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Soil-vegetation-climate interactions in arid landscapes: Effects of the North American monsoon on grass recruitment

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ABSTRACT

We used a daily time step, multi-layer simulation model of soil water dynamics to integrate effects of soils, vegetation, and climate on the recruitment of *Bouteloua eriopoda* (black grama), the historically dominant grass in the Chihuahuan Desert. We simulated landscapes at the Jornada ARS-LTER site with heterogeneous soil properties to compare: (1) a grass-dominated landscape in 1858 with the current shrub-dominated landscape (i.e., a change in vegetation structure), and (2) the current shrub-dominated landscape with future landscapes over a range of climate scenarios associated with the North American monsoon (i.e., a change in climate). A historic shift from high productivity grasslands to low productivity shrublands decreased simulated recruitment for most of the site; the amount of reduction depended on location-specific soil properties and changes in production. In some cases, soil properties interacted with vegetation structure: soils high in clay content maintained high recruitment even with a decrease in production. Wetter summers would increase recruitment in all vegetation types. Drier summers below 25% of current rainfall would decrease recruitment to negligible values (<0.03) throughout the landscape. We used our results to identify the conditions where recruitment of *B. eriopoda* is possible with and without significant modifications to soil and vegetation.

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1. Introduction

Woody plant encroachment into perennial grasslands has occurred globally throughout arid and semiarid regions over the past several centuries (Reynolds and Stafford Smith, 2002). Although the causes of this state change resulting in desertification are often site specific, the consequences are clear and consistent: conversion from grasslands to woody plant dominance results in increased wind and water erosion of soil and nutrients (Bird et al., 2007; Okin and Gillette, 2001; Wainwright et al., 2002), spread of invasive species (Masters and Sheley, 2001), changes in carbon dynamics (Jackson et al., 2002; Knapp et al., 2008) and loss of biodiversity and forage production (Ricketts et al., 1999). Reversal from woody plant-dominated systems back to perennial grasslands is difficult, and remediation efforts are often unsuccessful (Herrick et al., 2006).

Woody plant persistence following invasion is typically attributed to feedbacks between plants and soils that positively affect shrub growth and persistence (Schlesinger et al., 1990). Redistribution of soil, water, and nutrients from bare interspaces to beneath woody plant canopies results in "islands of fertility" that favor woody plants (Bhark and Small, 2003; Huxman et al., 2005; Kieft et al., 1998). However, shifts to woody plant dominance may also influence plant processes that limit grass recovery. Microenvironmental conditions associated with shrub invasion have been found to reduce grass viability, production, and storage of seeds in the soil compared with neighboring grasslands (Peters, 2002). Effects of shrublands on two key aspects of grass recruitment, seed germination and seedling establishment, may provide additional constraints on the ability of grasses to recover following shrub invasion, in particular for perennial grasses with low rates of seedling recruitment (Minnick and Coffin, 1999; Peters, 2000).

Recruitment of grass seedlings is expected to be affected by changes in vegetation structure and soil properties that influence soil water availability following grassland to shrubland conversion. Shrublands on the same soil type as arid grasslands likely have lower interception and transpiration losses due to lower leaf area, yet higher rates of evaporation as a result of lower production (Knapp et al., 2008). Because evaporation is often the primary control on water availability in arid regions (Loik et al., 2004), a shift to shrublands is expected to decrease water available to seedlings and reduce rates of establishment. However, if water available for

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transpiration exceeds losses to evaporation, then shrub encroachment could increase rates of grass establishment if more water is available to seedlings.

Effects of shrubs on water availability and grass recruitment may be either offset or amplified by future changes in climate. Although temperatures are increasing globally as a result of elevated concentrations of atmospheric carbon dioxide and other greenhouse gases, changes in precipitation are more uncertain (IPCC, 2007). For example, in the southwestern US and northwestern Mexico, there is no consistent pattern in global climate model scenario results for precipitation, and even the latest generation of models contained in the IPCC AR4 suite (IPCC, 2007) do not show significant model agreement for summer precipitation in the future. Directional changes in precipitation, particularly during the North American monsoon, are expected to affect rates of recruitment of perennial grasses based on previous studies of the timing of grass germination and establishment during the rainy monsoon season (Peters, 2000).

Simulation modeling provides one approach to integrating multiple drivers (climate, soils) and processes (evaporation, transpiration, infiltration) to investigate the effects of shrub encroachment on grass recruitment. A landscape approach is necessary to capture both spatial and temporal heterogeneity in arid systems (Peters et al., 2006a). We had two objectives for this study. *First*, we evaluated effects of historic changes in vegetation structure on the simulated probability of establishment of the perennial grass, *B. eriopoda* (black grama), a historic dominant in the Chihuahuan Desert. We simulated a landscape with heterogeneous soils that was predominantly grasslands in 1858, and compared these results with the same area that is currently shrub dominated. We expected that the probability of establishment would decrease, in general, following broad-scale shrub invasion, but that certain soil-vegetation combinations would be more sensitive to vegetation change than other locations because of differences in plant production and soil properties. *Second*, we evaluated effects of changes in climate on simulated probabilities of establishment of *B. eriopoda*. We compared spatial variation in recruitment under current climate with future predicted probabilities under an increase in temperature and either a directional increase or decrease in precipitation during the monsoon period (July 1–October 1). We expected that the probability of recruitment would have a positive relationship with precipitation, but that climatic effects would interact with vegetation and soils to create spatial variability in recruitment.

2. Data and methods

2.1. Study site

We evaluated the change in probability of recruitment of *B. eriopoda* through time for a site located in the northern Chihuahuan Desert, the Jornada ARS-LTER site (32.5 N, 106.8 W, 1188 m a.s.l.) in southern New Mexico, USA. Three shrubland types have replaced two grassland types throughout much of the Chihuahuan Desert, including the Jornada site. Shrub invasion of both grassland types is associated with significant soil loss and degradation. *Bouteloua eriopoda* grasslands have been replaced by *Prosopis glandulosa* (honey mesquite) on sandy basin soils, while *Pleurophis mutica* (tobosa) grasslands have been replaced by *Flourensia cernua* (tarbush) on clay loam soils in lower landscape positions. *Larrea tridentata* (creosotebush) now dominates gravelly and loamy soils formerly dominated by *P. mutica* and/or *B. eriopoda*.

The Jornada is typical of much of the American Southwest in that it was dominated by grasslands in 1858 (81% of the 100,000 ha area) and is currently dominated by shrublands (92% of the area) (Gibbens et al., 2005). Reasons for this shift in lifeform include overgrazing by livestock in the late 1800s to early 1900s combined with periodic drought, and reduction in fire frequency and increase in small animal population densities (Van Auken, 2000). Current livestock grazing intensities are much lower than historically (Fredrickson et al., 1998). In our analysis, seedling herbivory by animals was assumed to be negligible and seeds were assumed to always be available in order to focus on germination and establishment processes.

Climate at the Jornada is arid to semiarid with low annual precipitation (80 y avg = 23 cm/y) and high summer temperatures (80 y avg = 36 °C avg maximum in June). Most precipitation (60–80%) occurs during the North American monsoon that typically occurs from July 1 to October 31 (Wainwright, 2006). Global circulation models predict an increase of 3 °C in temperature for this region (IPCC, 2007), and either a decrease or an increase in precipitation as a result of elevated concentrations of atmospheric gases associated with global climate change (Kunkel et al., 1999; Seager et al., 2007).

2.2. Soil water simulation model

We used a multi-layer, daily time step simulation model (SOILWAT; Parton, 1978) to determine the probability of recruitment of *B. eriopoda* for spatially variable soils and vegetation in different time periods. Climate and soil texture are drivers, and vegetation structure is an input parameter. Processes simulated in

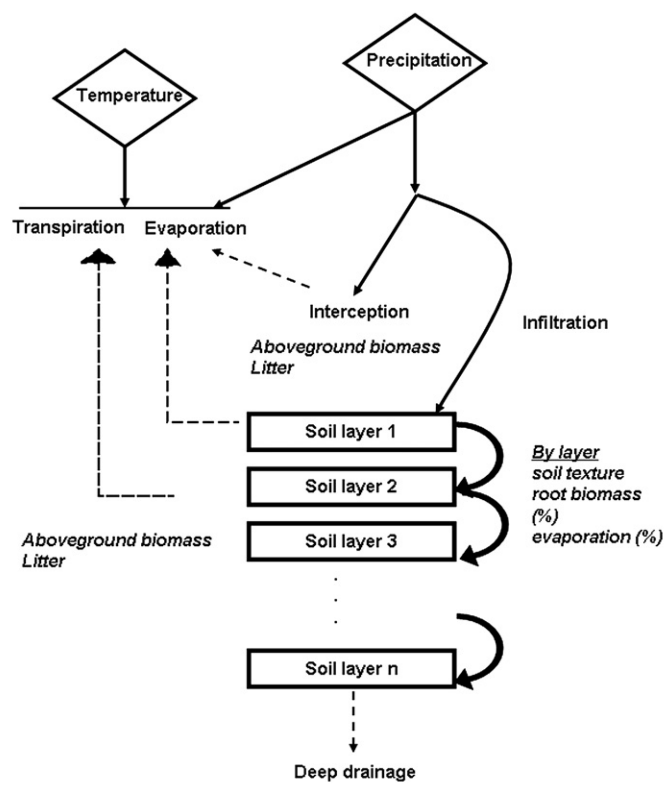

Fig. 1. The SOILWAT model simulates precipitation inputs, losses (dashed arrows) by interception from the plant canopy, bare soil evaporation, plant transpiration, and loss of water to deep drainage, and vertical redistribution of water between multiple layers of variable depth (modified from Parton, 1978). Infiltration is simulated using a tipping bucket approach where water moves vertically into the next layer after an upper layer becomes saturated. Climatic drivers are daily precipitation and air temperature. Input parameters include soil texture (% sand, silt, clay), percentage evaporation and percentage transpiration (i.e., root biomass) by depth in the soil profile, and monthly aboveground biomass and litter. Aboveground biomass and litter change with grass to shrub conversion from 1858 to present. Temperature and precipitation change with climate change scenarios between present and 2150.