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Mechanisms of shrub encroachment into Northern Chihuahuan Desert grasslands and impacts of climate change investigated using a cellular automata model

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ABSTRACT

Arid and semiarid grasslands of southwestern North America have changed dramatically over the last 150 years as a result of woody plant encroachment. Overgrazing, reduced fire frequency, and climate change are known drivers of woody plant encroachment into grasslands. In this study, relatively simple algorithms for encroachment factors (i.e., grazing, grassland fires, and seed dispersal by grazers) are proposed and implemented in the ecohydrological Cellular-Automata Tree Grass Shrub Simulator (CATGraSS). CATGraSS is used in a 7.3 km^2 rectangular domain located in central New Mexico along a zone of grassland to shrubland transition, where shrub encroachment is currently active. CATGraSS is calibrated and used to investigate the relative contributions of grazing, fire frequency, seed dispersal by herbivores and climate change on shrub abundance over a 150-year period of historical shrub encroachment. The impact of future climate change is examined using a model output that realistically represents current vegetation cover as initial condition, in a series of stochastic CATGraSS future climate simulations. Model simulations are found to be highly sensitive to the initial distribution of shrub cover. Encroachment factors more actively lead to shrub propagation within the domain when the model starts with randomly distributed individual shrubs. However, when shrubs are naturally evolved into clusters, the model response to encroachment factors is muted unless the effect of seed dispersal by herbivores is amplified. The relative contribution of different drivers on modeled shrub encroachment varied based on the initial shrub cover condition used in the model. When historical weather data is used, CATGraSS predicted loss of shrub and grass cover during the 1950 s drought. While future climate change is found to amplify shrub encroachment (~13% more shrub cover by 2100), grazing remains the dominant factor promoting shrub encroachment. When we modeled future climate change, however, encroachment still occurred at a reduced rate in the absence of grazing along with pre-grazing fire frequency because of lower shrub water stress leading to reduced shrub mortality which increases the probability of shrub establishment.

1. Introduction

Arid and semiarid grasslands of southwestern North America have changed dramatically over the last ~150 years as a result of woody plant encroachment (WPE) [5,16,19,47,85,93]. WPE is defined as an increase in the density, cover, and biomass of native trees or shrubs in grasslands [9,19,33,34,55]. Encroachment of native woody species has greatly changed the appearance and structure of many former semiarid grasslands to shrublands, brushlands, or woodlands [55]. Repeat photography clearly illustrates encroachment of juniper trees into grasslands west of Albuquerque, New Mexico, US (Fig. 1a and b) [3], and shrub encroachment into grasslands in southeastern Arizona, US (Fig. 1c, d and e) [9].

Recent studies have summarized the positive and negative impacts of WPE into neighboring plant communities during the past 150 years (e.g., [36,75]), however in many areas, such as the Southwestern US and Southern Africa, rapid expansion by shrubs has caused considerable concern because of increased soil erosion, reduced stream flows, altered wildlife habitat, reduced forage production, and changes in plant community composition and diversity [7,77,90–92].

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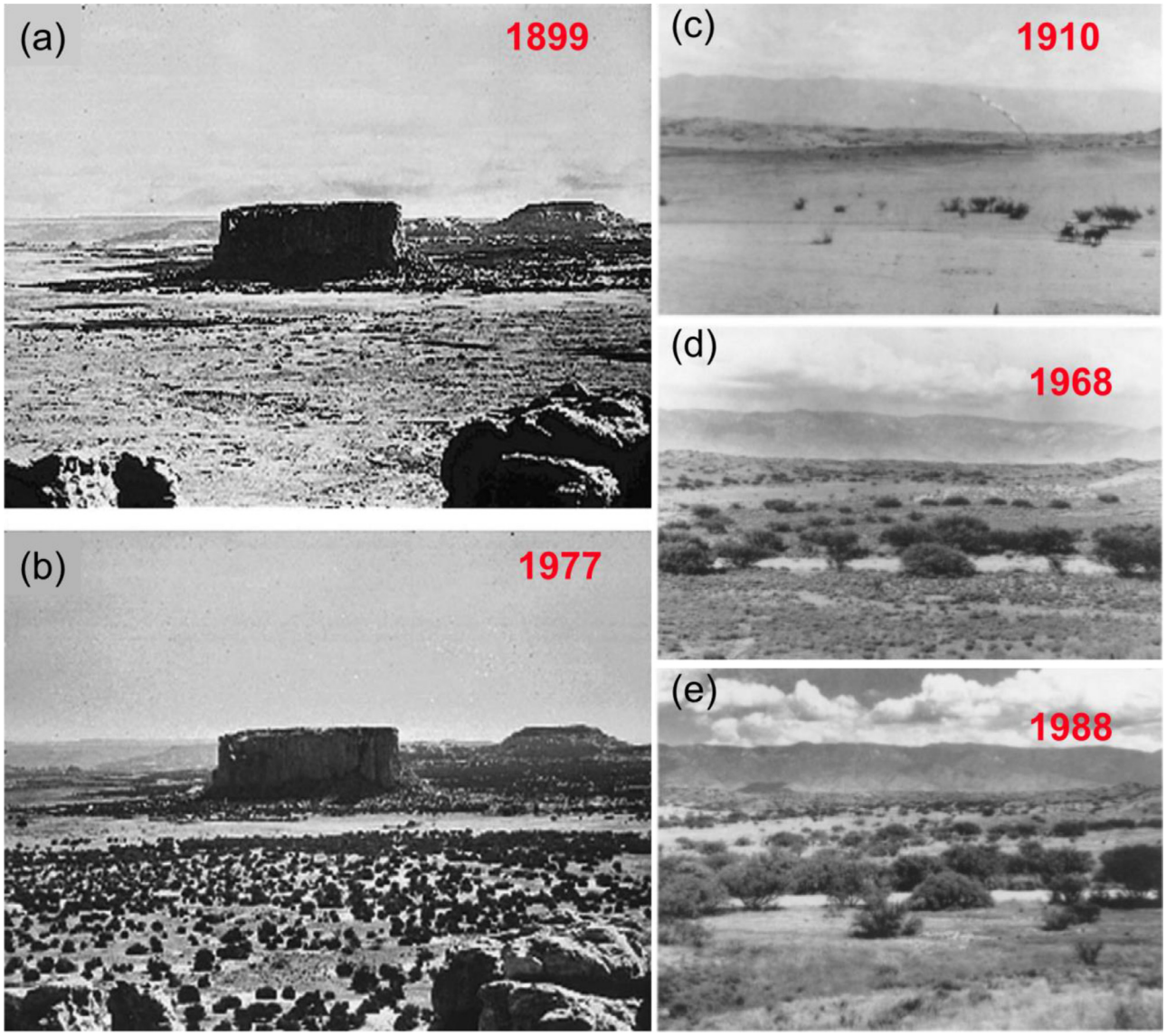

Fig. 1. Illustration of woody plant encroachment using repeat photography: juniper trees encroach into grasslands west of Albuquerque, New Mexico, USA. Photographs show Enchanted Mesa taken from Acoma Pueblo in (a) 1899 taken by W.H. Jackson, used with permission from the History Colorado, the Colorado Historical Society, and (b) 1977 taken by H.E. Malde, used with permission from the U.S. Geological Survey (from http://cpluhna.nau.edu/Research/grasslands1.htm, [3]). Shrub encroachment in grasslands in southeastern Arizona, USA: (c) 1910, photograph by O.E. Meinzer, courtesy of the U.S. Geological Survey, used with permission from Wiley library, (d) 1968, photograph by R.M. Turner, courtesy of the U.S. Geological Survey, used with permission from Wiley library, (e) 1988, photograph by C.J. Bahre (from [9]), used with permission from Wiley library.

Although some earlier studies have related WPE in semiarid grasslands to a single dominant factor, such as fire or grazing (e.g., [10,17,18,21]), growing evidence points to the interaction of several cascading factors driven by the introduction of domestic herbivores in the southwest US (e.g., Fig. 2; [34,63,92,93]). Essentially, loss of grass biomass and fine fuels through chronic high levels of grazing in this region have resulted in a significant reduction in grassland fire frequency from an approximate historic return period of 10 years to 100 years since the beginning of grazing [5,21,79,92]. Grassland fires suppress the growth and encroachment of trees and shrubs [31,44,93,97] and increase splash, runoff and aeolian erosion, with a subsequent homogenizing effect on spatial distribution of resources that may favor healthy grass regrowth [35,78,95]. With less frequent and more intense fires, woody plant mortality decreases as shown by several fire control experiments, and maturing woody plants produce seeds for dispersal to surrounding bare soil patches (e.g., [13,77,83]). In addition, deposition of resources eroded from burned and grazed patches promotes the formation of shrub patches, known as “islands of fertility” [26,79,85].

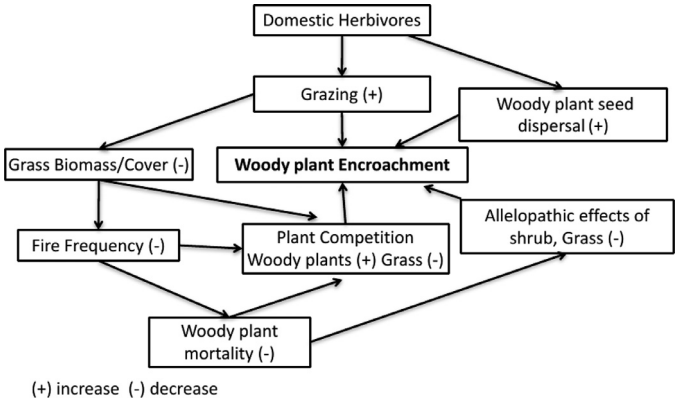

Fig. 2. Conceptual model illustrating interactions of processes associated with woody plant encroachment (WPE) in the southwest USA. Each WPE factor is indicated in a box. An arrow represents a direct impact from one factor to another. A plus (minus) sign indicates an increase (decrease) of the process inside the box as a result of the factor connected to it with an arrow.