Prescribed fire effects on erosion parameters in a perennial grassland

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A 2-year field experiment was undertaken to quantify the interacting effects of a late-spring prescribed burn and summer rainfall on seasonal runoff and erosion in a southern Arizona grassland. Six blocks with walled subplots (n=24) were installed on a hillslope to measure changes to plant, soil, and hydrologic variables in response to treatments. Increased bulk density, erosion, and runoff volumes; and lowered plant cover and water intake rates were observed within the burned plots following the first summer season. In the second year, higher bulk density, runoff volumes, and erosion measures were again observed within the burned plots, as well as lower plant cover, aggregate stability, and water intake rates. The results of this study indicate that following late-spring burning, semi-desert grasslands are susceptible to greater summer runoff and erosion compared to unburned grasslands.

Key Words: Arizona, sediment yield, summer rainfall

Following decades of active suppression, fire is being reintroduced to the grasslands of southern Arizona as a management tool to achieve some of the landscape values attributed to wildfire. Fire within these systems has historically preceded the start of the summer rainy season (Wright and Bailey 1982), restructuring the plant community by reducing woody plant numbers and increasing herbaceous plant diversity and abundance (Martin 1983, McPherson 1995, Wright and Bailey 1982). Within various Southwest perennial grass communities, the response of many aboveground plant attributes (i.e. biomass, seedling establishment, percent cover) has been either positive or neutral to burning (Biedenbender and Roundy 1996, Bock et al. 1995, Ford 1999, Wilson 1999). However, localized climatic conditions (i.e. winter drought) either preceding or following burning have been associated with the notable delay in community recovery (Wright 1979), as well as in the recovery of specific grass species (Wright and Bailey 1982).

The removal of vegetation soil cover by fire is an important driver of surface runoff and erosion processes, as it reduces the frequency and size of vegetated areas over the landscape (Baker 1988, Simanton and Renard 1981). Removal of vegetation exposes the soil surface to the energy of raindrop impact (Bennett 1974, Hester et al. 1997), affecting surface aggregate stability (Armstrong and Stein 1996, Gang et al. 1998, Warren 1987) and the permeability of surface soil layers to water infiltration (Baker 1988, Smith et al. 1990). In grasslands of the southwestern U.S., little is known about the interchanges between soil erosion and grassland community dynamics following a prescribed fire. A 2-year field experiment was undertaken to quantify the effects of prescribed fire and summer rainfall interactions on plant and soil parameters that affect summer runoff and erosion in a southern Arizona grassland.

Materials and Methods

The Elgin, Arizona study area (31° 62’ N 110° 52’ W), with an average elevation of 1,450 m, was characterized by perennial bunchgrasses occupying the uplands, oak woodlands in the drainages, and more than 30 years of livestock exclusion. The grass genera Eragrostis, Bouteloua, Lycurus, and Muhlenbergia dominated the site. Mimosa (Mimoso biuncifera Benth.), rabbit brush (Chrysothamnus nauseosus (Pall.) Britton), and various cacti were also present. The soil is a White House gravelly loam (Fine, mixed, superactive, thermic Ustic Haplorgids) (Richardson et al. 1979), and the study site has a 1 to 3% slope.
The study was a randomized complete block (block = replication) with 6 replications in a split-strip plot arrangement. The 4 treatment variations were a control, a prescribed burn, a rainfall simulation, and a rainfall simulation x prescribed burn interaction. Each block was established on a hillslope and contained 4 walled runoff subplots (3 m by 10 m) with sediment catchments. Sediment catchments were sheet metal boxes, each having covers to prevent rainfall contributions to runoff measures, set into the ground at the base of each plot. The seams of the boxes were sealed with silicone. A prescribed fire treatment was randomly applied to half of the plots in late May 1998. The plots were then split into strips for the application of a simulated summer rainfall event (63.5 mm hour\(^{-1}\) for 40 min. for an average depth of 43.2 mm ± 0.4 mm) using a rotating-boom rainfall simulator (Swanson 1965) at the end of June 1998. The rainfall simulation represented a storm return interval of approximately 3.5 years. Given the unpredictable timing of the summer rainy season, the simulated rainfall treatment was applied to ensure that surface erosion and sediment production would occur at the start of the growing season. Experimental design and weather limitations did not allow for the collection of sediment produced during rainfall simulation.

Permanently sampling points were established within each subplot to measure plant (n = 3) and soil parameters (n = 6). Sampling followed the summer growing seasons of 1998 and 1999. Vegetation variables were measured within quadrats (0.5 m by 0.5 m) centered upon the point marker. Percent aerial cover was ocularly estimated, graminine ramets and seedlings were counted, and ground-level grass clump caliper was used for basal area calculations. Within a quadrant subset (0.25 m by 0.25 m) annual herbaceous dicot cover was also ocularly estimated. Bulk density (Blake and Hartge 1986), percent water-stable aggregates (PSA) (Kemper and Rosenau 1986), and surface intake rates were measured. Soil cores (2 cm by 10 cm) were collected for PSA measurements, and bulk density measurements were taken for depths of 0–5 cm and 6–10 cm. Water intake rates were used as surrogate measures of infiltration under unsaturated soil conditions (Perroux and White 1988, Sullivan et al. 1996, White and Sully 1987). Measurements were conducted using a CSIRO designed disc permeameter at a single tension (negative pressure) 1.5 kPa, on a debris-cleared and leveled bed of silica sand within a soil embedded steel ring (unpublished, CSIRO 1988). Aggregates, sized 0.15–0.30 mm, were used as measures of aggregate stability as they represented the mean PSA of the soil samples. Informal tests with water droplets shows no evidence of post-burn hydrophobicity at the soil surface.

Runoff volumes and dried sediment weights were recorded for each subplot 1 July through 1 October. Runoff volumes were calculated from the runoff depth captured in the catchments following the rainfall simulation event and natural storms. There was no adjustment for potential evaporation or pan leakage. Catchments were drained after the sediment had settled out. The sediment was air-dried in the field, collected, oven dried at 90°C for 24 hours, and then weighed. Due to logistical limitations sediment yield was not determined for the simulation events. Sediment yields reflect the total sediment collected for the summer season. Summer rainfall data were collected on the research site for 2 years following treatment application. Additionally, local long-term (10-year average) rainfall data were available from the Audubon Research Ranch, Elgin, Ariz., located approximately 2.4 kilometers from the research site. Summer rainfall totals for 1998 (100.0 mm) and 1999 (106.0 mm) were above average (10-year average = 86.8 mm). Rainfall totals were below average (10-year average = 29.1 mm) for the falls of 1998 (12.5 mm) and 1999 (6.3 mm), and well below average (10-year average = 37.3 mm) for the winter of 1999 (2.0 mm) (O'Dea 2000).

There was no significant block by treatment interaction, and subplots were used as replicates. Effects of prescribed fire and simulated rainfall on plant (seedling and ramet numbers) and soil (bulk density, PSA) response variables were analyzed using analysis of variance (ANOVA). Water intake rates, plant cover, and basal area were analyzed with repeated measures ANOVA (SAS Institute, Inc. 1990). Soil depth increments (i.e. 0-5 cm and 6-10 cm) were used as covariates in tests of treatment effect on bulk density. Comparisons of treatment means for each year were made using least-squares means (Steel and Torrie 1980).

### Results

#### Plant Parameters

There were significant (p < 0.01) treatment effects on measured plant response variables in 1998 and 1999, results are summarized in Table 1. For both years, perennial grass cover and basal area were greater on unburned plots (i.e. control and rainfall simulation) than on burned plots. Recovery of the perennial grasses following the prescribed burn was slow, with little difference between 1998 and 1999. Plots treated with rainfall simulation only in 1998 had the greatest percent perennial grass cover, an effect of the additional watering and not in evidence in 1999. Mean basal area within the simulation x burn treatment was 2 to 4 times lower than values for the prescribed burn only treatment, and at least 4 times lower than the unburned treatments (Table 1). A significant within-subjects effect for time was found (p = 0.001) for both perennial cover and basal area, prompting the expected conclusion that cover and basal area changed with time in the population from which the sample was drawn. In 1998, while there was a reduction in perennial grass cover compared with unburned plots, annual dicot cover increased. All treated plots had greater annual cover compared with the control, with the greatest dicot increase within the simulation x burn plots. In the second post-treatment year, burned plots continued to have greater annual cover and less perennial cover than the unburned plots (Table 1).

<table>
<thead>
<tr>
<th>Cover</th>
<th>Basal Area</th>
<th>Cover</th>
<th>Basal Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>(cm(^2))</td>
<td>(%)</td>
</tr>
<tr>
<td>Perennial grasses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>20.4(^a)</td>
<td>254.8(^b)</td>
<td>31.9(^a)</td>
</tr>
<tr>
<td>Prescribed burn</td>
<td>9.0(^b)</td>
<td>185.3(^b)</td>
<td>19.0(^b)</td>
</tr>
<tr>
<td>Rainfall simulation</td>
<td>29.8(^a)</td>
<td>319.8(^b)</td>
<td>30.8(^a)</td>
</tr>
<tr>
<td>Simulation x burn</td>
<td>11.2(^c)</td>
<td>45.7(^b)</td>
<td>15.0(^c)</td>
</tr>
<tr>
<td>Annual dicots</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.9(^c)</td>
<td>-----</td>
<td>5.3(^b)</td>
</tr>
<tr>
<td>Prescribed burn</td>
<td>1.9(^a)</td>
<td>-----</td>
<td>10.1(^a)</td>
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<tr>
<td>Rainfall simulation</td>
<td>1.9(^a)</td>
<td>-----</td>
<td>3.8(^b)</td>
</tr>
<tr>
<td>Simulation x burn</td>
<td>3.2(^a)</td>
<td>-----</td>
<td>9.5(^a)</td>
</tr>
</tbody>
</table>

\(^a\) Significant (p < 0.05) differences among treatment means for each plant variable are denoted with different letters.
The perennial grasses regenerated primarily through the re-sprouting of residual grass clumps, with few new recruits becoming established. Seedlings were found within all treatments in 1998 and 1999, yet none survived the proceeding fall and winter droughts. In 1998, a significant treatment effect was observed for seedling number that was not observed the second year (P = 0.040). In 1998, the greatest number of seedlings counted was within the simulation x burn plots (3.4 seedlings m⁻²) compared to the other treatments (< 1 seedling m⁻²) (P ≤ 0.05). Counts were less than 1 seedling m⁻² for all treatments with no treatment effect in 1999. There was no treatment effect on ramet number in either 1998 or 1999. Ramets were only observed within the simulation x burn plots (0.4 ramet m⁻²) in 1998, and there were none found in 1999. Ramet number did not appear to be affected by either prescribed burning or the rainfall simulation.

**Soil Parameters**

Differences among treatments were observed for soil bulk density, aggregate stability (PSA), and water intake rates in 1998 and 1999 (Table 2). A significant treatment effect was observed for bulk density in 1998 (P = 0.014) and 1999 (P = 0.031), including a significant depth x treatment interaction in 1998 (P = 0.01). Increased bulk density with depth (i.e. 0-5 cm and 6-10 cm) (P ≤ 0.05) was observed in plots treated with rainfall simulation, but these changes were not evident in 1999. In 1998, bulk density (0-10 cm) was lowest within the control plots compared with the other treatments. In the following year, only bulk density within the simulation x burn plots was greater than the control (Table 2). There was a significant treatment effect on aggregate stability in 1999 (P = 0.009), but not in 1998. In 1999, aggregate stability was lower in the burned plots compared to the rainfall simulation only plots, but not with the control (Table 2). Significant treatment effects on water intake rates were observed in 1998 (P = 0.0001) and 1999 (P = 0.0001), with intake rates lower both years in the burned plots compared with the unburned (Table 2). A significant within-subjects effect for time was found (P = 0.001) for water intake rates, suggesting intake rates changed with time in the population from which it was sampled.

**Surface Runoff and Sediment Yield**

The simulated rainfall treatment contributed approximately 40% of the total summer rainfall and 52% of the total summer runoff volume for 1998. Simulated runoff volumes were greater in the burned plots than in the rainfall simulation only plots (P = 0.05). Excluding the contributions of the simulation treatment, total summer runoff from natural rainfall events was greater for the simulation x burn treatment compared to the other treatments (Table 3).

In comparing total rainfall (simulation + natural) for the summer months, a significant treatment effect for runoff volume was observed in 1998 (P = 0.0001) and 1999 (P = 0.0001). In 1998, total summer runoff volumes were higher for plots treated with the rainfall simulation, with the greatest measured runoff on the simulation x burn plots. Runoff volumes in the simulation only treatment were not significantly different from the control under natural rainfall, when the simulation was excluded. In 1999, total summer runoff volumes continued to be greater for the simulation x burn plots compared with the others (Table 3). Runoff in all treatments was higher in 1999 than in 1998 because of above average rainfall in the summer of 1999. There was a significant treatment effect on sediment production in 1998 (P = 0.011) and in 1999 (P = 0.004), with the greatest amount of sediment produced in the simulation x burn plots. Sediment production was lowest in the control plots; with no difference between the prescribed burn only and the rainfall simulation only plots. In 1998, sediment yields from all of the treated plots were greater than the control, with no significant difference between the prescribed burn only and the simulated rainfall only plots. In 1999, sediment yields from the burned treatments continued to be greater than the control, with the greatest yields coming from the simulation x burn plots (Table 3).

**Discussion**

Prescribed burns preceding the summer rainy season affect not only the perennial bunchgrass community, but also structural features of the surface soil layers. The perturbation of these grassland attributes affected runoff and erosion, as soil loss after a burn is strongly influenced by the frequency and size of exposed areas (Baker 1988, Meeuwis 1970). The decline in perennial grass cover, along with the lack of new recruits increased the frequency and size of non-vegetated area within the burned plots. The increased bare area exposed the soil surface to raindrop impact, and removed barriers to overland flow and sediment transport (Hester et al. 1997, Smith et. al. 1990), as well as the localized zones of greater infiltration associated with vegetation (Blackburn 1975, Thurow et al. 1986). While annual dicot cover increased in the burned plots, it did little to mitigate runoff volumes or sediment yield. The higher dicot cover in con-

### Table 2. Comparison of means among treatments of soil variables (10 cm depth)¹.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.53⁸</td>
<td>0.74⁸</td>
<td>14.7</td>
<td>1.60⁸</td>
<td>0.64⁸</td>
<td>12.8</td>
</tr>
<tr>
<td>Prescribed burn</td>
<td>1.65⁹</td>
<td>0.75⁸</td>
<td>9.7</td>
<td>1.59⁹</td>
<td>0.59⁹</td>
<td>8.0</td>
</tr>
<tr>
<td>Rainfall simulation</td>
<td>1.70⁸</td>
<td>0.82⁹</td>
<td>15.3</td>
<td>1.54⁹</td>
<td>0.73⁹</td>
<td>13.8</td>
</tr>
<tr>
<td>Simulation x burn</td>
<td>1.64¹⁰</td>
<td>0.83⁹</td>
<td>10.0</td>
<td>1.62¹</td>
<td>0.58⁹</td>
<td>8.9</td>
</tr>
</tbody>
</table>

¹Significant (p < 0.05) differences among treatment means for each plant variable are denoted with different letters.

### Table 3. Comparison among treatments of mean summer runoff volumes and sediment yields¹.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Runoff Volume</th>
<th>Sediment Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1998</td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>Natural</td>
</tr>
<tr>
<td>Control</td>
<td>175⁹</td>
<td>175⁹</td>
</tr>
<tr>
<td>Prescribed burn</td>
<td>182⁰</td>
<td>182⁰</td>
</tr>
<tr>
<td>Rainfall simulation</td>
<td>264⁰</td>
<td>543⁰</td>
</tr>
<tr>
<td>Simulation x burn</td>
<td>394⁰</td>
<td>808⁰</td>
</tr>
</tbody>
</table>

¹Significant (p < 0.05) differences among treatment means for each plant variable are denoted with different letters.
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juncture with lower perennial grass cover on areas burned and artificially eroded (i.e. simulation x burn) appeared to have a positive effect on runoff yields. The slow recovery of the perennials was unexpected following 2 years of above-average summer rainfall, as well as moist pre-burn soil conditions that was expected to mitigate plant damage and support a greater post-fire growth response (Wright 1979, Wright and Bailey 1982). Additionally, there was no notable grass mortality following the burn. Vegetative sprouting occurred almost immediately following the fire and was well established before the rainfall simulation. The delayed recovery of the grasses may have been a combination of 4 uncontrollable factors: a week of storms (total rainfall = 37.5 mm) immediately following the rainfall simulation, lack of grass recruitment, winter and fall droughts, and fire effects on the mycorrhizal community. Two days after the simulation treatment, the summer rains began. Storms came in every afternoon for 6 consecutive days, accounting for 40% of the season’s natural rainfall and with the simulation, approximately 60% of the summer total. While a storm of similar intensity to the simulation had occurred the previous year, it had not been in conjunction with a series of storms. With so much of the rainfall occurring in a short period, the large volumes of runoff and sediment produced in the burned plots may have damaged residual plants by exposing portions of the root system. Burning alone may damage aboveground growing points (Steuter and McPherson 1995), while erosion around the plant (i.e. pedestal) exposed previously protected plant parts. Desiccation of exposed roots, as well as damage to belowground growing points may explain the disproportionate decline of the perennials within burned plots treated with the rainfall simulation. Recruitment of new individuals within the grass community appeared to be predominantly influenced by environmental factors (e.g. drought) rather than by treatment characteristics. The largest seedling counts were recorded in 1998 within plots treated with the rainfall simulation, although seedlings were found within all treatments both years. However, none of the counted seedlings were able to survive the fall and winter droughts (Biedenbender and Roundy 1996). Gramineous ramets were also observed in 1998, but none were observed in the following year’s survey. Many grasses common to southern Arizona, such as blue grama (Bouteloua gracilis (H.B.K)), side-oats grama (B. curtipendula (Michx.) Torr.), and wolftail (Lycurus phleoides H.B.K.) have been reported to be harmed by spring fires that were followed by winters of below-average rainfall (Wright and Bailey 1982). Additionally, the mycorrhizal nature of these grasses is another important factor in their recovery. Prescribed burning inhibits the potential colonization of these grasses by mycorrhizal fungi (O’Dea 2000). Differential plant responses to colonization occur between and within different grass genera (Smith et al. 1999, Wilson and Hartnett 1998), influencing species growth and regeneration. Both plains lovegrass (Eragrostis intermedia Hitchc.) and Lehmann lovegrass (E. lehmanniana Nees.) were common to this study site, and were found to produce significantly greater biomass under greenhouse conditions when they were not colonized compared to when they were. In contrast, grama (Bouteloua spp.) and wolftail (Lycurus phleoides H.B.K.) grasses produced substantially less biomass when they were not colonized (O’Dea 2000). These results infer that the slow regrowth of the perennial grasses, specifically that of the wolftail and grama grasses were in part mitigated by a belowground response to the burn. Within this grassland, prescribed burning appears to affect the structure of surface soil layers. Soil structure influences water infiltration, runoff, and erosion through aggregate size distribution and stability (Armstrong and Stein 1996, Blackburn et al. 1992, Granger 1992). First year increases in bulk density and lowered water intake rates within the burned plots infer a treatment effect on the stability of surface soil layers, yet results indicate aggregate stability did not differ after treatment. The removal of vegetation cover promotes the erosion process by exposing surface aggregates and structures to destruction by raindrop impact (Bennett 1974, Hester et al. 1997, Smith et al. 1990, Thurow et al. 1986). Observed increases in bulk density and decreases in water intake rates may be a function of fine particle illuviation and subsequent surface sealing, common to bare or sparsely vegetated surfaces (Bresson and Cadot 1992, Stolte et al. 1997). By the second year, aggregate stability was lower within the burned plots compared to the unburned. However, high variability between means did not allow for significant differences to be observed. Greater bulk density, runoff volumes and sediment production were also observed. The decline in aggregate stability may be a function of low levels of soil organic carbon (SOC), as well as declines in root growth and rhizosphere activity. As soil organic matter may be considered limiting in the more arid ecosystems of the southwestern U.S. (Whitford 1986), its removal through burning may result in the loss of water stable aggregates (Tate 1987). However, changes in aggregate stability and bulk density were not found correlated to the paucity of SOC, which was on average 1.1% (O’Dea 2000). Nor were there significant differences in SOC levels among treatments in either year. While changes in SOC levels do not appear to fully answer questions regarding declines in aggregate stability, reductions in belowground plant growth may. The mechanical binding of soil particles and aggregates by roots, as well as the production of root exudates are important mechanisms by which soil aggregates are stabilized (Tisdall and Oades 1982). Slow grass regrowth within the burn treatments, along with evidence of pedestal formation and post-treatment death of some remnant individuals may have resulted in the overall decline of root biomass, growth rates, and exudate production. However, these root properties were not measured in this study, and this hypothesis was not tested. First year comparisons of burn effects showed declines in water intake rates on burned plots appeared to be the result of surface sealing associated with the loss of vegetation cover. Second year declines, while possibly affected by a surface seal may also be the result of structural changes to surface soil layers. More specifically, the result of a decline in aggregate stability affiliated with the decline in perennial grass cover. For both years, the declines in intake rates and perennial grass cover resulted in increased sediment yield from the burned plots, but not in runoff volumes. Perturbation of the southern Arizona perennial grasslands, such as with springtime burning, whether by lightening ignitions or prescription, appears to create an environment that enhances tycpic erosion rates. Natural erosion rates are enhanced following burning because of the loss of vegetation cover and the high intensity of the unpredictable convective summer storms. In this study, with the use of artificial erosion (i.e. rainfall simulation), soil loss in two-thirds of the simulation x burn plots had exceeded their T-values or soil loss tolerances of 11.2 tonnes ha' year' (5 tons acre' year') by the fall of 1998 (Richardson et al. 1979). Unfortunately,
neither experimental method nor weather safety concerns allowed the measurement of the simulation’s sediment contributions or the analysis of the effects of the consecutive storms on the sediment yields observed in the first season. However, it may be inferred that if like storms commonly occur, they may have the potential to initiate a large erosion event, which in turn may extend the long-term effects of prescribed burning. Moreover, we were not able to determine if the effect of the rainfall simulation was an increase in sediment yield that would correspond to the site receiving 30% more summer rainfall, or if the simulation itself created unaccounted for factors that confounded the study’s results. However, it may be inferred from study results that the amount of soil loss on unburned areas (i.e., simulation only plots) is similar to what that area would lose had it received 30% more summer rainfall.

Summary

The perennial grasslands of southern Arizona have historically burned primarily in the late spring. Fires are ignited by the dry lightning strikes that precede the summer convective storms, the major source precipitation in the grasslands. Land managers attempting to reintroduce fire into these systems often ignite fires in the spring to mimic the natural fire regime reported for the semi-desert grasslands (Wright and Bailey 1982). Following prescribed burning, results indicate that the reduction in perennial grass cover strongly contributes to increases in runoff volumes and sediment yield the first post-burn year. However, without further disturbance the site appears to return to erosion and runoff rates observed in unburned conditions, even without vegetation cover reaching pre-burn levels. Initial declines in surface water intake rates were attributed to sediment alluviation and surface sealing, the effects of which appeared to disappear after the first year. The adverse effects of prescribed burning occurred after large (i.e. rainfall simulation for this study) or sequential storm events, with the interaction of the burn and storms creating an environment of increased erosion. The interaction appeared to adversely affect plant and soil structural components, perpetuating above-average runoff and erosion events in relation to unburned conditions. The stochastic nature of the summer storms (i.e., return intervals, intensity, and timing) contributes to the risks associated with prescribed burning, and therefore there is a need for these storm effects to be investigated further to provide information for the planning of prescribed burns.

Literature Cited


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