

Soil evaporation 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, particularly the evaporation from bare soil, associated with *E. lehmanniana* invasion. Following a protracted drought, the Kendall grassland in the USDA-ARS Walnut Gulch Experimental Watershed in southeast Arizona transitioned from a diverse, native bunchgrass community to one dominated by *E. lehmanniana*. A network of 20 microlysimeters was deployed to measure daily soil evaporation (E_D) in 2005 and again in 2007 (pre- and post-invasion years, respectively). This was supported with continuous measurements of evapotranspiration (ET), precipitation (P), runoff (R), surface soil moisture (θ), and solar irradiance (L) at Kendall from 2002 to the present. An empirical equation was developed to derive E_D based on θ measured midday at 5 cm depth and average daily L . This was applied to years 2002–2007 during the vegetation growing season (June through October). Results confirmed that total ET over the growing season (ET_S) was a function of season-long infiltration (where $I_S = P_S - R_S$) for growing seasons over the past decade regardless of vegetation type, where ET_S/I_S was slightly greater than one in years drier than average and close to one in years with greater than average infiltration. 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*. Variation in E_S/ET_S ranged from 0.26 to 0.60 for years 2002–2007, where variation was related primarily to inter-annual precipitation patterns in the early season and to distinctive vegetation transformation in the middle season. These results are a first step toward understanding the ecohydrological consequences of *E. lehmanniana* invasion in semiarid grasslands.

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1. 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. *E. lehmanniana* produces a near monoculture that displaces native grasses, and in recent years, has expanded over a substantial portion of semiarid grasslands (Anable et al., 1992). The ecological effects of *E. lehmanniana* invasion have been well documented in studies showing *E. lehmanniana* dominance is associated with dramatically reduced plant and animal diversity (Bock et al., 1986; Bock and Bock, 1992a; McClaran and Anable, 1992; Jones and Bock, 2005). *E. lehmanniana* is also more resilient to grazing and fire than most native grasses, and this disturbance tolerance may facilitate long-term persis-

tence and dominance of *E. lehmanniana* in desert grasslands (Angel and McClaran, 2001; McClaran and Anable, 1992; McGlone and Huenneke, 2004; Geiger and McPherson, 2005; Bock and Bock, 1992b). 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. One study showed that *E. lehmanniana* is capable of utilizing soil water in the winter when native grass species are dormant, and that this might affect seasonal water balance (Frasier and Cox, 1994). *E. 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).

In semiarid environments, dramatic vegetation changes like *E. lehmanniana* invasion will not likely impact ET_S from a given site because seasonal evaporative demand almost always exceeds

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seasonal precipitation (Huxman et al., 2005). That is, the ratio of ET_S to infiltration (where I_S = seasonal precipitation (P_S) – seasonal runoff (R_S)) would be greater than or close to one regardless of vegetation differences (Wilcox et al., 2003). On the other hand, there is an expectation that the partitioning of ET into water lost by evaporation from soil and transpiration from plants would likely shift significantly with vegetation transition (Reynolds et al., 2000). Still, the magnitude and direction of this hydrologic shift is not well understood.

The partitioning of ET into components E and T at a given site is a complex and interactive function of both the vegetation type and the annual precipitation pattern (Norman et al., 1995). There is evidence that inter- and intra-seasonal precipitation patterns can cause substantial variations in E_S/ET_S when vegetation is unchanged (D'Odorico et al., 2000; Loik et al., 2004; Scott et al., 2006). The seasonal timing and size of episodic rainfall ("pulses") have been found to have a great influence on the E_S/ET_S ratio (Potts et al., 2006; Schwinning and Sala, 2004; Lane et al., 1983; Taylor, 2000). In some situations, the influences of precipitation timing and frequency on daily transpiration are more important than total precipitation (Emmerich and Verdugo, 2008b). Distribution of rainfall can result in wide variations in E_S/ET_S , varying in some cases by 60% without any change in perennial vegetation cover (Reynolds et al., 2000). This impact is exacerbated during drought conditions because year-to-year E_S/ET_S is especially sensitive to precipitation patterns for normal and below-normal amounts of rainfall (Reynolds et al., 2000). Within each year, the direct effect of precipitation patterns on T_S/ET_S is less pronounced during the wet season because T_S is sensitive to leaf area index (LAI), which in turn can depend on rainfall conditions over the previous weeks or years (Taylor, 2000). However, there is some evidence that T_S/ET_S will decrease with decreasing precipitation (Reynolds et al., 2000).

Information about the short-term dynamics of ecosystem physiology of native and invasive grasses has been gained from experimental stands with precipitation manipulation. Huxman et al. (2004) established plots of native grass (*Heteropogon contortus*) and the invasive *E. lehmanniana* beneath rainout manipulation shelters in southeast Arizona. They reported that invasive species stands had greater ET_D rates immediately following the precipitation pulse than did native stands. They explained that the greater plot-level water use for the *E. lehmanniana* was most likely a function of greater soil evaporation, rather than plant transpiration, because the transpiration activity following a pulse was shorter in non-native species than in native species. These insights into short-term dynamics based on plot-level studies offer a foundation for investigations of the long-term behavior of grasses during the transition from native to non-native grass assemblages.

The long-term hydrologic adjustment associated with *E. lehmanniana* invasion has been difficult to study because the instrumentation to measure ET_S , T_S and E_S are rarely in place before, during and after the vegetation transition. Only with measurements over a series of years will it be possible to discriminate the direction and magnitude of change associated with precipitation patterns and vegetation type. Large interannual variation in precipitation in dryland ecosystems could require multi-decadal measurements to understand associated variation in water budgets and soil water, yet few studies have attempted these measurements within semiarid areas (Kurc and Small, 2007).

The goal of this study was to use multi-year measurements that span a naturally occurring vegetation transition to quantify the change in surface water balance, particularly evaporative response, associated with *E. lehmanniana* invasion. Specifically, the objectives were to determine (1) the variation that can be expected in E_S/ET_S with a native-to-exotic grassland transition and (2) the key processes that control this variation. Because of the high potential

ET in dryland areas, E and T contend for available soil water and a reduction in one is almost guaranteed to result in an increase in the other (Loik et al., 2004). A basic premise of this study was that E_S/ET_S during the native-to-exotic grassland transition is largely a function of the variation 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 multi-year transition.

2. Study site, materials and methods

2.1. Study site

The Kendall grassland is located in the USDA-ARS Walnut Gulch Experimental Watershed (Renard et al., 2008) near Tombstone, Arizona (109°56'28"W 31°44'10"N, elevation 1526 m). Average annual precipitation from 1965 to 2007 was 341 mm with a mean annual ambient temperature of 17 °C. The climate is semiarid and the precipitation regime is dominated by the North American Monsoon with about 60% of the annual precipitation occurring during July, August and September. The soil at the site is primarily Stronghold (Coarse-loamy, mixed, superactive, Ustic Haplocalcids) with clay content ranging from 5 to 15% and slopes ranging from 4 to 9%. The total vegetation cover in 2005 was estimated to be 47% (King et al., 2008).

The near-complete transition from native-to-exotic grasses at Kendall was documented through photographs and standard vegetation cover, density and species measurements made at Kendall on a regular basis (King et al., 2008; Skirvin et al., 2008). In 2005, species composition along the historical vegetation transects was dominated by grama grasses (*Bouteloua* spp.), which composed nearly 40% of the total vegetation cover (termed relative dominance). In 2006, there was a dramatic transition during which the relative dominance of native species decreased to zero along the transects and the relative dominance of forb cover increased to >60%. From 2005 to 2007, the relative dominance of *E. lehmanniana* increased from 10% to nearly 30%. As a result, the vegetation composition changed from a typical semiarid native bunchgrass assemblage dominated by *Bouteloua* spp. in 2005 to a system dominated by the exotic *E. lehmanniana* and annual forbs in 2007 (Fig. 1).

2.2. Precipitation and runoff

Precipitation and runoff have been recorded at Kendall from 1965 to the present (Goodrich et al., 2008; Stone et al., 2008).

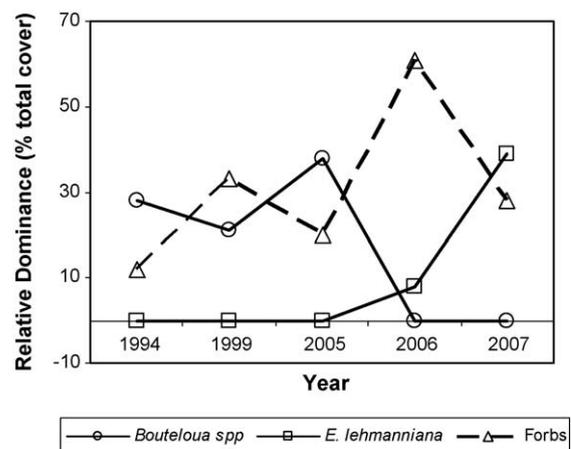


Fig. 1. The relative dominance of *Bouteloua* spp., *E. lehmanniana* and forbs at Kendall from 1994 to 2007.

Table 1

Precipitation patterns at Kendall for years 1998–2007 over periods August to mid-October (middle season), July (early season), January–March (winter) and January–December (annual). Infiltr refers to the sum of precipitation minus the sum of runoff (mm); #st > 2 mm and #st > 8 mm refer to the number of storms with infiltration >2 mm and >8 mm (respectively); and %dp < 10 day refers to the percent of dry periods (periods with no precipitation) that were shorter than 10 days. NA means data were not available.

	August to mid-October (days 215–285)				July	January–March	January–December
	#st > 2 mm	#st > 8 mm	%dp < 10 d	Infiltr (mm)	Infiltr	Infiltr	Infiltr
1998	7	4	78	93	104	NA	NA
1999	12	5	85	144	167	5	333
2000	15	8	93	201	67	11	439
2001	9	3	66	112	100	49	304
2002	12	4	73	92	82	27	235
2003	9	4	66	86	44	42	199
2004	10	5	78	99	44	104	293
2005	8	3	71	61	29	65	162
2006	19	8	89	153	63	7	231
2007	8	2	94	75	101	58	297
10-year average	10.9	4.6	79	111.6	80.1	41 [*]	277 [*]

^{*} 9-year average.

Precipitation is measured with a weighing-type recording rain-gage, and runoff is measured with a V-notched weir. Daily infiltration (I_D), defined as the total equivalent depth of water that enters the soil, was calculated by subtracting R_D from P_D (units of length). These values were then summed to compute a seasonal total value (I_S).

The temporal distribution of precipitation is generally described by the total precipitation, the size-class distribution of daily precipitation events and the size-class distribution of the interstorm periods. Loik et al. (2004) reported that, in warm areas, the importance of small precipitation events increase as mean annual precipitation decreases and importance of short dry periods increases as mean annual precipitation increases. In this study, the seasonal precipitation pattern (Table 1) was characterized by (1) the total infiltration, (2) the total number of precipitation events, where events were filtered to those >2 mm to account for interception of rainfall and subsequent evaporation, (3) the total number of “large” events, where large events were defined as those >8 mm (per Kurc and Small, 2004), and (4) the percentage of dry periods (periods with no precipitation) that were shorter than 10 days during the study period (per Loik et al., 2004).

2.3. Energy and water flux

Since 1990, meteorological data (including incoming solar irradiance, air temperature and wind speed) have been measured at 5- and/or 20-min intervals at Kendall (Keefer et al., 2008). Average daytime solar irradiance (L_D) was computed as the average of incoming solar irradiance measurements over the daylight

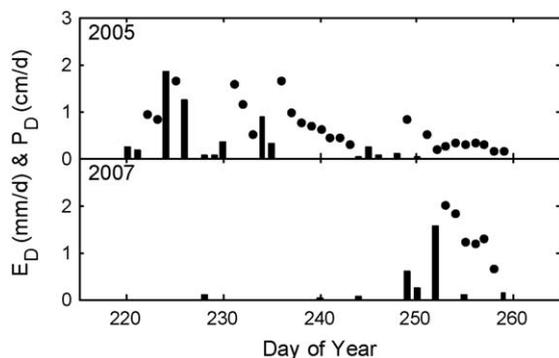


Fig. 2. Daily soil evaporation (E_D , mm d^{-1}) measured manually with a network of microlysimeters on days between rainfall events during the vegetation growing season in 2005 and 2007. The bars represent daily precipitation (cm d^{-1}).

period (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 ET at 20-min intervals, which were summed to give a value of daily ET_D (Emmerich and Verdugo, 2008a). 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) was installed at Kendall to measure E_D (Green, 2006) based largely on the design and deployment described by Boast and Robertson (1982). Microlysimeters of 76 mm diameter and 30 cm depth were installed in a cross-shaped pattern centered on the Bowen ratio system with a NW-SE transect (corresponding to the dominant wind directions) of 12 lysimeters spaced every 15 m and a NE-SW transect of 8 lysimeters every 20 m. Daily water loss was measured manually on days between rainfall events during the summer growing season in 2005 (Green, 2006) and for a more limited time in 2007. Ecosystem E_D was estimated to be the average of 20 ML measurements corrected for site-specific vegetation cover at Kendall according to Green (2006) (Fig. 2).

The net ecosystem exchange of carbon dioxide (NEE) was also measured at Kendall using the Bowen ratio system. 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 h (NEE_D^+) and negative values of NEE correspond to net assimilation over 24 h (NEE_D^-).

The trends of NEE_D in Fig. 3 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 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. During the early season, plant root activity is dependent on stimulation from an initial wetting event (Loik et al., 2004). At Kendall, Emmerich and Verdugo (2008b) reported that a minimum of 57–94 mm precipitation was needed to produce a net CO_2 uptake if an earlier Spring response had occurred. They reported that a minimum of 80–148 mm was needed when there was no Spring growing season. The “middle 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

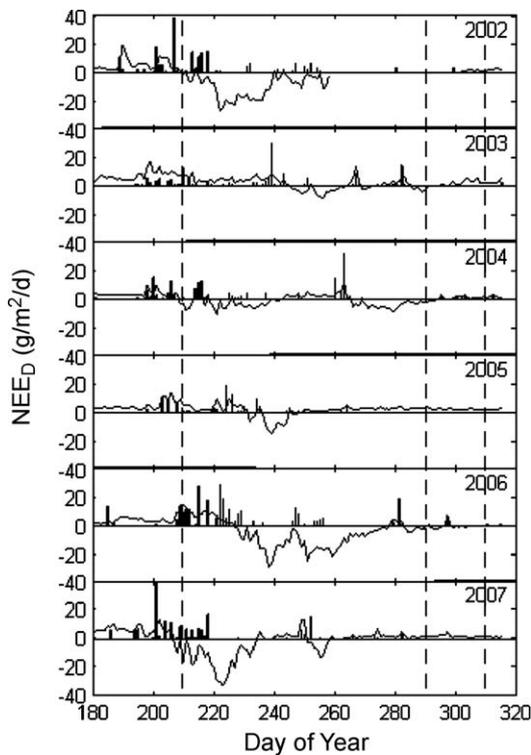


Fig. 3. The trends of daily net ecosystem exchange of CO_2 (NEE_D , solid line, $\text{g m}^{-2} \text{d}^{-1}$) and precipitation (bars, mm d^{-1}) for years 2002–2007, where vertical dashed lines delineate the analysis periods for this study: the early growing season (days 180–215), middle growing season (days 215–285) and entire growing season (days 180–315).

transpiring, and T_D could be assumed to reach a maximum: days 215–285.

From 2002 to 2007, volumetric soil moisture (θ) was measured at Kendall with Stevens Hydra Probe sensors placed horizontally at depths of 5 and 15 cm (θ_5 and θ_{15} , respectively) and measurements made at 20- to 30-min intervals (Paige and Keefer, 2008; Keefer et al., 2008). The sensors were located close to the Bowen ratio system and centered within the $180 \text{ m} \times 120 \text{ m}$ network of microlysimeters. The greatest variation in soil water occurred in

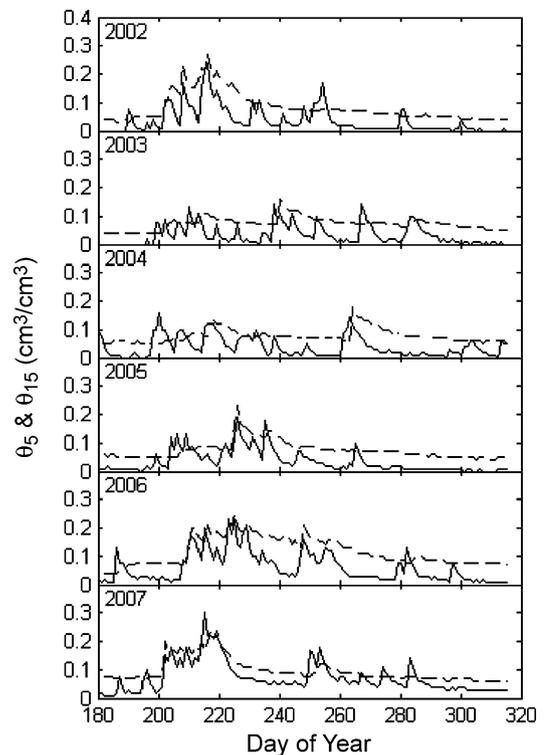


Fig. 4. Volumetric soil moisture measured at depths of 5 cm (θ_5 , solid line) and 15 cm (θ_{15} , dashed line) for years 2002–2007 at Kendall.

the top 5 cm and only the largest storms contributed to θ_{15} (Fig. 4). To determine if the measurements with the single soil moisture sensor at 5-cm depth were representative of the larger area covered by the microlysimeters, measurements of soil volumetric soil moisture at 5 cm at each ML was measured with a portable Delta-T ThetaProbe on two occasions in 2007 (days 249 and 250) and averaged for comparison with the θ_5 measured with the Stevens Hydra Probe. Results showed that the single Hydra Probe measurement was within $0.01 \text{ cm}^3 \text{ cm}^{-3}$ for values of θ_5 of 0.06 and 0.18. Though this was not an exhaustive comparison, the values were not dissimilar and offered support for the representation of the study area with the single Hydra Probe sensor.

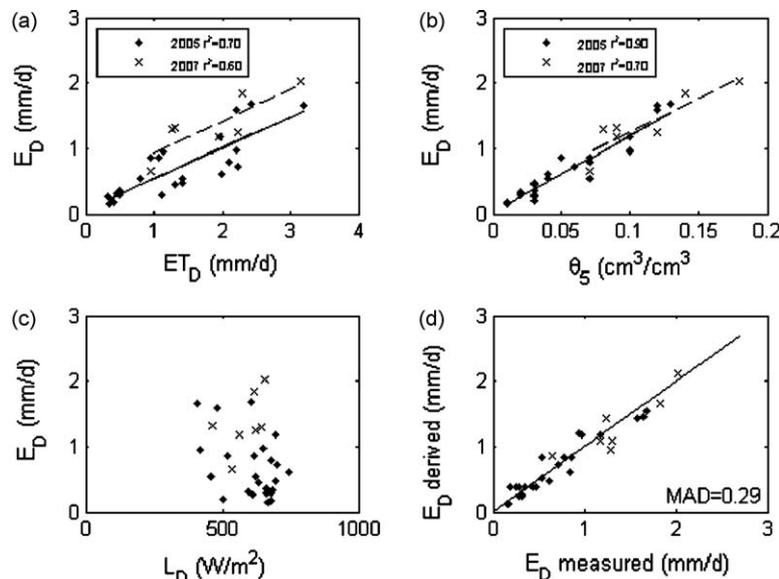


Fig. 5. The relations between daily soil evaporation (E_D) measured with microlysimeters versus (a) daily evapotranspiration (ET_D) measured with the Bowen ratio instrumentation, (b) soil moisture measured with the HydroProbe at 5 cm depth (θ_5), (c) average daily solar irradiance (L_D), and (d) E_D derived from θ_5 and L_D .

2.4. E_D from microlysimeter measurements—years 2005 and 2007

Daily soil evaporation was measured with ML on days between rainfall events during the vegetation growing season in 2005 and 2007 (Fig. 2). The measurements of ecosystem E_D were related to ET_D for the few days measured in 2005 and 2007 (Fig. 5a). The relation of E_D/ET_D differed in 2005 (an extremely dry year with vegetation dominated by *Bouteloua* spp.) and 2007 (a year of average infiltration with vegetation dominated by *E. lehmanniana*). E_D represented a greater portion of ET_D in 2007 than in 2005, implying that E_D/ET_D would be greater in 2007 than in 2005 over the growing season.

The ML measurements offered the opportunity to develop an empirical derivation of ET_D based on the assumptions that soil evaporation occurs at shallow depths (~0–10 cm) (Loik et al., 2004; Kurc and Small, 2004) and varies with available energy (Ben-Asher et al., 1983). With adequate available energy, soil evaporation is controlled largely by surface soil moisture (Brutsaert and Chen, 1995). A regression was fit to ML-measurements of E_D and midday measurements of θ_5 (Fig. 5b). 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} (Fig. 5c). As a result, it was possible to derive E_D from θ_5 and L_D using an equation based on multiple regression:

$$E_D = (8.78 \times 10^{-2}) + (11.66)\theta_5 - (1.02 \times 10^{-4})L_D \quad [r^2 = 0.91], \quad (1)$$

where Eq. (1) could be applied to days with $L_D > 400 \text{ W m}^{-2}$.

The comparison of E_D derived with Eq. (1) versus E_D measured with ML offers an indication of the error one might expect in application of the equation to other years, assuming the measurements of θ_5 and L_D continue to be accurate and the relation in Eq. (1) holds over several years for the Kendall site. The mean absolute difference (MAD) between the derived and measured E_D was only 0.3 mm d^{-1} and the values clustered around the 1:1 line in Fig. 5d. Given this good fit, Eq. (1) was used to derive E_D for years 2002–2007 for further analysis in the following sections.

2.5. Computation of hydrological and ecological conditions

This multi-year 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 2).

Regarding vegetation, it can be inferred from the vegetation measurements (Fig. 1) that for years 2002–2005 the vegetation cover was dominated by *Bouteloua* spp. (King et al., 2008). Year 2006 was a “transition” year in which *Bouteloua* spp. experienced a

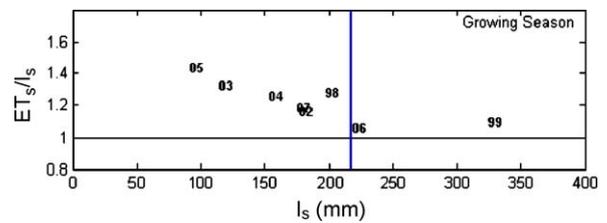


Fig. 6. The relation between the ratio of total growing season evapotranspiration over infiltration (ET_S/I_S) versus I_S for years 1998–2007 when continuous values of ET_D were available, where numbers represent the abbreviated year. The horizontal line represents $ET_S/I_S = 1.0$ and the vertical line represents the average I_S over the 30-year period from 1976 to 2007.

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*.

A basic premise underlying this study is that ET_S/I_S at Kendall would be close to one regardless of vegetation differences (Wilcox et al., 2003; Wilcox, 2002). For all the years with continuous ET_D measurements over this growing season, the ET_S/I_S was greater than one (Fig. 6). For years when infiltration was at or above the 30-year (1976–2007) average, ET_S/I_S was only slightly greater than one (1.06). For years when infiltration was below the 30-year average, ET_S/I_S increased with decreasing I_S .

Regarding hydrology, the measurements of I_S , NEE_S and ET_S/I_S through the growing season were used to identify years that were hydrologically similar. 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 , NEE_S and ET_S/I_S (Table 2) and similar temporal trends in NEE_D (Fig. 3). 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 .

3. Results and discussion

The stated objectives of this study were to determine (1) the variation that can be expected in E/ET with a native-to-exotic grassland transition and (2) the key processes that control this variation. Estimates of season-long E_D and concurrent measurements of ET_D made it possible to investigate the differences in E_D/ET_D that could be expected with different precipitation patterns and vegetation types. It was also possible to determine maximum E_D/ET_D , which was indicative of the limits imposed by the combination of precipitation patterns and vegetation type. 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.

Table 2

Comparison of vegetation and hydrological conditions over the growing season (days 180–315) for the years of the study 2002–2007. The dominant vegetation cover was taken from results presented in Fig. 1. ET_S/I_S refers to the ratio of seasonal evapotranspiration (ET_S) and infiltration (I_S); NEE range is the range of net ecosystem exchange over the growing season; and the last two columns indicate if the vegetation and precipitation patterns in the given year were considered similar to conditions in 2002, respectively, where a check mark indicates similarity.

	Dominant vegetation cover	ET_S/I_S	I_S (mm)	NEE range ($\text{g m}^{-2} \text{d}^{-1}$)	Vegetation similar to 2002?	Precipitation pattern similar to 2002?
2002	<i>Bouteloua</i> spp.	1.16	178	19 to –29	✓	✓
2003	<i>Bouteloua</i> spp.	1.32	114	18 to –9	✓	
2004	<i>Bouteloua</i> spp.	1.25	154	10 to –9	✓	
2005	<i>Bouteloua</i> spp.	1.43	91	15 to –15	✓	
2006	Assorted annual forbs	1.06	219	15 to –30		
2007	<i>E. lehmanniana</i>	1.18	175	15 to –31		✓

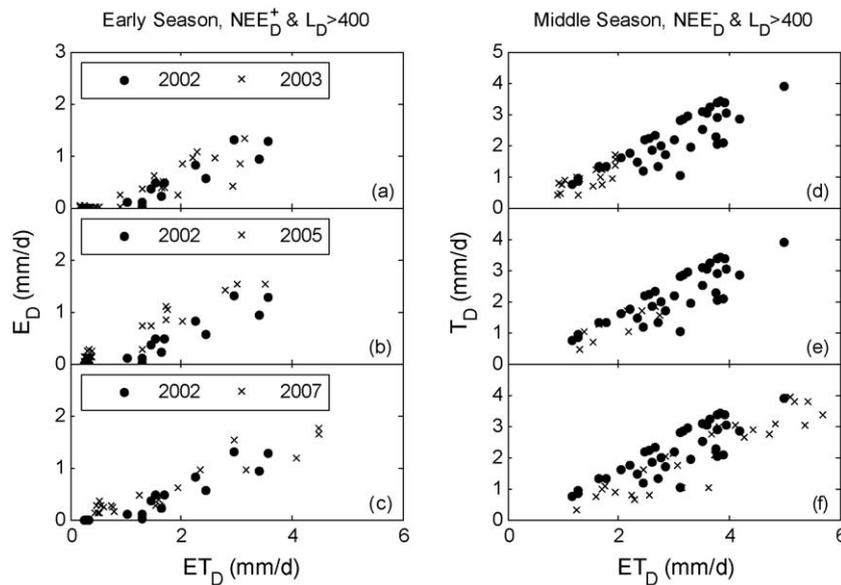


Fig. 7. (a–c) The relation between daily soil evaporation (E_D) and evapotranspiration (ET_D) in the early season (days 180–214) for days when $NEE_D > 2 \text{ g m}^{-2} \text{ d}^{-1}$ (NEE_D^+). (d–f) The relation between daily transpiration (T_D) and evapotranspiration (ET_D) in the mid-season (days 215–285) for days when $NEE_D < -2 \text{ g m}^{-2} \text{ d}^{-1}$ (NEE_D^-). Comparisons were made with year 2002, where year 2003 had similar vegetation but slightly lower precipitation, year 2005 had similar vegetation but much lower precipitation, and year 2007 had similar precipitation patterns but a different vegetation type (Table 2).

3.1. Maximum E_D/ET_D and T_D/ET_D —years 2002–2007

The relation between E_D and θ_5 and L_D (Eq. (1)) was applied to derive E_D for the growing seasons in years 2002–2007. Daily T_D was determined by subtracting E_D from measured ET_D . The analysis of vegetation and hydrologic similarity (Table 2) was used to determine which years could be compared to better understand the influences of vegetation and precipitation pattern on E_D/ET_D . We chose three years for comparison with 2002: 2003 had similar vegetation but slightly lower precipitation, 2005 had similar vegetation but extremely low precipitation, and 2007 had similar precipitation patterns but a different vegetation type. The latter comparison of years 2002 and 2007 facilitated one of our objectives, which was to better understand the impact of *E. lehmanniana* invasion on E_D/ET_D independent of variations in precipitation patterns.

3.1.1. E_D/ET_D early season

In the early season (before plants were fully active and at maximum leaf area) for days when $NEE_D > 2 \text{ g m}^{-2} \text{ d}^{-1}$, the relation between E_D and ET_D followed a similar trend in all years (Fig. 7a–c). That is, E_D increased with ET_D and reached a maximum amount apparently associated with potential (maximum) ET_D . The upper left edge of the E_D/ET_D relation expresses the maximum daily E_D/ET_D and the deviation from that edge indicates days when E_D/ET_D was below maximum due to increases in T_D . For all years, E_D reached a maximum value of near 2 mm d^{-1} during this early season, regardless of the precipitation pattern. Variation from the upper left edge was small indicating that T_D was relatively constant under the conditions of NEE_D^+ during the early season.

3.1.2. T_D/ET_D middle season

In the middle season for days when $NEE_D < -2 \text{ g m}^{-2} \text{ d}^{-1}$ (NEE_D^-), the relation between T_D and ET_D (Fig. 7d–f) followed the basic form expressed by Laio et al. (2001). That is, T_D increased with ET_D and reached a maximum amount which was determined by the type of plant and climatic conditions. The upper left edge of the T_D/ET_D relation expresses a near one-to-one relation between T_D and ET_D with an x -intercept expressing the minimal value of E

during the middle season. Deviations from that edge indicate days when T_D/ET_D was below maximum due primarily to increases in E_D immediately following storm events. During the driest years (2003–2005), T_D did not exceed 2 mm d^{-1} . In the wetter years (2002, 2006 and 2007), T_D reached as high as 4 mm d^{-1} likely determined by plant leaf area (Laio et al., 2001). This was unlike the maximum E_D , which was similar in all years of the study.

3.1.3. Maximum E_D/ET_D

Results showed that E_D and T_D reach a maximum value that was a linear function of ET_D (Fig. 7). By selecting the $\{E_D, ET_D\}$ and $\{T_D, ET_D\}$ data pairs associated with the upper left edge of the E_D and T_D versus ET_D relations (Fig. 7a–f), it was possible to determine the maximum E_D/ET_D and T_D/ET_D for the early and middle seasons for each study year (Fig. 8). This is expressed as a general linear form $\{y = a + bx\}$ by Guswa et al. (2002) that was fit to Kendall data as follows:

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

and

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

where a and b are coefficients determined by regressions shown in Fig. 8. For Eq. (2), the intercept of the linear relation between E_D and ET_D was near zero, as expected. For Eq. (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 below normal and vegetation cover was dominated by native grasses, values of maximum E_D/ET_D were similar (maximum $E_D/ET_D = 0.41$, Fig. 8a). For all other years maximum E_D/ET_D was higher, indicating an increase in E_D during the early season when precipitation was extremely low (maximum $E_D/ET_D = 0.60$ in 2005) or when vegetation had changed (maximum $E_D/ET_D = 0.51$ in 2007). The results for year 2006 were difficult to interpret because both precipitation pattern and vegetation type were different from that for all other years.

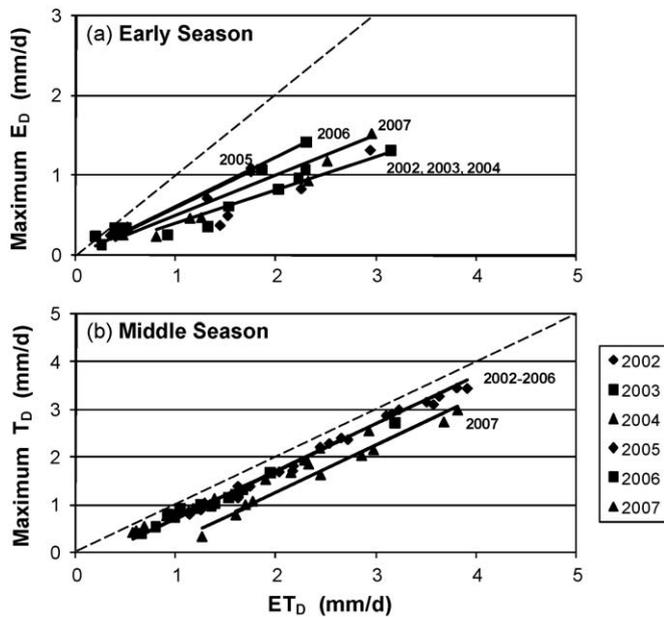


Fig. 8. The ratio of maximum daily soil evaporation to evapotranspiration (a, E_D/ET_D) and maximum transpiration to evapotranspiration (b, T_D/ET_D) for the early and middle seasons (respectively) for study year 2002–2007. Data were derived by selecting the (E_D, ET_D) and (T_D, ET_D) data pairs associated with the upper left edge of the E_D and T_D versus ET_D relations in Fig. 7. The solid lines represent regression lines for the years labeled in the figure, where (a) maximum $E_D = aET_D$ and (b) maximum $T_D = ET_D - b$ and $r^2 > 0.9$ for all regressions. The dashed line is the 1:1 line.

Values of maximum T_D/ET_D were similar for years 2002–2006, where maximum $T_D = ET_D - 0.3 \text{ mm d}^{-1}$ with a MAD of 0.09 mm d^{-1} (Fig. 8b). This can be interpreted to mean that the minimum value of E_D during the middle season in all years was close to 0.3 mm d^{-1} . This was similar to the value derived from the ML data for Kendall in 2005 by Moran et al. (2009). However, maximum T_D/ET_D in 2007 was strikingly different from all other years, where maximum $T_D = ET - 0.77 \text{ mm d}^{-1}$ (MAD = 0.09 mm d^{-1}). This means that the minimum value of middle-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. Cox et al. (1986) reported that 70% of the fine root biomass and 100% of the woody root biomass of Kendall native grasses was between 0 and 15 cm. 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 *Bouteloua* spp. decreased to zero and the cover was dominated by annual forbs. With the invasion of *E. lehmanniana* in 2007, much of the root biomass of *Bouteloua* spp. 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 LAI (not measured in this study). Huxman et al. (2004) hypothesized that lower LAI in *E. lehmanniana* plots may promote higher soil temperatures that would favor the evaporation of soil water rather than infiltration following rain events. This is supported by studies showing consistently drier soils and reduced canopy light interception in plots dominated by *E. lehmanniana* compared to the native grass *Heteropogon* (English et al., 2005) and lower litter coverage in plots dominated by *E. lehmanniana* (Yepez et al., 2005).

To put this finding in perspective, it is important to realize that E_D was derived primarily from θ_5 based on the relation between E_D and θ_5 determined from the 2005 and 2007 ML measurements (Eq. (1)). So, the results can be interpreted in relation to the volumetric soil moisture measured at 5 cm throughout the growing season of each year (Fig. 4). It is apparent that θ_5 hovered above $0.06 \text{ cm}^3 \text{ cm}^{-3}$ in 2007, despite long drydown periods that resulted in $\theta_5 = 0.03 \text{ cm}^3 \text{ cm}^{-3}$ in all other years, included 2006 which was exceptionally wet. We have confidence that the measurements of θ_5 were accurate to within about $0.03 \text{ cm}^3 \text{ cm}^{-3}$ and representative of the larger ecosystem due to spot validations in time and space of the *in situ* soil moisture sensor (e.g., Paige and Keefer, 2008) and the reasonable results obtained in Fig. 5b.

3.2. Early- and middle-season E_S/ET_S : years 2002–2007

To this point in the analysis, data have been filtered to values of NEE_D^+ during the early season and NEE_D^- during the middle season to better understand the limited E_D/ET_D and T_D/ET_D relations when E_D and T_D are favored (respectively). In this section, results are presented for all days during the growing season, limited only by $L_D > 400$ (due to the fact that Eq. (1) was determined with days when $L_D > 400$, Fig. 5c). Still, the data are split into the early season before the plants were fully active and middle season when plants are actively responsive to available soil moisture (Table 3).

In the early season (Fig. 9a), E_S/ET_S varied from 0.29 to 0.48 based just on precipitation patterns (2002–2005); and E_S/ET_S varied by only 0.31–0.36 based just on the *E. lehmanniana* transition (2002 and 2007). Thus, E_S/ET_S in the early season was

Table 3

Seasonal averages of midday soil moisture measured at 5 cm and 15 cm depths (θ_5 and θ_{15} , respectively, $\text{cm}^3 \text{ cm}^{-3}$), daytime solar irradiance (L_D , W m^{-2}), daily net ecosystem exchange (NEE_D , $\text{g m}^{-2} \text{ d}^{-1}$, averaged over the season), and the ratio of seasonal evaporation and seasonal evapotranspiration (E_S/ET_S), where $1 - E_S/ET_S = T_S/ET_S$ and T_S = seasonal transpiration. Before averaging, data were filtered to only days with $L_D > 400 \text{ W m}^{-2}$ to meet the restrictions of Eq. (1). NA means data were not available for the entire season (equipment failure in 2002).

	θ_5	θ_{15}	L_D	NEE_D	E_S/ET_S	T_S/ET_S
Early season (days 180–214)						
2002	0.04	0.06	602	4.1	0.31	0.69
2003	0.03	0.04	886	6.9	0.29	0.71
2004	0.04	0.05	636	1.9	0.30	0.70
2005	0.04	0.05	679	4.3	0.48	0.52
2006	0.04	0.06	670	4.0	0.43	0.57
2007	0.08	0.09	632	2.0	0.36	0.64
Middle season (days 215–285)						
2002	0.05	0.07	713	NA	0.26	0.74
2003	0.04	0.06	581	0.6	0.35	0.65
2004	0.04	0.07	594	-2.6	0.32	0.67
2005	0.05	0.07	586	0.5	0.46	0.54
2006	0.07	0.11	572	-9.2	0.36	0.64
2007	0.08	0.09	582	-3.7	0.60	0.40

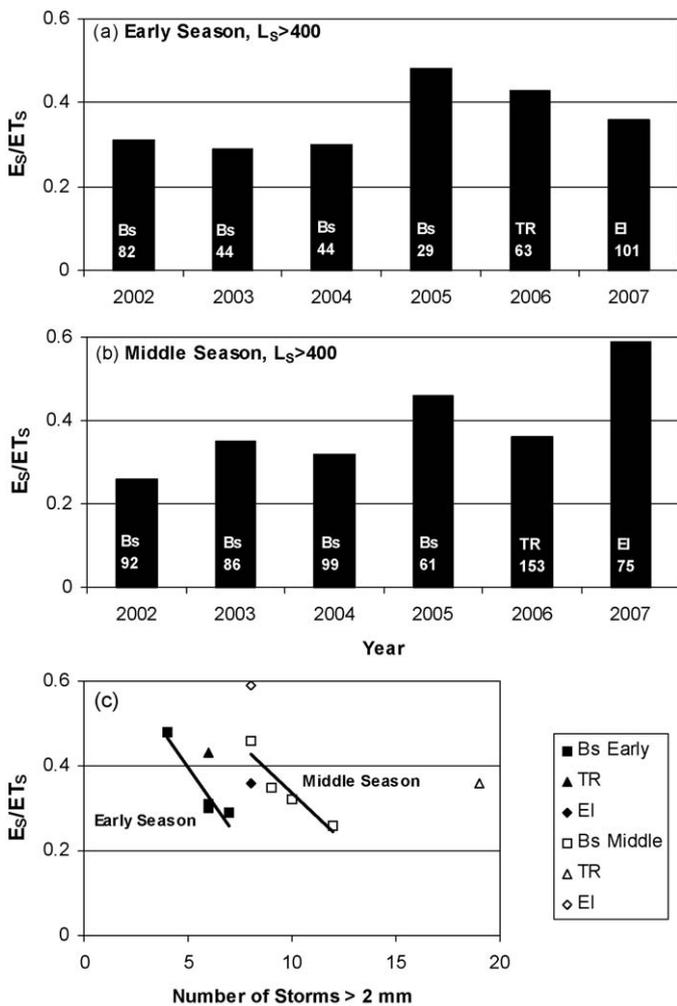


Fig. 9. Variation in the ratio of seasonal soil evaporation to evapotranspiration, E_s/ET_s , in (a) the early season (days 180–214) and (b) the middle season (days 215–285) for years 2002–2007 where “Bs” designates years when *Bouteloua* spp. dominated vegetation cover, “TR” designates years when vegetation was in transition with forbs dominating vegetation cover, and “EI” designates years with *E. lehmanniana* dominated vegetation cover. The seasonal infiltration (I_s) is given for each year by numbers on the bars in (a) and (b). The solid lines in (c) are best regression fits of the E_s/ET_s and number of storms > 2 mm during the season for years of similar vegetation type (2002–2005).

influenced primarily by precipitation patterns, and less so by vegetation type. This result is intuitive since the grassland vegetation is not fully responsive to available soil moisture during this period (Emmerich and Verdugo, 2008b).

In the middle season (Fig. 9b), E_s/ET_s varied from 0.26 to 0.46 based primarily on precipitation patterns (2002–2005); and E_s/ET_s more than doubled (from 0.26 to 0.60) based primarily on the *Bouteloua* spp. to *E. lehmanniana* transition (2002 and 2007). Thus, E_s/ET_s in the middle season was influenced substantially by both precipitation patterns and vegetation type. These results support the multitude of studies documenting the sensitivity of E_s/ET_s to precipitation patterns (e.g., Reynolds et al., 2000; Scott et al., 2006). The sensitivity of E_s/ET_s to the *E. lehmanniana* transition was heretofore unknown, but it follows the finding that maximum T_D/ET_D is lower for *E. lehmanniana* than for *Bouteloua* spp. as shown in Fig. 8.

Variation in E_s/ET_s can be explained by the number of storms in the early and middle seasons, *only when vegetation type remained the same*. The limited influence of vegetation type in the early season and substantial influence in the late season were illustrated

by the strong divergence of the 2006 (vegetation cover dominated by forbs) and 2007 (vegetation cover dominated by *E. lehmanniana*) data from the relation developed between E_s/ET_s and number of storms for 2002–2005 (vegetation cover dominated by native grasses) in Fig. 9c. This provides more evidence that the *E. lehmanniana* in 2007 was not responding to the precipitation pattern in the same way that the *Bouteloua* spp. responded in 2002–2005.

3.3. Growing season E_s/ET_s : years 2002 and 2007

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 (D180–315) 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 2; Fig. 6). However, results show that the partitioning of E_s and T_s was greatly changed. Apparently, the transition from an established grassland dominated by *Bouteloua* spp. to a stand dominated by young *E. lehmanniana* caused maximum E_D/ET_D to increase and maximum T_D/ET_D to decrease substantially (Fig. 8). As a result, E_s/ET_s over the growing season was more than twice as high in 2007 than in 2002 (Fig. 10).

These results need to be put into perspective by the limitations of this multi-year study of a naturally occurring vegetation transition. First, the time period (2002–2007) of this study only covers the early development of *E. lehmanniana*. We expect the trend to change if *E. lehmanniana* develops greater above- and below-ground biomass and possibly greater plant density in later years. Second, the study was conducted in years that experienced infiltration below or at the 30-year average (2002–2005 and 2007). There is evidence that the impact of precipitation patterns, and possibly vegetation variations, on year-to-year E_s/ET_s is exacerbated during normal and below-normal amounts of rainfall (Reynolds et al., 2000). Third, this analysis was based on a combination of measurements of E_D (with ML) and estimates of E_D (derived from θ_s and L_D for days with $L_D > 400$). Thus, the conclusions are biased by inclusion of only days when $L_D > 400$; however, over 90% of the days in the season fell into this category.

This is apparently the first study to monitor evaporative response to a naturally occurring *E. lehmanniana* invasion in Arizona, making it difficult to compare these results with other similar findings. Nonetheless, it is informative to compare this study with studies of evaporative response in other plant

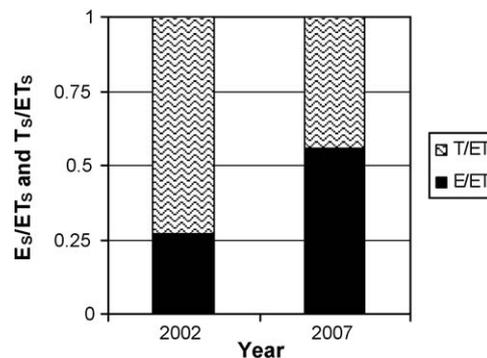


Fig. 10. Values of E_s/ET_s and T_s/ET_s over the growing season (days 180–315) in 2002 (pre-invasion) and 2007 (post-invasion) for years of average precipitation and similar precipitation patterns (Table 2). This represented an average of 119 days in 2002 and 122 days in 2007, due to filtering for days with $L_D > 400$ $W m^{-2}$.

communities. A shrub-dominated site (Lucky Hills) is located only 7 km west of Kendall in the WGEW. In 2003, E_s/ET_s (derived from T_s/ET_s measurements) at Lucky Hills was estimated to be 0.42 during the early season and about 0.30 during the middle season (Scott et al., 2006). This compares with values of $E_s/ET_s = 0.30$ and 0.35 measured for the *Bouteloua* spp. plant community at Kendall in that same year, 2003. This represents a situation when precipitation patterns were similar, but vegetation type and soil were distinctive. That is, the Lucky Hills soil is sandier than the Kendall soil, and the total below-ground biomass at the shrubland was measured to be almost five times greater than at the grassland (Cox et al., 1986). These characteristics may have combined to result in similar middle-season values of E_s/ET_s but different early season values of E_s/ET_s , though it is beyond this study to disentangle the influences of soil, root biomass and plant water use efficiency.

Our results for a naturally occurring *E. lehmanniana* invasion can also be compared to plot-scale studies for similar Holocene soils. Huxman et al. (2004) found that T_D/ET_D immediately following an irrigation pulse was ~ 0.1 for *E. lehmanniana* and >0.2 for the native (*H. contortus*) plant community. These values could be compared to the early season values of maximum T_D/ET_D at Kendall inferred from Fig. 8a, where $T_D/ET_D = 0.59$ for the native *Bouteloua* spp. and $T_D/ET_D = 0.49$ for the native *E. lehmanniana*. Though the magnitudes are different, the trend for T_D/ET_D to be greater for the native species is supported. The difference in magnitude could be explained by the differences in LAI that was found to be strongly correlated with T_D/ET_D regardless of plant species or soil (Huxman et al., 2004) and other differences induced by the plot-based study versus the naturally occurring vegetation transition at Kendall. Using a chamber-based isotope method, Yepez et al. (2005) estimated that T_D/ET_D in stands of *E. lehmanniana* were as high as 0.43 after an irrigation pulse, but decreased to 0.22 by day 7 as the soil dried. This value compares well with the early-season maximum T_D/ET_D estimate of 0.49 reported here for the native *E. lehmanniana*.

4. Conclusions

The goal of this study was to use long-term investigations of a naturally occurring vegetation transition to quantify the change in evaporative response to *E. lehmanniana* invasion. This study investigated the variation that can be expected in E/ET with *E. lehmanniana* invasion and the key processes that control this variation. Preliminary conclusions drawn from observations over 6 years in the Kendall semiarid grassland were:

- (1) The transitions from native grasses to *E. lehmanniana* did not affect the ratio of seasonal ET and infiltration (ET_s/I_s) over the growing season.
- (2) Maximum daily E_D/ET_D was influenced by both precipitation patterns and vegetation type; whereas, maximum daily T_D/ET_D was influenced by vegetation type, but not precipitation patterns.
- (3) Seasonal E_s/ET_s in the **early season** varied from 0.29 to 0.46 and was primarily influenced by precipitation patterns, and less so by vegetation type.
- (4) Seasonal E_s/ET_s in the **middle season** varied from 0.26 to 0.60 and was substantially influenced by both precipitation patterns and vegetation type.
- (5) Variation in seasonal E_s/ET_s was explained by the number of storms in the early and middle seasons, but only when vegetation type remained the same.
- (6) 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 patterns (i.e., 2002 and 2007).

These conclusions offer an insight into one aspect of the hydrological impact of the invasion of *E. lehmanniana*, that is, the evaporative response. In fact, there are a number of direct and indirect impacts on ecosystem hydrology that may be associated with *E. lehmanniana* invasion. Dominance of *E. lehmanniana* has been associated with drier soils (English et al., 2005), an earlier decline in NEE_D following a precipitation pulse (Huxman et al., 2004) and potential for higher above-ground biomass accumulation (Martin and Severson, 1988; Anable et al., 1992) that have numerous potential feedbacks to hydrological processes. With the transition from native grasses to *E. lehmanniana* at Kendall from 2005–2007, sediment discharge rates doubled per change in unit runoff rates (unpublished). It is still unknown whether these apparent changes in hydrology may combine to favor the persistence of *E. lehmanniana* dominance at this site and other semiarid grasslands.

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