Rangeland Hydrology and Erosion Model guide and Discussion for:
Short Grass Prairie Ecological Site, west Texas

1) General background

The Ecological Site for this example is a Deep Hardland Loamy 16-21" PZ (R077CY022TX)
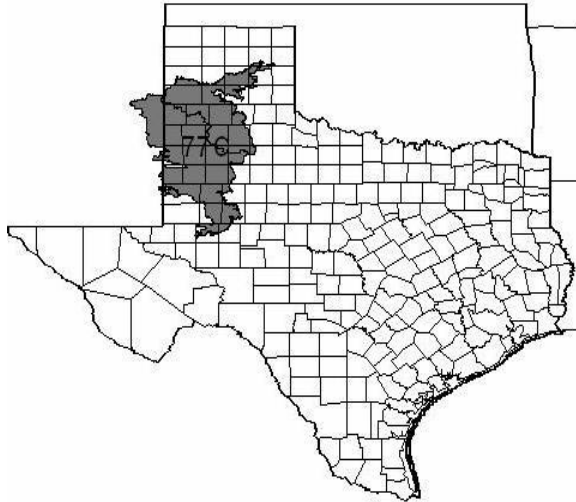Major land resource area (MLRA): 077C-Southern High Plains, Southern Part Ecological Site (ES).

Figure 1. Location of Major Land Resource Area and example of Reference plant community.

MLRA 77C is characterized by nearly level plains with numerous playa depressions, moderately sloping breaks along drainageways, and a steep escarpments along the eastern margin. This site occurs on the large nearly level to moderately sloping, well drained, moderately permeable soils formed in calcareous, loamy colluvium and slope alluvium derived from the Ogallala Formation of Miocene-Pliocene age. A few ancient drainage ways dissect this plateau and relatively shallow closed depressions are scattered throughout the area. The elevation ranges from 2,800 feet to 4,500 feet above sea level. Slopes range from 0 to 5 percent. The site is extensively used for cultivated cropland, as well as rangeland. The climate is semi-arid dry steppe. Mean annual precipitation is 21 inches. This site consists of very deep, well drained, moderately permeable soils that formed in loam and clay loam loess deposits. These are very well developed soils on old stable landforms and are moderately alkaline throughout. The soils have dark colored loam subsurface layers. Parent material is Eolian deposits from limestone origin. There are no surface fragments greater or less than 3 inches on the soil surface.
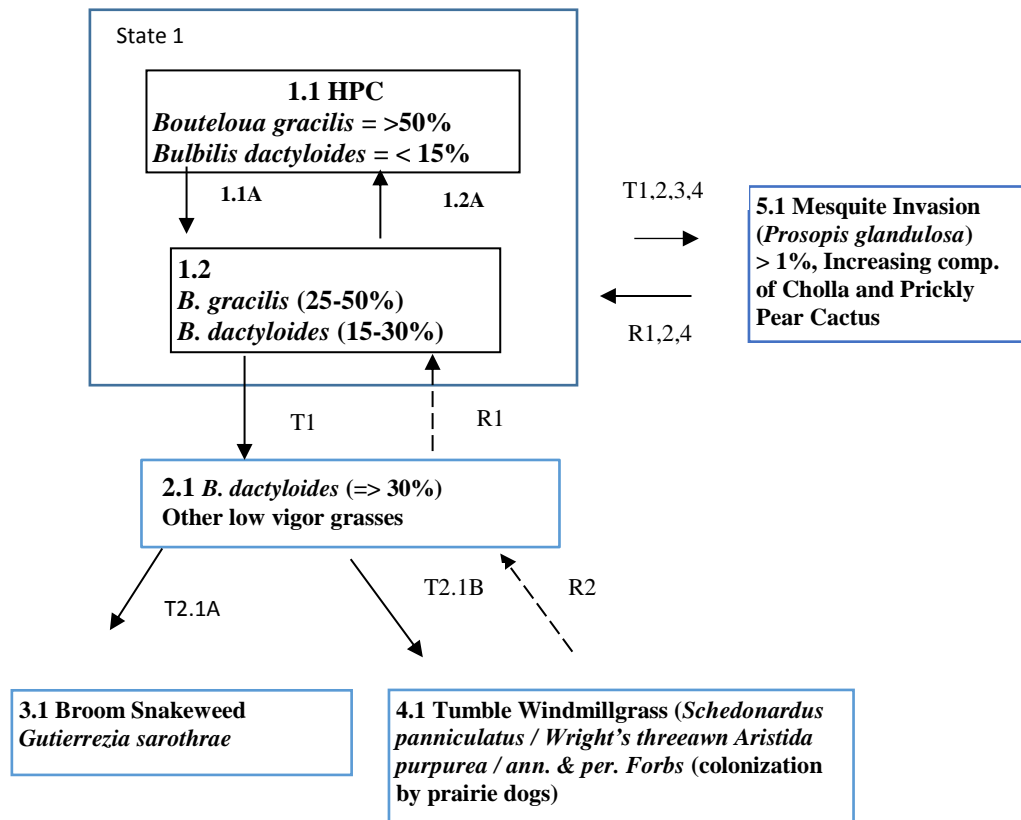
2) Ecological Site Description

The reference plant community (Figure 2) is shortgrass prairie grassland dominated by blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths] (60-70% composition by weight) and buffalograss [*Bulbilis dactyloides* (Nutt.) Raf. ex Kuntze] (15-25% composition by weight). Other shortgrass species, and a variety of forbs comprise the remaining plant composition. Typically, forbs contribute around 5 to 8 % of the total production. A few woody species, cholla cactus [*Cylindropuntia imbricata* (Haw.) F.M. Knuth], prickly pear (*Opuntia* spp.), broom snakeweed [*Gutierrezia sarothrae* (Pursh) Britton & Rusby] or occasional yucca (*Yucca* spp.) will be present, usually only 1 to 2% of the total plant community. Although, honey mesquite (*Prosopis glandulosa* Torr.) is not a native component species on this ecological site, it can be invasive. The Deep Hardland ecological site can exhibit high plant species richness and diversity (Spaeth 1990).

With continued heavy grazing pressure, the plant community shifts to a more equal distribution of blue grama (25-50%) and buffalograss (15-30%) (Figure 2, phase 1.2). In community phase 1.2, the soil can become more compacted and subsequently, rainfall infiltration capacity is reduced, and runoff increases. Further long-term grazing pressure can result in a transition to State 2.1 where buffalograss dominates the stand. Once buffalograss dominates the stand, transition to State 1 can be long-term (decades) because of the ecohydrologic dynamics of buffalograss (see RHEM modeling results and discussion). The dominant buffalograss state (2.1) also occurs as a transition from State 4.1, which results from prairie dog colonization and abandonment. This transition may take decades and depends on climate and management of the site.

Combinations of long-term heavy grazing pressure and drought can facilitate the increase of the native half shrub broom snakeweed. Sandier soil pockets and components within the ecological site are also more conducive to broom snakeweed invasion (Spaeth 1990). This low-growing (less than 0.5 m tall), suffrutescent plant is poisonous and is considered undesirable by many landowners because it suppresses growth of other native grasses and forbs. Allelopathy may be a factor as it is correlated with reduced grass and forb production, which enhances its own life cycle (Lowell 1980). Plant diversity is low in stands with dominance of broom snakeweed (Spaeth 1990).

Mesquite and cholla cactus can be invasive on this ecological site (State 5.1). Once this state becomes established, gains momentum, and woody densities increase, more stringent applications of conservation practices will be necessary (Brush Management, Prescribed Burning and Grazing). The economic inputs to convert State 5.1 to 2.1 can be high.

Black-tailed prairie dogs (*Cynomys ludovicianus*) often referred to as "ecosystem engineers" and "keystone species" (Lawton and Jones, 1995; Power et al., 1996) in shortgrass prairie can have a profound effect on grassland structure, composition, and ecosystem dynamics (Winter et al., 2002; Fahnestock et al., 2003). Where prairie dogs are abundant, grassland vegetation can be altered dramatically with extensive and persistent burrow systems. Prairie dogs have intrinsic biological value in grasslands; colonies can provide refugia for subdominant grasses, forbs, and shrubs (Coppock et al., 1983); soil structure and chemistry can be modified; nutrients can be altered (Whicker and Detling, 1988); and modifications in habitat can benefit other grassland animals (Clark et al., 1982; Lomolino and Smith, 2003). Although the disturbance regime can be extreme in active prairie dog colonies, floristic richness can be high, even greater than State 1.1 (Bonham and Lerwick, 1976; Klatt and Hein, 1978; Coppock et al., 1983; Martinsen, 1990; Spaeth 1990; Fahnestock and Detling, 2002). Soil surface physical and chemical conditions changes created by prairie dog colonization also have a significant effect on decreasing infiltration capacity, soil water storage, and increased runoff and erosion (see RHEM modelling results and discussion).

State 1

1.1 HPC
Bouteloua gracilis = >50%
Bulbilis dactyloides = < 15%

1.1A   1.2A

1.2
B. gracilis **(25-50%)**
B. dactyloides **(15-30%)**

T1,2,3,4

5.1 Mesquite Invasion
(*Prosopis glandulosa*)
> 1%, Increasing comp.
of Cholla and Prickly
Pear Cactus

R1,2,4

T1   R1

2.1 *B. dactyloides* **(=> 30%)**
Other low vigor grasses

T2.1A   T2.1B   R2

3.1 Broom Snakeweed
Gutierrezia sarothrae

4.1 Tumble Windmillgrass (*Schedonardus*
panniculatus / Wright's threeawn Aristida
purpurea / ann. & per. Forbs **(colonization**
by prairie dogs)

Legend

|	
1.1A	Lack of Prescribed Grazing, heavy grazing use
1.2 A	Prescribed grazing, above average spring, summer precipitation
T1	Traversed threshold, Transition from State 1 to 2; Lack of Prescribed Grazing, drought, prairie dog use
R1	Restoration from State 2.1 to 1.2; Tenuous, time factor could be decades; Climate pulse—above average summer precipitation; Prescribed grazing; Periodic deferment from grazing
T2.1A	Traversed threshold to State 3 due to stand deterioration, significant broom snakeweed increases > 2% cover
T2.1B	Traversed threshold to State 4 due to prairie dog colonization, significant bare ground increase
R2	Restoration from State 4.1 to 2.1 is tenuous, time factor could be decades, Climate pulse—above average summer precipitation; prescribed grazing; Periodic deferment from grazing
T1234	From any state, 1,2,3,4: Mesquite Invasion > 1%, increasing comp. of Cholla and Prickly Pear Cactus
R124	Restoration from State 5.1 to 1.2 will require one or more of the following conservation practices (brush management, prescribed burning, and prescribed grazing).
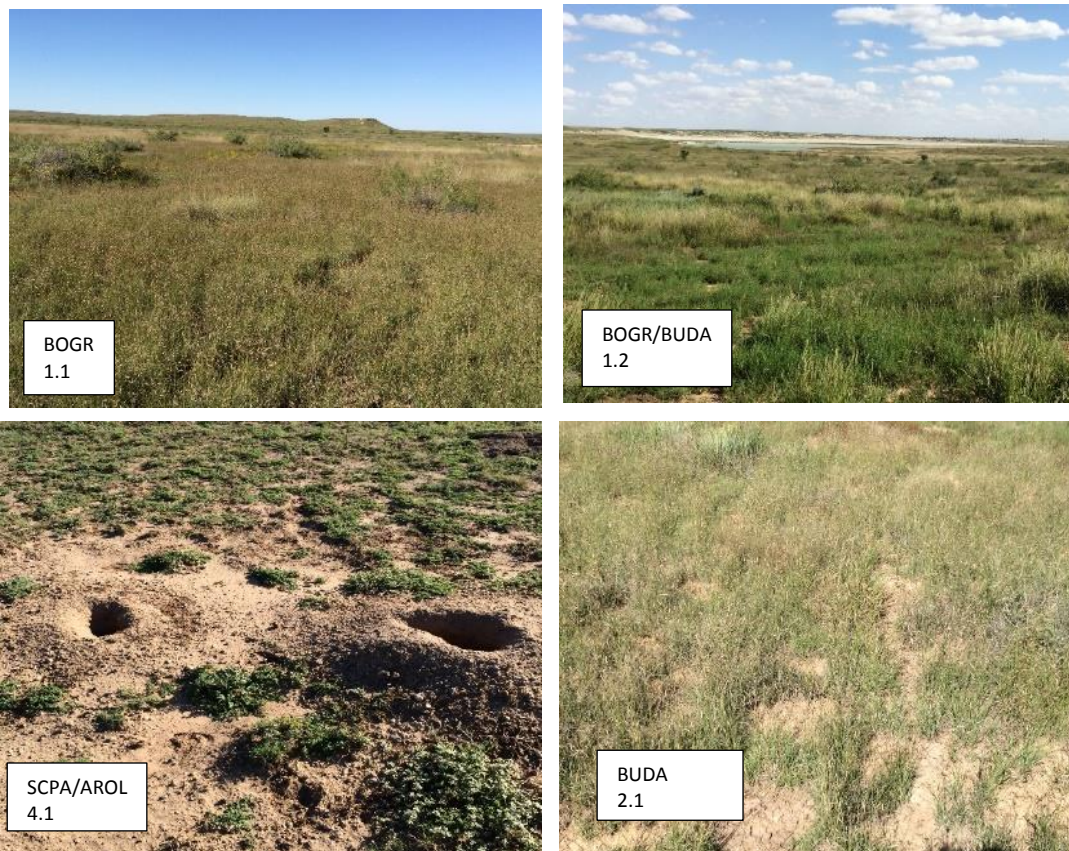
Figure 2 State and Transition Diagram for Ecological Site Deep Hardland site near Muleshoe, Texas illustrating State 1 (Reference plant community) and possible alternative states with recovery pathways and types of conservation practices needed to maintain or restore to respective states (photos by NRCS).

3) Soils

Existing soil texture components in the Deep Hardland Loamy Ecological site include loam, silty clay loam, and clay loam. This site should be revised to narrow the scope of soil particle size as silty clay loam and clay loam textural groups impose a significant hydrologic result because of the range of sand, silt, and clay.

4) Climate

ESD Climate Description: Climate is semi-arid dry steppe. Summers are hot with winters being generally mild with numerous cold fronts that drop temperatures into the single digits for 24 to 48 hours. Temperature extremes are the rule rather than the exception. Humidity is generally low and evaporation high. Wind speeds are highest in the spring and are generally southwesterly. Canadian and Pacific cold fronts come through the region in fall, winter and spring with predictability and temperature changes can be rapid. Mean average precipitation is 21 in, most of which comes in the form of rain and during the period from May through October. Snowfall averages around 15 inches but may be as little as 8 inches

or as much as 36 inches. Rainfall in the growing season often comes as intense showers of relatively short duration. Long-term droughts occur on the average of once every 20 years and may last as long as five to six years (during these drought years moisture during the growing season is from 50 to 60 percent of the mean.). Based on long-term records, approximately 60 percent of years are below the mean rainfall and approximately 40 percent are above the mean. May, June and July are the main growth months for perennial warm-season grasses; whereas, forbs make their growth somewhat earlier. Average frost free days are 205; freeze free days (210).

6) Modeling Results and Discussion

Table 1. RHEM model inputs for evaluation of hydrologic impact of transitions from one ecological state to another ecological state for Deep Hardland Loamy 16-21" PZ (R077CY022TX) site. Representative Soil Series is a Berda loam in the surface horizon.

Input Parameter	Reference State 1.1	State Phase 1.2	State 2.1	State 3.1	State 4.1
Soil Texture	Clay	Clay	Clay	Clay	Clay
Soil Water Saturation (%)	25	25	25	25	25
Slope length (ft)	100	100	100	100	100
Slope Shape	Linear	Linear	Linear	Linear	Linear
Slope Steepness (%)	2	2	2	2	2
Foliar canopy cover (%)					
Bunch grass Foliar cover (%)	90	45	0	25	5
Forbs and/or Annual Grass Foliar cover (%)	5	5	5	10	5
Sodgrass Foliar cover (%)	5	50	90	10	5
Woody Foliar cover (%)	0	0	0	0	90
Ground surface cover %					
Basal Cover (%)	10	6	5	1	1
Rock cover (%)	0	0	0	0	0
Litter Cover (%)	30	20	5	0	10
Biological Crusts Cover (%)	0	0	0	0	0

Figures 3 through 8 provide an overview of plant communities and summary of precipitation, runoff, sediment yield and soil loss rates for the annual average and 2, 5, 25, 50, and 100- year runoff recurrence intervals. For the Deep Hardland Loamy Ecological Site, hydrology and soil loss is highly variable across the respective states. As management and climate affect cover, production, and species composition, significant changes occur over time with respect to ecological changes (species composition) and hydrology. The decline of foliar plant cover and production affect the hydrologic regime; however, plant life/growth forms, such as tall grasses, mid grasses, shortgrasses, forbs, shrubs, halfshrubs, and trees, and their compositional differences on a site greatly influence infiltration and runoff dynamics. Infiltration is usually highest under trees and shrubs and decreases progressively in the following order: bunchgrass, sodgrass, and bare ground (Carlson et al., 1990; Thurow 1991; Weltz and Blackburn 1995).

Individual plant species also have a profound effect on hydrology and erosion dynamics i.e., different grasses, forbs, and shrubs (USDA-NRCS 2003, Spaeth 1996 a,b). Field studies have documented infiltration capacity with individual species composition. Dee et al., (1966) found that water infiltrated 3

times faster in blue grama and silver bluestem (*Bothriochloa saccharoides*) stands than areas dominated by annual weeds such as summer cypress (*Kochia scoparia*) and windmill grass (*Chloris verticillata*). Blue grama terminal infiltration capacity was about 4 times higher that buffalograss stands, holding soil type constant. Figure 3 shows comparative infiltration rates derived from rainfall simulation experiments for various ecological states and phases (Spaeth 1990). Initial infiltration capacity from the onset of rainfall to 25 minutes was slightly different for the reference state, blue grama (Bogr), and perennial broom snakeweed (Gusa) stands; however, long term infiltrability (near saturated hydraulic conductivity) were the same. The Gusa stands, indicative of low similarity index values, higher percentage of bare ground, low graminoid and forb cover, and high sub-shrub cover had infiltration rates similar to the reference Bogr stands (representative of high similarity index). This demonstrates that the Gusa stands, representative of low biotic integrity and similarity index [with significant changes in plant functional groups (graminoid-to-woody), high composition of invasive plants, and loss of native grass cover] still maintain adequate hydrologic function (Figures 3 and 4). However, soil loss was higher in Gusa stands compared to the reference stands (1.1 Bogr and 1.2 Bogr/Buda) due to higher bare ground under snakeweed canopy (Figure 5). What factors may be responsible for the near identical infiltration curves for the reference Bogr sands and the Gusa stands? The answer most likely is due to the morphology of the plants and coppice dune formation if present. Field studies show that infiltration capacity in bunchgrass stands have inherently higher rates compared to sodgrass stands (Mazurak and Conard 1959; Dee et al., 1966; Spaeth 1990, 1996a,b; Pierson et al., 2002). Some shrubs and half-shrubs are associated with coppice dunes or mounds composed of litter and wind transported soil. Coppice dunes form under broom snakeweed plants, which creates a zone of high infiltrability and low runoff. Field experiments show that surface soil organic carbon, bulk density, percentage silt, and infiltration and interrill erosion rates are significantly higher for shrub-coppice and shrub-interspace areas (Blackburn 1975; Johnson and Gordon 1988; Blackburn et al., 1990, 1992; Pierson et al., 1991).

Infiltration capacity of state phase 1.2 is different from the reference community 1.1, where blue grama is the dominant species (Figures 3 and 4). State phase 1.2 is representative of increasing buffalograss, where the ratio of blue grama and buffalograss is close to 1:1. As buffalograss increases in the stand, infiltration capacity decreases. This is also evident in state 2.1 where buffalograss occurs almost in a monoculture (Figures 3 and 4). Dominant stands of buffalograss (state 2.1; Figure 2) are common around the periphery of active prairie dog colonies and in pastures where grazing has been consistently heavy. Buffalograss is a short shoot plant (grazing tolerant plant with protected meristematic tissue, growing points), that is more tolerant to drought and hot temperatures than blue grama (Weaver 1954), and reproduces sexually (seed) and vegetatively (surface runners-stolons). Research shows that buffalograss also exhibits a dense shallow fibrous root system (root pan) that is correlated with significantly reduced infiltration capacity (Spaeth 1990, 1996). In some grass stands, where roots are found in the inter-aggregate pores, water repellent compounds form on soil aggregates and soil structural peds as a result of decaying organic matter and the production of humic and fulvic acids (Bisdome et al., 1993; Dekker and Ritsema 1996). Ritsema *et al.,* (1998) state that water repellency is considered a plant induced soil property. Sources of water repellent compounds include accumulated plant derived organic matter from mulch, decomposing roots and plant material, and root exudates (Doerr *et al.* 1996; Czarnes *et al.* 2000). Particulate organic matter contains plant and microbial produced compounds such as waxes (Franco *et al.* 2000; Schlossberg *et al.* 2005); humic acids (Spaccini *et al.* 2002); a presence of a protective water-repellent lattice of long-chain polymethylene compounds around soil aggregates (Shepherd *et al.* 2001); aliphatic C present in organic matter (Ellerbrock *et al.* 2005); mycorrhizal and saprobic soil fungi (Bond and Harris 1964; Paul and Clark 1996; Hallett and Young 1999; White *et al.* 2000; Rillig 2004); basidiomycete fungi (Bond and Harris 1964; Fidanza 2003); fungal proteins such as hydrophobins (Rillig 2005; Rillig and Mummey 2006); and fatty acids, fulvic acids, extracellular enzymes, polysaccharides (Bisdom *et al.* 1993; Kostka 2000; Eynard *et al.* 2006).

State 4.1 was produced by prairie dog colonization. Although plant cover is minimal in active colonies, plant species diversity can be greater than all the contrasting states associated with this ecological site (Spaeth 1990). In state 4.1, infiltration capacity is significantly reduced and erosion potential is higher than any of the other states represented in this ecological site (Figures 3 and 4). In summary, the extent of vegetation cover and individual plant species (within a life/growth form or contrasting growth habit) can be a primary factors that influence spatial and temporal variability of surface soil processes controlling infiltration and interrill erosion rates on rangeland.

In summary, vegetation can be a primary factor that influences the spatial and temporal variability of surface soil processes controlling infiltration and interrill erosion rates on rangeland.
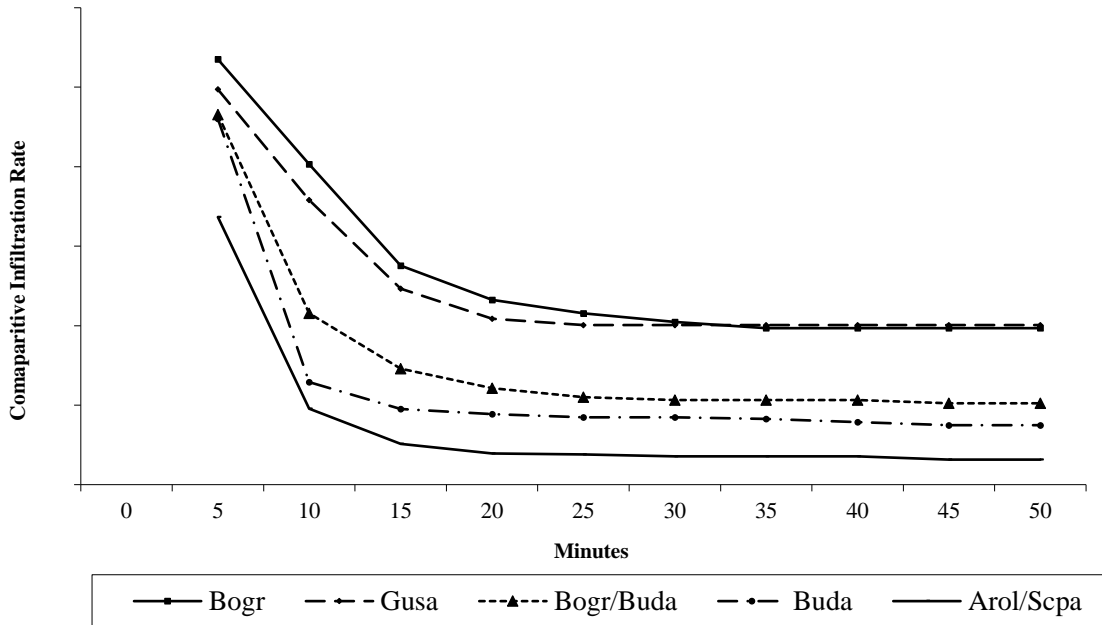

Figure 3. Comparative infiltration on 5 Ecological states associated with a Deep Hardland Loamy Ecological Site, Berda loam soil in west Texas. Reference State 1.1 Bogr = blue grama; State phase 1.2 Bogt/Buda (blue grama and buffalograss); State 2.1 Buda = buffalograss; State 3.1 Gusa = perennial broom snakeweed; and State 4.1 Arol = perennial threeawn, Scpa = Texas tumblegrass.
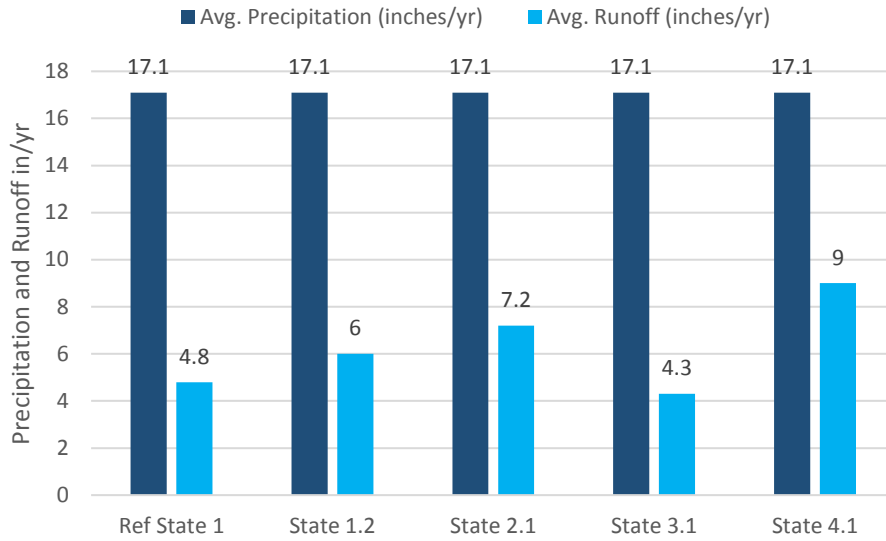
Figure 4. Rangeland Hydrology and Erosion Model estimated average annual precipitation and runoff for Deep Hardland Ecological Site by ecological state near Muleshoe, Texas.
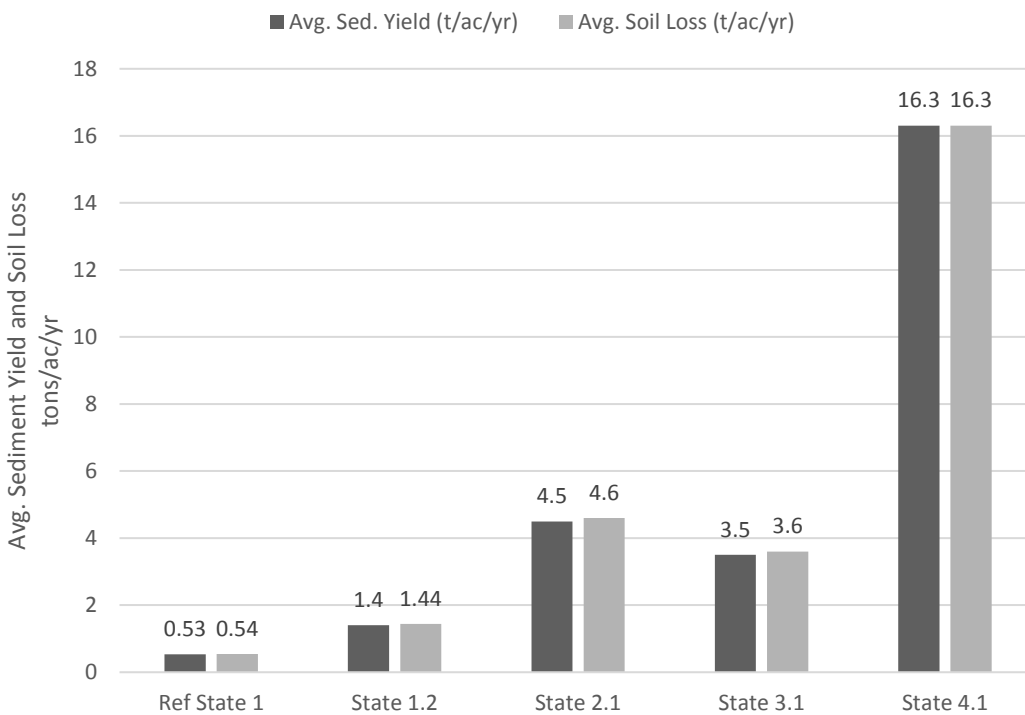

Figure 5. Rangeland Hydrology and Erosion Model estimated average annual sediment yield and soil loss for Deep Hardland Loamy Ecological Site by ecological state near Muleshoe, Texas.
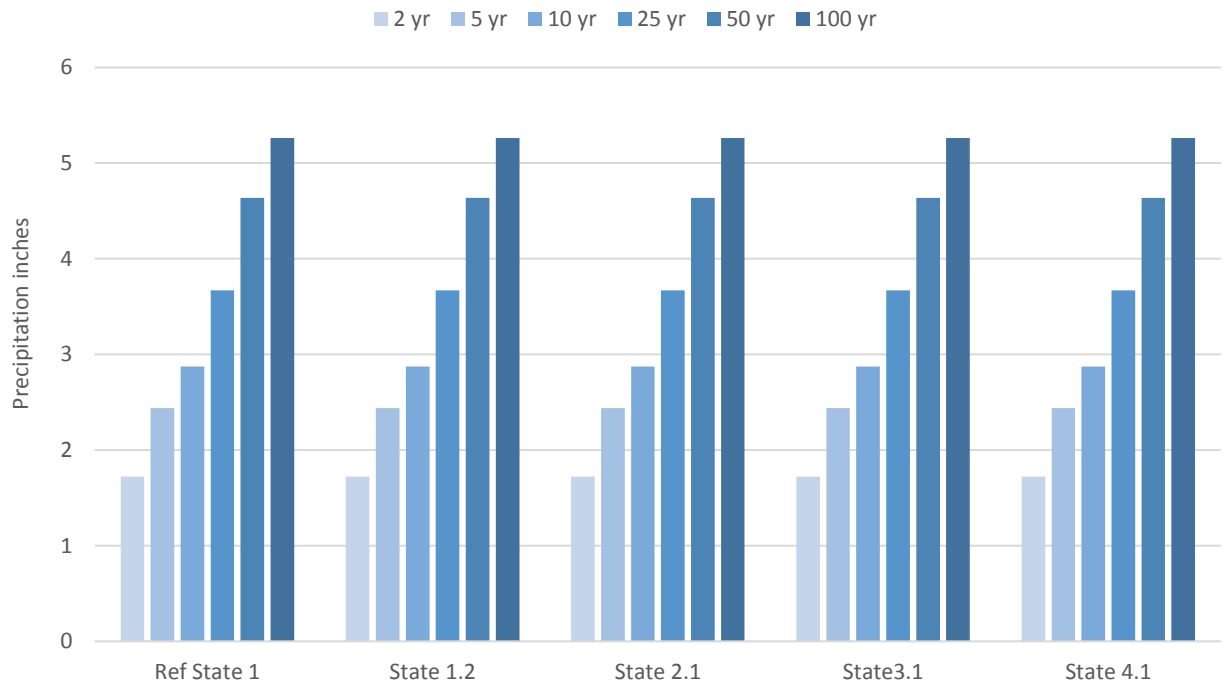
Figure 6. Rangeland Hydrology and Erosion Model estimated return period precipitation for Deep Hardland Loamy Ecological Site by ecological state near Muleshoe, Texas.
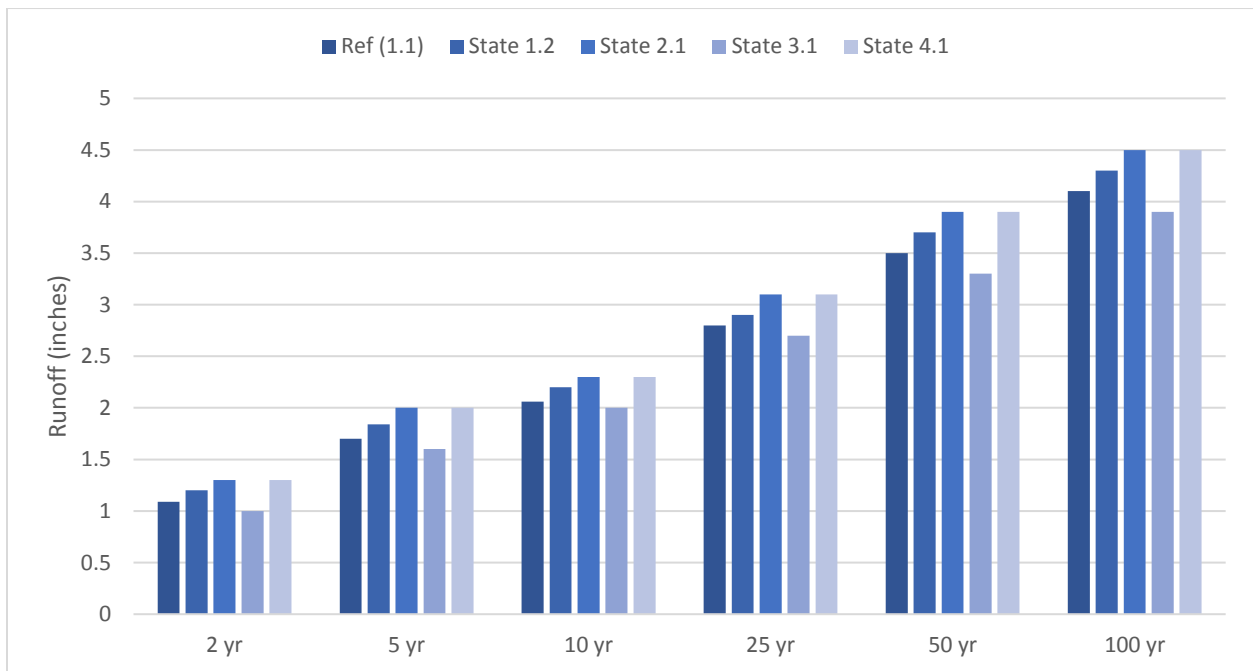
Figure 7. Rangeland Hydrology and Erosion Model estimated return period runoff for Deep Hardland Loamy Ecological Site by ecological state near Muleshoe, Texas.
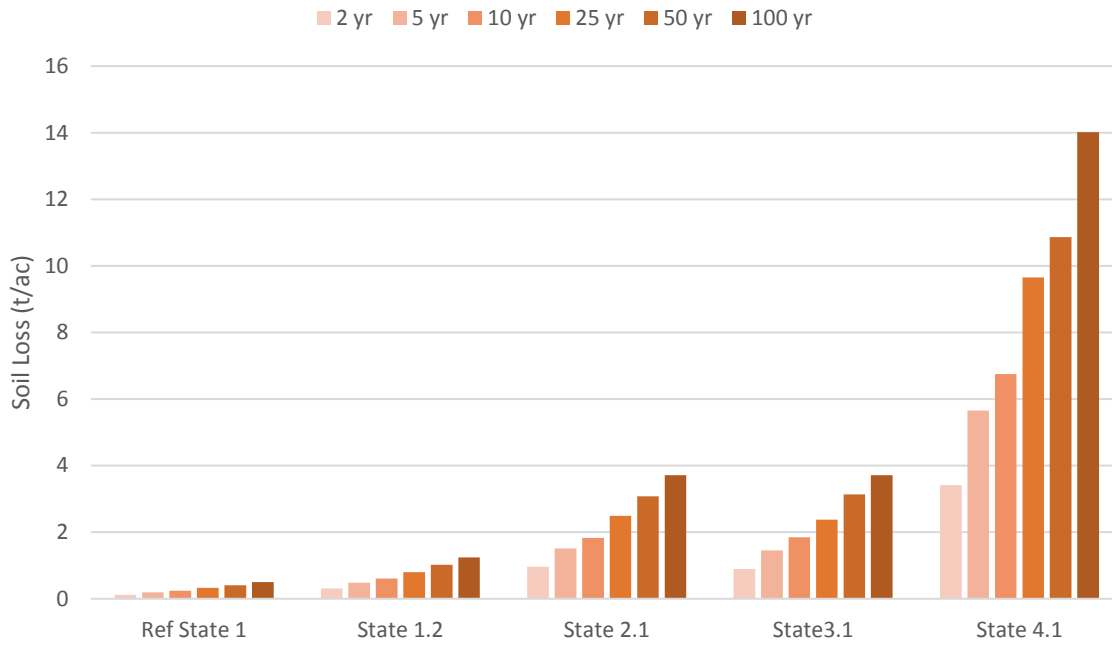

Figure 8. Rangeland Hydrology and Erosion Model estimated return period soil loss for Deep Hardland Loam Ecological Site by ecological state near Muleshoe, Texas.
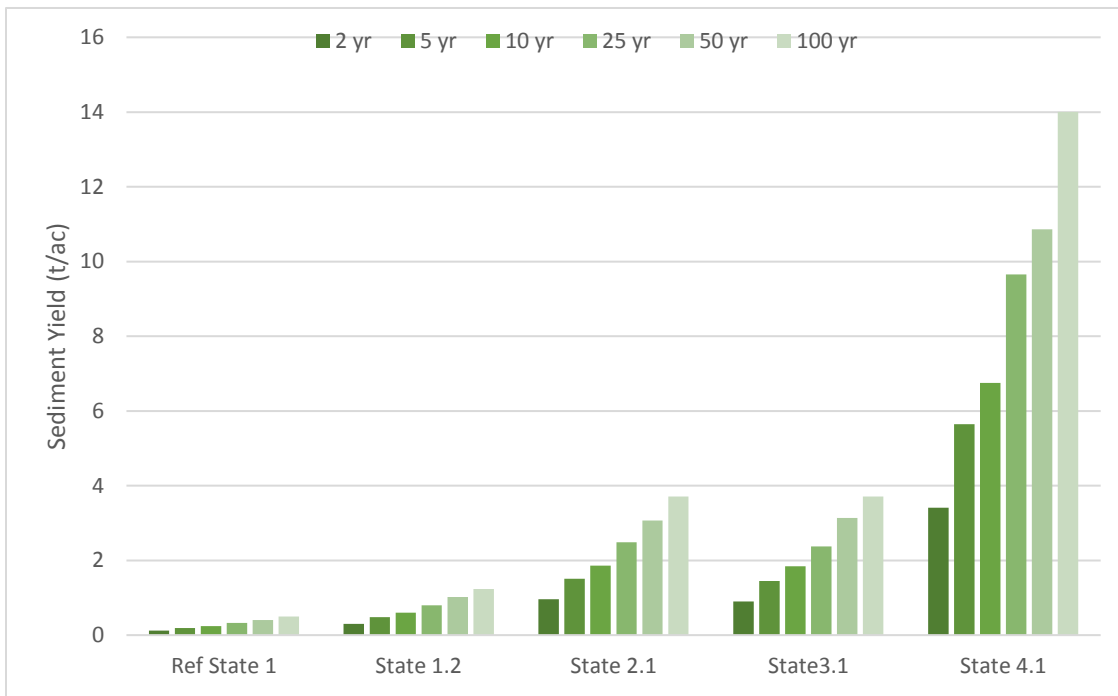
Figure 9. Rangeland Hydrology and Erosion Model estimated return period sediment yield for Deep Hardland Loam Ecological Site by ecological state near Muleshoe, Texas.

Table 2) Risk Assessment of Accelerate Soil Erosion

Range of Annual Soil Loss (ton/ac)	1.1 Bogr	1.2 Bogr/Buda	2.1 Buda	3.1 Gusa	4.1 Arol/Scpa
Low x < 0.49	0.5	0.03	0	0	0
Medium).49 <= X < 0.72	0.3	0.06	0	0	0
High 72 <= X < 1.03	0.15	0.22	0.01	0	0
Very High X > 1.03	0.05	0.7	0.97	1	1

Table 2 shows the risk assessments for the five states depicted in the state and transition diagram (Figure 2). Interpretations are as follows: there is a 50% change that soil loss will be less than 0.49 t/ac in the BOGR state, a 3% chance in Bogr/Buda, and zero % in Buda, Gusa, and Arol/Scpa. There is a 30% chance that soil loss will be within 0.49 and 0.72 t/ac in the Bogr state, 6% in Bogr/Buda. In the Bogr/Buda state, there is a 5% chance that soil loss will exceed 1.03 t/ac; whereas, the probability of soil loss exceeding 1.03 t/ac is high in Bogr/Buda (70%), Buda (97%), Gusa (100%), and Arol/Scpa (100%).

Table 3. Frequency Analysis by annual soil loss (ton/ac/year) by return period for Deep Hardland Ecological Site.

| Return Period	State 1.1 Bogr	State 1.2 Bogr-Buda	State 2.1 Buda	State 3.1 Gusa	State 4.1 Arol-Scpa
2	0.118	0.306	0.962	0.899	3.388
5	0.19	0.48	1.504	1.445	5.592
10	0.239	0.599	1.853	1.834	6.68
20	0.301	0.756	2.328	2.309	8.274
30	0.328	0.878	2.613	2.557	9.685
40	0.36	0.91	2.733	2.677	10.33
50	0.37	0.918	2.758	2.781	10.782
60	0.409	1.024	3.074	3.135	10.869
70	0.425	1.057	3.164	3.193	11.881
80	0.434	1.076	3.22	3.212	12.976
90	0.461	1.146	3.428	3.434	13.604
100	0.492	1.224	3.663	3.699	13.915
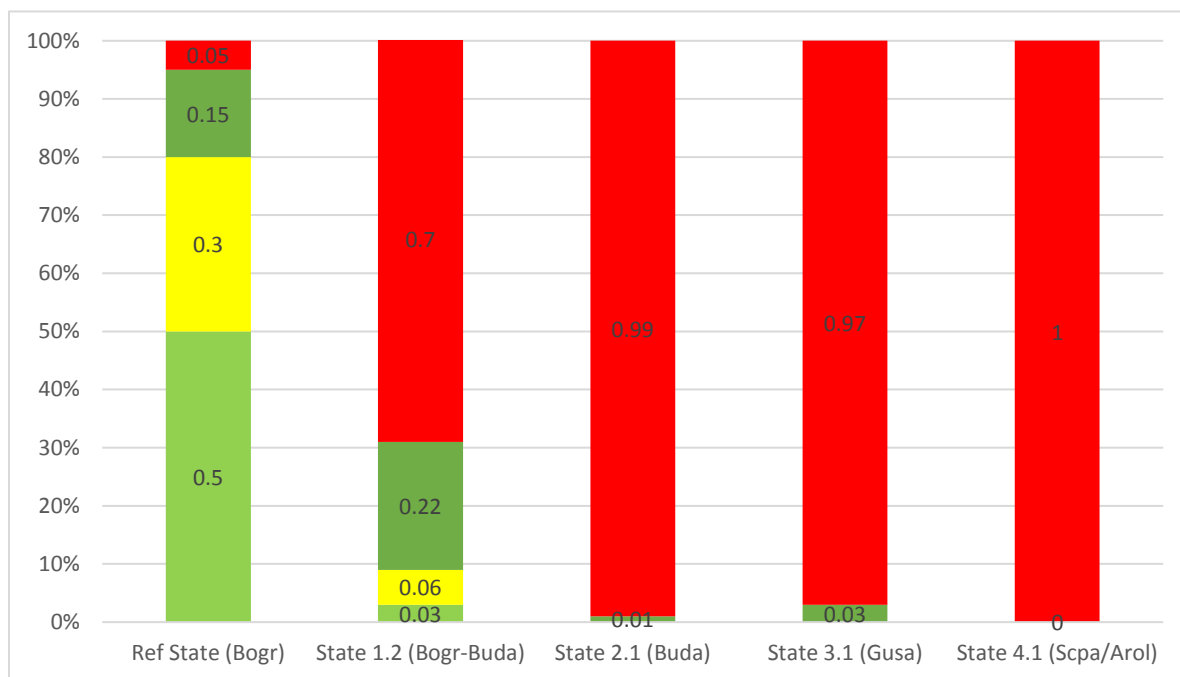
Figure 10. Probability of occurrence for yearly soil loss for all scenarios using erosion classes of Low (50%), Mediun (80%), High (95%), and Very High (>95%).

8 Summary

Analysis of the RHEM simulation runs on the Deep Hardland Loamy 16-21 inch precipitation ecological site provides a basis for interpreting the impacts of vegetative canopy cover, surface ground cover, and topography on dominant processes in controlling infiltration and runoff as well as sediment detachment, transport and deposition in overland flow at each state. Our results suggest that RHEM can predict runoff and erosion as a function of vegetation structure and behavior of different plant community phases and amount of cover for the different states.

There are significant differences in estimated annual soil erosion rate between the ecological states on this ecological site. The drivers are plant composition, largely the interaction between the two dominant C4 grass species, blue grama and buffalograss. As buffalograss increases in the stand, infiltration capacity will decrease. The causative factors are associated with root morphological differences between blue grama and buffalograss and the degree of water repellency found in buffalograss stands. Water repellent compounds appear to be associated with stands of buffalograss; although, more research is needed to confirm the dynamics. Prairie dog activity has a profound effect on biotic integrity, hydrologic function, soil and surface stability, and similarity index calculations. A high degree of bare ground and significant changes in plant composition are associated with prairie dog colonization. Runoff and soil loss can be extreme in Arol/Scpa. Broom snakeweed stands and the reference state, blue grama, exhibit the highest infiltration capacity on this site; however, broom snakeweed stands have significantly higher soil loss because of a depauperate understory and high bare ground in shrub interspaces.

High intensive convective storms can have a significant impact on this site. During 5, 10, 25, 50, and 100 year storms, where there is a high short burst of rainfall, a significant amount of runoff and soil loss will occur.

Management of this site should strive to maintain a higher ratio of blue grams to buffalograss. The threshold where increasing buffalograss begins to affect infiltration capacity is around 30% (Spaeth 1990). Infiltration experiments have also shown that plant related variables such as cover, biomass, and species composition largely influence infiltration dynamics during the early phases of rainfall (0-15 minutes); whereas, soil related variables such as bulk density, aggregate stability, and porosity influence infiltration as storms progress > 15 minutes.

References

Bisdom E.B.A, L.W. Dekker, and J.F.T. Schoute. (1993) Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. Geoderma 56, 105-118.

Blackburn, W.H., F.B. Pierson, and M.S. Seyfried. 1990. Spatial and temporal influence of soil frost on infiltration and erosion of sagebrush rangelands. Water Resources Bulletin 26:991-997.

Blackburn, W.H., F.B. Pierson, C.L. Hanson, T.L Thurow, and A.L. Hanson. 1992b. The spatial and temporal influence of vegetation on surface soil factors in semiarid rangelands. Transactions of the ASAE 35:479-486.

Bond R.E. and J.R. Harris. 1964. The influence of the microflora on physical properties of soils I. Effect associated with filamentous algae and fungi. Australian Journal of Soil Research 2, 111-122.

Bonham, C.D., and A. Lerwick. 1976. Vegetation changes induced by prairie dogs on shortgrass range. Journal of Range Management 29:221-225.

Carlson, D.H., Thurow, T.L., Knight, R.W., R.K.Heitschmidt. 1990. Effect of honey mesquite on the water balance of Texas Rolling Plains rangeland. Journal of Range Management, 491-496.

Clark, T.W., T.M. Campbell III, D.G. Socha, and D.E. Casey. 1982. Prairie dog colony attributes and associate vertebrate species. Great Basin Naturalist 42: 572-582.

Coppock, D.L., J.K. Detling, J.E. Ellis, and M.I. Dyer. 1983. Plant-herbivore interactions in a North American mixed-grass prairie. I. Effects of black-tailed prairie dogs on intraseasonal aboveground plant biomass and nutrient dynamics and plant species diversity. Oecologia 56:1-9.

Czarnes S., P.D. Hallett, A.G. Bengough, and I.M. Young. 2000. Root and microbial-derived mucilages affect soil structure and water transport. European Journal of Soil Science 51, 435-443.

Dee, R.F., Box, T.W. and E. Robertson Jr. 1966. Influence of grass vegetation on water intake of Pullman silty clay loam. Journal of Range Management, 77-79.

Dekker L.W., C.J. Ritsema, K. Oostindie, and O.H. Boersma. 1998. Effect of drying temperature on the severity of soil water repellency. Soil Science 163, 780-796.

Doerr S.H., R.A. Shakesby, and R.P.D. Walsh. (1996) Soil water repellency variation with depth and particle size fraction in burned and unburned *Eucalyptus globulus* and *Pinus pinaster* forest terrain in the Agueda basin, Portugal. Catena 27, 25-47.

Ellerbrock R.H., H.H. Gerke, J. Bachmann, and M.O. Goebel. 2005. Composition of organic matter fractions for explaining wettability of three forest soils. Soil Science Society America Journal 69, 57–66.

Eynard A, T.E. Schumacher, M.J. Lindstrom, D.D. Malo, and R.A. Kohl. (2006) Effects of aggregate structure and organic C on wettability of Ustolls. Soil Tillage Research 88, 205–216.

Fidanza M.A. 2003. Combination treatments for fairy ring prove effective. Turfgrass trends in Golfdom 59, 62-64.

Fahnestock, J.T. and J.K Detling. 2002. Bison-prairie dog-plant interactions in a North American mixed-grass prairie. Oecologia 132:86-95.

Franco, C.M.M., P.P Michelsen, and J.M. Oades. (2000) Amelioration of water repellency: application of slow release fertlisers to stimulate microbial breakdown of waxes. Journal of Hydrology 231-232, 342-351.

Hallett P.D. and I.M. Young. (1999) Changes to water repellence of soil aggregates caused by substrate-induced microbial activity. European Journal of Soil Science 50, 35-40.

Johnson, C.W. and N. E. Gordon. 1988. Runoff and erosion from rainfall simulator plots on sagebrush rangeland. Transactions of the American Society of Agricultural Engineers 31:421-427.

Kostka S.J. 2000. Amelioration of water repellency in highly managed soils and the enhancement of turfgrass performance through the systematic application of surfactants. Journal of Hydrology 231-232, 359-368.

Klatt, L.E. and D. Hein. 1978. Vegetative differences among active and abandoned towns of black-tailed prairie dogs (*Cynomys ludovicianus*). Journal of Range Management 31:315-   317.

Lawton, J.H., and C.G. Jones. 1995. Linking species and ecosystems: organisms as ecosystem engineers. Pages 141-150 in Linking Species and Ecosystems (C. G. Jones, J. H. Lawton editors). Chapman and Hall, New York.

Lomolino, M.V. and G.A. Smith. 2003. Terrestrial vertebrate communities at black-tailed prairie dog (*Cynomys ludovicianus*) towns. Biological Conservation 115:89-100.

Lowell, B.J. 1980. Factors affecting seed germination and seedling establishment of broom snakeweed. Thesis, New Mexico State Univ., Las Cruces, New Mexico. Martinsen, G.D., J.H. Cushman, and T.G. Whitham. 1990. Impact of pocket gopher disturbance on plant species diversity in a shortgrass prairie community. Oecologia 83: 132–138.

Mazarak, A.P., and E.C. Conrad. 1959. Rates of water entry in three great soil groups after seven years in grasses and small grains. Agron. J. 51:264-267.

Paul E.A. and F.E. Clark. 1996. 'Soil microbiology and biochemistry, second ed.' Academic Press: San Diego: California.

Pierson, F. B. and J.R. Wight. 1991. Variability of near-surface soil temperature on sagebrush rangeland. Journal of Range Management, 491-497.

Pierson, F.B., K.E. Spaeth, M.E. Weltz., and D.H. Carlson. 2002. Hydrologic response of diverse western rangelands. J. Range Management 55:558-570.

Power, M.E., D. Tilman, J.A. Estes, B.A. Mente, W.J. Bond, L.S. Mills, G. Daily, J.C. Castilla, J. Lubchenco, and R.T. Paine. 1996. Challenges in the quest for keystones. BioScience 46, 609–620.

Ritsema, C.J., L.W. Dekker, J.L. Nieber JL, and T.S. Steenhuis. 1998. Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil. Water Resources Research 34, 555–567.

Rillig M.C. 2004. Arbuscular mycorrhizae and terrestrial ecosystem processes. Ecology Letters 7, 740-754.

Rillig M.C. 2005. A connection between fungal hydrophobins and soil water repellency. Pedobiologia 49, 395-399.

Rillig M.C., D.L. Mummey. 2006. Mycorrhizas and soil structure. New Phytologist 171, 41-53

Schlossberg M.J., A.S. McNitt, and M.A. Fidanza. 2005. Development of water repellency in sand-based root zones. International Turfgrass Society 10, 1123-1130.

Shepherd T.G., S. Saggar, R.H. Newman, C.W. Ross, and J.L. Dando. 2001. Tillage-induced changes to soil structure and organic carbon fractions in New Zealand soils. Australian Journal of Soil Research 39, 465–489.

Spaccini R., A. Piccolo, C. Conte, G Haberhauer G, and H.H. Gerzabek. 2002. Increases soil organic carbon sequestration through hydrophobic protection by humic substances. Soil Biology and Biochemistry 34, 1839-1851.

Spaeth, K.E. 1990. Hydrologic and Ecological Assessments on a Discrete Range Site. Ph.D. Dissertation, Texas Tech Univ., Lubbock, Texas.

Spaeth, K. E., Pierson, F. B., Weltz, M. A., and J.B. Awang. 1996. Gradient analysis of infiltration and environmental variables as related to rangeland vegetation. Transactions of the ASAE, *39*(1), 67-77. Weaver, J. E. 1954. North American Prairie.

Spaeth, K.E., F.B. Pierson, M.A. Weltz, and G. Hendricks (eds.). 1996. Grazingland hydrology issues: perspectives for the 21st century. Society for Range Management, Denver, Colorado.

Thurow, T.L. 1991. Hydrology and erosion. p. 141-159. In: R.K. Heitschmidt and J.W. Stuth (eds.). Grazing management: an ecological perspective. Timber Press, Inc. Portland, Oregon.

Weltz, M., and W. H. Blackburn. 1995. Water budget for south Texas rangelands. J. Range Manage. 48: 45-52.

Whicker, A.D. and J.K Detling. 1988. Ecological consequences of prairie dog disturbances. BioScience, 38(11) 778.

White N.A., P.D. Hallett, D. Feeney, J.W. Palfreyman, and K. Ritz. 2000. Changes to water repellence of soil caused by the growth of white-rot fungi: studies using a novel microcosm system. FEMS Microbiology Letters 184, 73-77.

Winter, S.L., J.F. Cully Jr., and J.S. Pontius. 2002**.** Vegetation of prairie dog colonies and non-colonized short-grass prairie. Journal of Range Management 55:502-508.