ECOLOGICAL MODELLING 208 (2007) 91–101

available at www.sciencedirect.com

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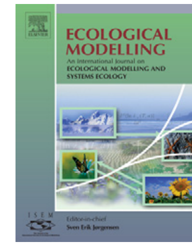

The stability of vegetation boundaries and the propagation of desertification in the American Southwest: A modelling approach

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ARTICLE INFO

Article history:
Received 10 March 2006
Received in revised form
12 April 2007
Accepted 18 April 2007

Keywords:
Jornada
Vegetation boundaries
Vegetation change
Ecosystem stability
Desertification

ABSTRACT

A process-based approach to spatially distributed, overland-flow modelling is employed to assess the impact of water and nutrient redistribution at the landscape scale caused by short, high-intensity rainstorm events across grassland–shrubland vegetation boundaries of a semi-arid ecosystem in the south-western United States. The modelling scenarios showed that simulated fluxes from shrubland into grassland lead to a gain of water resources but to a loss of nutrient resources in the grassland areas close to the boundary. Simulated fluxes from grasslands into shrublands do not lead to a gain of water resources, but to an increase of nutrient resources for the shrubland areas close to the boundary. On the basis of the modelling results, a new hypothesis for the on-going desertification process in the south-western United States is proposed. It is hypothesised that a vegetation boundary is stable when two conditions prevail to balance the lower resistance of grassland within the existing environmental setting with the higher resistance of shrubland: that the depletion of soil nutrients by the action of overland flow in the grassland zone close to the boundary is in balance with the replenishment rates of grassland by other nutrient cycling, and that the grassland gains enough water resources from the upslope shrublands. In contrast, a vegetation boundary potentially becomes unstable when the grassland acquires a competitive disadvantage towards shrubland regarding water benefit and nutrient depletion due to the combined effects of overland-flow dynamics and some external forces such as extensive overgrazing or climate change. The modelling results suggest that landscape linkages through the redistribution of water and soil resources across vegetation-transition zones at the landscape scale and feedback dynamics of overland-flow processes play a significant role in the persistence of land degradation in the US Southwest.

1. Introduction

Desertification and land degradation in the south-western part of the United States have led to a significant vegetation change from grassland to shrubland within the past 150 years (Buffington and Herbel, 1965). The degradation process continues even when external environmental stresses, such as heavy overgrazing, are removed (Whitford, 2002; Rango

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doi:10.1016/j.ecolmodel.2007.04.010

et al., 2002; Laycock, 1991); a fact which suggests that the ecosystem stability has been disturbed profoundly. The persistence and on-going propagation of desert shrubs has been related by Schlesinger et al. (1990) to the redistribution of water and nutrient resources at the plant–interspace scale. There is some suggestion in the results of Schlesinger et al. that redistribution at this scale leads to further redistributions at landscape scale (>5 km^2), and this idea is reinforced by feedbacks observed in the transfer of water and sediment and the consequent reorganization of the land surface as observed by Abrahams et al. (1995), Parsons et al. (1996) and Wainwright et al. (2000). More recently, Peters and Havstad (2006) have outlined the need to use a multi-scale approach to understand the drivers of land degradation in these areas, taking into consideration variations at patch-mosaic and vegetation association scales as well as the plant interspace.

It is hypothesised in this paper that boundaries between different vegetation associations are likely to be foci for progressive change. In particular, the role of runoff across vegetation boundaries between shrubland and grassland in these degradation processes may be crucial in explaining the ongoing degradation as significant amounts of overland flow are generated by high-intensity rainstorm events that frequently occur during the summer monsoon months in that region. Currently, only very limited quantitative information on this redistribution at the landscape scale is available as the spatial measurements of water and nutrient fluxes is problematic with increasing spatial extent. Parsons et al. (in press), for example, investigated the change of nutrient content of interrill runoff fluxes across shrubland and grassland boundaries in the Jornada Basin, Chihuahuan Desert. They argued that measurements from small runoff plots cannot be simply up-scaled to obtain estimates of landscape-scale nutrient fluxes. Thus, field plot measurements would only be able to give a very limited picture on the fluxes and are often not able to provide information on the spatial distributions of fluxes at the landscape scale, for example across vegetation boundaries, which might prove important for the explanation of land degradation processes.

To enable the investigation of spatial water and nutrient resource redistribution at the landscape scale, this research employed a previously tested, spatially distributed numerical modelling approach by Mueller et al. (in press) as an estimation approach for the assessment of ecosystem stability along vegetation boundaries between grasslands and shrublands. Once the water and nutrient fluxes are quantified through scenario calculations, the competitive advantage of shrubland towards grassland can be assessed and the stability and resilience of the ecosystem towards external factors such as overgrazing and climate change can be discussed.

1.1. *Study area*

The modelling studies concentrated on the computation of water and nutrient fluxes *between* vegetation associations across dominant vegetation boundaries between grassland and shrubland and *vice versa* in the Jornada Basin. The Jornada Basin (32°31′N, 106°47′W) is situated ca. 40 km NNE of Las Cruces, New Mexico, USA. The location experiences a semi-arid to arid climate with a mean annual precipitation of 245 mm and a mean annual potential evapotranspiration of 2204 mm. The majority (65%) of the precipitation falls as intense, short-duration, convective summer storms (Wainwright, 2005). Dominant shrubland associations of the region are creosotebush (*Larrea tridentate*), honey mesquite (*Prosopis glandulosa*) and tarbush (*Flourensia cernua*). The soils in the Jornada Basin consist mostly of Aridisols such as Haplargids, and Entisols such as Toripsamments. Jornada soils are highly interactive with the vegetation through plant–soil feedback processes (Buffington and Herbel, 1965; Bulloch and Neher, 1980).

Black grama grasslands occur typically on upland slopes and in the central plain of the basin with grass swards being degraded to various degrees. Creosotebush vegetation occurs within the lower and upper piedmont slopes of the basin. Tarbush vegetation is found within the lower piedmont slope and the alluvial plain. Mesquite shrubs exist predominantly in the eastern and central part of the Jornada Basin. Fig. 1 shows a vegetation map with the extent of the four vegetation types for the Jornada Experimental Range for the year 1998 (map data provided by the Jornada Experimental Range Agricultural Research Service, US Department of Agriculture, Las Cruces, New Mexico).

For the model scenarios of fluxes between vegetation associations, representative locations of currently existing vegetation boundaries from the vegetation map were selected for the model studies where overland flow occurred between relatively non-degraded, undisturbed black grama grassland and the three shrub types (and *vice versa*), and between creosotebush and mesquite and between creosotebush and tarbush within the Jornada Basin (Fig. 1). The other shrub combinations did not occur extensively in the Jornada Basin and were therefore not considered. The contributing area for each boundary scenario was chosen to extend over a distance of approximately 2 km upslope of the vegetation boundary, which was assumed to be large enough to avoid any edge effects. This perimeter was furthermore justified by the fact that high-intensity rainstorm events generally occur with a limited spatial coverage (Wainwright, 2005), and therefore the total area where significant amounts of overland flow is generated is assumed to be small. The exact locations of vegetation-boundary lines were identified by overlaying the vegetation-cover map from 1998 with high-resolution aerial photography provided by the Jornada Experimental Range Agricultural Research Service, US Department of Agriculture, Las Cruces, New Mexico.

1.2. *Methods*

1.2.1. *Description of the modelling approach*

Process-based, spatially distributed models were employed for the calculation of overland flow and dissolved nutrients in runoff generated by high-intensity rainstorm events. The hydrological model is based on a kinematic wave approximation to the St. Venant Equations for the routing of overland flow, Hortonian infiltration and Darcy-Weisbach flow equation as described by Scoging et al. (1992), Parsons et al. (1997) and Wainwright and Parsons (2002). The nutrient-transport is modelled by an advection–dispersion model as used by Havis et al. (1992) and Walton et al. (2000) and simulates the fluxes