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Soil erosion as affected by shrub encroachment in northeastern Patagonia.

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Abstract

Soil erosion is the primary cause of irreversible loss of soil productivity on most rangelands. In northeastern Patagonia, the increase in soil erosion has been closely associated with the increase in shrub cover in the grass or shrub-grass steppes. We used rainfall simulation to compare infiltration and sediment production from patches of grass, shrub-grass, and shrub steppes of the Punta Ninfas range site. Bare soil and gravel covers were higher and litter cover was lower in the shrub steppe than in the shrub-grass and the grass steppes. In the shrub inter-spaces of the shrub steppe, bulk density was greater and macroporosity and soil organic matter were lower ($P \leq 0.05$) than in the mounds beneath shrubs and in the grass and shrub-grass areas. Infiltration rate was 60 to 65% lower in the shrub steppe than in the grass and shrub-grass steppes, respectively. On the contrary, total sediment production and concentration were higher ($P \leq 0.05$) in the shrub steppe as compared to the grass and the shrub-grass areas. Gravel cover was the variable that best predicted infiltration and sediment production. The organic matter content of the sediment, mostly litter, in the shrub and the shrub-grass steppes were similar and greater ($P \leq 0.05$) than in the grass steppe. Runoff litter removal may represent one of the processes that drive the transition from shrub-grass to shrub steppes. High rates of sediment removal, mainly litter, from the shrub interspaces of the shrub steppe may limit the natural recovery of the soil physical and hydrological properties. These degraded patches fail to capture incident rainfall and restrict the possibilities for the recovery of perennial grasses favoring the dominance of shrubs.

Key Words: vegetation, litter, gravel cover; shrub, grass, shrub-grass steppes, organic matter removal, rainfall simulator, infiltration rate.

Resumen

La erosión de los suelos es la causa principal de las pérdidas irreversibles del potencial productivo de los suelos en la mayoría de los pastizales naturales. En el nordeste de Patagonia, el aumento de la erosión de los suelos ha estado estrechamente asociado al aumento de la cobertura de arbustos en las estepas herbáceas o arbustivas-herbáceas. Nosotros empleamos lluvia simulada para determinar la tasa de infiltración y la producción de sedimentos en parches de estepas herbáceas, arbustivas-herbáceas y arbustivas del sitio ecológico Punta Ninfas. Las coberturas de suelo desnudo y de gravas fueron mayores y la cobertura de mantillo menor en la estepa arbustiva respecto a las estepas arbustiva- herbácea y herbácea. En los espacios entre arbustos de la estepa arbustiva, la densidad aparente fue mayor y la macroporosidad y la materia orgánica fueron menores ($P \leq 0.05$) que en los montículos debajo de los arbustos y en las estepas arbustiva-herbácea y herbácea. La tasa de infiltración fue un 60 y un 65% mas baja en la estepa arbustiva que en las estepas herbácea y arbustiva-herbácea, respectivamente. Por el contrario, la producción total y la concentración de sedimentos fueron mas altas ($P \leq 0.05$) en la estepa arbustiva comparado con las estepas herbácea y arbustiva-herbácea. La cobertura de gravas fue la variable que mejor predijo la tasa de infiltración y la producción de sedimentos. El contenido de materia orgánica de los sedimentos, mayormente mantillo, fue similar en la estepa arbustiva y la arbustiva-herbácea y en ambas mayores ($P \leq 0.05$) que en la estepa herbácea. La remoción de mantillo por el escurrimiento superficial posiblemente represente uno de los procesos que provocan la transición de la estepa arbustiva-herbácea a la estepa arbustiva. Las altas tasas de remoción de sedimentos, principalmente mantillo, de los espacios entre arbustos de la estepa arbustiva pueden limitar la recuperación natural de las propiedades físicas e hidrológicas de los suelos. Estos parches degradados no pueden captar las lluvias incidentes, limitando así las posibilidades de recuperación de los pastos perennes y favoreciendo la dominancia de los arbustos.

Shrub encroachment and soil erosion have been identified as the main degradation processes in semi-arid grazing rangelands (Friedel 1991). Both processes can be closely related and in general erosion follows shrub invasion (Buffington and Herbel 1965). Schlesinger et al. (1990) suggest that overgrazing results in the redistribution of organic matter and nutrients and is the primary agent responsible for the current conversion of previously productive grasslands to unproductive mesquite (*Prosopis glandulosa* Torr.) shrublands.

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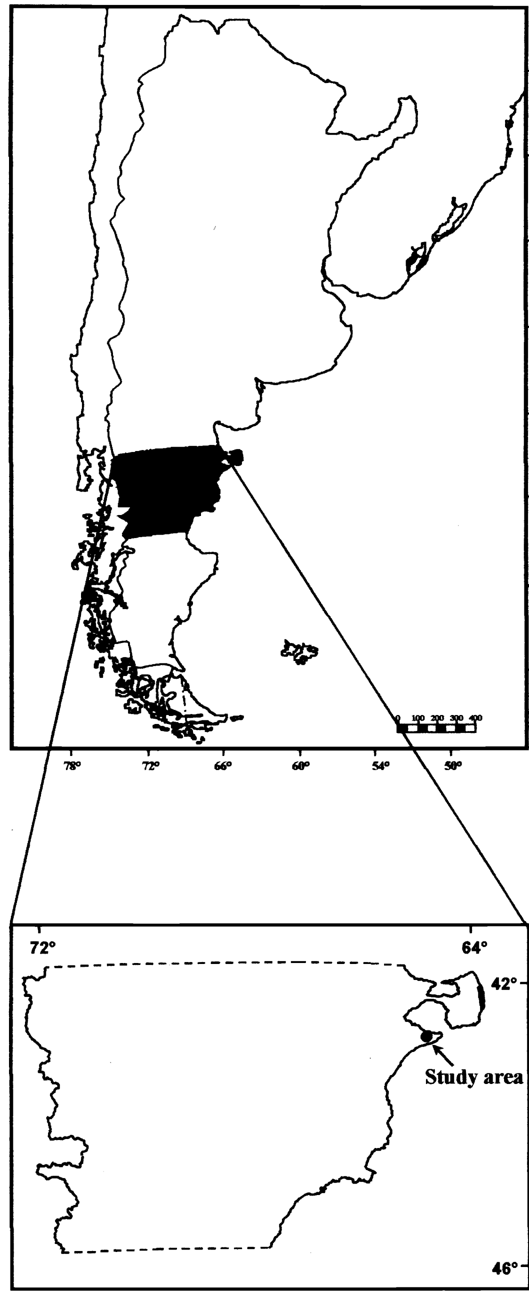
In most of the Patagonian rangelands, grazing appears to have modified the vegetation and accelerated soil erosion processes (Soriano et al. 1983, Ares et al. 1990). Changes in vegetation include the increase of low forage quality shrub species such as neneo (*Mulinum spinosum* (Cav.) Pers.) and quilenbai (*Chuquiraga avellanedae* Cav.) (Bertiller 1993, Beeskow et al. 1995) in some originally productive grasssland s.

In a range site of northeastern Patagonia, Beeskow et al. (1995) identified 3 stable states following the state and transition model proposed by Westoby et al. (1989). These states represent stable plant communities along a degradation gradient, with grass, shrub-grass, and shrub steppes representing a good, fair, and poor condition from a forage production perspective. However, no information exists on how well these plant communities protect the site against accelerated erosion. Recently, the Task Group on Unity in Concepts and Terminology (1995) proposed the concept of Desired Plant Community. The Desired Plant Community refers to any managed plant community that has the capability to protect the site against accelerated erosion. In this study we used rainfall simulation to assess how different plant communities on a range site of northeastern Patagonia influenced infiltration and interrill erosion.

Materials and Methods

Study Area

The study was conducted in the upper part of a flank pediment that extends from the plateau border to a playa lake in the Punta Ninfas area, 70 km east of Puerto Madryn in the NE portion of the Chubut province (43:00'S, 64:30'W) (Fig. 1). It is an undulating plateau dissected by coastal valleys and interrupted by numerous depressions with playa lakes. The climate is arid and temperate. Mean annual precipitation is 254 mm (1955–1992). Most of the rainfall occurs during the cold season from April to September. Mean annual temperature is 12.5°C. The mean annual wind velocity at 10 m above ground level is 4.6 m sec^{-1} (Barros 1983). Dominant soil in the flank pediment area is a Xeric Calciargids. This soil is shallow, with a loamy sand A horizon 10–15 cm thick, and a sandy loam B2t horizon 15–20 cm thick, underlain by a calcic horizon. A gravelly sand to sandy clay alluvium 50 to 80 cm thick forms the soil substratum. This deposit of Holocene age rests on tertiary sediments.



Southern extreme of South America with Argentina and the Chubut province.

Fig. 1. Location of the study area.

The study area is located in the ecotone between the Patagonian and Monte phytogeographic provinces. Principal species representing the first province are quilenbai and colapiche (*Nassauvia fuegiana* (Speg.) Cabrera), and coiron (*Stipa speciosa* Trin. and Rupr.). The cool season grasses flechilla (*S. tenuis* Phil.) and flechilla negra (*Piptochaetium napostaense* (Speg. Hackel ap Stuckert.)) are the main species of the Monte province.

Dominant plant physiognomy is a shrub-grass steppe although patches of grass steppe and shrub steppe are present. These physiognomic patches have been described as stable states (Beeskow et al. 1995). Within the grass and grass-shrub steppe patches a stable soil is present; in the shrub steppe, shrubs are associated with mounds and are distributed in a matrix of eroded soil with desert pavement and a low vegetation cover.

Sheep grazing for wool production was introduced in the area at the beginning of the last century. Continuous grazing is practiced extensively in pastures exceeding 2,500 ha. The mean stocking rate is 0.25 sheep ha^{-1}.

Experimental Procedures

We selected 3 homogeneous areas, 10 x 10 m each representing, the grass, shrub-grass, and shrub steppes. Inside these areas, 10 plots measuring 0.63 x 1.60 m (1 m^{-2}) were located in each plant community. Slope was homogeneous across the 3 areas with an average of 7.2%. Sheet metal frames were dug into the perimeter of the plots to channel the runoff generated by the simulated rainfall. Runoff leaving the lower border of the plots was channeled through a 5 cm diameter pipe connected to 5 liter containers. In December of 1994 and 1995, simulated rainfall was applied with a full cone, single nozzle rainfall simulator (Rostagno and Garayzar 1995) at an intensity of 100 mm hour^{-1}, during 30 minutes. This rainfall simulator produces a rainfall with a kinetic energy equivalent to 66% of the kinetic energy of a natural rainfall at the same intensity. In the study area, high intensity rainfall can occur from December to March. A rainfall event with the intensity and duration of the simulated rainfall occurs about once per 100 years (Vicenty et al. 1984). Runoff was collected at 1 and 2 minutes after rainfall initiation, and then at 5 minutes intervals in separate containers and determined by volume. Time to runoff was recorded for each plot. Infiltration rate was calculated for each interval as the difference between the applied rainfall and the runoff collected for each interval. Total runoff was passed through a 44 μm sieve. The sediment coarser than 44 μm was recovered dried at 105° C for 24 hours and weighed. The weight of the sediment < 44 μm was calculated using 50 ml aliquot. After drying and weighing, the total sediment <44 μm was calculated considering total runoff volume, then it was added to the > μ4 mm sediment and converted to kg ha^{-1}.

Previous to simulated rainfall application, ground cover (vegetation, litter, bare soil, and gravel) was determined using the point quadrat method (Goodall 1953). A metal frame with holes every 5 cm was placed on the plot and 66 points were measured in each plot. The slope of the plots was determined using the same frame as for ground cover.

A 130 cm^{-3} soil core (0 to 5 cm) was sampled for bulk density, root, and gravel content determinations from an area adjacent to each plot. Roots were separated by hand, washed, dried at 105° C and weighed; gravel was separated with a 2 μm sieve. Soil samples from this same depth were collected and analyzed for texture by the pipette method (Day 1965), and organic matter by the loss on ignition method (Davies 1974). Total porosity was calculated as: (1-bulk density/particle density) considering a particle density of 2.65 g cm^{-3} and macroporosity as the difference between water content at saturation and at field capacity (Helalia 1993). Field capacity (moisture equivalent) was estimated by centrifuging saturated samples (30 min; 2440 rpm).

Data Analysis

Data were analyzed using correlation (Pearson) to assess the linear association of the variables and stepwise multiple regression to identify the variables that best predicted infiltration and sediment production. Analyses of variance were performed on the terminal infiltration and sediment (mineral and organic) production data using the SPSS package. Mean separation with the protected LSD was used to compare infiltration and sediment production in each plant community. Significant levels were determined at $P \leq 0.05$.

Table 1. Average canopy and ground cover (%) characteristics (standard deviation) for each plant community at the Punta Ninfas range site, Patagonia.

	Grass Steppe	Shrub-Grass Steppe	Shrub Steppe
		(%)	
Shrubs	0	23.0 (10.8)	28.4 (9.8)
Perennial Grasses	24.4 (1.1)	19.0 (8.4)	5.6 (4.4)
Perennial Dicot	7.4 (3.5)	1.8 (1.2)	0.2 (0.4)
Annuals	12.8 (3.0)	11.4 (8.1)	3.8 (1.3)
Bare Soil	18.8 (2.9)	15.2 (5.0)	20.6 (6.6)
Gravel	11.8 (1.9)	11.6 (3.4)	32.8 (12.8)
Litter	24.0 (3.7)	16.9 (5.7)	6.4 (4.4)

Results and Discussion

Surface characteristics

Soil surface characteristics and plant cover for each plant community are presented in Table 1. Total vegetation cover presented the highest value in the shrub-grass steppe and the lowest in the shrub steppe, respectively. In the shrub steppe, the main changes relative to the shrub-grass community were decreased litter and herbaceous vegetation cover and increased gravel cover. In the shrub steppe where erosion has been more intense than in the other plant communities, the A horizon remaining beneath the shrubs as well as the accumulation of wind blown and splashed material give rise to small mounds associated with the shrubs, mainly quilenbai. However, the increase in bare soil cover in the shrub steppe was less than 2% compared to the grass steppe.

Soil characteristics of the grass and the shrub-grass steppes were similar and differed greatly with those of the shrub steppe (Table 2). The 2 contrasting surface conditions present in the shrub steppe (mounds beneath the shrubs and desert pavement covered areas in the shrub interspaces) were also different in term of soil characteristics. Sand, organic matter, and root content were significantly lower; gravel and bulk density were higher in the eroded shrub interspaces of the shrub

Table 2. Average soil characteristics (standard deviation), 0 to 5 cm soil depth, for each plant community and 2 microsites in the shrub steppe at the Punta Ninfas range site, Patagonia.

	Grass	Shrub-Grass	Shrub Steppe	
	Steppe	Steppe	SI	Mounds
Bulk Density (Mg m^{-3})	1.06 (0.07)	1.10 (0.11)	1.36 (0.15)	1.07 (0.05)
Macroporosity (%)	31.9 (1.2)	30.1 (3.2)	17.1 (2.3)	33.1 (1.8)
Gravel Content (%)	17.4 (9.2)	17.1 (8.4)	31.7 (14.5)	5.3 (3.6)
Sand (%)	73.0 (3.8)	75.0 (5.1)	61.2 (6.4)	83.1 (2.9)
Root Content (g m^{-2})	145.6 (31.1)	134.2 (28.6)	20.3 (9.3)	380.0 (83.0)
Organic matter (%)	2.49 (0.29)	2.67 (0.36)	1.46 (0.19)	2.23 (0.31)

SI= shrub interspaces

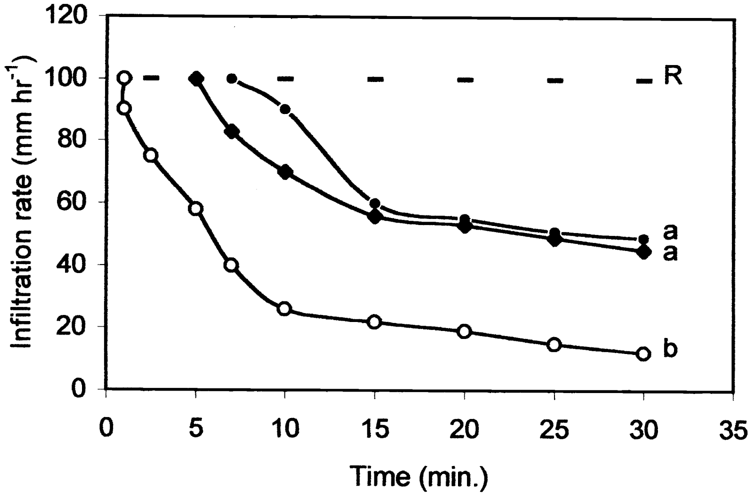


Fig. 2. Average infiltration rate across the 30 minute simulated rainfall for the soils of the shrub-grass (●), grass (◆), and shrub (○) steppes at Punta Ninfas range site, Patagonia. R is applied rainfall intensity. Plant community means with the same letter are not significantly different (P ≥ 0.05).

steppe as compared to the soil of the other plant communities. These differences were greater with respect to the soils beneath the shrubs (mounds) of the shrub steppe.

Infiltration Characteristics

Infiltration curves for each plant community are presented in Fig. 2. In the grass and the shrub-grass communities, runoff started at 5 and 7 min after rainfall initiation, respectively. This difference can be a result of the higher water interception/retention of the shrub canopy in the shrub-grass community. In these communities, the infiltration curves were similar after 15 min of the rainfall initiation. In the shrub steppe, runoff started at less than 1 min after rainfall initiation. In this plant community, the infiltration rate decreased abruptly the first 10 min; after which it decreased more slowly until the end of the simulated rainfall.

Terminal infiltration rate in the grass and shrub-grass steppes were similar and significantly higher than in the shrub steppe. Stepwise regression analysis using the variables presented in Table 1 as independent variables, gave us the following predictive model for infiltration rate (IR) at 30 min:

$$IR = 39.4 - 0.79 \text{ Gravel cover} + 1.33 \text{ Annuals}; R^2 = 0.69 \ (P = 0.001) \quad (1)$$

Our results produced a negative relationship between gravel cover and infiltration rate (r = -0.74). Similar results were found in a degraded shrub steppe with a Typic Torriorthent soil (Rostagno 1989). However, field-plot data on the relationship between coarse fragments cover and runoff (or infiltration rate) are contradictory (Poesen 1992). Mehan (1986) showed that coarse fragments on the soil surface of rangelands tended to increase infiltration rates. It appears that as more soil surface was exposed, more of the soil surface develops a crust thus reducing infiltration rates.

In our study, gravel cover integrated soil and soil surface characteristics which were considered to negatively affect the soil infiltrability. Thus, in the shrub interspaces of the shrub steppe, where the higher gravel cover was found, gravel is well embedded in a surface crust. Valentin (1994) found a reduction in infiltration rate with increasing cover of embedded rock fragments. Equally, the shrub interspace soil presents a higher bulk density (Table 2) as compared to the soils of the shrub-grass and the grass communities as well as the mound soils. The increase in bulk density of the shrub-interspace soil of the shrub steppe represents a proportional decrease in macroporosity (Table 2). Because of their texture (loamy sand and sandy loam), the soils of the study area are susceptible to crust formation (Poesen 1988). However, a crust develops only in the shrub interspaces of the shrub steppe, probably related to the low organic matter content and low litter and grass cover of this soil.

The cover of annual plants was selected as the second variable of importance by the regression analysis. Annual cover was negatively related to gravel cover (r = –0.56) and integrated other soil surface variables considered to positively affect the soil infiltration (i.e., perennial grass and litter cover).

To assess the differences in infiltration capacity of the degraded soils of the shrub interspaces and the mounds beneath shrubs in the shrub steppe, we determined their infiltration capacity separately by means of 15 cm diameter cylinders. Average (and standard deviation) infiltration rates for the first 10 minutes were 8.3 (3.5) and 175 (14.0) mm $hour^{-1}$ for the shrub interspace and the mound, respectively. In the grass steppe the average infiltration rate was 103.7 (22.0) mm $hour^{-1}$. Although measurements of infiltration capacity using cylinder infiltrometers tend to exceed the true (vertical) infiltration capacity (Tricker 1978), our results show the large hydrological contrast between the crusted soil of the shrub interspaces and the mounds. It is interesting to notice that the infiltration rate of the soil beneath the shrub (mound) was also significantly higher than in the soil of the grass steppe. Thus, although the quilenbai positively affected the infiltrability of the soil under its canopy, the patches where quilenbai is dominant had the lowest infiltration.

Sediment Production

Sediment production in the grass and the shrub-grass steppes were similar and significantly lower than in the shrub steppe (Fig. 3). In the shrub steppe the sediment concentration was also significantly higher than in the other communities. Sediment concentration may provide a better measure of the erodibility of each soil surface condition. However, sediment concentration was low, 2.4, 1.7, and 1.8 g $liter^{-1}$ for the shrub, shrub-grass, and grass steppes, respectively. Sediment concentrations as high as 40 g $liter^{-1}$ were recorded in a shrub steppe with a Typic Torriorthent soil with a natural rainfall event (Rostagno et al. 1999). The low bare soil cover in the grass, shrub grass, and shrub steppes (<21%) and the low kinetic energy of the simulated rainfall (66% of a natural rainfall event of the same intensity) may have limited sediment detachment by raindrop impact.

Stepwise regression analysis using the variables presented in Table 1 as predictors produced the following predictive model for sediment production (SP): SP (g m^{-2}) = 11.6 + 3.0 Gravel cover (%); R^2= 0.46 (P = 0.005), indicating that sediment production increased as gravel cover increased. This result is apparently contradictory, as gravel cover has been shown to decrease interrill erosion in most cases

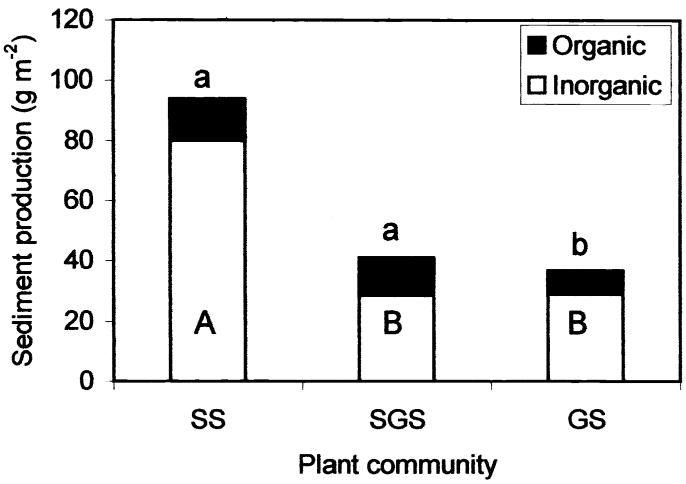


Fig. 3. Inorganic and organic sediment production for the shrub, shrub-grass, and grass steppes at the Punta Ninfas range site, Patagonia. Plant community means with the same lowercase and uppercase letters are not significantly different ($P \geq 0.05$) for the organic and inorganic sediment production, respectively.

(Poesen et al. 1994). In the study area, gravel cover was negatively associated to herbaceous vegetation ($r = -0.61$) and litter cover ($r = -0.68$). The highest value of gravel cover was present in the shrub interspaces of the shrub steppe where a soil surface condition of low infiltrability and high runoff production dominates. Although gravel cover may decrease sediment production, it seems to be less effective than vegetal (Wilcox and Wood 1989) and litter cover (Benkobi et al. 1993) to protect the soil from erosion. For example, Benkobi et al. (1993) found that the litter and gravel cover necessary to reduce soil loss to 50% of bare ground was 60% and 85%, respectively. While both gravel and litter decrease sediment detachment by raindrop impact proportional to their cover, litter more effectively absorbs the erosive and transport energies of overland flow, reducing flow velocities, and increasing deposition.

Sediment Organic Matter Content

The organic matter content of the sediment was significantly higher in shrub and in the shrub-grass communities than in the grass community (Fig. 3). Although a high proportion of organic matter in the sediment was plant residues, organic matter content in the sediment was inversely proportional to litter cover. In the shrub steppe where litter cover was much lower than in the other plant communities, the high amount of runoff generated in this community may explain the higher amount of organic matter in the sediment. The decrease in litter cover following the decrease of grass cover may increase the erodibility of these soils. In the grass community, litter cover accounted for 26% of the ground cover and decreased to 6.4% in the shrub steppe. Decline in the production of litter because of the low herbaceous cover in the shrub interspaces and the high potential for litter removal by runoff from these areas may increase the hydrological and physical differences between the communities. In the shrub steppe, the litter produced by shrubs (leaves, twigs, and inflorescence) accumulates beneath the shrubs and very little, if any, is spread beyond the shrub canopy. This decrease in vegetation and litter cover in the shrub steppe is reflected in the lower organic matter content of the shrub interspace soil (Table 2). A mechanism by which litter may enter the shrub interspaces of the shrub steppe is the deposition of litter carried by runoff generated from the surrounding grass or shrub-grass communities. In the shrub-grass steppe, the sediment organic matter content was also higher than in the grass steppe, and proportionally higher (percent of mineral sediment) than in the shrub steppe.

Shrub Encroachment, Soil Erosion, and Sustainable Production

Although the main cause of the decline in herbaceous vegetation producing the change from shrub-grass to shrub steppes in shrub invaded areas (i.e., shrub competition, intense grazing, etc.) is not clear, it is clear that past erosion in the shrub steppe has changed the characteristics of the soil and the distribution of soil resources. The positive feedback between past erosion and present erosion rate may further increase the differences between the grass or grass-shrub and the shrub-dominated communities. This will also tend to increase the contrast between soils beneath shrubs and the soils of the shrub interspaces. Schlesinger et al. (1990) considered the increase in soil heterogeneity in shrub invaded areas as an indicator of rangeland degradation.

It is important to notice that differences in total plant cover between the grass and shrub steppes were small (i.e., < 5%). It seems that more important than total plant cover as causative factor in interrill as well as rill erosion, is plant cover distribution (Weltz et al. 1998). Thus, while in the grass steppe plant cover was homogeneously distributed, in the shrub steppe it was concentrated in small patches. Plant cover distribution determines the size of the patches of bare soil (or of gravel covered and crusted soil). De Soyza et al. (1998) defined a bare patch index (bpi = mean size of bare patches x proportion of bare soil) as a desertification indicator for the Chihuahuan Desert. They found that sites with high percentage of shrubs and sites near livestock watering points had the greatest bare patch index.

Equally important is the connection among bare patches. In the shrub steppe, the degraded shrub interspaces connect each other allowing the runoff to leave the local plant community (i.e., the shrub steppe patch) and eventually the range site. Under present land use (i.e., continuous grazing) an increase in the size and numbers of shrub steppe patches (degraded patches) can be expected, as shrubs are little affected by grazing. The grass steppe can be considered the Desired Plant Community (Task Group on Unity in Concept and Terminology 1995) for the site as it best meets forage production objectives. However, both, the grass and the shrub-grass steppes have the capability to protect the site against accelerated erosion.

In this range site where erosion dramatically changes the hydrological properties of the soil, the application of shrub control techniques (i.e. prescribed fire) that effectively help to restore the grass cover should be applied in the first stages of shrub invasion (i.e., in the shrub-grass steppe state). In areas close to the study site accidental fires have temporarily reversed shrub-dominated communities back to grass steppes. It is also probable that a grazing scheme that includes spring rest might favor perennial grasses in the shrub-grass steppes, slowing or reversing shrub cover increase. Bork et al. (1998) found in a sagebrush steppe that grazing during the spring increased live shrubs and decreased perennial grasses cover as compared to a fall-grazed treatment. In the shrub steppe where degradation has severely affected the soil characteristics, it is less probable that herbaceous vegetation cover may be restored and sustainable management be achieved, unless a technique of water conservation is applied. However, because of drastic changes in soil properties, this plant community may persist and represent a different ecological site.

Conclusions

Soil surface characteristics as well as soil infiltrability and sediment production differed significantly in shrub dominated and grass or grass-shrub dominated plant communities on the same range site. In the Punta Ninfas range site, a continuous grass cover may coexist with a shrub cover of approximately 25%. Although the shrub-grass steppe is undesirable from a forage production perspective because the main shrubs have a very low forage value, soil conservation is not different from the grass steppe. On the contrary, the shrub-dominated community represents a poor condition from a forage production and a soil and water conservation perspective. Although the development of a dense desert pavement in the eroded shrub interspaces of the shrub steppe may limit sediment detachment, and thus, sediment production, the high runoff production from these areas keep the erosion rate of the shrub steppe above the erosion rates of the other communities.

The high rate of organic matter (mainly litter) and water losses from the shrub steppe may limit the natural recovery of the soil physical and hydrological properties and the possibilities for the re-establishement of the perennial grasses, and favor the dominance of shrubs.

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