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Nutrient losses in runoff from grassland and shrubland habitats in Southern New Mexico: I. rainfall simulation experiments

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Abstract. Rainfall simulation experiments were performed in areas of semiarid grassland (*Bouteloua eriopoda*) and arid shrubland (*Larrea tridentata*) in the Chihuahuan desert of New Mexico. The objective was to compare the runoff of nitrogen (N) and phosphorus (P) from these habitats to assess whether losses of soil nutrients are associated with the invasion of grasslands by shrubs. Runoff losses from grass- and shrub-dominated plots were similar, and much less than from bare plots located in the shrubland. Weighted average concentrations of total dissolved N compounds in runoff were greatest in the grassland (1.72 mg/l) and lowest in bare plots in the shrubland (0.55 mg/l). More than half of the N transported in runoff was carried in dissolved organic compounds. In grassland and shrub plots, the total N loss was highly correlated to the total volume of discharge. We estimate that the total annual loss of N in runoff is 0.25 kg/ha/yr in grasslands and 0.43 kg/ha/yr in shrublands – consistent with the depletion of soil N during desertification of these habitats. Losses of P from both habitats were very small.

Introduction

During the last century, desert shrubs have invaded large areas of semiarid grassland that were historically dominated by black grama (*Bouteloua eriopoda*) in southern New Mexico (Buffington & Herbel 1965). This change in vegetation, a form of desertification, is associated with losses and redistributions of soil nutrients by wind and water (Schlesinger et al. 1990, 1996). In various regions of the world, losses of grass cover are associated with lower rates of soil water infiltration and greater runoff (Elwell & Stocking 1976; Zöbisch 1993; Gutierrez & Hernandez 1996; Castillo et al. 1997). In the Chihuahuan desert of New Mexico, Bach et al. (1986) found greater infiltration of soil water under grass cover, and Abrahams et al. (1995) used rainfall simulations to show greater interrill runoff and erosion on shrub-dominated areas in southern Arizona. Few studies have examined the losses of soil fertility which are thought to exacerbate the desertification of semiarid grasslands. The objective of this study was to compare the losses of dissolved nitrogen (N) and phosphorus (P) in the runoff from grass- and shrub-dominated plots in the Jornada Basin of southern New Mexico.

Study area and methods

This study was undertaken at the Chihuahuan Desert Rangeland Research Center, 40 km northeast of Las Cruces, in Doña Ana County, New Mexico, as part of the Jornada Basin Long-Term Ecological Research (LTER) program. Vegetation of the study area has been described by Stein and Ludwig (1979), and soils were mapped by Rojas (1995). Mean annual precipitation at the study site is 230 mm/yr, with about 60% derived from convectional, monsoonal thunderstorms during the late summer. These summer storms, in contrast to lower intensity synoptic winter storms, often generate surface runoff. During a recent 3-year period, there were 48 summer storms, delivering > 3.6 mm/each and generating 24 runoff events (Tromble 1988).

The grassland studied was located on the alluvial piedmont of Mount Summerford, a quartz monzonite batholith that forms the northern-most peak of the Doña Ana Mountains. This grassland is dominated by *Bouteloua eriopoda* with soils of late Holocene age that are classified as Ustic Haplargids (Lajtha & Schlesinger 1988; Rojas 1995). The topography drains eastward with a slope of approximately 6.3°. The shrublands selected for study were located in two areas dominated by creosotebush (*Larrea tridentata*). One area was approximately 600 m downslope from the grassland. It was located on Typic Haplargid soils of mid-Holocene age derived from Mount Summerford alluvium (Marion et al. 1990). The other shrubland site was located 1200 m to the southeast on Typic Haplargid soils formed in alluvial igneous materials from the Doña Ana Mountains. The average slope in the area of the shrubland plots was 2.4°. All of the sites have been free of grazing since 1981.

Rainfall simulations in the grassland were performed on six plots, each 1×2 m in dimension. Plant cover in each of these plots was about 50%, composed of individual clumps of *B. eriopoda*, which are typically each about 20 cm in diameter. In the shrubland, 1×1 m plots were centered on individual shrubs (n = 8) or in bare areas between shrubs (n = 10). The 1×1 m size was selected for these plots so that the shrub plots would not extend beyond the perimeter of the shrub canopy.

A field-portable rainfall simulator, developed and described by Luk et al. (1986), was used to apply water at a nominal rate of 140 mm hr^{-1} to these plots. This simulator delivers rainfall with 90% of the kinetic energy of natural rainfall and a comparable drop-size distribution. All rainfall simulations were performed during the dry season, during June 1995 and 1996, on initially dry soils. Each simulation lasted 30 min, and the actual rainfall delivered to each plot was measured in an array of 6 wedge-shaped raingages located around the periphery of each plot. The mean rainfall intensity was 146, 118, and 136 mm/hr during the rainfall simulations on grassland, shrub-, and intershrub plots, respectively.

Runoff rates (discharge) were determined by taking timed volumetric samples of the water discharged from a trough placed along the lowest side of the plot. Once runoff commenced, it increased rapidly, so samples of the outflow were initially collected at 30-s intervals. Later in the experiment, when runoff stabilized, samples were collected at longer intervals ranging from 2 to 4 min. Samples were collected in polypropylene bottles. The duration of the sampling lasted 15 s early in the experiment and ranged from 20 to 30 s later in the experiment, depending on the fill time of the sample bottle. Following each simulation, the surface cover of fines (i.e., materials <2 mm diameter), gravel (material ≥ 2 mm), plant litter, and vegetation was estimated for each plot using a grid of 200 points.

Runoff samples were filtered through pre-rinsed 0.45-μ Millipore HA filters, and analyzed for NH_4, NO_3, and PO_4 using standard methods on a Traacs 800 Autoanalyzer. Inorganic N is taken as the sum of NH_4-N + NO_3-N. Each sample was then subjected to a persulfate digestion (D'Elia et al. 1977) and reanalyzed. The difference between the digested and undigested concentrations is assumed to represent dissolved organic forms of N and P. Contents of N and P in the applied water were subtracted from the contents in runoff to estimate the net losses in runoff.

All data associated with this publication are accessible via the World Wide Web at http://jornada.nmsu.edu.

Results

Discharge

Peak discharge was usually attained 5 to 10 min after the beginning of simulated rainfall (Figure 1). In the majority of cases, this rate of discharge was maintained for the remainder of the experiment; however, in a small number

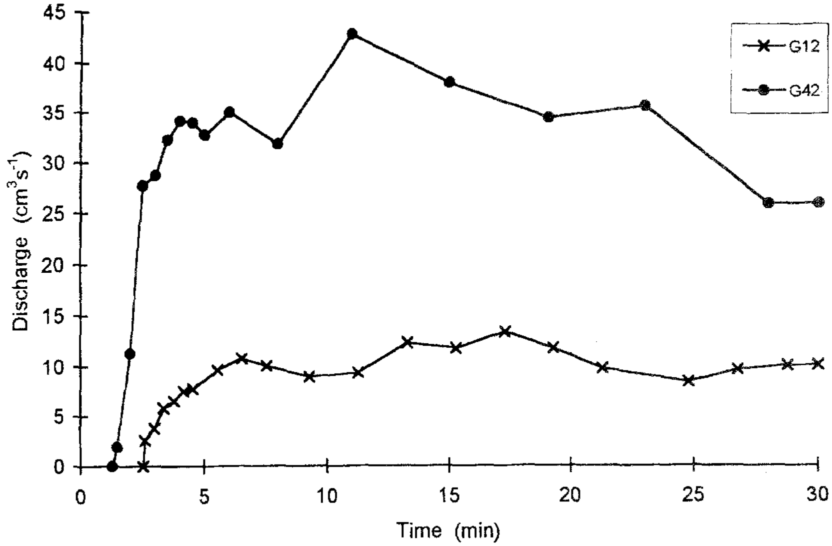

Figure 1. Changes in the discharge of runoff during a rainfall simulation experiment on two grassland plots (G12 and G42).

of the grassland and shrub plots, runoff declined during the latter part of the experiment. The grassland and shrub plots also showed greater variability in asymptotic peak discharge than seen in the intershrub plots. Mean volumetric runoff coefficients (total water yield as a proportion of total incident rainfall) were 24.2%, 29.9%, and 55.4% for the grassland, shrub, and intershrub plots, respectively. Weighting the latter two values by the proportion of the landscape covered by shrubs (38%) and intershrub areas (62%) gave an overall runoff coefficient of 45.7% for the shrubland habitat (Figure 2). Thus, in the rainfall simulation experiments, the runoff from shrublands was 1.8 times greater than that from grasslands.

Nitrogen concentration and yield

In a small number of cases, there was a brief rise in the concentration of total dissolved nitrogen (TDN) shortly after the start of discharge, but in the great majority of the plots, the concentration of TDN declined with time for the duration of runoff (Figure 3). A similar pattern was seen for the concentration of dissolved organic nitrogen (DON). Among all samples from each type of plot, concentrations of TDN were inversely correlated to discharge volume (Figure 4a–c).

Volume-weighted mean concentrations of TDN (total N loss divided by total water loss) were 1.72 mg/l, 1.44 mg/l, and 0.55 mg/l for the grassland, shrub, and intershrub plots, respectively. Weighted by the average cover of

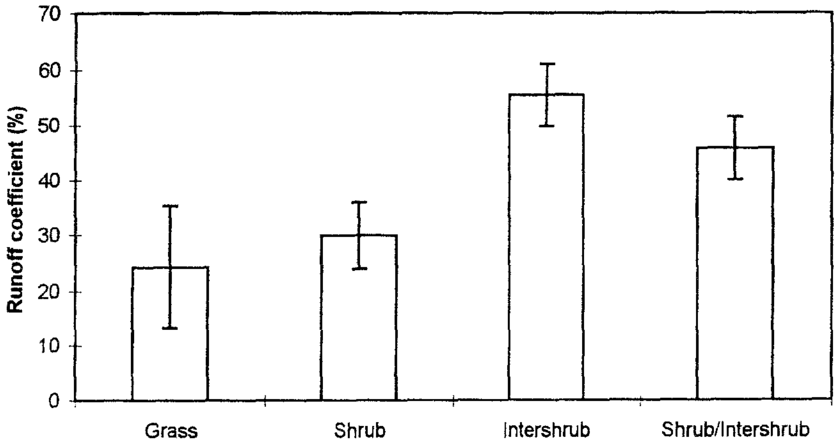

Figure 2. Runoff coefficient (Discharge/precipitation × 100% ± S.D.) for field plots used for rainfall simulation experiments. Shrub/intershrub is the estimated discharge from shrublands, obtained by weighting the relative shrub (38%) and intershrub (62%) cover on the landscape.

shrub (38%) and intershrub (62%) areas on the landscape, the mean TDN concentration was 0.77 mg/l in the runoff from shrublands. Thus, the concentration of TDN in the runoff from grasslands was 2.23 times greater than that of the shrubland. Volume-weighted mean concentrations of DON were 1.00 mg/l, 0.87 mg/l and 0.41 mg/l for the grassland, shrub, and intershrub plots, respectively. Weighted by the average cover of shrub and intershrub areas, the mean concentration of DON in the runoff from shrublands was 0.52 mg/l. Thus, the DON concentration in the runoff of grasslands was 1.9 times greater than in the runoff from shrublands.

Mean total N yields were 0.0294, 0.0227, and 0.0176 g/m^2 for the simulation experiments on grassland, shrub, and intershrub plots, respectively. The cover-weighted mean yield in the shrubland was 0.0195 g/m^2 (Figure 5). The higher yields from the grassland than from the shrubland reflect the higher concentrations of N in the runoff from the grassland and occurred despite lower runoff coefficients. Likewise, in the shrubland, the higher yields from the shrub plots reflect higher N concentrations in runoff and occurred despite lower runoff coefficients than found for the intershrub plots.

Mean organic nitrogen yields were 0.0165, 0.0127, 0.0122 g/m^2 for the grassland, shrub, and intershrub plots, respectively (Figure 5). The cover-weighted mean yield was 0.0124 g/m^2 in the shrubland. Mean organic N yield as a percentage of total N yield was 56.1%, 55.9%, and 69.3% for the grassland, shrub, and intershrub plots, respectively. The cover-weighted mean DON yield for shrublands was 64.2% of TDN. Thus, the higher yield of total N from the grassland was largely derived from the inorganic fraction.

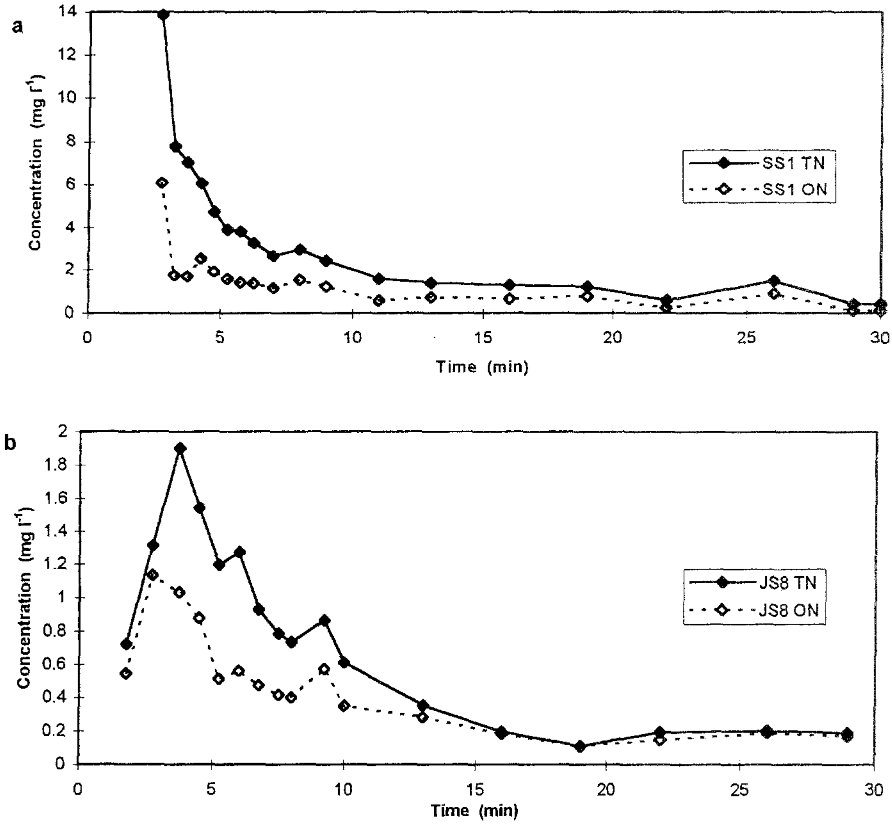

Figure 3. An example of the changes in the concentration of dissolved nitrogen during a rainfall simulation experiment on two shrub plots (SS1 and JS8). The solid lines are for total dissolved nitrogen and the dashed lines for dissolved organic nitrogen.

Figure 6 shows the ratio of organic- to total-N yield at 5-min intervals throughout the rainfall simulation experiments. This ratio was consistently higher in the intershrub plots than in grassland or shrub plots, which behaved similarly to each other. For all plots, this ratio tended to increase significantly during the course of the experiments.

Phosphorus concentration and yield

Phosphorus concentrations were low and highly variable in the runoff from all plots. Dissolved inorganic P accounted for 98% of the loss of soluble P from grassland plots, where the total P yield was correlated (r = 0.86) to the total volume of discharge. In contrast, dissolved organic P dominated the yield of soluble P from shrubland plots. Losses of P from plots located in the shrub

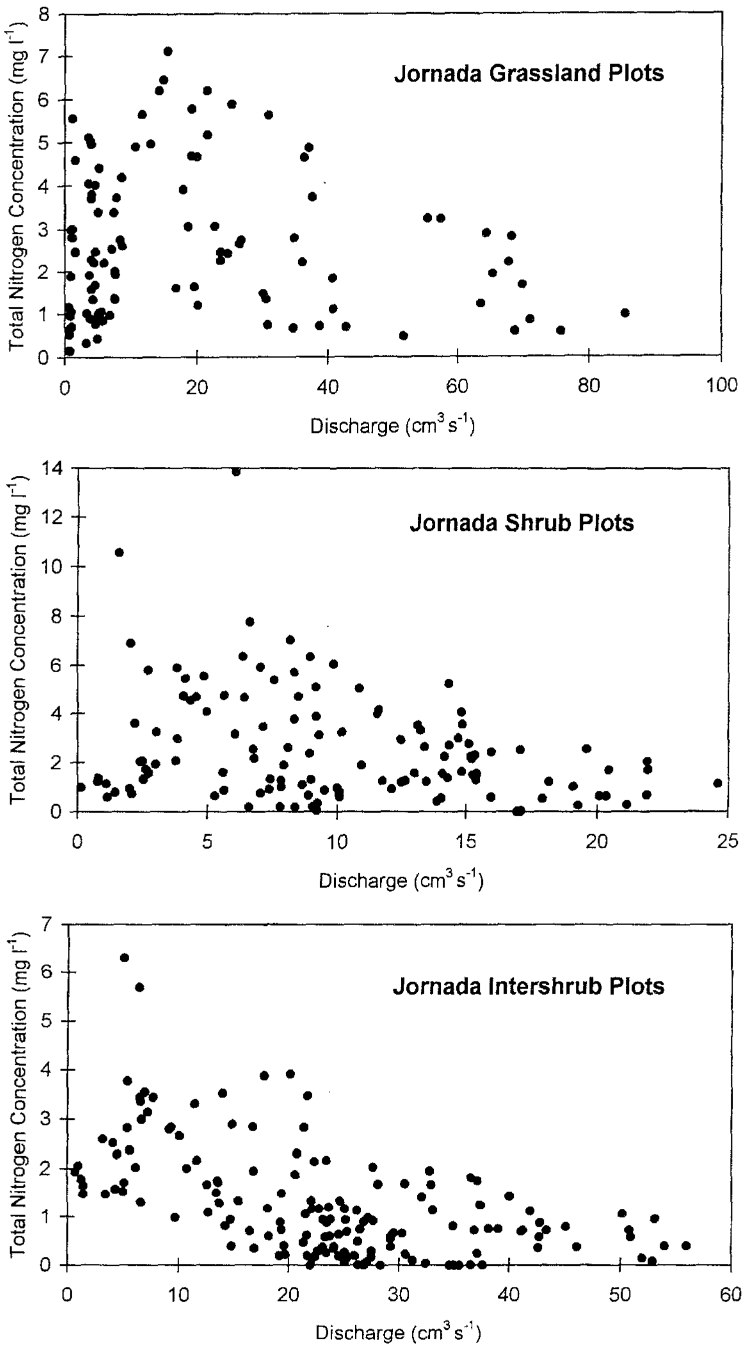

Figure 4. Relationship between the concentration of nitrogen in individual samples of runoff as a function of the rate of discharge at the time of sampling for: a) grassland [$C = 2.744 - 0.010(Q)$, $r = 0.122$, $p = 0.207$], b) shrub [$C = 3.453 - 0.102(Q)$, $r = 0.263$, $p = 0.002$], and c) intershrub (bare) plots [$C = 2.365 - 0.049(Q)$, $r = 0.553$, $p < 0.001$].

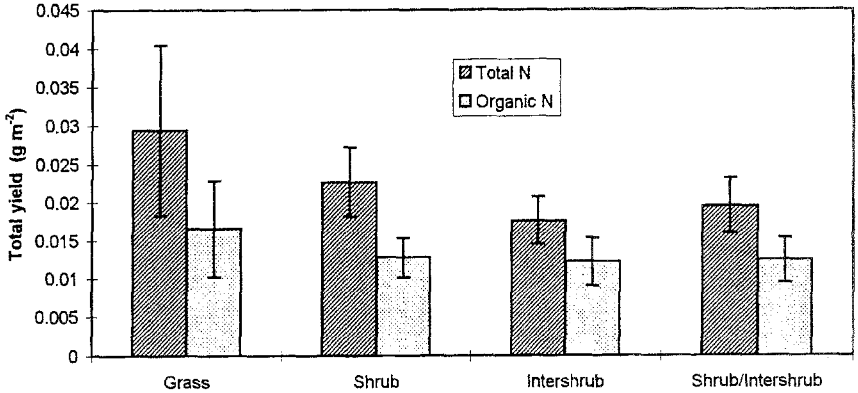

Figure 5. Mean yield (g/m^2 $\pm$ S.D.) of total dissolved nitrogen and organic nitrogen from rainfall simulation plots. (see caption to Figure 2).

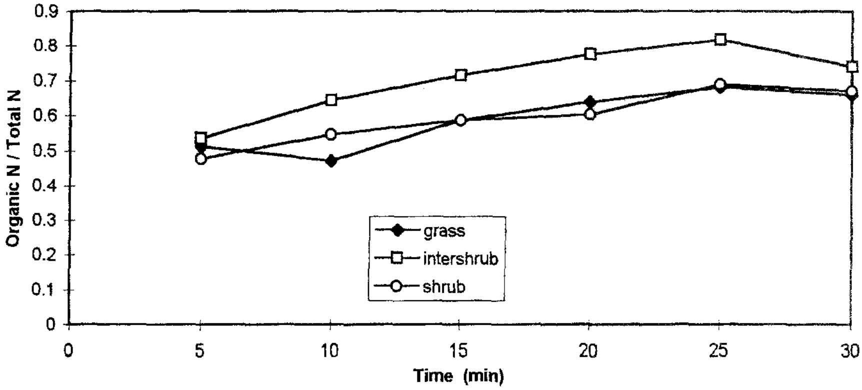

Figure 6. Yield of dissolved organic nitrogen as a percentage of total dissolved nitrogen during the rainfall simulation experiments on different plots.

interspaces were very small (Figure 7), and correlated (r = 0.98) only with the concentration of total dissolved P in the sample.

Discussion

Comparisons of runoff between grass and shrub plots are compromised somewhat by the greater intensity of rainfall applied in grasslands and the greater topographic slope of the grassland plots. In the rainfall simulation experiments, grassland plots generated about the same volume of runoff as shrub plots, but less than plots located on barren, intershrub areas, which occupy 60 to 70% of the area in shrublands (Schlesinger et al. 1996). Despite the greater runoff from the bare intershrub soils, relatively little N and P was

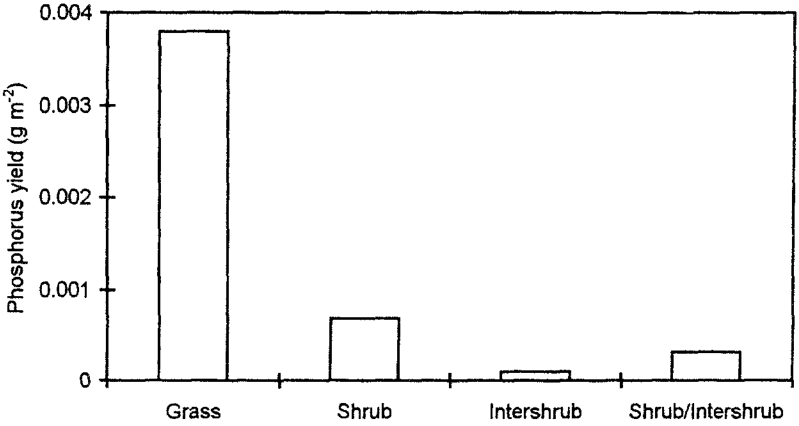

Figure 7. Mean total phosphorus yield (g/m^2) from runoff plots during the rainfall simulation experiments.

lost, presumably because these soils have low nutrient contents (Schlesinger et al. 1996). The volume-weighted mean concentration of TDN in the runoff from grassland and shrub-dominated plots, 1.72 and 1.44 mgN/l, respectively, was much higher than the concentration in the runoff from intershrub plots (0.55 mgN/l).

For grassland and shrub plots, nitrogen yield was always more highly correlated with water yield than with N concentration, whereas the reverse was true for the intershrub plots (Table 1). The standard deviation of water yield was always greater than the standard deviation of N concentration for grassland and shrub plots, but less than the standard deviations of these variables on intershrub plots. This suggests that intershrub plots were similar in their ability to generate runoff but different in their ability to supply N compared to grassland and shrub surfaces. Given that intershrub plots were virtually devoid of both live and dead organic matter, whereas the grassland and shrub plots had varying covers of vegetation and litter, the greater hydrological uniformity of the intershrub plots is not surprising. It is less obvious, however, why the intershrub plots were more variable in their supply of N, and in particular organic N, than were the grassland and shrub plots. There were no significant correlations between our measures of surface properties in these plots and their yield of runoff or N.

Rainstorms with a duration and intensity of the rainfall simulation experiments (i.e. 140 mm/hr for 30 min) are very infrequent in southern New Mexico, so a nitrogen loss of 0.0294 g/m^2 ($\approx$0.3 kg/ha) as a result of such a storm may be a rare event in Chihuahuan desert grasslands. During a 3-year period, the maximum intensity of rainfall recorded at the LTER weather station was 137.3 mm/hr, and this intensity was only maintained for 1 min on

Table 1. Correlation coefficients for the relation between important variables determining the yield of dissolved nitrogen during rainfall simulation experiments, and standard deviations of the mean of these variables among experimental plots.

Variables	Grassland	Shrub	Intershrub
Correlation Coefficients			
Total N Yield and:			
Water Yield	0.977*	0.739*	−0.410
TDN Concentration	0.271	0.379	0.917*
Organic N Yield and:			
Water Yield	0.965*	0.531	−0.547
DON Concentration	0.093	0.494	0.979*
Inorganic N Yield and:			
Water Yield	0.975*	0.846*	0.779*
DIN Concentration	0.613	0.506	0.785*
Standard Deviations			
Water Yield	0.715	0.324	0.167
TDN Concentration	0.158	0.236	0.381
DON Concentration	0.188	0.316	0.693
DIN Concentration	0.201	0.201	0.170
N	6	8	10

* ($P < 0.05$).

two occasions, 26 June and 14 September 1996 (Wainwright, unpublished). We chose a high rainfall intensity for our experiments to help elucidate differences between grass- and shrub-dominated areas.

Bolton et al. (1991) suggested that a useful statistic to compare nutrient losses in arid lands – where runoff is local and episodic and the topographic slopes are variable – is the volume-weighted mean concentration (mgN/l) divided by 100, which is equivalent to the loss of nitrogen (kg/ha) per milliliter of runoff. Over a 6-year period, 1989–1994, an average of 14.6 mm/yr of runoff (5.7% of incident precipitation) was measured on 8 instrumented 2×2 m runoff plots in two grasslands of the Jornada basin (unpublished data). Using the volume-weighted mean concentration of 1.72 mgN/l for the TDN in the runoff from grasslands, nitrogen losses were calculated to equal 0.25 kg/ha/yr. This is about 10% of the estimated annual deposition of N from the atmosphere in the southwestern U.S. (Peterjohn & Schlesinger 1990). The relative infrequency of storms as intense as our rainfall simulations suggests that undisturbed grassland soils are not declining in nutrient content as a result of the transport of dissolved substances by fluvial erosion. Grassland soils may lose additional N in the transport of suspended materials, not measured in our work (e.g., Gifford & Busby 1973), but they may also derive additional N inputs from the activities of N-fixing bacteria that occur in the rhizosphere of the grasses (Herman et al. 1993).

To estimate the annual loss of nitrogen from shrublands, the volume-weighted mean concentrations of TDN in runoff (1.44 mgN/l for shrub plots and 0.55 mgN/l for intershrub plots) were weighted by the runoff and proportional land area of shrubs (38%) and intershrub spaces (62%), and then multiplied by a runoff estimate of 56.2 mm/yr (18% of incident precipitation) determined on four 2×2 m plots monitored in creosotebush scrub during the same 6-year period as for grasslands (unpublished data). The calculated nitrogen loss was 0.43 kg/ha/yr. The higher loss of TDN from shrublands than from grasslands is entirely due to the $3.8\times$ greater runoff measured in shrublands during the long-term field studies – a greater difference than seen in our rainfall simulation experiments (Figure 2). At the landscape-scale, the loss of N from shrublands is also likely to exceed that from grasslands, where a large amount of the material mobilized by fluvial processes is redeposited locally (Parsons et al. 1993; Tongway & Ludwig 1994).

Our data are consistent with a large body of literature that suggests that dissolved organic nitrogen contributes a significant fraction of the N lost in runoff from terrestrial ecosystems (Meybeck 1982; Hedin et al. 1995). Despite the sparseness of arid-land vegetation, DON was >50% of the TDN measured in the runoff from grassland and shrub plots, and nearly 70% of the N lost from the barren soils of the intershrub plots. The total yield of N during the duration of each rainfall simulation was negatively curvilinear (Figure 8), suggesting that the decline in concentration with time was not simply due to dilution by the increasing runoff but due to depletion of the pool of available N in the soil. The decline was greater for dissolved inorganic forms of nitrogen (NH_4 and NO_3) than for dissolved organic nitrogen, so DON became an increasing fraction of the total N yield with an increasing duration of runoff.

Our rainfall simulations were performed on dry soils at the end of the dry season. In 1995, there was no antecedent rainfall for 3 months prior to our simulation experiments; in 1996 there was no antecedent rainfall for 2 months. High concentrations of DON may be associated with the first runoff events of the wet season, with lower amounts of organic nitrogen lost in subsequent events. Working in the Sonoran desert of Arizona, Fisher and Grimm (1985) found that DON accounted for 40% of the total N lost from an arid shrubland in a rainstorm on 22 August 1982; runoff from storms on two subsequent days contained only 28% and 4% of the TDN in organic forms. While organic nitrogen may constitute a large portion of the TDN in dry

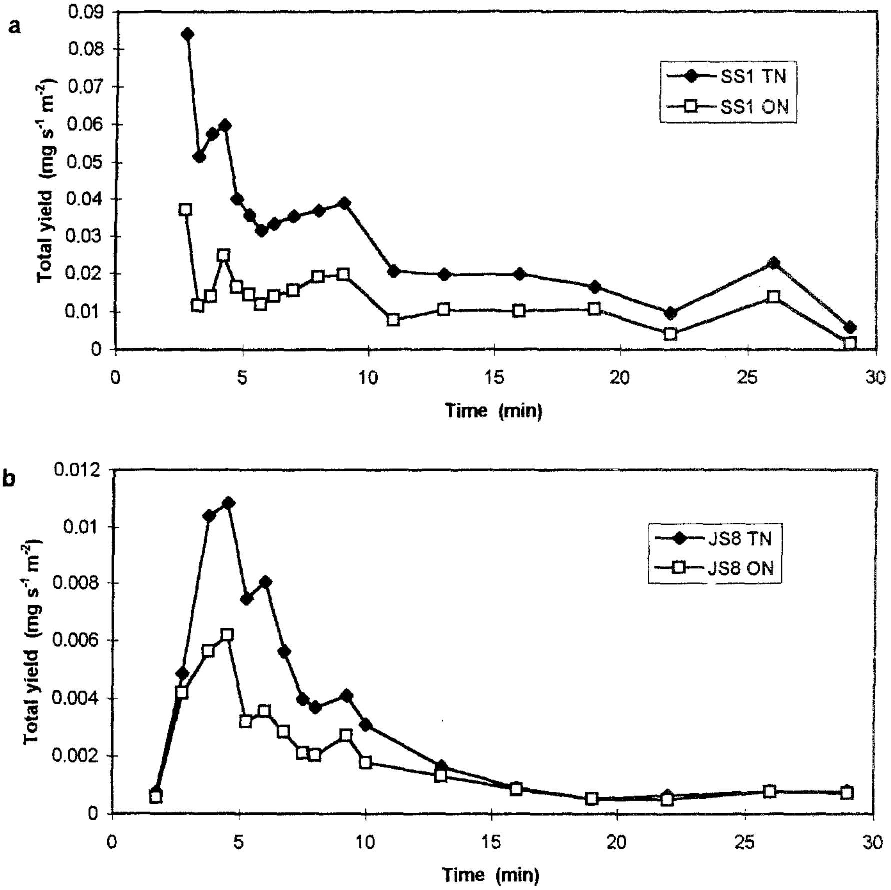

Figure 8. Yield of organic and total dissolved nitrogen in discharge as a function of time during rainfall simulation experiments.

soils, much of the organic N may be mineralized to inorganic forms during the progression of the wet season.

Organic phosphorus compounds composed more than 70% of the soluble P lost from shrub plots. Recent work by Cross (1994) found that organic P constituted an important component of the soil P in desert shrublands, in which most inorganic P is held in unavailable complexes with Ca and $CaCO_3$ minerals (Lajtha & Bloomer 1988). In contrast, the large losses of inorganic P from grassland soils may be due to the lower contents of $CaCO_3$ in the surface horizons of those soils (Lajtha & Schlesinger 1988). However, even the mean loss of 0.00378 gP/m^2 during the 30-min rainfall simulations on grasslands is $\ll$ 1% of the pool of available (resin + bicarbonate-extractable) P in the surface 1 cm of grassland soils (Lajtha & Schlesinger 1988).

Conclusions

The rainfall simulation experiments showed that more runoff is generated from the bare soils between shrubs than from soils covered by creosotebush or semiarid grasses. Because bare soils comprise about 60% of the area of the shrublands, the overall amount of runoff is greater in shrublands than in grasslands. The nitrogen concentration, however, is lower in the runoff from shrublands, because the bare soils have low contents of available N (Schlesinger et al. 1996). Even so, the long-term nitrogen losses are greater in shrublands, as a result of a greater volume of runoff than in grasslands. When plant cover is reduced and semiarid grasslands are invaded by shrubs, nutrient losses are likely to increase, exacerbating the desertification of this region of New Mexico.

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