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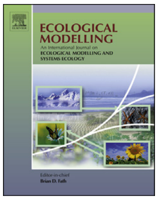

Combining ecohydrologic and transition probability-based modeling to simulate vegetation dynamics in a semi-arid rangeland

Elizabeth G. King[a,*], Trenton E. Franz[b,1]

[a] University of Gerogia, Odum School of Ecology, 140 E. Green St., Athens, GA 30602, United States
[b] University of Nebraska–Lincoln, School of Natural Resources, 3310 Holdrege St., Lincoln, NE 68583, United States

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ABSTRACT

Drylands support pastoralist social–ecological systems around the world. Ecological function in these water-limited environments frequently depends on tightly coupled, nonlinear interactions between water, soil, vegetation, and herbivores. Numerous complexity-based approaches have modeled localized ecohydrological feedbacks to yield insights into dryland landscape organization and emergent dynamics. The relevance of these models to management and sustainability continues to increase as researchers incorporate ecological processes at multiple scales and social–ecological variables like herding practices. However, many processes vary in their importance depending on ecological context, so there is a continuing need to construct models tailored to different contexts. We developed a model for semi-arid rangelands that experience highly variable rainfall, substantial Hortonian runoff during rain events, patchy vegetation structure, and grazing-influenced patch transitions. The model couples an existing, mechanistic cellular automata model of hillslope water balance with a dynamic vegetation model in which probabilistic transitions between bare, annual grass, perennial grass patches depend on soil moisture and grazing intensity. The model was parameterized based on a field site in Kenya, from which we had empirical hydrological measurements and several years of patch-to-hillslope scale measurements of vegetation structure. The model domain is a 100 × 100 grid of 2 × 2 m cells, it simulates seasonal cycles of growing seasons followed by dry seasons, and it computes daily soil moisture based on stochastic rainfall forcings. Patch type transitions can occur twice during each seasonal cycle: at the end of the growing season, with probabilities based on average growing-season soil moisture availability; and at the end of the dry season, with probabilities based on grazing intensity and antecedent growing-season soil moisture. By parameterizing grazing intensity as a per-patch impact, it can be interpreted as the degree of forage depletion at which a herder decides to leave the area. We conducted a series of simulation experiments, principally altering runoff channelization and grazing intensity. The model generated plausible vegetation dynamics across the range of grazing intensities simulated. Vegetation cover fluctuated seasonally, but never collapsed completely, even at the highest grazing intensity. At low to intermediate grazing, we observed multi-decadal switches in fractional perennial cover, triggered by periods of below- or above-average rainfall. At low to intermediate grazing intensities, we noted emergent spatial patterning in the form of a step-like increase in vegetation density in the lower half of the domain. With a vegetation patch transitions governed by mechanistic water balance dynamics as well as grazing intensities that represent herder decision-making, the model holds great potential for further explorations of how land use, climate, and spatial heterogeneity affect the functioning of a dryland pastoralist social–ecological system.

1. Introduction

Arid and semi-arid lands cover 41% of the Earth's land surface (Reynolds et al., 2007), and over 70% of global drylands occur in developing countries (Millennium Ecosystem Assessment, 2005). Drylands are characterized not only by low annual precipitation relative to potential evapotranspiration, but also by high spatiotemporal variability in rainfall. These conditions often make

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[*] Corresponding author. Tel.: +1 352 262 3378.
E-mail addresses: egking@uga.edu (E.G. King), tfranz2@unl.edu (T.E. Franz).
[1] Tel.:+1 402 472 8718.

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drylands marginal or unsuitable for rainfed agriculture, but they can support extensive livestock production with mobile herds that track forage availability as it fluctuates through space and time. Globally, drylands support hundreds of millions of pastoralists, who derive all or most of their livelihood from livestock husbandry (Reynolds et al., 2007). While a range of adaptations have historically allowed pastoralist societies to cope with harsh and variable environmental conditions, today many are facing ongoing pressures of loss of land rights, limited mobility, land degradation, and climate change—trends whose combined effects are undermining the resilience of both livelihoods and landscapes in pastoralist social–ecological systems (Catley et al., 2013). Understanding the interactions between land use, climate change, and landscape structure and function are central to studying and promoting sustainability in drylands.

The organization and functioning of dryland ecosystems tends to be governed by tightly coupled interactions and feedbacks between water, soil, and vegetation. Dryland vegetation is typically spatially heterogeneous, with patches of individual plants or vegetation separated by bare or sparse interpatch areas (Deblauwe et al., 2008). This structural heterogeneity becomes self-reinforcing through its effects on soil moisture distribution and resulting vegetation responses. Rainfall events in drylands tend to be infrequent and intense, often exceeding the rate of infiltration and generating Hortonian surface flows except where soils are very sandy (Wilcox and Newman, 2005; Saco et al., 2006). Vegetation patches act to slow or obstruct surface flows, leading to higher infiltration in patches (Ludwig et al., 2005). Also, vegetated patches tend to feed back positively on soil moisture during the growing season by reducing evaporation following rainfall (Franz et al., 2012). Greater soil moisture availability facilitates greater plant growth, and increased soil permeability from root growth and associated biotic activity (Rietkerk et al., 2002). Greater flow obstruction and soil permeability results in enhanced local water infiltration in subsequent rainfall events. In the bare interpatch areas, on the other hand, limited infiltration and greater evaporative exposure result in lower soil moisture, which in turn limits subsequent vegetation growth and infiltration (Breshears et al., 2009).

The two sets of positive feedbacks occurring respectively in vegetated and bare patches, and lateral resource redistribution between them, can generate the hallmark self-organized patchy structure of dryland vegetation (King et al., 2012). These so-called scale-dependent feedbacks can also generate emergent temporal dynamics of nonlinear changes and threshold behaviors in response to incremental changes in environmental conditions such as mean annual precipitation (Rietkerk and van de Koppel, 1997; Turnbull et al., 2012). Using Turing-like activation–inhibition equations, several modeling studies have identified threshold levels of precipitation that result in two possible alternative stable states (bare or vegetated) and a single, self-reinforcing bare state (Rietkerk and Van de Koppel, 2008; Kéfi et al., 2010). The domination of self-reinforcing bare conditions thus offers a process-based definition of dryland degradation or desertification (Reynolds et al., 2007).

Grazing can affect patch-based water–soil–vegetation feedbacks, and thereby cause nonlinear changes in emergent landscape function. Heavy grazing can weaken the resource-conserving feedbacks in vegetation patches: by reducing vegetation cover, the landscape after a dry season is less able to intercept runoff in the next rainfall event, reduce evaporation, or convert soil moisture into plant productivity (van de Koppel et al., 2002; Rietkerk et al., 2004). Modeling studies (Rietkerk et al., 1996; Kefi et al., 2007) as well as empirical research (Rietkerk et al., 2000) have shown nonlinear and threshold changes in vegetation structure and productivity in response to increasing grazing intensity. Dryland grazing systems have become a flagship ecosystem for studying emergent nonlinearities and catastrophic regime shifts to degraded states (Scheffer et al., 2001); and continue to provide a fertile context for developing modeling approaches that link localized ecological interactions and emergent system behaviors.

A key challenge is to build models that integrate these complexities appropriately for a given environmental and land use context. To meet this challenge, many scholars approach dryland grazing systems from the perspective of complex adaptive systems, using spatially explicit cellular automata (CA) and agent-based models (ABMs) to understand the dynamics and behaviors that emerge from localized interactions and processes. Such models use rules based on conditions experienced by individual entities to determine the decisions, dynamics and/or state transitions for each entity in a system. When CA models are used to track the dynamics of individual cells in a spatial matrix, they provide advantageous tools for understanding and projecting the response of dryland systems to climate and land use drivers. As system-wide properties emerge from local dynamics, subsequent localized dynamics can respond to system-wide changes, creating a coupling of processes across scales (Wiegand et al., 2003). Another advantage of such models arises because many emergent landscape- or ecosystem-level behaviors are difficult or impossible to study empirically because of the necessary spatial or temporal extent of the study, and inability to manipulate, replicate, or control the variables of interest (Perry and Enright, 2006). In simulation models, those system-level behaviors emerge based on smaller scale processes, for which there is often more useful data and causal relations among variables are better understood (Grimm et al., 2005).

Several research programs have capitalized on the flexibility of grid-based simulation approaches, tailoring models to specific ecological contexts and research questions by incorporating different processes and varying degrees of mechanistic reality for those processes, in order to strike a balance between parsimony, complexity, and ecological relevance (Tietjen and Jeltsch, 2007). For example, a family of patch-based simulation models was developed to simulate effects of grazing intensity and rainfall variability on shrub-grass dynamics in the sandy soils of the southern Kalahari in Africa (Jeltsch et al., 1996, 1997a,b, 1998; Weber et al., 2000). In order to simulate the emergent outcomes of woody-herbaceous plant competition under different environmental conditions, the models: aggregated yearly rainfall to assign classes of soil moisture availability in two soil layers; simulated grass–shrub competition for water; incorporated different additional processes such as grazing, fire, and disturbance; and applied rules for transitions of herbaceous and woody vegetated grid cells. Another dryland model, EcoHy D, incorporated a hydrological submodel with greater mechanistic detail, including different wetting front and macropore infiltration rates, and unidirectional surface runoff (Tietjen et al., 2009), and coupled it with a detailed demographic submodel of herbaceous and woody vegetation dynamics, which also sought to investigate woody cover change (shrub encroachment) in response to changing rainfall patterns, CO_2 levels, and grazing (Tietjen et al., 2010; Lohmann et al., 2012). The grid-based Mediterranean vegetation models developed by Koniak and Noy-Meir (2009) and Bar Massada et al. (2009), on the other hand, do not explicitly include ecohydrological dynamics, but instead utilize continuous probability functions to describe how different ecological processes (succession, grazing, fire, land clearing) and plant demographic rates (reproduction, dispersal, colonization, mortality, etc.) interact to affect transition rates between different plant functional types.

The goal of our research was to develop a new grid-based model tailored to the specific context of drylands that have: (1) patchy vegetation, (2) relatively low infiltration rates, (3) complex two-dimensional runoff patterns, and (4) limited availability of data regarding fine-scale or mechanistic plant demographic responses to stressors. These conditions characterize our study area in north-central Kenya as well as many African, Australian, Mediterranean,