo. J. 7(1): 358.

Robinson, D.A., H. Abdu, S.B. Jones, M. Seyfried, I. Lebron, and R. Knight. 2008. Eco-Geophysical Imaging of Watershed-Scale Soil Patterns Links with Plant Community Spatial Patterns. Vadose Zo. J. 7: 1132.

Rodríguez-Iturbe, I., and A. Porporato. 2005. Ecohydrology of water-controlled ecosystems. Soil moisture and plant dynamics. Cambridge University Press.

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. Rangel. Ecol. Manag. 66(4): 445–453.

Soil Survey Staff. 1980. United States Department of Agriculture - Natural Resources Conservation Service: Soil Survey of Whitman County, Washington. Nat. Resour. Conserv. Serv.: 110.

Tesfa, T.K., D.G. Tarboton, D.W. Watson, K. a T. Schreuders, M.E. Baker, and R.M. Wallace. 2011. Extraction of hydrological proximity measures from DEMs using parallel processing. Environ. Model. Softw. 26: 1696–1709.

Tokunaga, A.A. 2006. Effects of bulk density and soil strength on the growth of blue wildrye (Elymus glaucus Buckl.).

Unger, P., and T. Kaspar. 1994. Soil compaction and root growth: a review. Agron. J. (1959).

Vereecken, H., and J. Huisman. 2008. On the value of soil moisture measurements in vadose zone hydrology: A review. Water Resour. Res. 44(4): 1–21.

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 Sci. 166(7): 441–452.

Watanabe, T. 1994. Soil erosion on yak-grazing steps in the Langtang Himal, Nepal. Mt. Res. Dev. 14(2): 171–179.

Weihs, B.J.B., and J.F.J. Shroder. 2011. Mega-terracettes and related ungulate activities in Loess Hills, Iowa, USA. Zeitschrift für Geomorphol. 55: 45–61.

Western, A.W., R.B. Grayson, and G. Blöschl. 2002. Scaling of Soil Moisture: A Hydrologic Perspective. Annu. Rev. Earth Planet. Sci. 30: 149–180.

Western, A., R. Grayson, G. Bloschl, G.R. Willgoose, and T.A. McMahon. 1999. Observed spatial organization of soil moisture and its relation to terrain indices. Water Resour. Res. 35(3): 797–810.

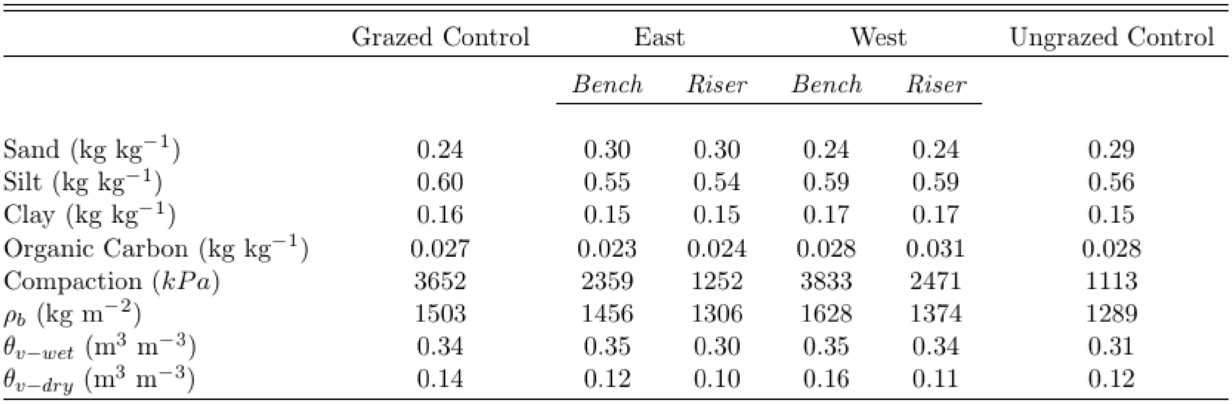
Wilson, D., A. Western, and R. Grayson. 2004. Identifying and quantifying sources of variability in temporal and spatial soil moisture observations. Water Resour. Res. 40(2): 1–10.

Zhang, R. 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Sci. Soc. Am. J. 61: 1024–1030.

Table 1.1 Data collected at all field sites presented as mean values.

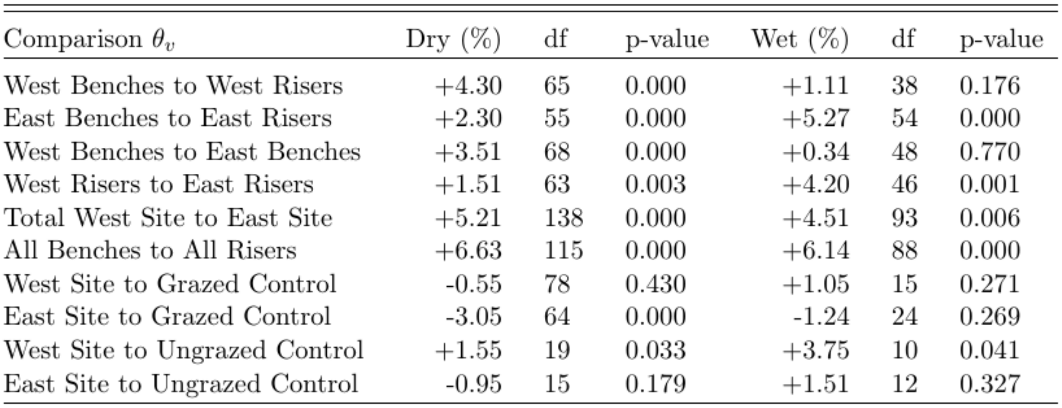
Site	Grazed Control	East	West	Ungrazed Control
Elevation (m)	356	354	370	362
Aspect (Azimuth)	268	95	286	290
Slope (^{o})	28	49	26	22
Soil Class	Silt Loam	Silt Loam	Silt Loam	Silt Loam
Veg Cover (%)	4.2	65	36.5	95
Cattle Density (AU ha^{-1})	10	0.05	10	-
Grazing Period	Sept-March	April-June	Sept-March	-
Grazing Intensity	High	Moderate-Low	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 1.2 Mean soil characteristic values across all field sites. Volumetric water content (θ_v) is separated by 'wet' and 'dry' season to illustrate annual variations.



	Grazed Control	East		West		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
ρ_b (kg m^{-2})	1503	1456	1306	1628	1374	1289
θ_{v-wet} (m^3 m^{-3})	0.34	0.35	0.30	0.35	0.34	0.31
θ_{v-dry} (m^3 m^{-3})	0.14	0.12	0.10	0.16	0.11	0.12

Table 1.3 An increase in volumetric water content (θ_v) between terracette bench and riser features was observed across all terracette sites, presented here as percent change. The East site (moderate-low density of cattle) shows lower θ_v during both wet and dry seasons when compared to the Grazed Control site, with no statistical difference when compared to the Ungrazed Control site. The West site (high density of cattle) shows no statistical difference in θ_v when compared to the Grazed Control site, however, greater θ_v during both 'wet' and 'dry' seasons was observed when compared to the Ungrazed Control site.



Comparison θ_v	Dry (%)	df	p-value	Wet (%)	df	p-value
West Benches to West Risers	+4.30	65	0.000	+1.11	38	0.176
East Benches to East Risers	+2.30	55	0.000	+5.27	54	0.000
West Benches to East Benches	+3.51	68	0.000	+0.34	48	0.770
West Risers to East Risers	+1.51	63	0.003	+4.20	46	0.001
Total West Site to East Site	+5.21	138	0.000	+4.51	93	0.006
All Benches to All Risers	+6.63	115	0.000	+6.14	88	0.000
West Site to Grazed Control	-0.55	78	0.430	+1.05	15	0.271
East Site to Grazed Control	-3.05	64	0.000	-1.24	24	0.269
West Site to Ungrazed Control	+1.55	19	0.033	+3.75	10	0.041
East Site to Ungrazed Control	-0.95	15	0.179	+1.51	12	0.327

Table 1.4 Mean volumetric water content (θ_v), and standard deviation (Stdev) during 'dry' and 'wet' seasonal variation for all terracette and control field sites in Figure 2. Degrees of freedom (df) and p-values represent significant differences between 'wet' and 'dry' data comparisons.

	θ_{v-dry} (m^3 m^{-3})	Stdev$_{-dry}$	θ_{v-wet} (m^3 m^{-3})	Stdev$_{-wet}$	df	p-value
East Benches	0.123	±0.025	0.350	±0.038	46	0.000
East Risers	0.100	±0.020	0.300	±0.051	49	0.000
West Benches	0.158	±0.032	0.353	±0.026	29	0.000
West Risers	0.115	±0.020	0.342	±0.027	37	0.000
Grazed Control	0.142	±0.028	0.337	±0.025	16	0.000
Ungrazed Control	0.121	±0.018	0.310	±0.018	11	0.000

Figure 1.1 Terracettes on the north bank of the Snake River near Clarkston, WA (photograph by the author).

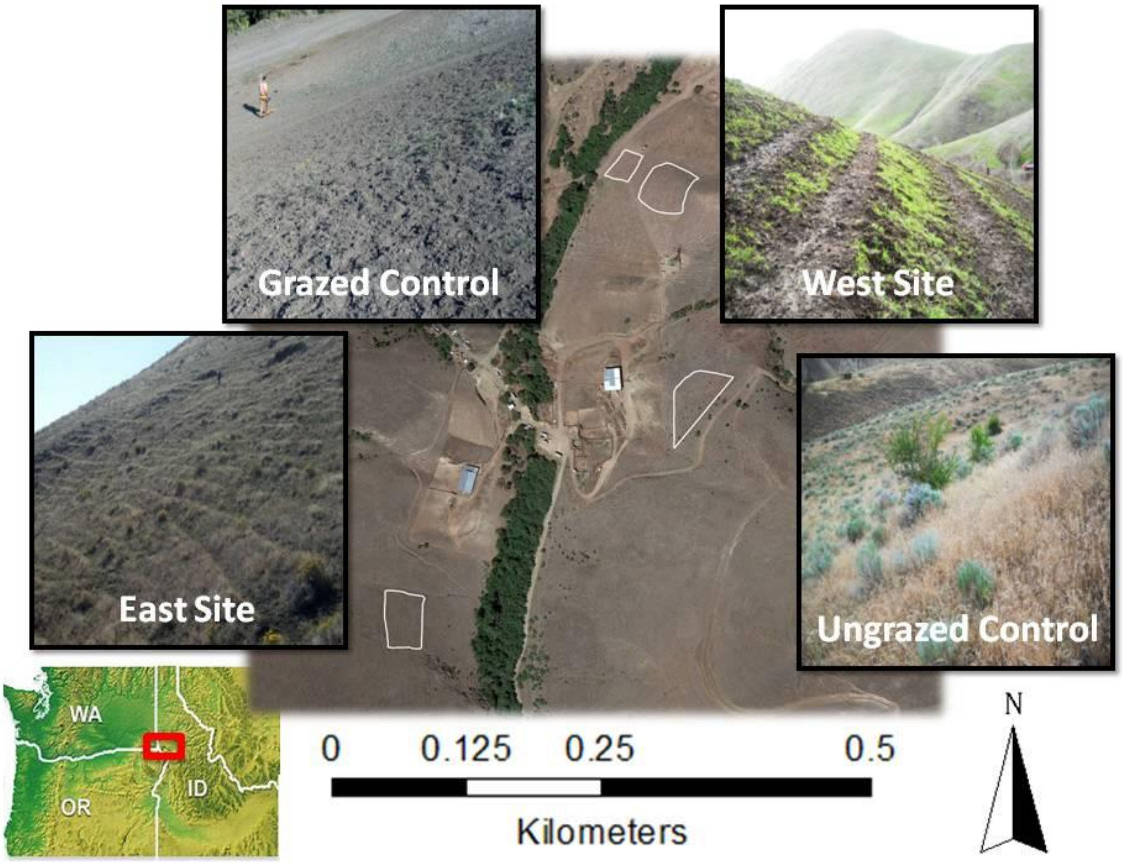


Figure 1.2 Study area map and sample site locations near Clarkston, WA on the north bank of the Snake River. Images are of the; ‘West’ site terracettes with high-density cattle stocking; ‘East’ site terracettes with moderate-low density cattle stocking; ‘Grazed Control’ non-terracette site with high-density cattle stocking; and ‘Ungrazed Control’ non-terracette site with grazing excluded.

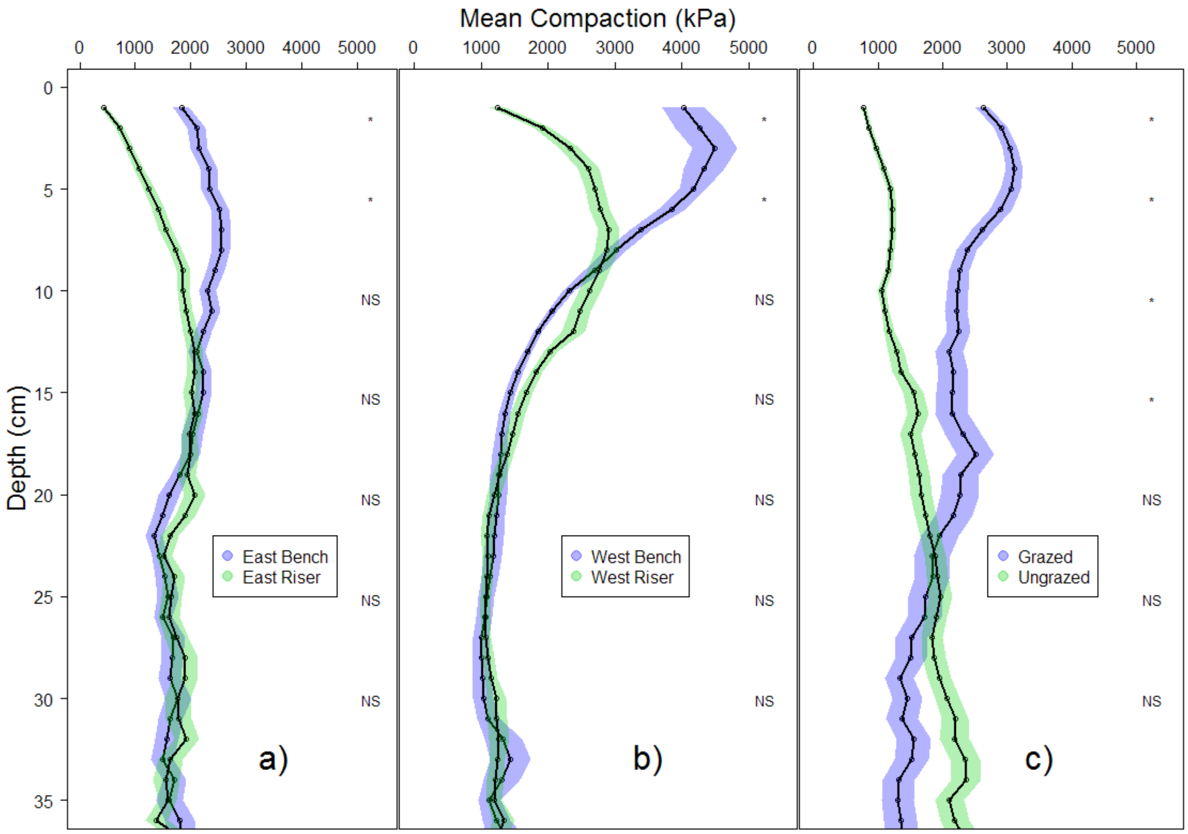


Figure 1.3 A comparison of compaction in the upper 35 cm of a soil profile for terracette and non-terracette sites. Significant (*) and Non-significant (NS) differences at α = 0.05 **a)** Compaction on the East site between benches and risers during the 'wet' season 2014. **b)** Compaction on the West site between benches and risers during the 'wet' season 2014. **c)** Compaction on the Grazed Control and Ungrazed Control sites during the 'wet' season 2014. Samples (n = 60+) at each site were collected to a depth of >30 cm or bedrock refusal. Compaction sampling was not performed during the 'dry' season due to mechanical impedance by soil conditions. Negligible differences in compaction between benches and risers were observed at a depth of >10 cm on terracette sites and at depths >15 cm on non-terracette sites.

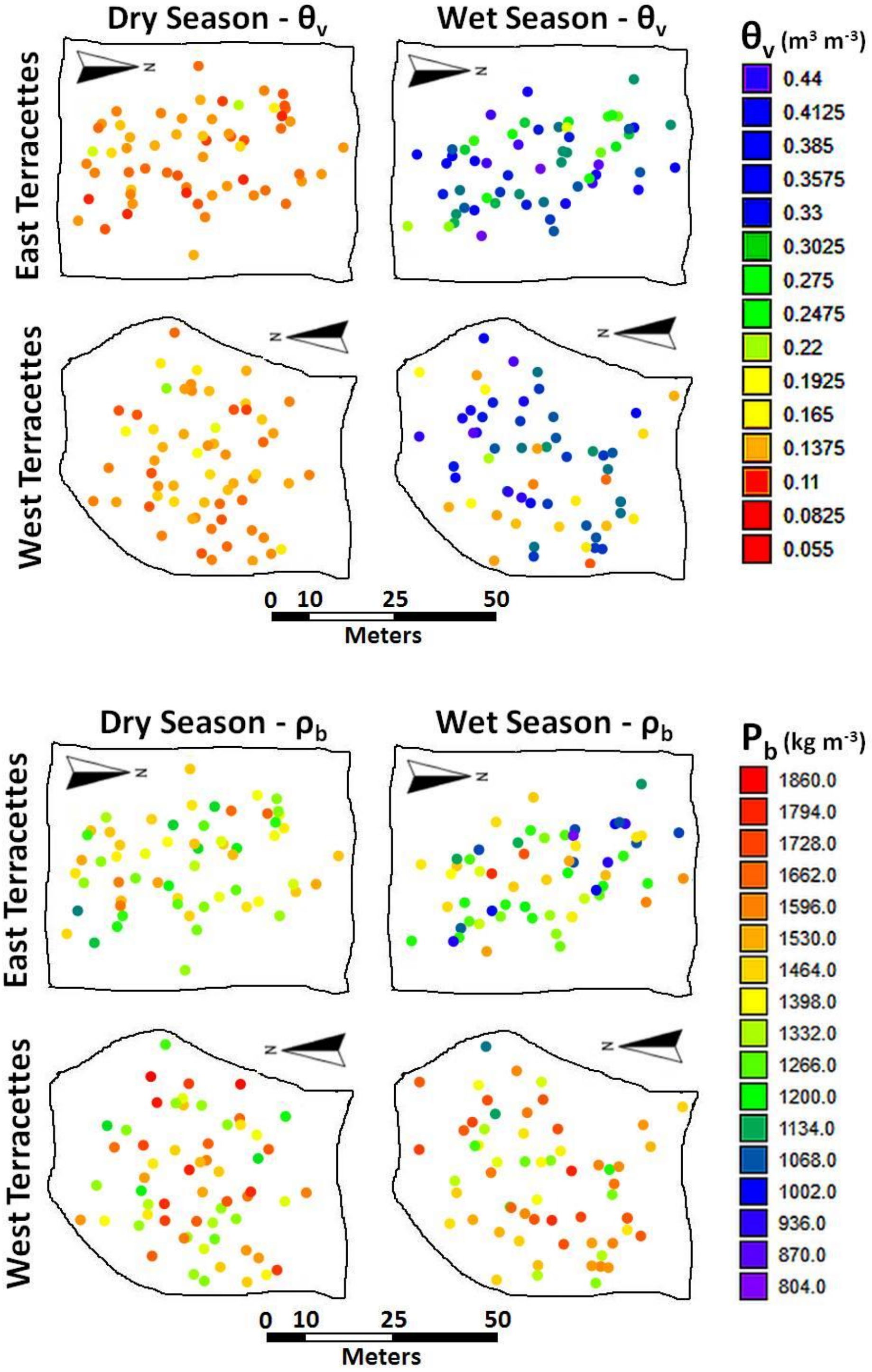


Figure 1.4 Spatial variation of volumetric water content (θ_v) and bulk density (ρ_b) observed on the East and West terracette sites were statistically insignificant during 'wet' and 'dry' seasonal conditions, with the exception of the West site during the wet season in 2014.

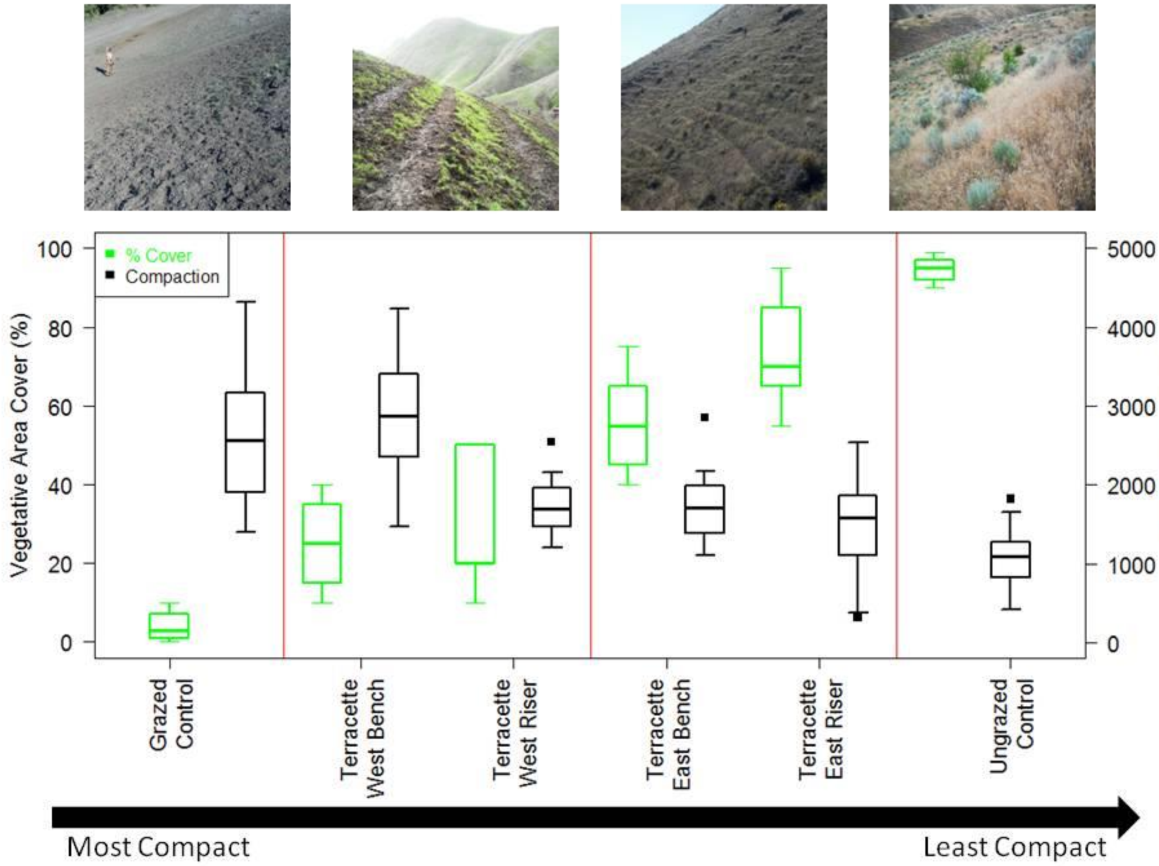


Figure 1.5 An inverse relationship ($R^2 = 0.86$) between vegetative cover and compaction across all sampling locations was observed. Compaction values are represented as the mean in the upper 10 cm of each penetrometer profile (n = 60+) collected at a 1 cm measurement frequency using a Cone Penetrometer (Model CP401 by Rimik, Toowoomba, Australia). Vegetation survey data was gathered following the protocol described by Herrick et al. (2005). The images above each column depict the vegetative conditions at each site as compaction increased from ‘high’ to ‘low’ (left to right).

Chapter 2. Assessing the Importance of Terracette Hydrology in a Semiarid Rangeland Environment

Corrao, M.V., R. Heinse, J.U.H. Eitel, B. Cosens, and T.E. Link

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Abstract

In the semiarid western U.S. water plays a defining role in land use, with soil moisture, vegetation, and microtopography being key variables in the hydrologic function of ecosystems. Previous research has not addressed the influence of site aspect, vegetation, or slope gradient on terracette soil moisture patterns in semiarid rangelands. Therefore, the objectives of this study were to: 1) assess the influence of terracette site aspect, vegetation cover, and slope on soil moisture conditions; 2) conceptualize variable conditions at the hillslope scale given terracette morphology; and 3) estimate the spatial extent of terracettes at a regional scale. To accomplish these objectives the simultaneous heat and water (SHAW) model was used to simulate soil water dynamics of terracettes given variations in site aspect, vegetative cover and slope. These results were then coupled with terrestrial laser scans, and a 1000 point, 20.3 ha plot-size, statewide assessment of terracette extent using digital orthoimagery and global information system (GIS). Our modeling results indicated; 1) site aspect had minimal influence (±0.005 $m^3\ m^{-3}$) on terracette soil moisture with southern azimuths (>90° and <225°) having less mean volumetric water content (θ_v) than northern azimuths (>225° and <90°); 2) vegetation, represented as leaf area index (LAI), had the single-most influential effect on terracette θ_v demonstrated by an inverse relationship of increasing LAI (0.00 to 1.08) to decreasing mean θ_v (0.20 to 0.17 $m^3\ m^{-3}$); and 3) slope increases of ≥15% on northern azimuths increased mean θ_v (+0.015 $m^3\ m^{-3}$), with a contrasting relationship on southern azimuths, of decreasing mean θ_v (-0.008 $m^3\ m^{-3}$) with slope increases of ≥15%. Additionally, laser scans enabled the development of fine-resolution (<5cm) digital terrain models (DTMs) used to quantify terracette bench and riser percent-area through supervised classification. These results showed bench width and riser length can be estimated from mean site slope (R^2 = 0.82 risers and R^2 = 0.93 benches). Results from an aerial orthoimagery/GIS assessment estimated >159,000 ha of terracettes within the State of Idaho, with >41,000 ha (~26%) occurring on lands managed as grazing

allotments. An increased understanding of the hydrologic interactions between cattle density, vegetation, and terracettes will aide land managers in their selection and application of best management practices on these lands.

Introduction

In the semiarid western U.S. water plays a defining role in land use (Pringle, 2000; Jessel and Jacobs, 2005), with soil moisture, vegetation, and microtopography (in length scales from decimeter to meter) being key variables in the hydrologic function of ecosystems ranging in scale from local to regional. At the regional scale soil moisture buffers interactions between the land surface and the atmosphere, by moderating the exchange and partitioning of water and energy fluxes (Vereecken and Huisman, 2008). At the local scale soil moisture and microtopography are spatially highly variable (Western et al., 2002) and influence infiltration (Bergkamp et al., 1996; Bergkamp, 1998), runoff (Frei and Fleckenstein, 2014), and erosion (Dabney et al., 2001; Liu and Singh, 2004; Mayor et al., 2008). Ecologically, the availability of soil moisture in semiarid lands acts as the dominant control affecting the structure, function and diversity of vegetation in an ecosystem (Rodríguez-Iturbe and Porporato, 2005). The interactions of soil moisture and topography are known to impact hydrologic and geomorphic processes (Tesfa et al., 2011), influence residence time and runoff generation (Dunne et al., 1991), and represent vital information needed in qualitative and quantitative modeling of surface flow and erosion at multiple scales (Bronstert and Plate, 1997; Nakayama and Watanabe, 2006).

Microtopography, described as soil surface variations of < 1m vertical relief (Moser et al., 2007) are commonly included in the broader framework of topographic heterogeneity describing patterns of vertical relief at many spatial scales formed by geologic, hydrologic, physical, and biological processes (Larkin et al., 2006). Microtopographic features referred to as ‘cat steps’ (Buckhouse and Krueger, 1981) or ‘terracettes’ (Ødum, 1922) (Fig. 1) are repetitious ‘bench’, path-like, and ‘riser’, slope-like, features that exist on hill sides of greater than 15° in the semiarid environments of the western U.S. (Rahm, 1962), as well as throughout the world (Rumball, 1966; Radcliffe, 1968; Gallart et al., 1993; Kück and Lewis, 2002; Wilson et al., 2004; Henck et al., 2010). The majority of research surrounding terracettes is focused on formational mechanisms (Rahm, 1962; Buckhouse and Krueger, 1981; Watanabe, 1994; Bielecki and Mueller, 2002; Kück and Lewis, 2002). Research on soil moisture differences between bench and riser features is limited and has primarily occurred in temperate climates (annual precipitation 1194 mm) in New Zealand (Rumball, 1966; Radcliffe, 1968). Field observations of terracette influences on overland flow in semiarid Mediterranean environments have demonstrated the ability of vegetation at the outer edge of terracette benches to increase infiltration sufficiently to cease overland flow for some episodic rain events (Bergkamp 1998). Similarly, overland flow simulations have demonstrated microtopography, similar to terracettes, can reduce the net runoff and erosion in semiarid systems during rainfall events by buffering velocity through reduced slope-length, and depression storage (Liu and Singh, 2004; Mayor et al., 2008). Research demonstrating greater soil moisture on terracette benches as opposed to risers and significantly higher soil moisture on terracette sites as opposed to non-terracette sites under active gazing (Corrao et al., 2015), is the only study we are aware of that quantifies plot-scale terracette soil moisture patterns in semiarid rangelands.

Understanding soil moisture dynamics in semiarid lands is hampered by a lack of morphologic information at the plot scale (<1m) (Bergkamp, 1998; Frei and Fleckenstein, 2014) and the tedious and often poor spatial resolution of traditional soil surface measurement techniques, leading to inadequacy of surface descriptive data (Eitel et al., 2011). These and other limitations brought on by computational resource demands at fine resolutions (Frei et al., 2010; Tesfa et al., 2011), have led to a lack of explicit representation of microtopography in hydrologic models. This continues to persist despite our ability to now accurately map microtopography using terrestrial lidar (Eitel et al., 2011), and a general recognition that influences of microtopography on soil moisture patterns can increase the accuracy of response variables such as surface runoff and sediment transport (Bronstert and Plate, 1997; Savabi, 2001; Mapfumo et al., 2004; Easton et al., 2008; Antoine et al., 2012). Therefore, mechanistic relationships between microtopography and soil water content dynamics at the plot scale are needed at the hillslope and catchment (50 ha) scale (Bergkamp, 1998), in order to improve hydrologic modeling efforts of erosion, infiltration, (Dunne et al., 1991; Frei et al., 2010; Gerke et al., 2010), surface/subsurface flow (Mcnamara et al., 2005; Mayor et al., 2008), and ecological processes in semiarid rangelands (Robinson, 2008).

Long-term spatially extensive datasets of soil moisture are uncommon due to resource requirements specific to training needs for sophisticated sampling equipment or labor-intensive manual sampling techniques (Hymer et al., 2000). However, hydrologic models such as the soil-vegetation-atmosphere transfer (SVAT), simultaneous heat and water (SHAW) model have the ability to simulate soil moisture under variable vegetation conditions to include the influence of heat and water transfer in the near-surface soil-atmosphere interface (Flerchinger and Saxton, 1989). The need for this process-based understanding for terracette sites is exemplified in our knowledge that soil surface hydrology and soil moisture are affected by land management practices such as grazing which can alter vegetation and soil structural conditions (Paton and Houlbrooke, 2010).

With the introduction of digital photogrammetry, laser profile meters, and time-of-flight terrestrial laser scanning (TLS), we can now rapidly estimate natural variations in soil surface features at fine resolution (<5 cm) and large spatial scales (Eitel et al., 2011). Such data is needed for scaling-up the mechanistic functions of terracettes and associated soil moisture patterns beyond the plot-scale. In contrast with traditional surface measurement techniques, TLS provides faster scanning times, minutes instead of hours (Sankey et al., 2011), and greater spatial coverage (>100 m^2) (Prokop et al., 2008; Staley et al., 2010) at sub-centimeter resolution (Nuttens et al., 2012). Terrestrial laser scanning technology has been applied in modeling of hillslope instability and erosion (Morris et al., 2012), wildfire (Staley et al., 2010), soil aeolian transport (Sankey et al., 2011), and soil surface microtopography in relation to concentrated flow paths (Eitel et al., 2011). Additionally, the use of model simulation and fine resolution spatial data to estimate the influence of terracette morphology on soil moisture patterns can increase our understanding plot-level terracette soil moisture and the potential influence it has on management decisions for semiarid rangeland sites with terracettes.

The importance of sustainable rangeland management (Alderfer and Robinson, 1947; Dormaar et al., 1989; Holechek et al., 1999) and growing interest to address water, erosion and sedimentation challenges in semiarid ecosystems (Laycock and Conrad, 1967; Bilotta et al., 2007; Schmalz et al., 2013), highlights the need to further contextualize the hydrologic response of terracettes at the plot-scale and quantify the regional extent of these features in semiarid ecosystems. Previous research encompassing terracettes and soil moisture has occurred predominantly in environments other than semiarid, as pointed out in Corrao et al., (2015), or through studies of surface hydrological investigations that do not address the gaps of how, or why, terracette soil moisture varies spatially on semiarid hillslopes. The overarching goal of this research was to improve the plot-level understanding of terracette-soil moisture interactions and up-scale results to the hillslope or regional scale. In order to address these goals our objectives were: 1) assess the influence of terracette site aspect, vegetation cover, and slope on soil moisture conditions vie hydrologic modeling; 2) conceptualize how these dynamics may be manifested at the hillslope scale using TLS to identify bench and riser percent-area within a terracette site; and 3) estimate the spatial distribution and frequency of occurrence of terracette systems, and provide one example using the state of Idaho.

Methods

Site Description – This study was conducted from 2013 to 2015 on an active cattle ranch near Clarkston, WA (46°26’ N, 117°08’ W), in Whitman County north of the Snake River. Long-term precipitation and air temperature data was provided by the Nez Perce County Regional Airfield at Lewiston, ID, located 12.5 km SE of the site at 437 m elevation. Mean (30-year average) annual precipitation and temperature for the area were 312.7 mm and 11.7°C, respectively. Study site soils are predominately silt loam textured Kuhl-Alpowa complex per the Whitman County, Washington Soil Survey (Soil Survey Staff, 1980). Soils are shallow and moderately well-drained, average saturated hydraulic conductivity (K_s) of 20.6 mm/hr (Corrao et al., 2015), with an average mineral horizon depth of 15 to 30 cm. Long-term-hourly solar radiation and snow density data for this site were provided by the U.S. Regional Climate Reference Network (USCRN) station CRNH0203 near Spokane, WA approximately 140 km north of the study area.

Experimental Design – Two terracette field sites with differing aspects, terracette development, cattle densities, and site characteristics (Corrao et al., 2015) were established near Clarkston, WA (Fig. 1). Previously collected *in-situ* data was used as model inputs for a one-dimensional soil-vegetation-atmosphere transfer (SVAT) model to assess the influence of vegetation, slope and aspect on terracette soil moisture differences between bench and riser features. Following modeling the two terracette field sites were scanned with a Leica ScanStation 2 (Leica Geosystems Inc. Heerbrugg, Switzerland) time-of-flight terrestrial laser scanning system for characterization of terracette microtopography through the creation of a site digital terrain model (DTM). DTMs were used to up-scale plot-level model results to a hillslope scale and quantify the percent-area of each site represented by bench condition or riser condition. Lastly, a quantification of terracettes using publically available digital orthoimagery (1-m resolution) from the Inside Idaho database (http://inside.uidaho.edu/) was completed to estimate the spatial extent of terracettes throughout the State of Idaho and provide an up-scaled example of potential terracette function at a regional scale.

Soil-Vegetation-Atmosphere Transfer Modeling – The SHAW was selected based on its extensive use in semi- and seasonally-arid ecosystems (Flerchinger et al., 1996b; Hymer et al., 2000; Link et al., 2004; Zhao et al., 2010), and ability to simulate soil moisture conditions influenced by soil characteristics, as well as variable slope, aspect, and vegetation conditions (Flerchinger, 2000). The SHAW model uses a modified version of the Richards equation to calculate θ_v based on the input parameters for each model node, and linear interpolation is used to calculate θ_v between nodes (Flerchinger and Saxton, 1989). Model simulations were completed to specifically assess the sensitivity of θ_v to changes in slope gradient, site aspect and LAI independently, for the purpose of identifying conditions influencing terracette/soil moisture relationships.

We used hourly climate data from October, 2011 to February, 2015 describing temperature, precipitation, windspeed, relative humidity, and solar radiation, as provided by pairing the Lewiston, ID and Spokane, WA hourly datasets described above. The parameters of LAI and biomass (kg m^{-2}) for each simulation were estimated from previous research at the Reynolds Creek Experimental Watershed where similar conditions were assumed based on field measures of sagebrush/grass-cover habitat type, precipitation (340mm), loamy soil type (Vitale-Itca-Rubble), annual mean temperature (8° C), and variable slope (2 to 60%) (Clark and Seyfried, 2001; Finzel et al., 2012). LAI was simulated from 0 (no vegetation) to 1.08 (maximum simulated vegetation for the given site conditions) with corresponding biomass conditions from 0 to 0.16 kg m^{-2} respectively. Field data collected *in situ* from previous research by Corrao et al., (2015) were used to define the individual soil node parameters (Table 1), with the exception of saturated hydraulic conductivity (Ks), and air-entry potential (ψ_e) which were estimated by pedotransfer functions through the neural network prediction tool ROSETTA (Schaap et al., 2001).

Multiple predictive simulations were completed using the local sensitivity analysis methods of perturbation-response for site-specific variables as described by Du et al., (2013). Simulations were completed using eight increments at the azimuths of N (360°), NE (45°), E (90°), SE (135°), S (180°), SW (225°),W (270°), and NW (315°), for each parameter of interest (aspect, LAI, slope). Simulated hourly θ_v were used to test model using the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) for comparisons to field observations. Further analysis of simulations was completed using student paired two-sample t-tests to identify statistically significant differences in mean θ_v between site conditions. Data analysis and visualization were completed using the open source statistical software, R version 3.1.2 (R Development Core Team, 2014).

Terrestrial Laser Scanning – Sub-decimeter resolution scans of each site were collected using a time-of-flight TLS Leica ScanStation 2 (Leica Geosystems Inc. Heerbrugg, Switzerland). This TLS instrument employs a green (532 nm) scanning laser with a beam diameter of 4 mm at < 50 m. The instrument has a pulse rate of 50,000 points s^{-1}, a maximum sample density of <1mm, and a range of 134 m at 18% albedo (http://hds.leica-geosystems.com) (Eitel et al., 2011). Each field site was scanned from multiple angles to minimize occlusion effects thereby improving the accuracy of the scans (e.g. see Van der Zande et al., 2006). A set of four geostationary reflector targets served as control points for each site at each TLS scanning position to spatially reference scans during point cloud processing.

Individual scans were imported into the Cyclone (Version 8.0, Leica Geosystems Inc., Heerbrugg, Switzerland) software package and merged into a single point-cloud for each site using the control-point coordinates in the translation and rotation algorithm within the software. Digital terrain models (DTM) were derived using an Interactive Data Language (IDL, Version 8.4, Exelis Visual Information Solutions, Virginia, USA) script (available from authors upon request) based on the approach outlined in Eitel et al., (2011). We used the deterministic method of linear interpolation to grid the TLS point cloud data, given the understanding of this methods computational speed and accuracy (Lloyd and Atkinson, 2006; Bater and Coops, 2009).

Supervised classification using the ENVI (Version 5.2, Exelis Visual Information Solutions, Virginia, USA) graphical software package was completed for each DTM raster image to classify the percentage of “bench” and “riser” morphology at each site. Classification of bench and riser features was completed within the rasterized DTM image using the polygon ENVI tool by manually digitizing multiple examples of each feature based on pixel value similar to the analysis presented by Fassnacht et al., (2009) in assessing snow-surface roughness from digital imagery. The polygons were then grouped into the “bench” or “riser” training class and assigned a color to assist in visualizing features. The minimum distance method (e.g. pixel classification based on proximity of majority-similar pixels) was used to apply the training classes to each ENVI raster image with a smoothing parameter of three-pixels and an aggregation of 30. The aggregation parameter groups areas of 30 pixels not joined to their respective classification to be ignored. This was helpful in removing small missing-data locations, caused by terracette riser shadows, from scans that would otherwise be falsely classified as bench area.

Additional field measures of terracette features consisting of three transects established perpendicular to terracette formation at both field sites were collected for verification of TLS results. Field measures consisted of bench width, riser length, individual-feature slope and total site slope measurements following the methods described by Rumball, (1966) for terracettes in New Zealand.

Statewide Terracette Quantification – Quantifying the occurrence of terracettes within the State of Idaho was a critical step in assessing the relevance of terracette mechanistic function beyond the plot-scale. Terracettes were quantified through ocular assessment of 1000, 20.3 ha plots throughout the State of Idaho. Selection of sample plot locations was completed using the “Natural Color” digital orthoimagery series dataset (1 m resolution) (Idaho State Office, 2012) in ArcToolbox 10.1 (ESRI, 2011) to stratify grazing lands within the State of Idaho into four groups based on management (BLM, United States Forest Service (USFS), Private and Other). The ‘other’ category included Tribal, State, and Federal Park lands. Within each ownership group, 250 study plots were randomly selected.

Point files were exported from ArcGIS to Google Earth (version 7.1.2.2041) as a secondary measurement (conformation) of assessment area slope. Plot area was determined using ArcMap 10.1 at a scale of 1:1500, which yielded a plot size of 20.3 ha. At a scale of

1:1500, 250 observation points totaled 5,075 ha of within each of the four management classifications for a total of 20,300 ha statewide. Verified UTM coordinates and classification information describing dominant slope, vegetation, and aspect of each plot were entered into the attributes table of the four ArcGIS land management polygons. Dominant vegetation was visually classified by the observer as; (1) grasses, (2) shrubs/brush, or (3) forest. Site aspect was classified in the four cardinal directions as; (1) North, (2) East, (3) South, and (4) West. If aspect was not visually definable through the digital elevation models (DEMs) available in ArcMap 10.1 or Google Earth an “n/a” was entered into the attributes table. Site slope was determined in Google Earth using elevation and distance as noted by changing UTM coordinates across the plot in an up-slope direction. A topographic slope >15% was given a “1” and <15% a “0” in the attributes table of the GIS land management classification file. The threshold of 15% was selected as a conservative measurement based on previous terracette research describing the relationship of terracettes to steeper slopes, predominantly greater than 15% (Rahm, 1962; Radcliffe, 1968; Anderson, 1972; Dec et al., 2012).

Terracette aerial-extent within each 20.3 ha plot were estimated through manual digitization of visual terracette features within a plot using the polygon tool in ArcMap 10.1. The calculation of terracette-acres for each land management classification as well as across all 20,300 ha was completed in Microsoft Office Excel 2007. The results of our 1000 plot terracette analysis where then extrapolated to the total acreage of each land management classification within the State of Idaho. Following quantification of terracette extent these sites were further separated by aspect and dominant vegetation.

Results

SHAW Model Simulations – Simulated θ_v at a depth of 10 cm is presented in Figure 2 for bench and riser conditions at both the ‘East’ and ‘West’ terracette sites as described in (Corrao et al., 2015). Aspect had the greatest influence on θ_v for the less compact riser conditions with an annual mean θ_v of 0.20 m^3 m^{-3} for a northern aspect, and 0.17 m^3 m^{-3} on a southern aspect (Fig. 3b). Riser conditions under high cattle stocking showed a similar trend in higher θ_v for a north aspect as compared to a south with a respective increase of 0.01 m^3 m^{-3} for the northern simulations. The bench conditions of both sites showed no significant difference in simulated θ_v with regard to changing aspect. However, bench conditions under the highest cattle density (West site) consistently had a 0.009 m^3 m^{-3} or greater difference in θ_v over the bench conditions under moderate- to low-density stocking, 0.004 m^3 m^{-3} or greater difference over the high cattle stocking (West site) riser conditions, and 0.02 to 0.04 m^3 m^{-3} greater difference over the moderate- to low-density cattle stocking (East site) riser conditions.

Simulations of θ_v for bench and riser conditions separately for each site showed incremental changes of $\geq$45 degrees for riser conditions resulted in a noticeable increase (more northern adjustment) or decrease (more southern adjustment) in soil moisture. Additionally, simulations of aspect showed differences in θ_v for nearly all site conditions, with the exception of azimuths from 90° to 270° where high-density stocking (West site) riser conditions and moderate- to low-density stocking (East site) bench conditions were similar (Figure 3).

Leaf area index had the single greatest influence on θ_v for all site condition simulations. A notable inverse relationship of increasing LAI (0.15 to 1.08) to decreasing mean θ_v (0.20 to 0.17 m^3 m^{-3}) for all sites is displayed in Figure 3a. Conversely, simulation results showed an increase in mean θ_v (0.013 m^3 m^{-3}) from bare soil conditions (LAI 0.00) to sparely vegetated conditions (LAI of 0.15) for all sites. Soil moisture for the moderate- to low-density cattle stocking (East site) riser conditions were most dramatically influenced by changes in LAI ranging from a high of 0.21 m^3 m^{-3} to a low of 0.14 m^3 m^{-3}. All sites showed a decrease in θ_v with incrementally increasing LAI values of 0.15 or greater. Within-site differences of mean θ_v were notable between sites for all simulated LAI increments, with the exception of the high-density stocked (West site) risers and the moderate- to low-density stocked (East site) benches at simulated LAI values of >0.15 and <0.62 (Fig. 3a).

Slope gradient simulations were separated into runs of 180 azimuth (South) and 360 azimuth (North) given the differences in θ_v observed from previous SHAW analysis for aspect and LAI. The northern aspects showed increasing θ_v with increasing slope gradient (mean +0.015 m^3 m^{-3}) with the southern aspects showing a contrasting relationship of decreasing θ_v (mean -0.008 m^3 m^{-3}) with increasing slope (Fig. 3c & 3d). For a northern aspect under moderate- to low-density cattle stocking (East site) incremental increases in slope gradient of <8% showed resulted in higher θ_v for both benches and risers. Similar results of increased θ_v were observed for the high-density cattle stocking (West site) conditions for benches and risers with slope gradient increases of >15%. Simulation of θ_v for all site conditions on a southern aspect resulted in an opposing, but similar trend in changing θ_v (mean -0.007 $m^3\ m^{-3}$) for all sites with increasing slope (0 to 65%). Differences in mean θ_v between bench and riser features for both north and south aspect simulations were distinguishable, with the exception of West site bench and riser features on a northern aspect between 0 and 36% slope.

Terrestrial Laser Scanning – Terracette morphology resulting from analysis of TLS point cloud data were used to identify and quantify the spatial organization of microtopography, and facilitate supervised classification of bench and riser features (Fig. 4). Manual field-transect measurements were used to validate TLS scans and guide the accuracy of supervised classification analysis (Table 2). The combination of TLS scanning results and field transect measurements of terracettes yielded a predictive-model of bench and riser feature-dimension given average site slope (Fig. 5).

Terracette Quantification – Analysis of 1000 plots over four land management classifications was completed throughout the State of Idaho (Fig. 6). A total of 159,527 ha of terracettes were estimated based on survey observations extrapolated to the total land area for each ownership classification (Table 3). The percent of hill slope terracette area by ownership classification was Private (4.06%), BLM (2.96%), Other (2.28%), and USFS (0.91%).

Discussion

SHAW Model Simulations – We acknowledge the Nash-Sutcliffe coefficients suggest a less-than optimum model fit to measured mean soil moisture, likely resulting from a limited number of field samples for θ_v throughout the modeled time period for each soil condition ($n = \leq 35$). This is in-part due to the sporadic occurrence of precipitation and critical influence of precipitation on soil moisture in these environments. Additional field data on a more temporally consistent basis may lead to much higher model confidence. However, our model results for terracette sites (presented as bench and riser composite θ_v from simulations) showed increased θ_v at more northern aspects and decreased θ_v for more southern aspects, likely partially the result of the latitude and sun angle at these sites increasing the exposure of soil surfaces to solar radiation and thereby, increasing moisture exchange processes (Dingman, 2002). With changes in aspect mean site θ_v remained nearly unchanged for the highly compacted (3833 kPa) heavily trampled bench sites as compared to less compacted (1252 kPa) riser sites. Our simulation results showed the influence of increases in bulk density, reduced soil porosity, and increased vegetation were influential in reducing θ_v on terracettes under low density cattle stocking. These results are similar to those presented by Villamil et al., (2001) showing the potential for greater soil moisture due to smaller pore-size distribution in highly compacted soils of similar texture influenced by grazing. Furthermore, the conditions of terracettes in this study are generally similar to the results of Rumball, (1966) who observed three-times greater compaction on benches as compared to risers to a depth of >10 cm. Field sampling of soil conditions for these sites shown terracette risers had greater porosity, organic matter and hydraulic conductivity highly trampled benches (Corrao et al., 2015), further supporting our model results of increased soil drainage, and decreased mean compaction (1252 kPa) on risers as compared to benches. Additionally, our model results are supported by previous literature demonstrating the ability of compacted soils, >2500 kPa, to impede plant root growth (Gerard et al., 1982) tying directly to the influence of vegetation on soil moisture through evapotranspiration (Unger and Kaspar, 1994; Dec et al., 2012).

Model results of increasing vegetation (represented by LAI) showed a reduction of θ_v across all site conditions as LAI increased with the exception of the transition between bare soil and an LAI of 0.15. An increase in θ_v with an initial plant cover establishment is likely a result of a modeled reduction in solar radiative heating at the soil surface leading to reduced evaporation (Flerchinger, 2000) and is reasonable given the results of previous research describing the mechanics of bare soil evaporative moisture flux and vegetation (Flerchinger et al., 1996a; Cornelis et al., 2009; Frei and Fleckenstein, 2014). Our SHAW results showing increased LAI reduces θ_v under the high-density cattle stocking (West site) conditions are a reflection of the compacted conditions of these site soils and the ability of compaction to limit vegetative growth.

High-density animal stocking rates (10 AU ha^{-1}) during the wet season conditions (December – April) when vegetative growth is most pronounced in this area suggests the likelihood of our West site to attain an LAI value of 1.08 is unrealistic, given the current management. Our assumption of terracette benches having less vegetative cover in general for grazed terracette hillslopes does contradict the results of Rumball, (1966) who observed root biomass in the upper 10 cm for a sheep-grazed New Zealand rangeland soil to be 88% for benches and 71% for risers, concluding there was a vegetative preference for bench conditions. It is advantageous to note however, that the mean compaction of terracette bench soils in their study was 2,560 kPa, nearly 33% less compact than our West site bench samples and 8% more compact than our East site bench samples. Furthermore, the climate differences between New Zealand and the semiarid western U.S., namely precipitation (>500 mm and <500 mm) respectively (Radcliffe, 1968), are substantial and have the potential to supply a much greater volume of water for vegetative growth and subsequently improved soil for those areas.

Slope simulations in SHAW resulted in an inverse relationship of increasing slope gradient to decreasing θ_v for south facing aspects (180 AZ) and an opposing positive relationship of increasing slope and increasing θ_v on north facing aspects (360 AZ). The results for southern aspect simulations are in part similar to those of Rumball, (1966) who observed significant decreasing θ_v with increasing slope classes of 0-10%, 10-30%, 30-45%, and 45-90% through analysis of 120 core samples across multiple sites. However, the results of Rumball, (1966) did not include an assessment of aspect in the reported slope influences to θ_v. Through simulation results we observed increased soil moisture for northern aspects to be at least partially indicative of reduced exposure to shortwave radiation and a reduction in plant transpiration as a condition of the more northern latitude (lower sun angle) of these sites (Flerchinger and Saxton, 1989; Flerchinger, 2000).

Modeled slope influence on θ_v for both terracette sites shown, a north aspect (360 AZ) given high-density or moderate- to low-density cattle stocking conditions yielded an increase of θ_v for both benches and risers with as little as an +8% change in slope. Simulation results for an opposing south aspect (180 AZ) resulted in a similar but opposing trend of decreased θ_v with greater increases of slope gradient. It was observed that high-density stocking riser conditions and moderate- to low-density stocking bench conditions exhibited similar responses in θ_v to changing slope for both the north and south aspect simulations. Additionally, our results suggest changes in θ_v may be at least partially influenced by compaction as demonstrated by measured compaction values of 3833, 2471, 2359, and 1252 kPa with corresponding simulated slope increases of +22, +15, +15 and +8% required for a notable change in θ_v.

The resulting bench and riser classifications, shown previously in Table 2, indicates increased terracette-site slope leads to increasing length of risers and decreasing width of benches. These findings are supported by those of previous research describing increased riser length between terracette benches as a result of increasing slope angle (Bates, 1935; Rumball, 1966). These conclusions were also illustrated by Howard and Higgins, (1987) who described a site slope of 50% and a bench width of 36 cm had a riser length of approximately 150 cm as opposed to a site slope of 10 degrees with a riser length of approximately 110 cm. Similarly, Watanabe, (1994) using the methods of Howard and Higgins, (1987), demonstrated that slopes of 24 and 48% had riser lengths of approximately 50 and 140 cm respectfully, for pastures with predominately cattle grazing similar to the sites in this study. Our results are further supported by those of Anderson, (1972) who described ‘normal’ terracettes as displaying wider treads at lower slope angles and even wider risers with slope angles correlating to that of the total site slope through a classification of 215 sites throughout Western Britain. In more recent research on ‘mega’ terracettes, 80 - 100 cm greater than ‘normal’ terracettes (Anderson, 1972), has shown mean bench widths and riser heights on steeper slopes were 78% and172% of those found on sites with less slope, respectively (Weihs and Shroder, 2011).

The value of bench and riser morphological classification given slope is important in defining the role of terracettes in these semiarid ecosystems. This can be exemplified by coupling the mechanistic understanding of terracettes and θ_v by Corrao et al., (2015), and the SHAW results of aspect, LAI and slope to θ_v form this research with the morphological classification of terracette features for the estimation of total terracette slope θ_v (Fig. 7). Because terracette benches were shown to have greater θ_v than risers regardless of the differing cattle use conditions, as measured in this study, the prediction of bench width and riser length allows the calculation of percent-area for both features when coupled with slope of a terracette hillside and horizontal extent. The result is a relatively ‘quick and straightforward' estimate of mean terracette site θ_v which can be compared to other terracette or non-terracette hillslopes within a localized area, thereby, potentially reducing the necessity of exhaustive field sampling and analysis for general-purpose field assessments of θ_v (Table 4). The example in Table 4 shows an average of more than 3% greater soil moisture for the given conditions of the high-density cattle stocking (West terracette site) in this study with a slope of 26%, opposed to the same site with a slope of 49%.

Our results indicated >54% of terracettes may occur on north and west aspects, and that ~87% of these sites may be dominated by grass cover with the remaining ~13% dominated by shrub-height vegetation or timber. Our results of terracette occurrence on grass dominated hillslopes are in agreement with those presented in previous research in New Zealand where 122 terracette transect surveys at 22 separate sites reported a dominant grass cover of between 52 and 88% (Rumball, 1966). The relevance of these findings are indicative of the challenges facing rangeland management of semiarid grasslands in the western U.S. influenced by complex interactions of biotic and abiotic factors (e.g. water, soil, vegetation and anthropogenic use). We believe the results of this research provide valuable insight into one aspect of semiarid rangeland hydrology that has the potential to influence the sustainability of these ecosystems.

Conclusions

This research build on previous terracette work describing the differences in soil moisture content at the plot-scale between bench and riser features. Through use of the SHAW model we investigated the influence of aspect, vegetation, and slope on patterns of soil moisture for terracettes under semiarid rangeland conditions. Simulation results show vegetative cover is the most significant driver of terracette soil moisture spatial variability, with minimal influence on mean annual soil moisture resulting from changing aspect. The use of time-of-flight TLS allowed the quantification of terracette bench and riser percent-area and facilitated the calculation of terracette site composite soil moisture given changes in site slope gradient. These results indicated that as site slope increases terracette benches decreased in width thereby representing a smaller area of a terracette hillslope. The significance of increased site slope was demonstrated when site soil moisture is calculated based on measured bench and riser area given our understanding of different soil moisture conditions for these features. These results have the potential to up-scale terracette soil moisture patterns from plot-scale research to larger spatial extents.

By combining *in situ* measurements with model simulations of θ_v, given variable aspect, LAI and slope for four different soil conditions, we assessed terracette hydrologic response on an actively grazed silt loam soil under semiarid climatic conditions. Through a combination of field measurements, modeling results, and TLS scan analysis we were able to quantify percent-area of bench and riser features as a function of slope gradient, and offer estimates of potential θ_v on terracette sites given a subset of variable conditions. With more than 28% of Idaho's public lands designated as grazing allotments, and the results of this study showing a potential of 159,000 ha of terracettes within the State (>40,000 on public grazing lands), future research should increase the scope of this study to patterns of soil moisture on terracettes across a wider variety of site conditions, and assess the implications of increases in terracette soil moisture on biomass production and rangeland erosion for actively grazed sites under differing animal-stocking densities.

Literature Cited

Alderfer, R., and R. Robinson. 1947. Runoff from pastures in relation to grazing intensity and soil compaction. J. Am. Soc. Agron. 39(11): 948–958.

Anderson, E.W. 1972. Terracettes: A suggested classification. R. Geogr. Soc. 4(1): 17–20.

Antoine, M., C. Chalon, F. Darboux, M. Javaux, and C. Bielders. 2012. Estimating changes in effective values of surface detention, depression storage and friction factor at the interrill scale, using a cheap and fast method to mold the soil surface micro-topography. Catena 91: 10–20.

Bater, C.W., and N.C. Coops. 2009. Evaluating error associated with lidar-derived DEM interpolation. Comput. Geosci. 35(2): 289–300.

Bates, G.H. 1935. The vegetation of footpath, sidewalks, cart tracks and gateways. J. Ecol. 23(2): 470–487.

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.

Bergkamp, G., L.H. Cammeraat, and J. Martinez-Fernandez. 1996. Water movement and vegetation patterns on shrubland and an abandoned field in two desertification-threatened areas in Spain. Earth Surf. Process. Landforms 21: 1073–1090.

Bielecki, A., and K. Mueller. 2002. Origin of terraced hillslopes on active folds in the southern San Joaquin Valley, California. Geomorphology 42(1-2): 131–152.

Bilotta, G.S., R.E. Brazier, and P.M. Haygarth. 2007. The impacts of grazing animals on the quality of soils, vegetation, and surface waters in intensively managed grasslands. Adv. Agron. 94: 237–280.

Bronstert, A., and E.J. Plate. 1997. Modeling of runoff generation and soil moisture dynamics for hillslopes and micro catchments. J. Hydrol. 198: 177–195.

Buckhouse, J., and W. Krueger. 1981. What Caused Those Terracettes?. Rangelands Arch. 3(2): 72–73.

Clark, P., and M. Seyfried. 2001. Point sampling for leaf area index in sagebrush steppe communities. J. Range Manag. 54: 589–594.

Cornelis, W., K. Steppe, and D. Gabriels. 2009. Soil-plant-atmosphere dynamics. p. 1–8. *In* Encyclopedia of Life Support Systems (EOLSS).

Corrao, M.V., R. Heinse, J.U.H. Eitel, 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.

Dabney, S., D. Flanagan, and D. Yoder. 2001. Modeling temporal changes in erosion rates due to benching between vegetative barriers. p. 710–713. *In* Ascough II, J.C., Flanagan, D.C. (eds.), American Society of Agricultural Engineers. American Society of Agricultural Engineers, Honolulu, HI.

Dec, D., J. Dörner, O. Balocchi, and I. López. 2012. Temporal dynamics of hydraulic and mechanical properties of an Andosol under grazing. Soil Tillage Res. 125: 44–51.

Dingman, S.L. 2002. Physical hydrology. 2nd ed. Prentive-Hall Inc., Upper Saddle River, NJ.

Dormaar, J.F., S. Smoliak, and W.D. Willms. 1989. Vegetation and soil responses to short-duration grazing on fescue grasslands. J. Range Manag. 42(3): 252–256.

Du, E., T.E. Link, J. a. Gravelle, and J. a. Hubbart. 2013. Validation and sensitivity test of the distributed hydrology soil-vegetation model (DHSVM) in a forested mountain watershed. Hydrol. Process. 6210(December 2013): 6196–6210.

Dunne, T., W. Zhang, and B.F. Aubry. 1991. Effects of rainfall, vegetation, and microtopography on infiltration and runoff. Water Resour. Res. 27(9): 2271–2285.

Easton, Z., D. Fuka, and M. Walter. 2008. Re-conceptualizing the soil and water assessment tool (SWAT) model to predict runoff from variable source areas. J. Hydrol. 348(3-4): 279–291.

Eitel, J., C. Williams, and L. Vierling. 2011. Suitability of terrestrial laser scanning for studying surface roughness effects on concentrated flow erosion processes in rangelands. Catena 87(3): 398–407.

ESRI. 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Fassnacht, S.R., J.D. Stednick, J.S. Deems, and M. V. Corrao. 2009. Metrics for assessing snow surface roughness from digital imagery. Water Resour. Res. 45(4): 1–6.

Finzel, J. a., M.S. Seyfried, M. a. Weltz, J.R. Kiniry, M.-V. V. Johnson, and K.L. Launchbaugh. 2012. Indirect Measurement of Leaf Area Index in Sagebrush-Steppe Rangelands. Rangel. Ecol. Manag. 65(2): 208–212.

Flerchinger, G.N. 2000. The Simultaneous Heat and Water (SHAW) Model Version 3.0: Technical Documentation. : 1–29.

Flerchinger, G.N., C.L. Hanson, W.P. Kustas, and M.A. Weltz. 1996a. Modeling Evapotranspiration on Semi-Arid Rangelands. p. 1–6. *In* On: compact disk, C.T. Bathala (ed.), North American Water and Environment Congress.

Flerchinger, G.N., C.L. Hanson, and J.R. Wight. 1996b. Modeling evapotranspiration and surface energy budgets across a watershed. Water Resour. Res. 32(8): 2539–2548.

Flerchinger, G.N., and K.E. Saxton. 1989. Simultaneous heat and water model of a freezing snow-residue-soil system II. Field verification. Am. Soc. Agric. Eng. 32(2): 573–578.

Frei, S., and J.H. Fleckenstein. 2014. Representing effects of micro-topography on runoff generation and sub-surface flow patterns by using superficial rill/depression storage height variations. Environ. Model. Softw. 52: 5–18.

Frei, S., G. Lischeid, and J.H. Fleckenstein. 2010. Effects of micro-topography on surface-subsurface exchange and runoff generation in a virtual riparian wetland - A modeling study. Adv. Water Resour. 33(11): 1388–1401.

Gallart, F., J. Puigdefabregas, and G. del Barrio. 1993. Computer simulation of high mountain terracettes as interaction between vegetation growth and sediment movement. Catena 20: 529–542.

Gerard, C., P. Sexton, and G. Shaw. 1982. Physical factors influencing soil strength and root growth. Agron. J.: 875–879.

Gerke, H., P. Germann, and J. Nieber. 2010. Preferential and unstable flow: From the pore to the catchment scale. Vadose Zo. J. 9(2): 207.

Henck, A., J. Taylor, H. Lu, Y. Li, Q. Yang, B. Grub, S.J. Breslow, A. Robbins, A. Elliott, T. Hinckley, J. Combs, L. Urgenson, S. Widder, X. Hu, Z. Ma, Y. Yuan, D. Jian, X. Liao, and Y. Tang. 2010. Anthropogenic hillslope terraces and swidden agriculture in Jiuzhaigou National Park, northern Sichuan, China. Quat. Res. 73(2): 201–207.

Holechek, J., H. Gomez, F. Molinar, and D. Galt. 1999. Grazing studies: what we’ve learned. Rangelands 21(2): 12–16.

Howard, J.K., and C.G. Higgins. 1987. Dimensions of grazing-step terracettes and their significance. p. 545–568. *In* Proceedings of the First International Conference on Geomorphology.

Hymer, D.C., M.S. Moran, and T.O. Keefer. 2000. Soil Water Evaluation Using a Hydrologic Model and Calibrated Sensor Network. Soil Sci. Soc. Am. J. 64(1): 319.

Idaho State Office. 2012. Interactive Numeric and Spatial Information Data Engine (INSIDE) Idaho. U.S. Dep. Inter. Bur. L. Manag.Available at www.insideidaho.org, File: ide1.IDSD1.RANGE_NOC_GrazingAllotments_PUB_100K_POLY.

Jessel, B., and J. Jacobs. 2005. Land use scenario development and stakeholder involvement as tools for watershed management within the Havel River Basin. Limnol. - Ecol. Manag. Inl. Waters 35(3): 220–233.

Kück, K., and C. Lewis. 2002. Terracettes and active gelifluction terraces in the Drakensberg of the Province of the Eastern Cape, South Africa: a process study. p. 1–23. *In* The South African Geographical Journal. Proceedings of the South African Geographical Society.

Larkin, D., G. Vivian-Smith, and J.B. Zedler. 2006. Topographic heterogeneity theory and ecological restoration. p. 142–164. *In* Falk, D.A., Palmer, M.A., Zedler, J.B. (eds.), Foundations of Restoration Ecology. Island Press, Washington, DC, USA.

Laycock, W., and P. Conrad. 1967. Effect of grazing on soil compaction as measured by bulk density on a high elevation cattle range. J. Range Manag.: 136–140.

Link, T.E., G.N. Flerchinger, M. Unsworth, and D. Marks. 2004. Simulation of Water and Energy Fluxes in an Old-Growth Seasonal Temperate Rain Forest Using the Simultaneous Heat and Water (SHAW) Model. J. Hydrometeorol. 5: 443–457.

Liu, Q., and V. Singh. 2004. Effect of microtopography, slope length and gradient, and vegetative cover on overland flow through simulation. J. Hydrol. Eng. 9(5): 375–382.

Lloyd, C.D., and P.M. Atkinson. 2006. Deriving ground surface digital elevation models from LiDAR data with geostatistics. Int. J. Geogr. Inf. Sci. 20(5): 535–563.

Mapfumo, E., D.S. Chanasyk, and W.D. Willms. 2004. Simulating daily soil water under foothills fescue grazing with the soil and water assessment tool model (Alberta, Canada). Hydrol. Process. 18(15): 2787–2800.

Mayor, Á.G., S. Bautista, E.E. Small, M. Dixon, and J. Bellot. 2008. Measurement of the connectivity of runoff source areas as determined by vegetation pattern and topography: A tool for assessing potential water and soil losses in. Water Resour. Res. 44(10): 1–13.

Mcnamara, J.P., D. Chandler, M. Seyfried, and S. Achet. 2005. Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt-driven catchment. Hydrol. Process. 19: 4023–4038.

Morris, R., D. Dragovich, and B. Ostendorf. 2012. Hillslope erosion and post-fire sediment trapping at Mount Bold, South Australia. p. 42–50. *In* Wildfire and Water Quality: Processes, Impacts and Challenges. International Association of Hydrological Sciences, Banf, Canada.

Moser, K., C. Ahn, and G. Noe. 2007. Characterization of microtopography and its influence on vegetation patterns in created wetlands. Wetlands 27(4): 1081–1097.

Nakayama, T., and M. Watanabe. 2006. Simulation of spring snowmelt runoff by considering micro-topography and phase changes in soil layer. Hydrol. Earth Syst. Sci. Discuss. 3(4): 2101–2144.

Nash, J., and J. Sutcliffe. 1970. River flow forecasting through conceptual models. Part 1: A discussion of principles. J. Hydrol. 10(3): 282–290.

Nuttens, T., A. DeWulf, G. Deruyter, C. Stal, H. DeBacker, and K. Schotte. 2012. Application of laser scanning for deformation measurements: a comparison between different types of scanning instruments. p. 1–13. *In* FIG Working Week. Rome, Italy.

Ødum, H. 1922. Om“ Faarestiernes” natur (CA Reitzel, Ed.). København, I kommission hos.

Paton, R.J., and D.J. Houlbrooke. 2010. Recovery of soil physical quality under repeated dryland and irrigated winter forage crops grazed by sheep or cattle. Proc. New Zeal. Grassl. Assoc. 72: 223–225.

Pringle, C. 2000. Threats to US public lands from cumulative hydrologic alterations outside of their boundaries. Ecol. Appl. 10(4): 971–989.

Prokop, A., M. Schirmer, M. Rub, M. Lehning, and M. Stocker. 2008. A comparison of measurement methods: terrestrial laser scanning, tachymetry and snow probing for the determination of the spatial snow-depth distribution on slopes. p. 210–216. *In* Annals of Glaciology.

Radcliffe, J. 1968. Soil conditions on tracked hillside pastures. New Zeal. J. Agric. Res. 11(2): 359–370.

Rahm, D. 1962. The Terracette Problem. Northwest Sci. 36(3): 65–80.

Robinson, D.A. 2008. Soil moisture measurement for ecological and hydrological watershed-scale observatories: A review. Vadose Zo. J. 7(1): 358.

Rodríguez-Iturbe, I., and A. Porporato. 2005. Ecohydrology of water-controlled ecosystems. Soil moisture and plant dynamics. Cambridge University Press.

Rumball, P.J. 1966. A study of pasture pattern in relation to microtopography. Master Agric. Sci. (Thesis), Massey Univ.: 1–133.

Sankey, J., J. Eitel, and N. Glenn. 2011. Quantifying relationships of burning, roughness, and potential dust emission with laser altimetry of soil surfaces at submeter scales. Geomorphology 135(1-2): 181–190.

Savabi, M. 2001. Determining soil water characteristics for application of WEPP model in south Florida. Trans. ASAE 44(1): 59–70.

Schaap, M.G., F.J. Leij, and M.T. van Genuchten. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251: 163–176.

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. Rangel. Ecol. Manag. 66(4): 445–453.

Soil Survey Staff. 1980. United States Department of Agriculture - Natural Resources Conservation Service: Soil Survey of Whitman County, Washington.

Staley, D., T. Wasklewicz, and J. Kean. 2010. Observations of drainage network change in a recently burned watershed using terrestrial laser scanning. p. 4849. *In* EGU General Assembly.

Tesfa, T.K., D.G. Tarboton, D.W. Watson, K. a T. Schreuders, M.E. Baker, and R.M. Wallace. 2011. Extraction of hydrological proximity measures from DEMs using parallel processing. Environ. Model. Softw. 26: 1696–1709.

Unger, P., and T. Kaspar. 1994. Soil compaction and root growth: a review. Agron. J. 86: 759–766.

Vereecken, H., and J. Huisman. 2008. On the value of soil moisture measurements in vadose zone hydrology: A review. Water Resour. Res. 44(4): 1–21.

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 Sci. 166(7): 441–452.

Watanabe, T. 1994. Soil erosion on yak-grazing steps in the Langtang Himal, Nepal. Mt. Res. Dev. 14(2): 171–179.

Weihs, B.J.B., and J.F.J. Shroder. 2011. Mega-terracettes and related ungulate activities in Loess Hills, Iowa, USA. Zeitschrift für Geomorphol. 55: 45–61.

Western, A.W., R.B. Grayson, and G. Blöschl. 2002. Scaling of Soil Moisture: A Hydrologic Perspective. Annu. Rev. Earth Planet. Sci. 30: 149–180.

Wilson, D., A. Western, and R. Grayson. 2004. Identifying and quantifying sources of variability in temporal and spatial soil moisture observations. Water Resour. Res. 40(2): 1–10.

Van der Zande, D., W. Hoet, I. Jonckheere, J. van Aardt, and P. Coppin. 2006. Influence of measurement set-up of ground-based LiDAR for derivation of tree structure. Agric. For. Meteorol. 141(2-4): 147–160.

Zhao, Y., S. Peth, R. Horn, J. Krümmelbein, B. Ketzer, Y. Gao, J. Doerner, C. Bernhofer, and X. Peng. 2010. Modeling grazing effects on coupled water and heat fluxes in Inner Mongolia grassland. Soil Tillage Res. 109(2): 75–86.

Table 2.1 Simultaneous Heat and Water (SHAW) model inputs for terracette simulations.

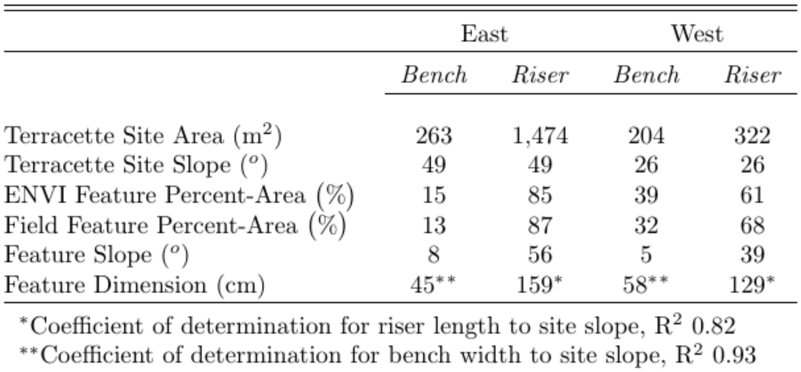
Site Perameter	East		West	
	Bench	*Riser*	*Bench*	*Riser*
Average Site Elevation (m)	370	370	370	370
Solar Noon	12:15	12:15	12:15	12:15
Average Site Aspect (AZ)	95	95	286	286
Average Slope (^{o})	8	49	5	26
No. of Plant Species Simulated	1	1	0	1
No. of Soil Nodes in Profile	20	20	20	20
Profile Depth Simulated (cm)	110	110	110	110
Leaf Area Index (LAI)	0.31	0.46	0	0.15
Plant Biomass (kg m^{-2})	0.05	0.07	0.0	0.02
Soil Roughness (cm)	5	5	5	5
Depth of Ponding (cm)	0.5	0.5	0.5	0.5
Dry Soil Albedo (a_d)	0.225	0.225	0.225	0.225
Moist Soil Albedo Exponent (a_a)	1.75	1.75	1.75	1.75
Sand (%)	22.7[a]	25.2[a]	19.3[a]	13.7[a]
Silt (%)	59.1[a]	56.7[a]	59.4[a]	64.9[a]
Clay (%)	18.2[a]	18.1[a]	21.3[a]	21.4[a]
Rock Content (%)	0.0[a]	0.0[a]	0.0[a]	0.0[a]
Organic Matter (%)	2.3[a]	2.4[a]	2.9[a]	3.0[a]
ρ_b (kg m^{-2})	1419.22[a]	1223.22[a]	1635.00[a]	1350.60[a]
K$_s$ (cm hr^{-1})	1.64[a]	1.86[a]	1.42[a]	1.65[a]
K$_{s-lateral}$ (cm hr^{-1})	0.0	0.0	0.0	0.0
Air Entry (ψ_e)	-0.030	-0.003	-0.100	-0.025
θ_s (m^3 m^{-3})	0.43[a]	0.50[a]	0.39[a]	0.43[a]
Pore Size Dist. BC (λ)	0.34*	0.50*	0.25*	0.45*
θ_r (m^3 m^{-3})	0.01	0.01	0.01	0.01
Pore Conductivity BC	2.0**	2.0**	2.0**	2.0**

[a] Parameter specific to 10 cm soil depth for simulation.

* Brooks-Corey pore size distribution parameter.

** Brooks-Corey pore conductivity.

Table 2.2 Area extent of bench and riser features at two terracette sites with differing slope and aspect. Resulting percent-area for benches and risers from field measurements is also shown for comparison.

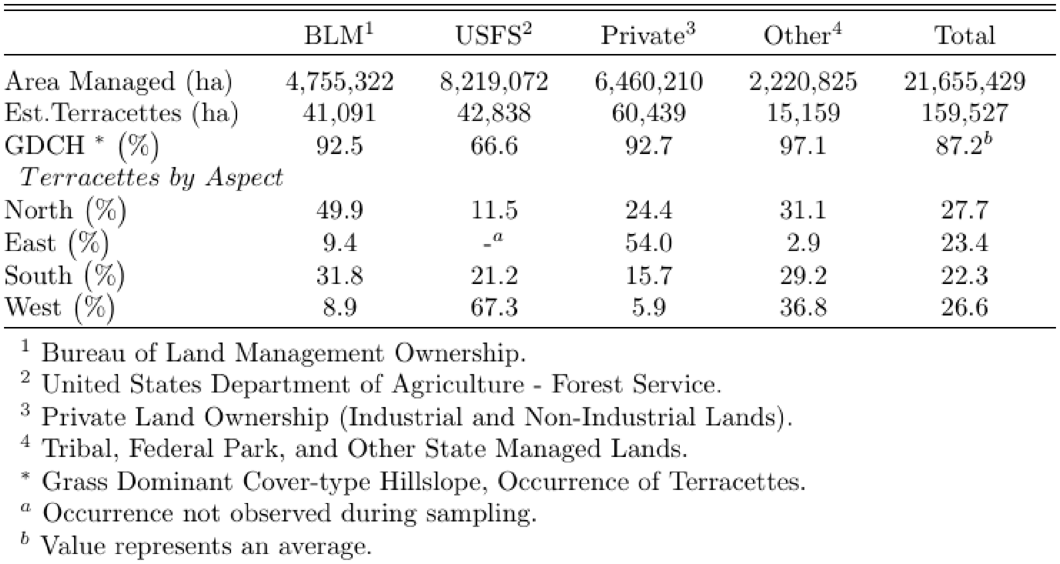


	East		West	
	Bench	*Riser*	*Bench*	*Riser*
Terracette Site Area (m^2)	263	1,474	204	322
Terracette Site Slope (^{o})	49	49	26	26
ENVI Feature Percent-Area (%)	15	85	39	61
Field Feature Percent-Area (%)	13	87	32	68
Feature Slope (^{o})	8	56	5	39
Feature Dimension (cm)	45**	159*	58**	129*

*Coefficient of determination for riser length to site slope, R^2 0.82

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

Table 2.3 Results of a 1000 random point assessment for terracettes across the State of Idaho.



	BLM[1]	USFS[2]	Private[3]	Other[4]	Total
Area Managed (ha)	4,755,322	8,219,072	6,460,210	2,220,825	21,655,429
Est.Terracettes (ha)	41,091	42,838	60,439	15,159	159,527
GDCH * (%)	92.5	66.6	92.7	97.1	87.2[b]
Terracettes by Aspect					
North (%)	49.9	11.5	24.4	31.1	27.7
East (%)	9.4	-[a]	54.0	2.9	23.4
South (%)	31.8	21.2	15.7	29.2	22.3
West (%)	8.9	67.3	5.9	36.8	26.6

[1] Bureau of Land Management Ownership.

[2] United States Department of Agriculture - Forest Service.

[3] Private Land Ownership (Industrial and Non-Industrial Lands).

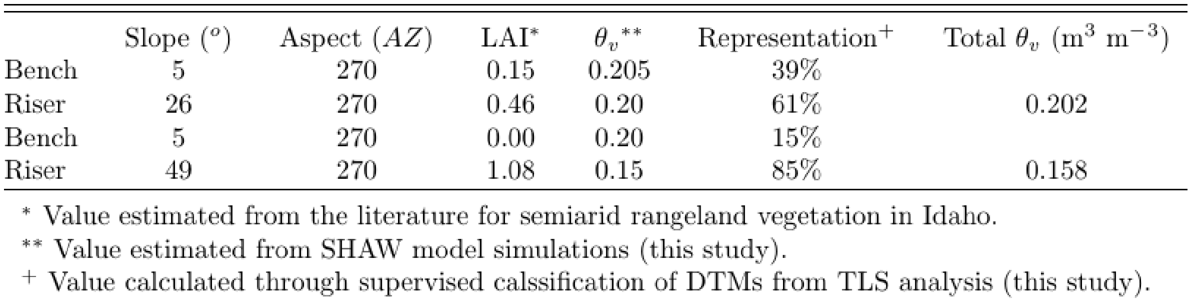
[4] Tribal, Federal Park, and Other State Managed Lands.

* Grass Dominant Cover-type Hillslope, Occurrence of Terracettes.

[a] Occurrence not observed during sampling.

[b] Value represents an average.

Table 2.4 Conceptual estimate of soil moisture for a semiarid terracette rangeland area given field assessment measurements of total-site slope, aspect, and vegetative cover (represented by leaf area index, LAI), showing the potential for a difference in soil moisture of 4.4% between these two sites. Site conditions were assumed to be those of the high-density cattle stocking and site soil characteristics of the risers presented in this study.



	Slope (^{o})	Aspect (AZ)	LAI*	θ_v**	Representation+	Total θ_v (m^3 m^{-3})
Bench	5	270	0.15	0.205	39%	
Riser	26	270	0.46	0.20	61%	0.202
Bench	5	270	0.00	0.20	15%	
Riser	49	270	1.08	0.15	85%	0.158

[*] Value estimated from the literature for semiarid rangeland vegetation in Idaho.

[**] Value estimated from SHAW model simulations (this study).

[+] Value calculated through supervised calssification of DTMs from TLS analysis (this study).

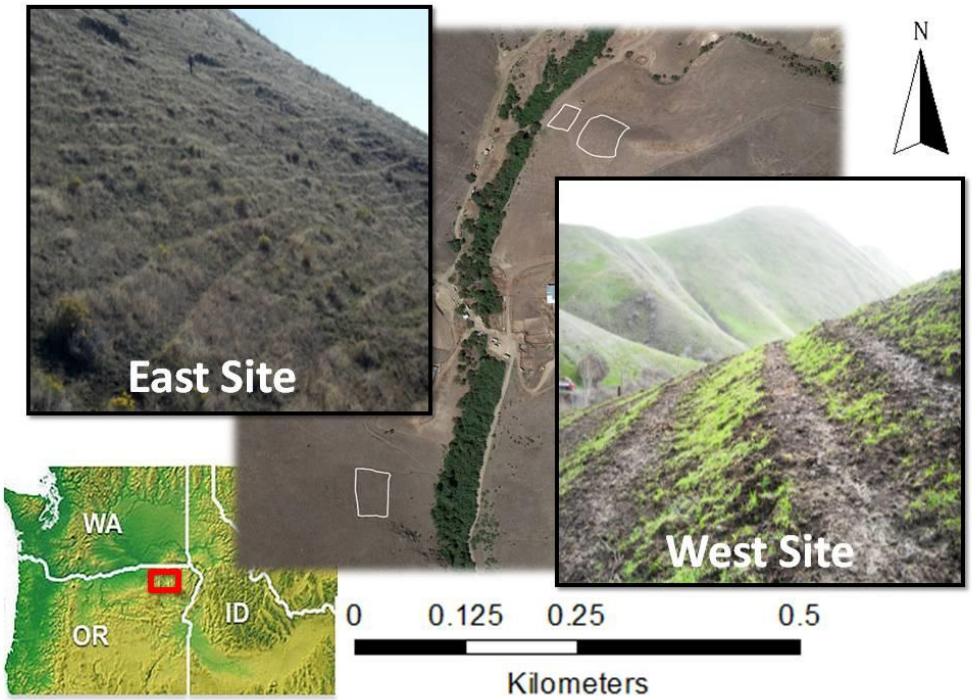


Figure 2.1 Study area map for sample site locations and site attributes near Clarkston, WA on the north bank of the Snake River. The ‘West’ site has terracettes and a high-density cattle stocking, the ‘East’ site has terracettes with moderate- to low-density cattle stocking.

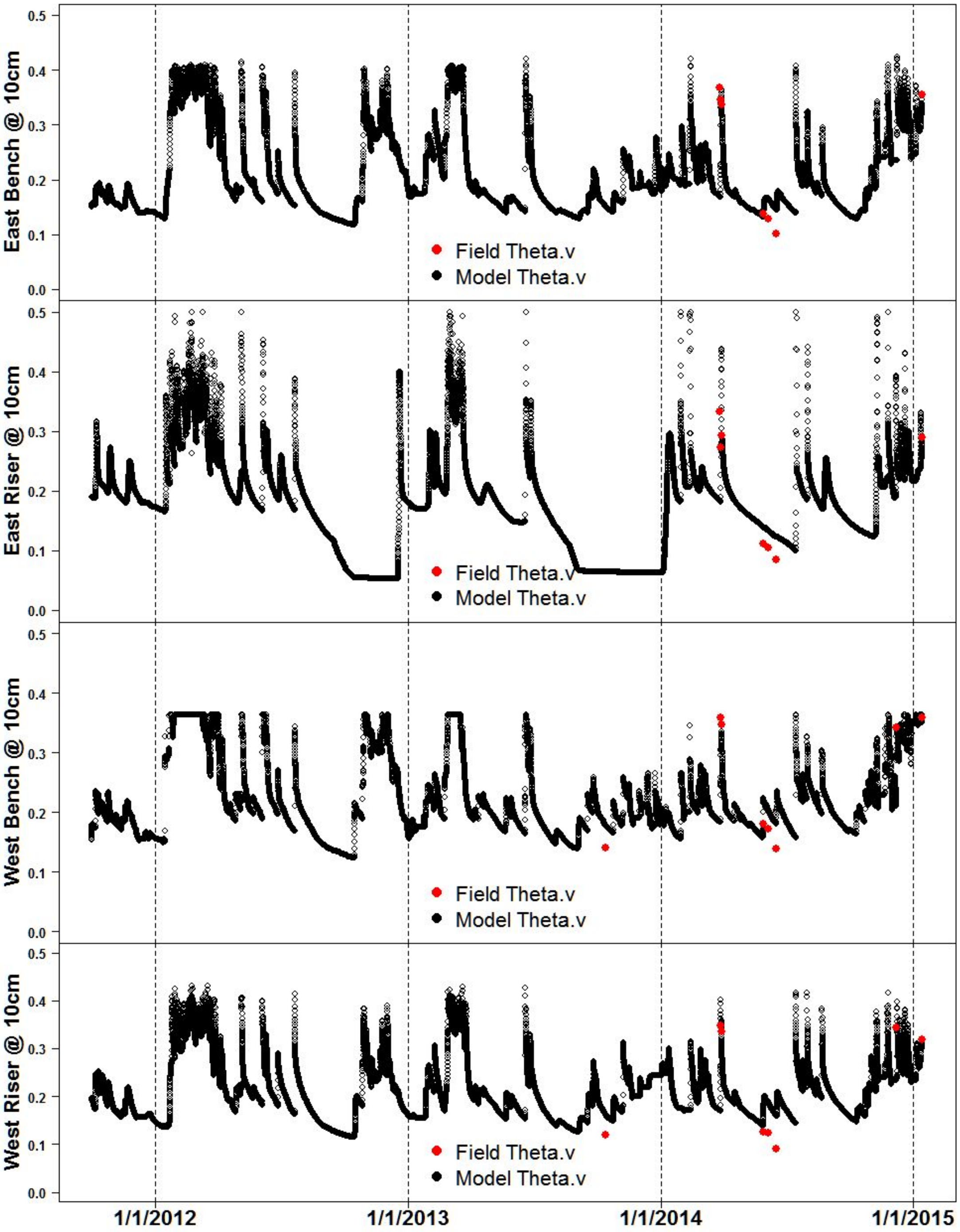


Figure 2.2 Simultaneous Heat and Water (SHAW) model simulation of soil moisture at the Clarkston, Washington sites based on 2011 – 2015 climate data and previously collected field samples for; East site benches, East site risers, West site benches and West site risers. Nash-Sutcliffe model efficiently (NSE) was 0.51, 0.61, 0.85, and 0.76 for EB, ER, WB, and WR simulations, respectively.

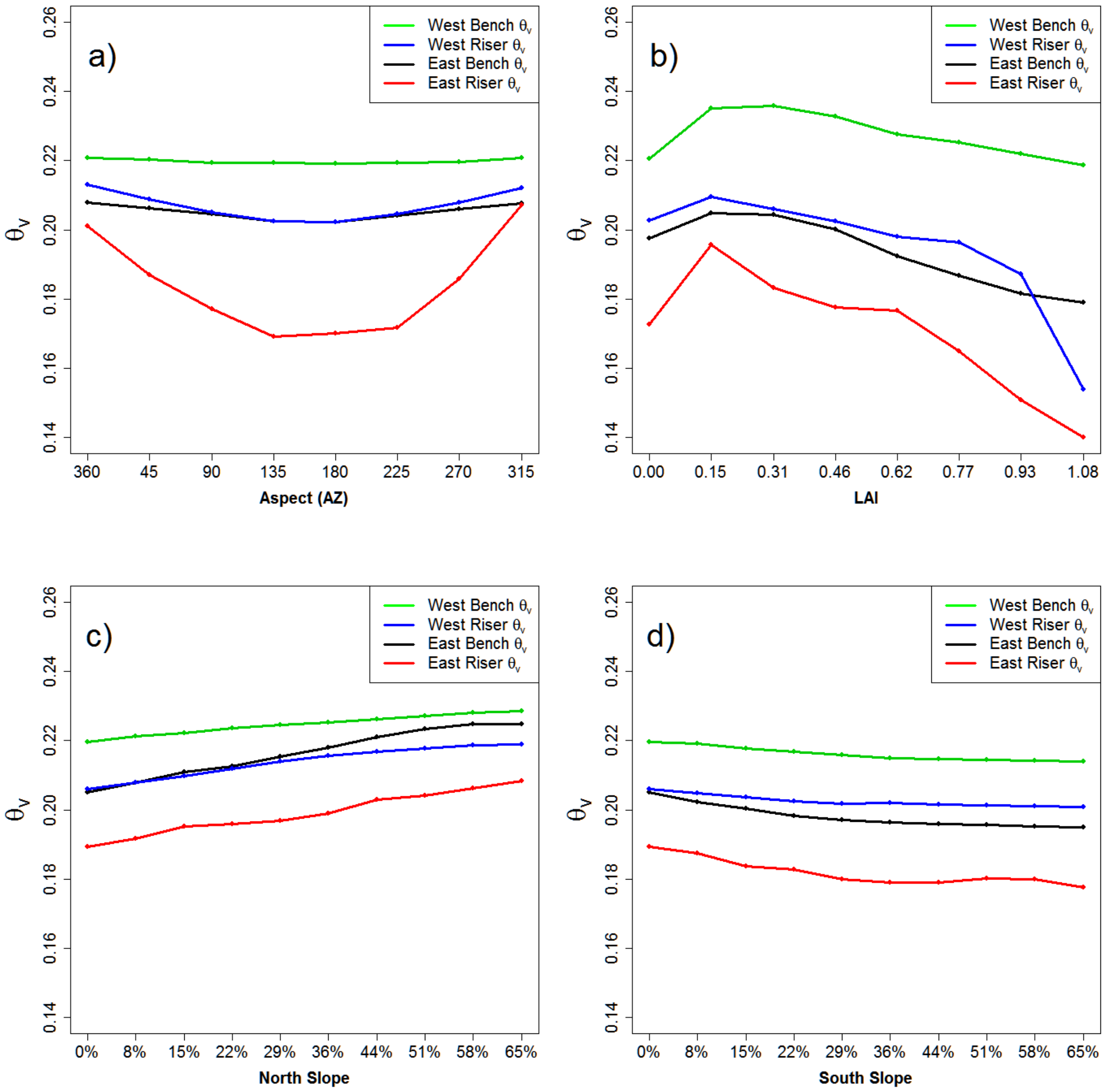


Figure 2.3 a) Simultaneous Heat and Water (SHAW) model simulated mean θ_v as a function of aspect for bench and riser features at the East (moderate- to low-density cattle stocking) and West (high-density cattle stocking) terracette sites. Simulation results for aspect showed greater θ_v for bench conditions as compared to riser conditions for all sites, a decrease in θ_v for riser conditions on south facing aspects as opposed to more northern aspects, and nearly no change in θ_v for bench conditions with respect to site aspect. **b)** SHAW simulated mean θ_v as a function of leaf area index (LAI) for bench and riser features at the East and West terracette sites. LAI results showed higher θ_v on benches as compared to risers across all sites and a decrease in digital orthoimagery with respect to increasing LAI. **c) and d)** Comparison of SHAW simulated mean θ_v as a function of changing slope on both a 360 azimuth (North) and 180 azimuth (South) aspect site. Simulation results showed an increasing trend in θ_v for northern aspects and decreasing trend in θ_v for southern aspects.

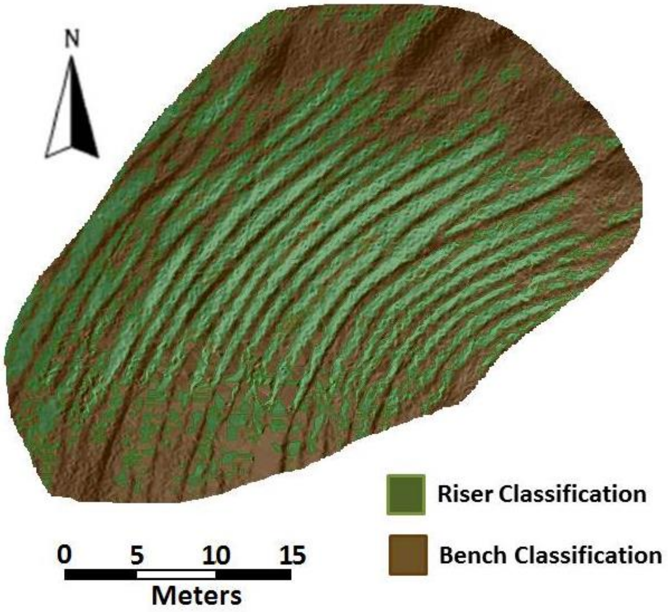


Figure 2.4 Bench and Riser features derived from terrestrial laser scanning data for the West terracette field site near Clarkston, WA (“black” areas represent ‘no data’ conditions).

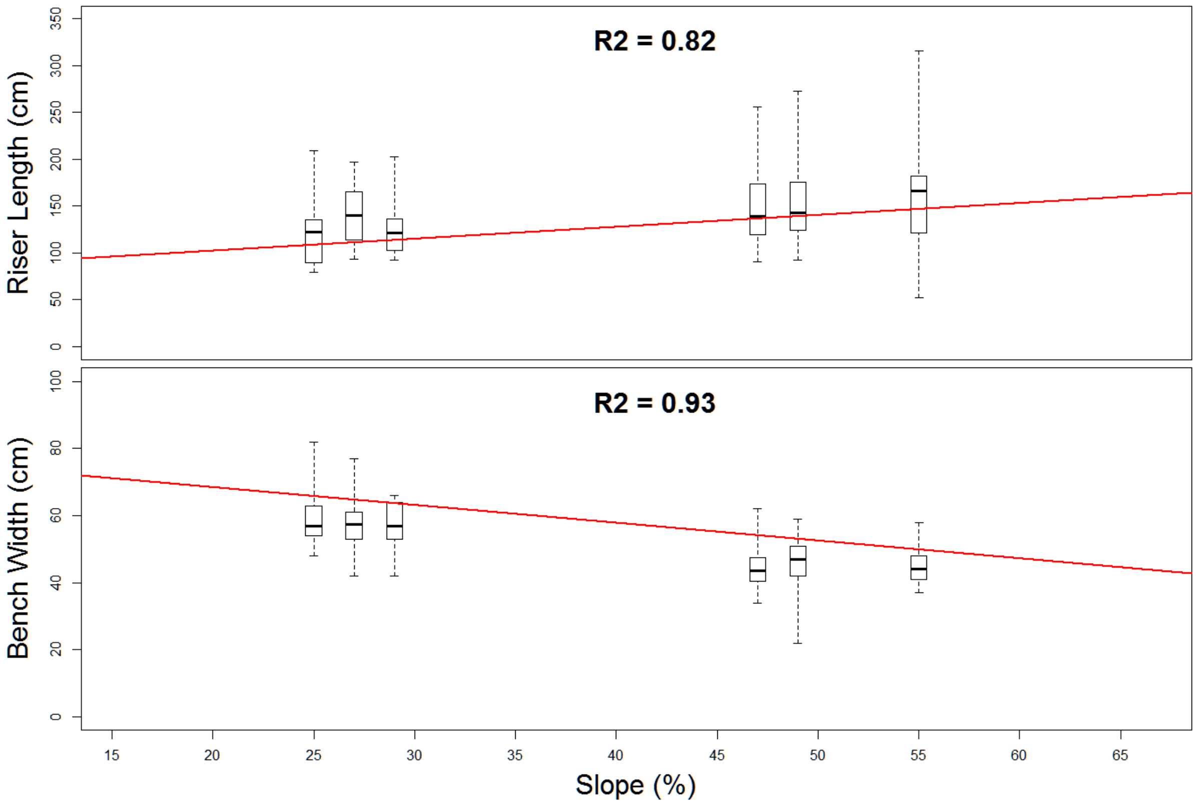


Figure 2.5 Field assessment of terracette morphological bench and riser conditions at two terracette sites near Clarkston, WA. Results show a trend of increasing riser length (distance between bench features) and decreasing bench width related to increasing slope gradient for six transects.

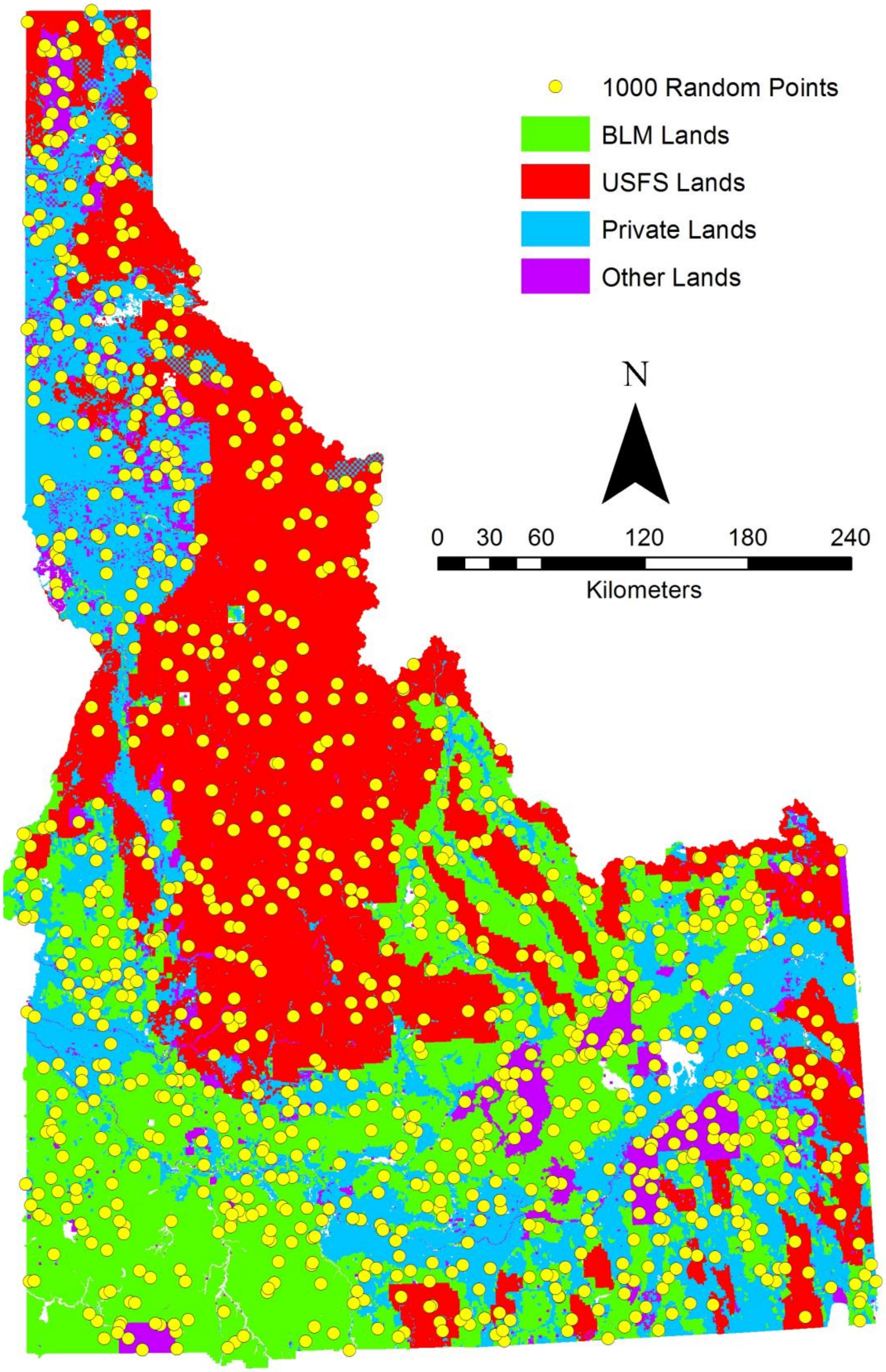


Figure 2.6 An assessment of 1000 random sample plots of 20.3 ha each within Idaho was completed to quantify terracette acreage and categorize occurrence by dominant slope, aspect, vegetation type and ownership.

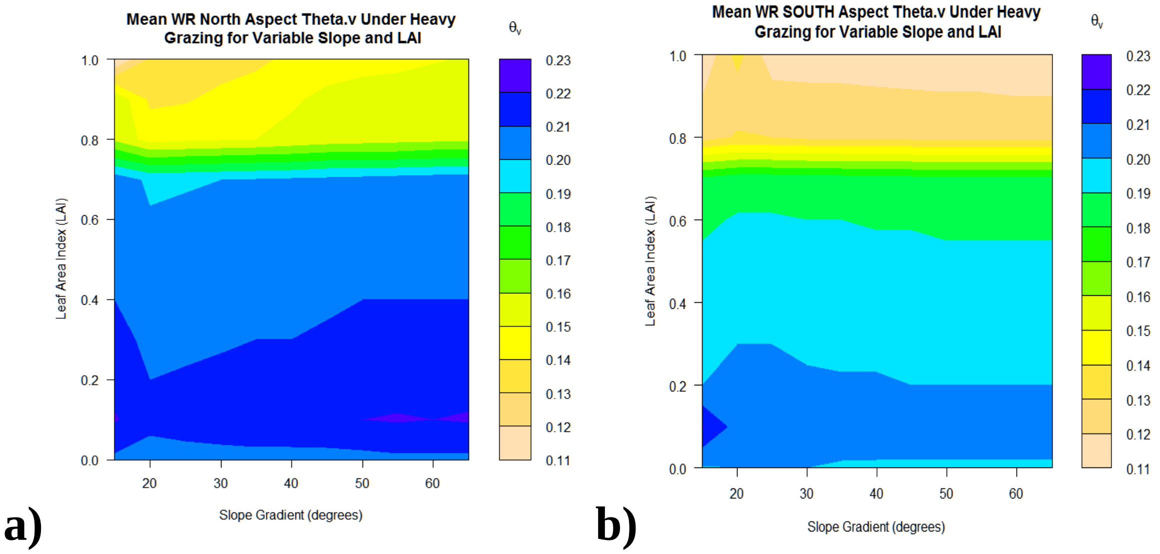


Figure 2.7 A contour plot showing soil moisture estimates for a semiarid terracette site subject to high-density cattle stocking on a silt loam soil given **a)** variable vegetation (leaf area index (LAI)) and slope gradient for a north aspect (360 azimuth), and **b)** variable LAI and slope gradient and simulated for a south aspect (180 azimuth). Simulation results show greater overall soil moisture on northern aspects (270 to 90 azimuth) as compared to south, and increased soil moisture with increasing site slope and decreasing vegetation (LAI) regardless of aspect.

Chapter 3. Using Science to Bridge Management and Policy: Terracette Hydrologic Function and Water Quality Best Management Practices in Idaho

Corrao, M.V., B. Cosens, R. Heinse, J.U.H. Eitel, and T.E. Link

Current Status: Submitted to *Rangelands Journal*

On The Ground

1) Nonpoint source pollution is a leading cause of water quality degradation on 40% of the semiarid lands within the western U.S., with sediment from runoff on agricultural lands making up 15%.

2). Managing nonpoint source pollution through best management practices (BMPs), relies on site-specific knowledge and voluntary application.

3) 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.

4) Vegetation and microtopographic land forms play an important role in hillslope erosion, emphasizing the importance of the nearly 160,000 ha of terracettes within Idaho.

5) Our measurements of terracette hydrologic function and terracette existence on more than 159,000 hectares within Idaho enabled an estimate of potential erosion and sediment, emphasizing the value of scientific site-specific research for land managers.

6) This study provides an example of the role of microtopographic landforms in nonpoint source pollution and the value of site-specific studies in implementation of State and Federal water quality policy.

Keywords: Rangelands, Terracettes, Erosion, Water, Policy, Best Management Practices

Nonpoint source pollution (NPS) 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 Nation[1]. Degraded waters within the United Sates are identified by 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 U.S. 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" identified by the EPA and defined by the CWA, as best management practices (BMPs) (FWPCA 319(b)). 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[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 for 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 rural land owners [5] conservation districts and local interest groups.

Nearly 40% of the semiarid land in the western U.S 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 U.S. has expanded by more than 60% while the private acreage of rangelands (not counting public leases) has decreased by more than 15% [9]. Within the State of Idaho 6 million ha (~28%) of public lands are managed as grazing allotments and nearly all 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]. The association of erosion and microtopography has shown features such as terracettes dominate many semiarid rangelands, and may play a critical role in the management of these lands[11]. 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 vegetation growth, runoff, and erosion[12,13]. Understanding these complex hydrologic interactions at the pasture-scale is critical in 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, and as a key variable in ecosystem function [14], was the driving motivation behind this research aimed at improving our understanding of the effects of terracettes on hydrologic processes. Our newly gained process understanding, coupled with a statewide terracette survey led to (i) a discussion of terracette-influenced soil water on semiarid rangelands, (ii), an estimate of potential NPS pollution (sediment) as a result of terracettes, and (iii) potential implications for rangeland management.

Terracettes and Semiarid Rangelands

Microtopographic features referred to as ‘terracettes’ [14] are repetitious ‘benches’, path-like, and ‘risers’, slope-like, features common in semiarid environments such as those throughout the western U.S. [15] (Figure 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 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 as a result of less plant transpiration and altered soil pore-structure [18,20]. Vegetation is vital to rangeland use as feed for grazing animals [10], and has shown the ability to reduce hillslope runoff by increasing infiltration at the outer edge of benches (Bergkamp 1998). The hydrologic interactions of terracette features may be significant in reducing erosion and increasing the amount of soil water on a hillslope. The significance of this may be represented as a microtopographic land-form capable of reducing NPS pollution, similar to human-ascribed BMPs.

Assessing the Hydrologic Function of Terracettes in Idaho

Field conditions (e.g. soil water content, soil texture, compaction, infiltration, and vegetation cover) at two terracette and two non-terracette sites were gathered from 2013 to 2015 [11] (Figure 2 and Table 1 & 2). The two terracette field sites exhibited differing aspects (East and West), bench and riser dimensions, cattle stocking densities, and site characteristics. Vegetative cover, bare earth, rock and litter percent were also surveyed during June 2013 at all sites. Subsequently, a detailed topographic survey was completed for both terracette sites with a Leica ScanStation II terrestrial laser scanner (TLS) for the creation of digital terrain models (DTMs) to characterize bench and riser morphology. Laser scanning results were cross-referenced with manual measurements of terracette profiles across three transects at each site. Based on the TLS derived DTMs, the relative percent-area of benches and risers was calculated and multivariate analysis of variance was used to test for differences in soil water and compaction between features within a site and between sites. Two-sample, equal-variance, Student's *t*- tests were used to assess the statistical significance of differences in soil water and compaction between benches and risers under differing site conditions. Based on Student's *t* -test results, it was hypothesized that differences in soil water and compaction between benches and risers exist on most actively grazed rangelands in semiarid areas.

The Rangeland Hydrology and Erosion Model (RHEM), specifically designed for rangeland erosion predictions [21], was used to estimate soil erosion for the terracette sites sampled in this study given our measured field conditions. Other studies have shown RHEM results to be a reasonable prediction of disturbed [22] and undisturbed [21] 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' using measured site characteristics and an assumed representative slope length of 2 m, based on the average slope length of a single bench/riser feature profile. The results of these simulations were then combined into a composite 'terracette' site by adding the erosion/sediment rates for bench and riser features together based on the percent-area of each feature from the TLS results.

To conceptualize terracette influences at a regional scale a quantification of the extent of terracettes was completed within the State of Idaho through a 1000 plot survey of 20.3 ha plots using publically available remotely sensed "Natural Color" digital orthoimagery and geographic information system (GIS) data from the Inside Idaho database [23] (Figure 3). Survey data included manual digitization of; visible terracettes within each plot, plot average slope (°), 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 East and West sites using RHEM. Modeling estimates were used 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

The hydrological processes observed on terracette sites are depicted in the conceptual model of terracette function in Figure 4. Cattle densities for the East and West terracette sites were representative of moderate/low-density (0.05 AU ha) and high-density (10 AU ha), respectively. During examination of the field data collected for terracette and non-terracette sites a trend of increased soil compaction with increased cattle stocking was noted. This trend persisted throughout the data as shown by the significantly greater compaction on terracette benches as opposed to risers as well as greater overall mean site compaction for sites with higher animal stocking rates compared to those of less or no cattle influence. Similarly, compaction was positively correlated to soil water content demonstrated through an observed increase in soil water (>6%) on terracette benches as opposed to risers and also between the more compact West terracette site (>2%) versus all other sites including the Ungrazed control site.

Vegetative cover differed greatly between all sites (Table 1), further emphasizing the trend associated with compaction and soil water. Terracette and non-terracette sites both exhibited reduced vegetative cover with increasing compaction [11]. For sample plots with compaction values greater than 2500 kPa (~363 pounds per square inch), soil surfaces were mostly devoid of vegetation and surface organic matter. These highly compacted plots also had the greatest soil water levels for measurements in the upper 10 cm as compared to sites with compaction lower than 2500 kPa. Additionally, plots with the highest vegetation density also had the lowest soil water, corroborating the suggested mechanism by which plants reduce soil water by transpiration.

Using regression analysis, transect measurements of bench and riser dimension across terracette sites showed a positive trend of decreasing bench width (Coefficient of determination, $R^2 = 0.93$) and increasing riser length ($R^2 = 0.82$) with increasing slope gradient. The results of the supervised classification for bench and riser percent-area from the TLS scan DTMs showed that a slope of 15°, bench and riser features comprised equal parts of plot conditions ~50%, however, at an average site slope of 65° risers comprised nearly 100% of plot conditions. These results compared well to field measured percent-area for East and West site benches and risers ($R^2 = 0.60$ and 0.97) and ($R^2 =0.82$ and 0.86), respectively. The RHEM modeling for individual bench and riser simulated conditions and DTM bench and riser percent-area calculations shown in Table 3 were combined to estimated annual runoff, sediment and soil loss for each site. These estimates emphasize the influence of compaction and vegetative cover on both terracette sites as well as the Grazed and Ungrazed non-terracette control sites (Table 3).

Nonpoint Source Pollution, Terracettes, and Rangeland Management

Cattle on terracette sites can increase soil compaction and soil water [8]. This is most noticeable in well-developed soils like loams and clays which are more easily compacted due to a higher percentage of smaller soil particles. Compacted soil commonly have a reduced pore-space leading to increased soil water-holding capacity, and potentially more plant available water [20]. The ability of compaction to influence plant root-growth, as shown in previous research [19], is exemplified in our results through the conditions observed on terracette benches under high-density cattle stocking.

Vegetation, soil water and microtopography are key variables in semiarid rangeland runoff and erosion processes, influencing rainfall infiltration and altering the velocity and pathways of overland flow [12]. Knowledge of the specific physical characteristics for a site defines the challenges faced by managers in sustainable use, and the effectiveness of BMPs selected to mitigate negative impacts [24]. Terracette hydrology and vegetative interactions 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.* (2015). Understanding the mechanistic and hydrologic function of terracettes can reduce erosion and sedimentation for some rangeland sites through improving the effectiveness of BMPs, such as cattle stocking density or rotational grazing duration, for terracette-site specific conditions.

Rangeland BMPs can be improved through scientific assessment of terracette hydrology and the influence of management decisions that aids managers in better articulating the value of decisions and justification of needed resources. Justifying management decisions is critical, given the importance of communication from land managers and scientists [26], in the development and application of BMPs [3,5], as well as the legitimacy it can generate given successful practice. Balancing land use and NPS pollution brings science and management together at many levels [26], and provides an example of how understanding site-specific conditions is needed to guide management decisions all within the framework of established natural resource policy.

The significance of NPS pollution policy stems in part; from our knowledge that 40% of the impacts to streams in the U.S. are derived from agricultural lands [1], from the role policy has in guiding management of these lands, and through the tools (e.g. research, modeling, BMPs) available for mitigation of land use impacts and the achievement of sustainable conditions. Within the goal of rangeland sustainability; management faces the challenge of addressing NPS pollution and maintaining a balance between land use, economic viability, 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) (Table 4), for use in the management of NPS pollution on rangelands [27]. There are however many more management practices being tested and applied on lands throughout the western U.S. that may provide similar or improved results for specific areas, emphasizing the importance of continued collaboration and communication between scientists, managers and policy makers.

The results of this study showing the potential for >159,000 ha of terracettes within the State of Idaho, and an estimated sediment yield of 0.11 ton ha^{-1} yr^{-1} for moderate to low-density cattle stocking ('East') and 0.35 ton ha^{-1} yr^{-1} for high-density cattle stocking ('West') terracette sites, shows a statewide potential for 17,500 to 55,600 tonnes of sediment to be generated annually. For comparison purposes, the Ungrazed Control site conditions of this study were estimated to produce a potential 1,500 ton yr^{-1}, and the non-terracette Grazed (extreme scenario) site conditions were estimated to produce a potential 1.38 million ton yr^{-1} of sediment under the modeling assumption that these respective conditions occurred on ~159,000 ha. Model results of erosional rates per unit area are similar to those presented in the literature for disturbed and undisturbed rangelands [21,28,29], further supporting the importance of BMPs targeting rangeland erosion and to mitigate any potential impacts to stream water quality. It should be acknowledged that the influence of local climate variability, site conditions, and erosional potential vary greatly, and although the results of this study are likely reasonable relative predictions, they may not apply throughout Idaho without site-specific information.

The most effective BMPs [3,4] are selected based on site-specific knowledge commonly founded in a landowner or manager's understanding of an area they oversee and the animals they raise. The results of this research are limited in scope, however the framework used to provide this example of how a microtopographic landform such as terracettes is connected with State and Federal clean water concerns and the sustainability of rangelands may be of value and provides a vivid example, with far-reaching application.

Conclusions

This and previous terracette research emphasize the importance of vegetation and the significant role plants can have in reducing soil erosion and increasing soil infiltration. The amount of modeled potential sediment for each of the site conditions in the study demonstrates the importance of tailoring rangeland management decisions, such as animal stocking rates, to site-specific conditions where animal traffic can influence soil characteristics. Additionally, our results showed terracettes on steeper slopes had less bench area and increased potential sediment, with the opposite observed as slope decreased. We speculate this may be due in part to changes in travel-path width as slope varies, leading to increases in bench disturbance and compaction on steeper sites. Our observations are similar to previous research noting the influences of cattle hoof impacts 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 local NPS pollution better than a more indiscriminate application based on local hydrologic or climatic conditions [5], however, the value of site-specific data and localized BMP success has the potential to influence practices at a regional scale where similar conditions may exists. The estimation of more than 6 million ha of rangelands in Idaho alone and the importance of understanding terracette hydrology, their occurrence at a state-scale, and the relationship of these features to land use, will provide value to the managers and policy makers 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. The value of communicating management knowledge tied to site-specific science can be great, and play a vital role in the application of BMPs [5], the development of balanced natural resource policy, and maintaining or achieving 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; nevertheless, increasing our understanding of the hydrologic function on these lands inevitably helps to mitigate potential impacts and secure their use for future generations.

Literature Cited

1. USEPA. National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle. Washington, DC 20460; 2009. 43 p.

2. IDEQ. Idaho’s 2010 Integrated Report - Final. Boise, Idaho; 2011. 102 p.

3. Ice G. History of innovative best management practice development and its role in addressing water quality limited waterbodies. Journal of Environmental Engineering. 2004;130(6):684–689.

4. D’Arcy B, Frost A. The role of best management practices in alleviating water quality problems associated with diffuse pollution. Science of the Total Environment. 2001;265:359–367.

5. Pannell D, Marshall G, Barr N, Curtis A, Vanclay F, Wilkinson R. Understanding and promoting adoption of conservation practices by rural landholders. Australian Journal of Experimental Agriculture. 2006;46(11):1407.

6. Emmerich W. Ecosystem water use efficiency in a semiarid shrubland and grassland community. Rangeland Ecology & Management. 2007;60(September):464–470.

7. Saco PM, Willgoose GR, Hancock GR. Eco-geomorphology of banded vegetation patterns in arid and semi-arid regions. Hydrology and Earth System Sciences. 2007;11(6):1717–1730.

8. Krueger W, Sanderson M, Cropper JB, Miller-Goodman M, Kelley CE, Pieper RD, Shaver PL, Trlica MJ. Environmental impacts of livestock on US grazing lands. Council for Agricultural Science and Technology. 2002;22:1–16.

9. Trimble S, Mendel A. The cow as a geomorphic agent—a critical review. Geomorphology. 1995;13:233–253.

10. Holechek JL. An Approach for Setting the Stocking Rate. Rangelands. 1988;10:10–14.

11. Corrao MV, Heinse R, Eitel JUH, Link TE. 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. Moscow, Idaho: University of Idaho, Ph.D. Dissertation, Chapter 1; 2015. 1-15 p.

12. Bergkamp G. A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. Catena. 1998;33(3-4):201–220.

13. Robinson DA. Soil moisture measurement for ecological and hydrological watershed-scale observatories: A review. Vadose Zone Journal. 2008;7(1):358.

14. Pringle C. Threats to US public lands from cumulative hydrologic alterations outside of their boundaries. Ecological Applications. 2000;10(4):971–989.

15. Ødum H. Om“ Faarestiernes” natur. Reitzel CA, editor. København, I kommission hos; 1922. 29 p.

16. Rahm D. The Terracette Problem. Northwest Science. 1962;36(3):65–80.

17. Gifford G, Hawkins R. Hydrologic impact of grazing on infiltration: a critical review. Water Resources Research. 1978;14(2).

18. Schmalz HJ, Taylor R V., Johnson TN, Kennedy PL, DeBano SJ, Newingham B a., McDaniel P a. Soil Morphologic Properties and Cattle Stocking Rate Affect Dynamic Soil Properties. Rangeland Ecology & Management. 2013;66(4):445–453.

19. Gerard C, Sexton P, Shaw G. Physical factors influencing soil strength and root growth. Agronomy Journal. 1982:875–879.

20. Villamil MB, Amiotti NM, Peinemann N. Soil Degradation Related To Overgrazing in the Semi-Arid Southern Caldenal Area of Argentina. Soil Science. 2001;166(7):441–452.

21. Nearing MA, Wei H, Stone JJ, Pierson FB, Spaeth KE, Weltz MA, Flanagan DC, Hernandez M. A rangeland hydrology and erosion model. The American Society of Agricultural and Biological Engineers. 2011;54(3):1–9.

22. Al-Hamdan OZ, Hernandez M, Pierson FB, Nearing M a., Williams CJ, Stone JJ, Boll J, Weltz M a. Rangeland hydrology and erosion model (RHEM) enhancements for applications on disturbed rangelands. Hydrological Processes. 2014;29(3):445–457.

23. Idaho State Office. Interactive Numeric and Spatial Information Data Engine (INSIDE) Idaho. U.S. Department of the Interior, Bureau of Land Management. 2012.

24. Rittenburg RA, Squires AL, Boll J, Brooks ES, Easton ZM, Steenhuis TS. Agricultural BMP Effectiveness and Dominant Hydrological Flow Paths: Concepts and a Review. Journal of the American Water Resources Association. 2015:1–25.

25. Brooks ES, Saia SM, Boll J, Wetzel L, Easton ZM, Steenhuis TS. Assessing BMP Effectiveness and Guiding BMP Planning Using Process-Based Modeling. Journal of the American Water Resources Association. 2015:1–16.

26. Likens GE. The role of science in decision making: Does evidence-based science drive environmental policy? Frontiers in Ecology and the Environment. 2010;8(6):1–9.

27. NRCS. Conservation Practices. National Conservation Practice Standards. 2013.

28. Wei H, Nearing MA, Stone JJ, Guertin DP, Spaeth KE, Pierson FB, Nichols MH, Moffet CA. A New Splash and Sheet Erosion Equation for Rangelands. Soil Science Society of America Journal. 2010;73(4):1386–1392.

29. Al-Hamdan O, Pierson F. Risk assessment of erosion from concentrated flow on rangelands using overland flow distribution and shear stress partitioning. Transactions of the ASABE. 2013;56(2):539–548.

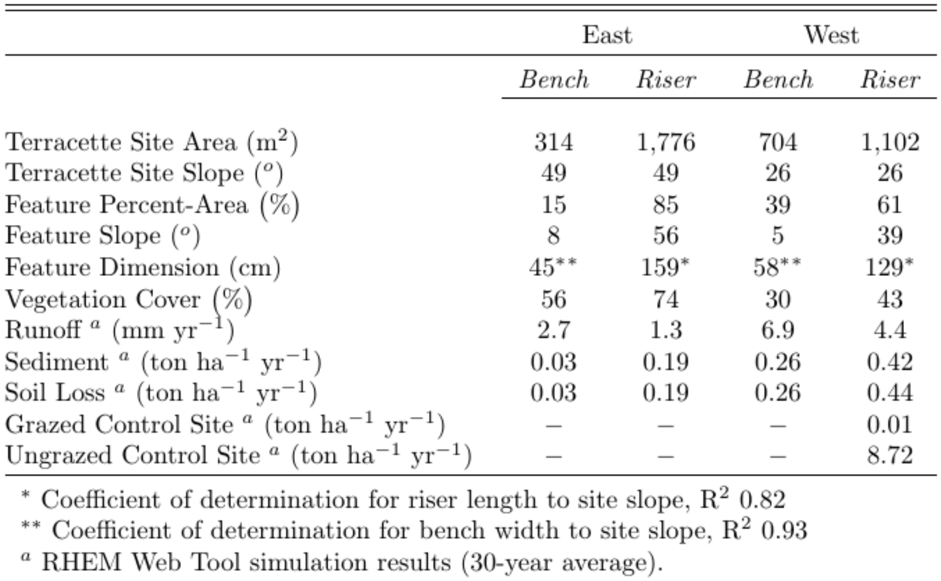
Table 3.1 Data collected at all field sites presented as averages within a site [11].

Site	Grazed Control	East	West	Ungrazed Control
Elevation (m)	356	354	370	362
Aspect (Azimuth)	268	95	286	290
Slope (^{o})	28	49	26	22
Soil Class	Silt Loam	Silt Loam	Silt Loam	Silt Loam
Veg 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	Moderate-Low	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 3.2 Mean soil characteristic values across all field sites. Volumetric soil water content (θ_v) is separated by spring-winter ‘wet’, and summer-fall ‘dry’, season to illustrate annual variations [11].

	Grazed Control	East		West		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^{-2})	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

Table 3.3 East and West terracette site percent-area of benches and risers at differing slope gradients (all values presented are means). Measured site attributes for two terracette hillslopes were used in the Rangeland Hydrology and Erosion Model (RHEM) to estimate annual runoff, sediment, and soil loss for bench and riser conditions individually. The results showed increased slope gradient led to increased runoff, sediment, and soil loss, but that increased vegetation could reduce the influences of increased slope. Model results suggesting greater erosion and sediment loss on risers is likely the result of greater feature despite greater vegetation cover.



	East		West	
	Bench	*Riser*	*Bench*	*Riser*
Terracette Site Area (m^2)	314	1,776	704	1,102
Terracette Site Slope (^{o})	49	49	26	26
Feature Percent-Area (%)	15	85	39	61
Feature Slope (^{o})	8	56	5	39
Feature Dimension (cm)	45**	159*	58**	129*
Vegetation Cover (%)	56	74	30	43
Runoff [a] (mm yr^{-1})	2.7	1.3	6.9	4.4
Sediment [a] (ton ha^{-1} yr^{-1})	0.03	0.19	0.26	0.42
Soil Loss [a] (ton ha^{-1} yr^{-1})	0.03	0.19	0.26	0.44
Grazed Control Site [a] (ton ha^{-1} yr^{-1})	–	–	–	0.01
Ungrazed Control Site [a] (ton ha^{-1} yr^{-1})	–	–	–	8.72

* Coefficient of determination for riser length to site slope, R^2 0.82

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

[a] RHEM Web Tool simulation results (30-year average).

Table 3.4 Best management practices for rangelands targeting water quality conditions as published by the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) [27].

Best Management Practice Title[1]	NRCS CPS[2]
Fencing	(Code 382)
Forage and Biomass Planting	(Code 512)
Grazing Land Mechanical Treatment	(Code 548)
Heavy Use Area Protection	(Code 561)
Herbaceous Weed Control	(Code 315)
Livestock Pipeline	(Code 516)
Livestock Shelter Structure	(Code 576)
Monitoring Wells	(Code 353)
Mulching	(Code 484)
Nutrient Management	(Code 590)
Ponds	(Code 378)
Pond Sealing or Lining	(Code 521)
Precision Land Forming	(Code 462)
Prescribed Grazing	(Code 528)
Range Planting	(Code 550)
Restoration and Management of Rare and Declining Habitats	(Code 643)
Riparian Herbaceous Cover	(Code 390)
Road/Trail/Landing Closure and Treatment	(Code 654)
Sediment Basins	(Code 350)
Silvopasture Establishment	(Code 381)
Spring Development	(Code 574)
Streambank and Shoreline Protection	(Code 580)
Stream Crossings	(Code 578)
Stream Habitat Improvement and Management	(Code 395)
Terraces	(Code 600)
Tree/Shrub Establishment	(Code 612)
Upland Wildlife Habitat Management	(Code 645)
Vegetated Treatment Area	(Code 635)
Vegetative Barriers	(Code 601)
Water and Sediment Control Basins	(Code 638)
Water Wells	(Code 642)
Watering Facility	(Code 614)
Wetlands	(Codes 658, 659, 657)
Windbreak/Shelterbelt Establishment	(Code 380)

[1] USDA NRCS Field Office Technical Guide, 2013
http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/fotg/

[2] USDA NRCS Conservation Practice Standard (Nez Perce County, ID)

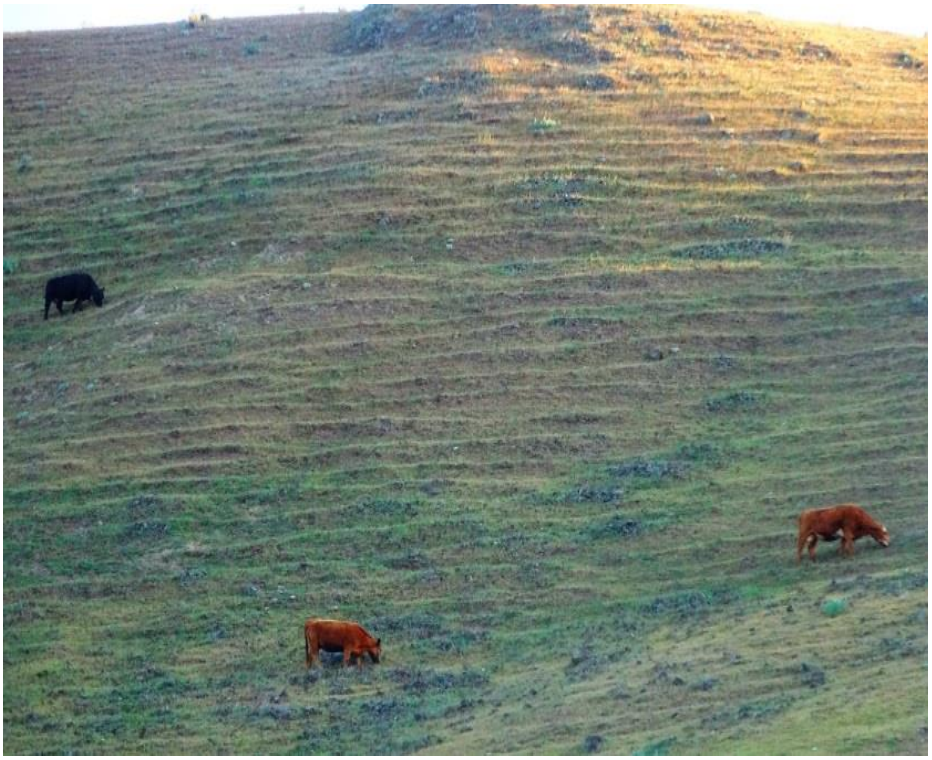


Figure 3.1 Semiarid rangeland terracettes near Clarkston, Washington on the north bank of the Snake River, March, 2014 (Photograph by Mark Corrao).

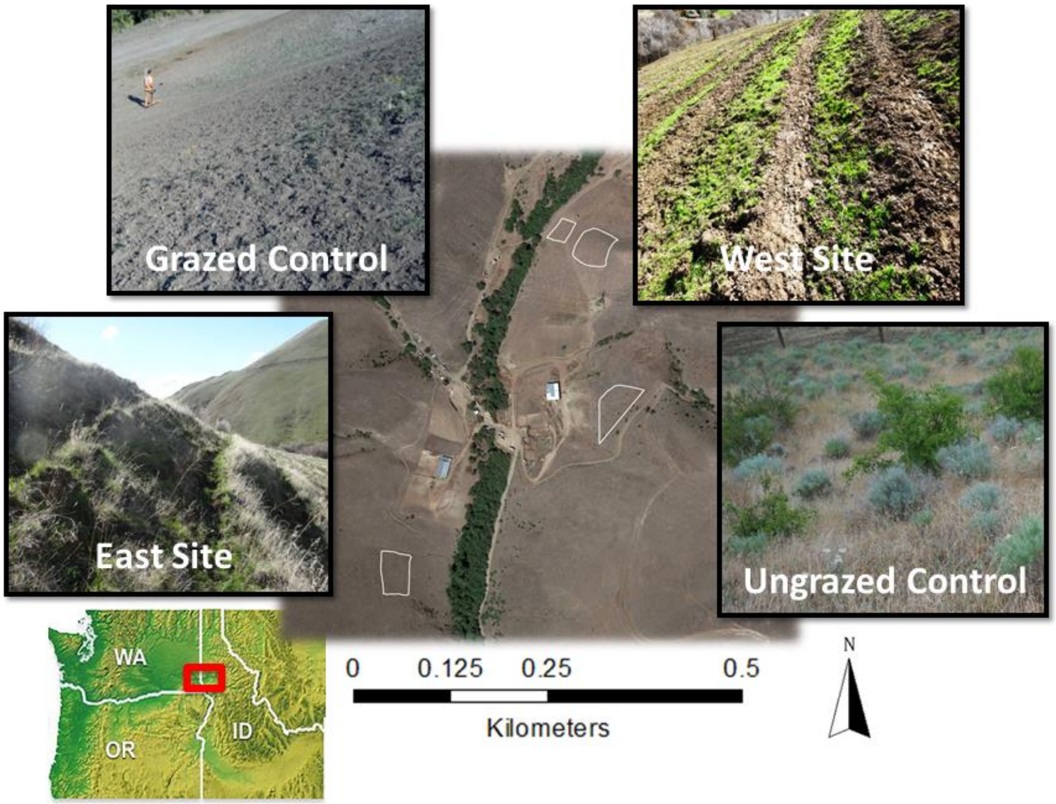


Figure 3.2 Study area map and sample site locations near Clarkston, WA on the north bank of the Snake River. Images are of the; 'West' site terracettes with high-density cattle stocking; 'East' site terracettes with moderate-low density cattle stocking; 'Grazed Control' non-terracette site with high-density cattle stocking; and 'Ungrazed Control' non-terracette site with grazing excluded.

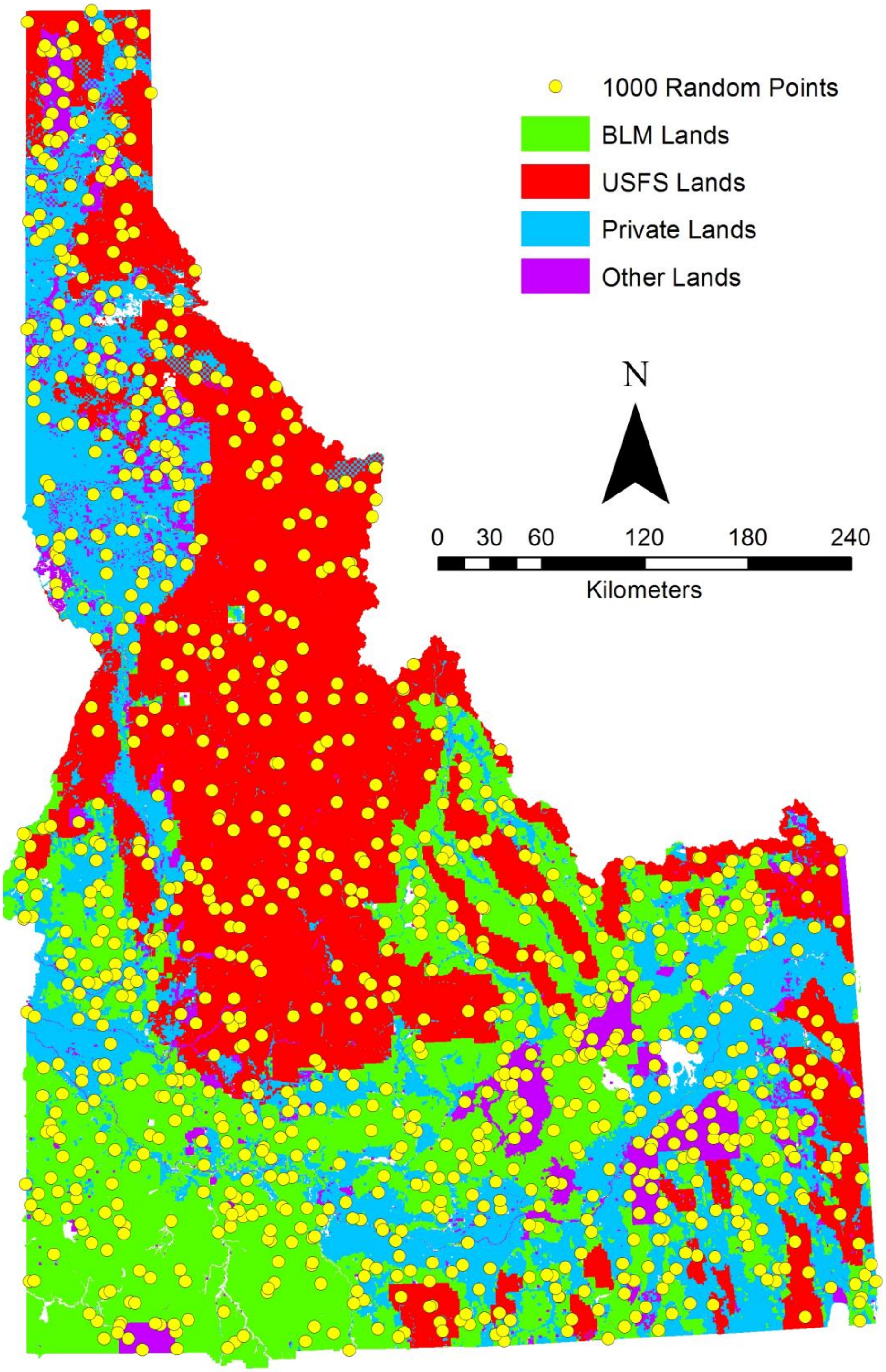


Figure 3.3 An assessment of 1000 random sample locations of 20.3 ha each within the State of Idaho was completed to quantify terracette aerial extent and categorize occurrence by dominant slope, aspect, vegetation type and ownership. Aerial extent of terracettes was used to estimate potential erosion generated from terracette sites as opposed to non-terracette sites.

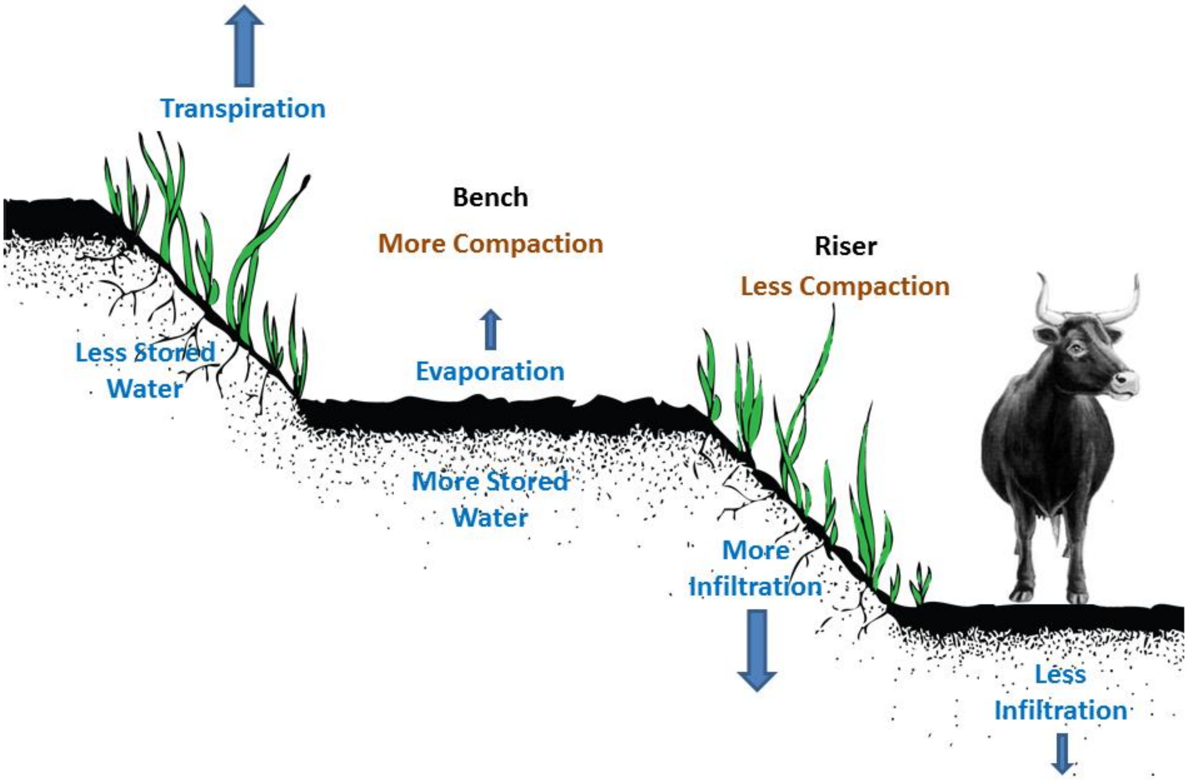


Figure 3.4 The influence of increased soil compaction leads to greater soil water storage in the upper layers of terracette benches as compared to the less compacted conditions of risers. Compaction values >2500 kPa resulted in vegetation on risers and un-vegetated soil surfaces on benches for highly compacted sites due to the ability of compaction to reduce plant root growth and soil infiltration rates. Increased infiltration and compaction can result in increased surface runoff and erosion, however, vegetation on terracette risers can reduce runoff from benches by slowing overland flow velocities and increasing soil infiltration, thereby trapping sediment [12].