



Numerical investigation of spatial pattern in a vegetation model with feedback function

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ABSTRACT

The vegetative cover in semi-arid lands typically occurs as patches of individual species more or less separated from one another by bare ground. Klausmeier [1999. Regular and irregular patterns in semiarid vegetation. *Science* 284 (5421), 1826–1828] reported that the vegetation striped patterns can grow lying along the contours of gentle slopes. He has proposed a model of vegetation stripes based on competition for water. In this paper, our main aim is to study the positive feedback effects between the water and biomass on the vegetation spatial pattern formation within a nonsaturated soil, which arises from the suction of water by the roots and processes of water resource redistribution. According to the dispersion relation formula, we discuss the changes of the wavelength, wave speed, as well as the conditions of the spatial pattern formation. Our numerical results show that trees are more sensitive than grasses to the positive feedback function to format the spatial heterogenous pattern, and the stronger positive feedback increases the parameters region where vegetation bands occur, which indicates that the positive feedback raises the possibility of shift from green to desert states in semi-arid areas for the long term. Our numerical results also show that the positive feedback can increase the migration velocity of the vegetation stripes.

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1. Introduction

In these semi-arid environments, vegetation is not homogeneous, but rather self-organized into spatial patterns¹ (Guttal and Jayaprakash, 2007; Kéfi et al., 2007b; Barbier et al., 2006; Rietkerk et al., 2004; Scanlon et al., 2007; Meron et al., 2007; Esteban and Fairén, 2006; Solé, 2007). Banded spatial patterns of vegetation are a central feature of these semi-arid areas. Many types of spatial patterns including bands, labyrinth, spots, stripes, and gaps (von Hardenberg et al., 2001; Klausmeier, 1999) in these areas have been observed in the field. Vegetation patterns, a subfield of spatial ecology (Bascompte and Sole, 1998; Tilman and Kareiva, 1997), have been extensively studied by arid land ecologists (see Aguiar and Sala, 1999; Tongway et al., 2001; Valentin and d'Herbès, 1999; Rietkerk et al., 2004, and references therein). One of the typical spatial pattern is striped pattern in the

semi-arid areas. It occurs in regions of low woodlands or tall shrublands, on gentle slope of about 0.25% gradient (Valentin et al., 1999). In this case, vegetation is concentrated into bands running along the contours of the hill, typically of width 100–250 m wide. These stripes of vegetation are separated by gaps, typically of width 200–1000 m, in which vegetation is sparse or absent (Sherratt, 2005; Valentin et al., 1999; Valentin and d'Herbès, 1999; Lejeunea et al., 1999; Barbier et al., 2006).² Recently, studies show that the rapid shifts from green to desert states are possible due to rising temperatures, declining rainfall, and increased grazing (Rietkerk et al., 2004; Kéfi et al., 2007b; Solé, 2007). As we know, arid and semi-arid ecosystems cover near one-third of Earth's lands surface, it is a pressing need for quantitative ways to help forecast such shifts (Rietkerk et al., 2004).

Recent analysis of ecosystem dynamics has shown the possibility of a sudden, catastrophic change from one ecosystem type to another (Scheffer et al., 2001; Rietkerk et al., 2004). However, there is a continuing debate on the mechanism

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¹ Spatial self-organization is not imposed on any system but emerges from fine-scale interactions owing to internal causes (see Rietkerk et al., 2004; Rohani et al., 1997; Esteban and Fairén, 2006; Barbier et al., 2006). However, some ecologists think there is no evidence that vegetation is self-organized in the field.

² For detailed data about vegetation stripes in the field see the works of Valentin et al. (Valentin and d'Herbès, 1999; Valentin et al., 1999; Barbier et al., 2006; Rietkerk et al., 2004).

responsible for vegetation spatial patterns. A number of factors driving these vegetation pattern formation have been identified, but there is not a clear consensus on the key factors or processes that produce different outcomes under seemingly similar conditions (Havstad et al., 2006). The two most commonly cited drivers of this vegetation pattern formation are the separate and interactive effects of drought and livestock overgrazing³ (Archer, 1994; Rietkerk and van de Koppel, 1997). Furthermore, the dominating driving forces in arid lands are water scarcity, plant competition over water resources, and redistribution of water by runoff and diffusion, and moreover associated with positive feedbacks between vegetation and its most limiting resource water (von Hardenberg et al., 2001; Scheffer et al., 2005; Peters and Havstad, 2006), climate (Adams and Carr, 2003; D'Odorico et al., 2005; Rodriguez-Iturbe et al., 1999), soil storage capacity, and rainfall interception (Isham et al., 2005; Rodriguez-Iturbe et al., 1999). More recently some frameworks have combined vertical penetration and horizontal advection of water at the plant scale (Breshears and Barnes, 1999) and focused on the importance of water runoff at patch scales to landscape scale processes (Peters and Havstad, 2006; Ludwig et al., 2005; Kéfi et al., 2007a; Scanlon et al., 2007; Solé, 2007). Specially, Kéfi et al. (2007a) and Scanlon et al. (2007) explore the problem of how vegetation in semi-arid ecosystems is organized in space and time. A notable finding is that the size distribution of vegetation clusters in undisturbed plots falls off as a power law: most patches of vegetation are of small size, but a few of them are very large, in which the power law is also the result of internal dynamic processes driven by local interactions (Solé, 2007; Scanlon et al., 2007). Competition for water and the positive feedback between water availability and plant growth are widely recognized as the underlying cause of vegetation patterning in other studies (von Hardenberg et al., 2001; Scheffer et al., 2005; Peters and Havstad, 2006; Adams and Carr, 2003). The phenomenon of positive feedback has remarkable significance. It often exists between vegetation and soil moisture. Two different mechanisms are often invoked to explain these feedbacks at different scales. At the regional or subcontinental scales, vegetation may affect the rainfall regime as suggested by simulations with global and regional circulation models (Zeng et al., 1999). At smaller scales, a positive feedback explains the existence of moister soils beneath vegetation canopies with respect to adjacent bare soil plots. These feedbacks have often been attributed to the large infiltration capacity of vegetated soils, due to their lower exposure to rain splash compaction and the higher hydraulic conductivity resulting from root action (Hettiaratchi, 1990), such as shape growth of the root and so forth.

Recent model studies on dryland vegetation support the view of vegetation pattern formation as a symmetry-breaking phenomenon (Cross and Hohenberg, 1993). Based on this mechanism, the vegetation has been observed to form spatial patterns in several independent models (Lefever and Lejeune, 1997; von Hardenberg et al., 2001; Klausmeier, 1999; Okayasu and Aizawa, 2001; Rietkerk et al., 2002, 2004). One of them is proposed by Klausmeier (1999), from which pattern formation in semi-arid areas can be studied and which shows that numerical solutions of his model do predict vegetation stripe formation. For appropriate parameters, the vegetation stripes are maintained and the moist soil on the uphill side of a stripe creates a tendency for the stripes to gradually migrate uphill. Klausmeier's model plays a key role in the vegetation patterns formation since it expresses relationship between plant communities and water-limited systems with relatively simple formulation. Klausmeier's model has been

studied with linear stability analysis and nonlinear bifurcations numerical study recently by Sherratt (2005) and Sherratt and Lord (2007). The authors derive formulate for the wavelength and migration speed of the predicted patterns on the original Klausmeier's model. Their results show that Klausmeier's model can predict the vegetation central feature including width and migration speed. However, the details of the feedback processes remain unclear yet on this model. In the present paper, we concern about the vegetation pattern formation with the positive feedback function arising from processes of water resource redistribution which results from the suction of water by the roots on the model proposed by Klausmeier (1999). We derive the formula of the dispersion relation for pattern formation by using Laplace transform methods which is convenient for finding spatial symmetry-breaking conditions in the case when the systems include diffusion and advection. Our results show that this feedback function has notable effect on the traveling spatial pattern. These results have been confirmed by numerical calculation using open software from the XMDS project (<http://www.xmds.org>) (Cochrane et al., 2008; Collicutt and Drummond, 2001).

2. Model

Based on the original Klausmeier's model, in the present paper, the main new ingredient in the modified model (1) is the introduction of a new positive feedback term—processes of water resource redistribution resulting from the suction of water by the roots.⁴ The modified model for the plant biomass density $n(r, t)$ and the ground water density $w(r, t)$ is as follows:

$$\frac{\partial n}{\partial t} = \overbrace{wn^2}^{\text{plant growth}} - \overbrace{mn}^{\text{plant loss}} + \overbrace{\nabla^2 n}^{\text{dispersal}}, \quad (1a)$$

$$\begin{aligned} \frac{\partial w}{\partial t} = & \underbrace{a}_{\text{rainfall}} - \underbrace{w}_{\text{evaporation}} - \underbrace{wn^2}_{\text{uptake by plants}} + \underbrace{v(\partial w/\partial x)}_{\text{flow downhill}} \\ & + \underbrace{\delta \nabla^2 (w - \beta n)}_{\text{feedback plant vs water redistribution}}, \end{aligned} \quad (1b)$$

where all quantities are in nondimensional form and $\nabla^2 = (\partial^2/\partial x^2)$ or $\nabla^2 = (\partial^2/\partial x^2) + (\partial^2/\partial y^2)$ denotes the one- and two-dimensional Laplacian operator, respectively. The parameters' rescalings are taken from Klausmeier (1999) and Sherratt and Lord (2007). Although the notation is different, the meaning of the terms in Eq. (1a) has the same description as in Klausmeier (1999). The term wn^2 describes plant growth as nonlinear with water resource w for dry soil. The term mn accounts for plant biomass lost only through density-independent mortality and maintenance. The spread of plants, both by clonal reproduction and by seed dispersal is modeled by the diffusion term $\nabla^2 n$ (Murray, 1993). In general, the water resource is coupled to the plant biomass through various feedback processes including reduced evaporation by shading (*shading feedback*), increased infiltration at vegetation patches (*infiltration feedback*) and water uptake by plant's roots (*uptake feedback*) (Gilad et al., 2007; Rietkerk et al., 2002) as well as the other feedbacks (see the discussion in Section 6). The term wn^2 in the original Klausmeier's model can also be regarded as uptake feedback to promote the growth of plants. In addition, the physical environments of the soil play a key role on water uptake by plants. The process of water distribution is one of them. Our goal here is to

³ This scenario represents desertification due to over-grazing in the dimensionless model (1) is captured by the biomass-loss rate, m .

⁴ Note that here the term *suction* is different from *uptake*, see the work by Hillel (1998) and the explanation in text for the new term in Eq. (1b).

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