Soil Evaporative Response to Lehmann Lovegrass *Eragrostis lehmanniana* Invasion in a Semiarid Watershed

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Abstract

Across the western United States, warm-season grasslands are being invaded by the exotic perennial grass *Eragrostis lehmanniana* (Lehmann lovegrass). The objective of this study was to quantify the change in surface water balance associated with *E. lehmanniana* invasion. Following a protracted drought, the Kendall grassland in the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) in southeast Arizona transitioned from a native bunchgrass community to one dominated by *E. lehmanniana*. A network of microlysimeters was deployed at Kendall to measure daily soil evaporation (E_D), and an empirical model was developed to predict E_D based on soil moisture (θ) measured at 5 cm depth and average daily solar radiation (L). Results confirmed that total evapotranspiration over the growing season (ET_S) was a function of season-long infiltration (I_S) regardless of vegetation type, where ET_S/I_S was close to one. For years of similar precipitation patterns and ET_S/I_S, the contribution of evaporation E to ET for the growing season (E_S/ET_S) doubled with the invasion of *E. lehmanniana*. These results are a first step toward understanding the initiation and persistence of *E. lehmanniana* invasion.

Keywords: invasive grasses, ecohydrology

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Introduction

The invasion of the exotic grass, *Eragrostis lehmanniana* (Lehmann lovegrass) into native desert grasslands is of great concern to ranchers and land managers throughout the Southwestern United States. *Eragrostis lehmanniana* produces a near monoculture that displaces native grasses and in recent years has expanded over a substantial portion of semiarid grasslands of the desert southwest (McClaran and Anable 1992). The ecological effects of *E. lehmanniana* invasion have been well documented in studies showing that *E. lehmanniana* dominance is associated with dramatically reduced plant and animal diversity (Jones and Bock 2005). *Eragrostis lehmanniana* is also less sensitive to grazing and fire than most native grasses, and this disturbance tolerance may facilitate long-term persistence and dominance of *E. lehmanniana* in desert grasslands (McClaran and Anable 1992). There is far less known about the impact of *E. lehmanniana* invasion on ecosystem hydrology, despite the fact that it is a common invasive species in the desert southwest where water is scarce. *Eragrostis lehmanniana* can have smaller plant basal areas yet higher plant densities than native bunchgrasses, resulting in little change in grass biomass compared to pre-invasion levels. Consequently, it is difficult to determine if *E. lehmanniana* invasion will affect ecosystem water balance, and if so, if it will cause an increase or decrease in total season-long evapotranspiration (ET_S), soil evaporation (E_S), and (or) plant transpiration (T_S).

The goal of this study was to use multiyear measurements of a naturally occurring vegetation transition to quantify the change in surface water balance, particularly soil evaporative response, associated with *E. lehmanniana* invasion. Specifically, the objectives were to determine (1) the variability that

can be expected in E_S/ET_S with a native-to-exotic grassland transition, and (2) the key processes that control this variability. A basic premise of this study was that seasonal E_S/ET_S during the native-to-exotic grassland transition is largely a function of the variability in precipitation and the vegetation, and that the impact of these two factors on E_S/ET_S could be decoupled by analysis of measurements made throughout the multiyear transition.

Methods

The study was conducted in the Kendall grassland in southeast Arizona (Renard et al. 2008), which shifted from a grassland dominated by the native bunchgrass *Bouteloua eriopoda* (Torr.) Torr. (black grama) in 2005 to near complete dominance by the exotic *E. lehmanniana* in 2007.

Precipitation, runoff, and meteorological conditions have been recorded at Kendall over the past decade (Goodrich et al. 2008, Stone et al. 2008, Keefer et al. 2008). Precipitation is measured with a weighing-type recording raingage, and runoff is measured with a V-notched weir for the small Kendall subwatershed. Daily infiltration (I_D), defined as the total equivalent depth of water that enters the soil, was computed by subtracting daily runoff from daily precipitation (units of length). These values were then summed to compute a season total value (I_S). Average daily solar radiation (L_D) was computed as the average of incoming solar radiation measurements over the daylight period, generally from 8 a.m. to 6 p.m. during the growing season (W/m^2). This value was then averaged to compute a seasonal value (L_S).

From 1997 through 2007, a Bowen ratio system was on site to measure diurnal ET at 20-min intervals, summed to give a value of daily ET_D (Emmerich and Verdugo 2008). The Bowen ratio system was placed near the meteorological station with a fetch of 200+ m in all directions. In 2005, a network of 20 microlysimeters (ML) were installed at Kendall to measure E_D (Green 2006). Microlysimeters of 76-mm diameter and 30-cm depth were installed in a cross-shaped pattern centered on the Bowen ratio system over an area of 60 x 60 m. Daily E_D was measured manually on days between rainfall events during the vegetation growing season in 2005 (Green 2006) and for a more limited time in 2007.

The net ecosystem exchange of carbon dioxide (NEE) was also measured at Kendall using a Licor 7500 open path CO_2/H_2O analyzer. NEE represents the respiration by microorganisms and plants that release CO_2 to the atmosphere and the fixation of CO_2 that occurs during photosynthesis, where the latter is associated with the concurrent water loss due to T. The notation used in this paper was adopted from that presented by Kurc and Small (2007), where positive values of NEE correspond to net respiration over 24 hours (NEE_D^+) and negative values of NEE correspond to net assimilation over 24 hours (NEE_D^-).

The trends of NEE_D (not shown) were used to discriminate three analysis periods. The "growing season" was the time period when perennial plants were likely to be green and transpiring **and** the majority of the North American Monsoon (NAM) precipitation was encompassed: days 180–315. The "early season" was defined as the period when NEE_D was generally positive, precipitation was increasing from the dry June period, and T_D could be assumed to be low allowing E_D to reach a maximum: days 180–214. The "mid season" was defined as the period when NEE_D was likely to be negative at some point, plants had received sufficient precipitation to be actively transpiring, and T_D could be assumed to reach a maximum: days 215–285.

From 2003 to the present, volumetric soil moisture (θ) has been measured at Kendall at two depths (5 and 15 cm) at 20- to 30-min intervals with Stevens Hydra Probe sensors (Keefer et al. 2008). The sensors were located close to the Bowen ratio system and centered within the 60 x 60 m network of microlysimeters. Soil moisture measured at 5 cm (θ_5) was assumed to characterize the surface soil moisture from 0 to 5cm.

Hydrological and ecological conditions

This multiyear investigation was designed to allow discrimination of the change in E_S/ET_S associated with the influences of annual precipitation patterns and vegetation type. The first step was to identify years of similar vegetation and hydrology that could be compared and contrasted in further analysis (Table 1).

Vegetation measurements showed that for years 2002–2005 the vegetation cover was dominated by *B. eriopoda* (King et al. 2008). Year 2006 was a "transition" year in which *B. eriopoda* experienced a drastic die-off, the *E. lehmanniana* was increasing its

presence, and the annual forbs represented the dominant vegetation cover. By year 2007, the vegetation cover was dominated by *E. lehmanniana*. This groups the years into those dominated by *B. eriopoda* (2002–2005), by forbs (2006), and by *E. lehmanniana* (2007).

A basic assumption underlying this study is that ET_S/I_S over the water year at Kendall would be greater than or close to one regardless of vegetation differences (Table 1). For years when infiltration was at or above the 30-yr average (215 mm/yr), ET_S/I_S was only slightly greater than one (1.06). For years when infiltration was below the 30-yr average, ET_S/I_S increased with decreasing I_S according to the function
$ET_S/I_S = (-2.34 \times 10^{-3}) + 1.62(I_S)$ {r^2=0.77}.

Over the period from 2002 to 2007, there are only two years that were hydrologically similar: years 2002 and 2007. They had nearly identical I_S, minimum NEE_D, and ET_S/I_S (Table 1). All other years were determined to have exclusive hydrologic patterns. Years 2005 and 2006 were the polar extremes, where year 2006 had substantially more precipitation than any other year and year 2005 had substantially less. Years 2003 and 2004 had similar total precipitation but it was distributed differently, where precipitation in year 2003 was distributed evenly throughout the growing season, and the precipitation pattern in year 2004 was bi-modal resulting in a strongly bi-modal trend in NEE_D.

Table 1. Comparison of vegetation and hydrological conditions over the growing season (days 180–315). Veg refers to the dominant vegetation type (*B.e.* is *B. eriopoda* and *E. l.* is *E. lehmanniana*), ET_S/I_S refers to the ratio of seasonal evapotranspiration (ET_S) and infiltration (I_S); NEE min is the minimum daily net ecosystem exchange over the growing season; and the last two columns indicate if the vegetation and precipitation patterns were considered similar.

Year	Veg	ET_S/I_S	I_S	NEE min	Veg sim?	Pcp sim?
2002	*B. e.*	1.16	178	-29	√	√
2003	*B. e.*	1.32	114	-9	√	
2004	*B. e.*	1.25	154	-9	√	
2005	*B. e.*	1.43	91	-15	√	
2006	forbs	1.06	219	-30		
2007	*E. l.*	1.18	175	-31		√

Results and Discussion

The stated objectives of this study were to determine (1) the variability that can be expected in E/ET with a native-to-exotic grassland transition, and (2) the key processes that control this variability. Analysis of data was conducted in several steps. First, the measurements made with microlysimeters in 2005 (pre-invasion) and 2007 (post-invasion) were were used to develop an empirical model to estimate E_D from measurements of θ_5 and L_D throughout the season for all years (2002–2007). These estimates of season-long E_D and concurrent measurements of ET_D made it possible to investigate the trends in E_D/ET_D that could be expected with different precipitation patterns and vegetation types. Finally, we were able to use the seasonal E_S/ET_S estimates to determine the impact of *E. lehmanniana* invasion on ecosystem water balance.

E_D from microlysimeter measurements

The ML measurements offered the opportunity to develop an empirical model of ET_D based on the assumptions that soil evaporation occurs at shallow depths (5–15 cm) and varies with available energy (Loik et al. 2004). A regression was fit to ML measurements of E_D and midday measurements of θ_5 (Figure 1A). Similarly, the relation between ML measurements of E_D and L_D was explored, but there was no significant relation for the days of ML measurements when values of L_D were greater than 400 W/m^2 (Figure 1B). As a result, it was possible to predict E_D from θ_5 and L_D using an equation derived from multiple regression,

$$E_D = (8.78 \times 10^{-2}) + (11.66)\theta_5 - (1.02 \times 10^{-4})L_D \qquad (1)$$

with r^2=0.91, where Equation 1 could be applied to days with L_D>400 W/m^2.

The comparison of E_D modeled with Equation 1 versus E_D measured with ML offers an indication of the error one might expect in application of the model to other years, assuming the measurements of θ_5 and L_D continue to be accurate and the relation in Equation 1 holds over several years for the Kendall site. The mean absolute difference (MAD) between the modeled and measured E_D was only 0.3 mm/d and the values clustered around the 1:1 line in Figure 1C. Given this good fit, Equation 1 was used to estimate E_D for years

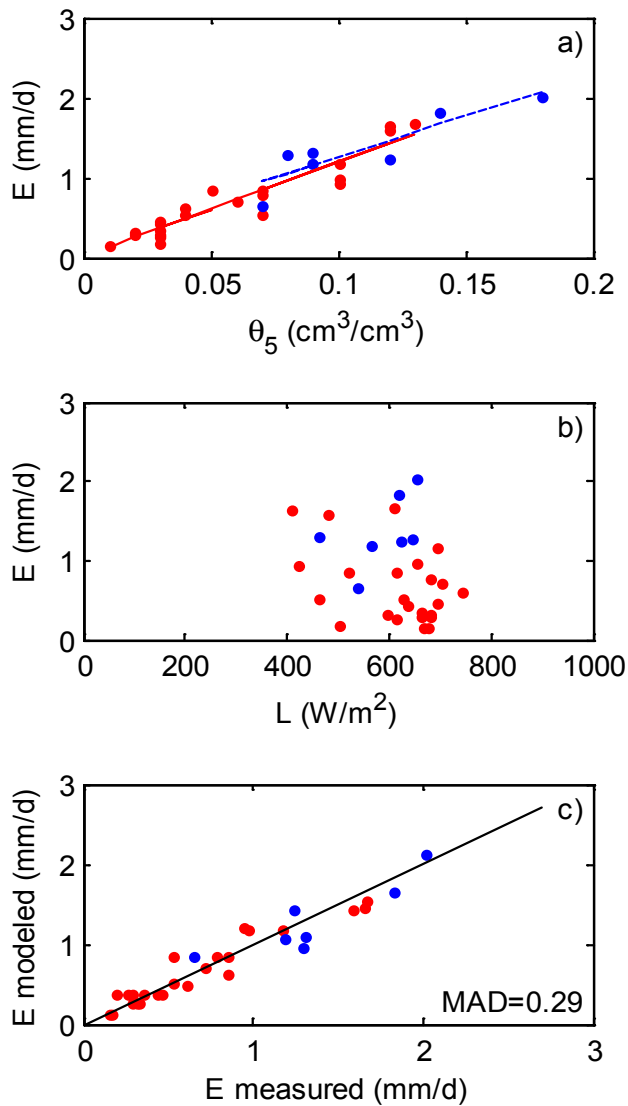2002–2007 for further analysis in the following sections.

Figure 1. The relations between E_D measured with microlysimeters versus (A) soil moisture at 5 cm depth (θ_5), (B) average daily solar radiation (L_D), and (C) E_D modeled with θ_5 and L_D.

Maximum E_D/ET_D and T_D/ET_D

Results demonstrated that E_D and T_D reach a maximum value that was a linear function of ET_D (not shown here). By selecting the $\{E_D, ET_D\}$ and $\{T_D, ET_D\}$ data pairs associated with the left edge of the E_D and T_D versus ET_D relations, it was possible to determine the maximum E_D/ET_D and T_D/ET_D for the early and mid seasons for each study year (Figure 2). This is expressed as a general linear form $\{y=a+bx\}$ by Guswa et al. (2002) that was fit to Kendall data as follows:

$$Maximum\ E_D = aET_D, \text{ and} \qquad (2)$$

$$Maximum\ T_D = ET_D\text{-}b, \qquad (3)$$

where a and b are coefficients determined by regressions illustrated in Figure 2. For Equation 2, the intercept of the linear relation between E_D and ET_D was near zero, as expected. For Equation 3, the slope of the relation between T_D and ET_D was near one and the intercept b was related to the minimal value of E_D for the season.

For years 2002–2004, when precipitation was slightly below normal and vegetation cover was dominated by *B. eriopoda,* values of maximum E_D/ET_D were similar (maximum $E_D/ET_D = 0.41$) (Figure 2A). For all other years maximum E_D/ET_D was higher, indicating an increase in E_D during the early season when precipitation is extremely low (maximum $E_D/ET_D = 0.60$ in 2005) or when vegetation has changed (maximum $E_D/ET_D = 0.51$ in 2007). The results for year 2006 are difficult to interpret because there was a simultaneous change in both precipitation pattern and vegetation type.

Values of maximum T_D/ET_D were similar for years 2002–2006, where maximum $T_D = ET_D\text{-}0.3$ mm/d with a MAD of 0.09 mm/d (Figure 2B). This can be interpreted to mean that the minimum value of E_D during the mid-season in all years was close to 0.3 mm/d. This was similar to the value derived from the ML data for Kendall in 2005 by Moran et al. (2008). However, maximum T_D/ET_D in 2007 was strikingly different from all other years, where maximum $T_D = ET\text{-}0.77$ mm/d (MAD=0.09 mm/d). This means that the minimum value of mid-season E_D was more than double that estimated for any other year in the study. This could be explained by the distribution of root biomass at Kendall. Cox et al. (1986) reported that 70 percent of the fine root biomass at Kendall was between 0 and 6 inches in year 1983. Assuming the same vegetation persisted in years 2002–2005 (according to King et al. 2008), this root biomass was sustained until 2006 when the relative dominance of *B. eriopoda* decreased to zero and the cover was dominated by annual forbs. With the invasion of *E. lehmanniana* in 2007, much of the *B. eriopoda* root biomass was dead and perhaps not replaced with similar biomass during the early period of

E. lehmanniana establishment. It may also be explained by differences in leaf area index (not measured in this study). Huxman et al. (2004) hypothesized that lower LAI in *E. lehmanniana* plots may promote higher soil temperatures, which would favor the evaporation of soil water rather than infiltration following rain events.

Growing season E_S/ET_S

A basic ecohydrological question was posed in the introduction: Does *E. lehmanniana* invasion affect ecosystem water balance, and if so, will it cause an increase or decrease in ET_S, E_S, and (or) T_S? A preliminary answer can be found by comparing the evaporative response over the entire growing season (days 180–315) in years 2002 and 2007, when precipitation patterns were similar but vegetation was not. First, the ET_S and ET_S/I_S in 2002 and 2007 were nearly identical, despite the dramatic vegetation transition (Table 1). However, results show that the partitioning of E_S and T_S was greatly changed. Apparently, the rapid transition from an established native grassland dominated by *B. eriopoda* to a new stand dominated by the exotic *E. lehmanniana* has caused maximum E_D/ET_D to increase and maximum T_D/ET_D to decrease substantially (Figure 2). As a result, E_S/ET_S over the growing season was twice as high in 2007 than in 2002, while both years had average precipitation and similar precipitation patterns (Figure 3).

Conclusions

This study investigated the variability that can be expected in E/ET with *E. lehmanniana* invasion and the key processes that control this variability. Preliminary conclusions drawn from observations over six years in the Kendall semiarid grassland were:
1. The transitions from *B. eriopoda* to *E. lehmanniana* did not affect ET_S/I_S over the growing season.
2. Maximum daily E_D/ET_D was influenced by both precipitation patterns and vegetation type; maximum daily T_D/ET_D was influenced by vegetation type but not precipitation patterns.
3. Regarding the basic question about whether *E. lehmanniana* invasion would cause an increase or decrease in E_S, results showed that E_S/ET_S over the growing season doubled during years of average precipitation and similar precipitation pattern (i.e., 2002 and 2007).
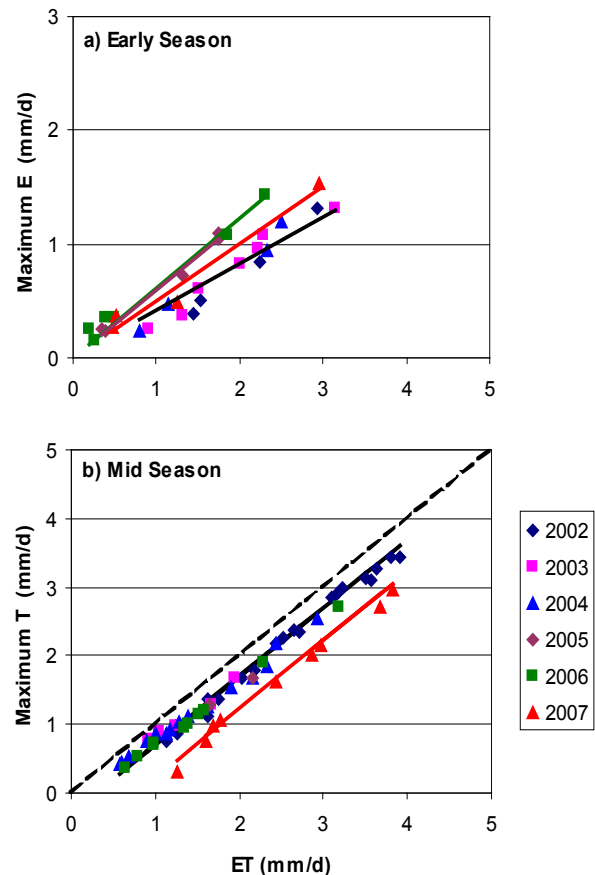

Figure 2. The maximum (A) E_D/ET_D and (B) T_D/ET_D for the early and mid seasons (respectively) for study years 2002–2007. The solid lines represent (A) maximum $E_D =aET_D$ and (B) maximum $T_D = ET_D-b$, and the dashed line is the 1:1 line for T_D/ET_D.
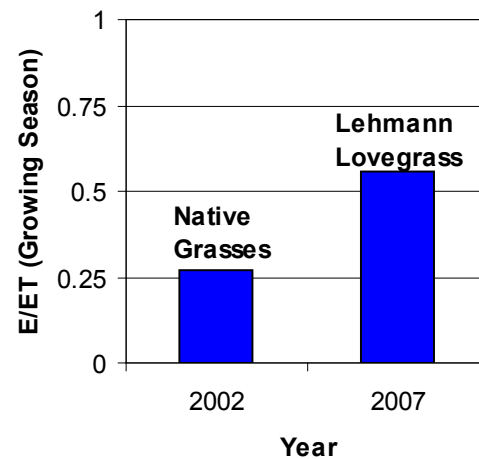

Figure 3. Values of E_S/ET_S over the growing season (days 180–315) in 2002 (pre-invasion) and 2007 (post-invasion) for years of average precipitation and similar precipitation patterns (Table 1).

Acknowledgments

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