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Formation of banded vegetation patterns resulted from interactions between sediment deposition and vegetation growth

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ABSTRACT

This research investigates the formation of banded vegetation patterns on hillslopes affected by interactions between sediment deposition and vegetation growth. The following two perspectives in the formation of these patterns are taken into consideration: (a) increased sediment deposition from plant interception, and (b) reduced plant biomass caused by sediment accumulation. A spatial model is proposed to describe how the interactions between sediment deposition and vegetation growth promote self-organization of banded vegetation patterns. Based on theoretical and numerical analyses of the proposed spatial model, vegetation bands can result from a Turing instability mechanism. The banded vegetation patterns obtained in this research resemble patterns reported in the literature. Moreover, measured by sediment dynamics, the variation of hillslope landform can be described. The model predicts how treads on hillslopes evolve with the banded patterns. Thus, we provide a quantitative interpretation for coevolution of vegetation patterns and landforms under effects of sediment redistribution.

1. Introduction

Banded vegetation patterns exist widely in the world's ecosystems [1–6]. Such patterns comprise alternating bands of vegetation and bare ground, and are a characteristic feature of landscapes in many arid and semiarid areas [7–9]. These patterns have been widely studied through field investigations and theoretical analysis due to their widespread occurrence and special features [10].

A large number of hypotheses aim to comprehend the self-organization of these patterns [8,10–14]. One important hypothesis addresses the nonlinear feedback between plant biomass and water resources of runoff–runon systems [15,16]. Rainfall on bare soil bands barely infiltrates, but runs downhill into vegetated bands and accumulates. Plant biomass can be greatly magnified in vegetated areas due to uptake of soil water by plant roots.

Many dynamic models based on feedback mechanisms of plant biomass and water resources have been established [8,10,11,15–20]. Two are regarded as core spatial vegetation-water models. The Klausmeier model addresses the formation of banded vegetation patterns in semiarid regions driven by feedback between biomass and water infiltration [8]. The second, proposed by HilleRisLambers et al. [15] and Rietkerk et al. [11], describes the water budget in detail as both soil and

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surface water. This model produces vegetation patterns of spots, labyrinths, gaps, and regular bands, dependent on rainfall and slope gradient [11]. The two models and their modified versions provide significant understanding of core mechanistic processes of vegetation pattern formation [21].

In the published literature on banded vegetation patterns, only a few researchers have considered the importance of micro-geomorphic processes [22–27]. Processes of soil erosion, sediment transport, and sediment deposition exert great influence on vegetation growth. A substantial amount of sediment is intercepted, trapped, and accumulated at vegetation patches [28,29]. Because the topsoil layer varies with soil erosion and sediment deposition, vegetation growth is greatly affected. Field observations and laboratory experiments show that soil erosion and/or sediment deposition may promote the development of banded vegetation patterns on hillslopes [1,28,30–35].

Considering the influences of soil variation aids understanding of the formation of banded vegetation patterns. For vegetation growth on hillslopes, soil factors dominate the water resource. First, mineral nutrition and water resources necessary for vegetation growth are stored in the soil layer. Second, soil provides a stable environment for vegetation growth. Disturbance of the soil by geomorphic processes leads to variations of water resources and nutrients for plants, affecting vegetation growth [36]. Thornes [37] and Zhang [38] proposed theoretical frameworks regarding the ecology of erosion and eroded ecosystems. From this perspective, focusing on influences of soil variation is more important than considering water resource effects on banded vegetation patterns. Moreover, soil thickness can be directly measured, reflecting variations of microtopography in banded patterns.

The natural world indeed offers examples of the formation of vegetation patterns resulting from soil variation. As observed by Gallart et al. [32], "grassed stairs" and terracette patterns are common features in the central Pyrenees. Generally, the terracettes are restricted to an altitudinal range between 1700 and 2700 m. The total plant cover of the terracette surfaces is often between 30 and 35%, and the main building species are bunchgrasses such as *Festuca eskia*, *Festuca gautieri*, *Sesleria cerulea*, etc. The growth habit of bunchgrasses results in a slow radial growth rate of the clump, and therefore the bunch reaches a high plant density in the clumps, while leaving areas of bare soil among them. On flat or gentle slopes, the bunch growth habit produces a mosaic of more or less circular random phases. As the gradient becomes steeper, bunches become roughly semicircular and tend to connect together, giving a pattern of continuous treads and risers following topographic contours.

Based on the ecological observations of Gallart et al. [32], substantial sediments are transported by overland flow and settle in vegetated areas intercepted by vegetation. Under negative influences of the accumulated sediments, small-scale vegetation bands appear on hillslopes. Thus, the interactions between sediment deposition and vegetation growth promote self-organization of banded vegetation patterns on hillslopes. However, little literature exists on this topic. A dynamic model of sediment deposition and vegetation growth on hillslopes is still needed for quantitative analysis of patterns that result from such interactions.

In this study, a spatial dynamic model is established, describing dynamics of sediment deposition and vegetation growth, based on the field observations of Gallart et al. [32]. The model aims to theoretically investigate the mechanism for the spontaneous emergence of banded patterns and stepped topography in the above case of the central Pyrenees as well as other cases with similar interactions and environmental conditions. Considering the characteristics of vegetation growth and sediment deposition in the above case, the spatial model is parameterized and utilized to simulate and analyze the formation process of banded vegetation patterns. However, it should be noted that the Pyrenees sites studied here are characterized by more humid climatic conditions than the arid and semiarid regions studied in much of the literature. Therefore, the model developed here is site-specific in that the feedbacks between sediment deposition and vegetation growth are likely more important than those between water redistribution and vegetation growth in the emergence of banded vegetation.

In developing the dynamic model of sediment deposition and vegetation growth, Thornes' thought, which directly integrates geomorphic and ecological processes [37,39–41], is accepted. Via Turing analysis and numerical simulations on the model, the process and mechanism of formation of banded vegetation patterns are addressed. In this research, banded vegetation patterns describe a stable state of spatially heterogeneous vegetation, which shifts under influences exerted by sediment accumulation on vegetation growth.

2. Development of the model for formation of banded vegetation patterns

The dynamic model describes the formation of banded vegetation patterns on hillslopes, which is mainly influenced by the interactions between sediment deposition and vegetation growth.

2.1. Interactions between sediment deposition and vegetation growth

Although many studies use the feedback mechanisms between water and biomass to interpret vegetation pattern formation, vegetation pattern formation can result from the interactions between geomorphic processes and vegetation growth [23,27,37,40,42–44]. Hoffman et al. [45] concluded that the "current mathematical models of pattern formation in drylands typically consider only an infiltration-vegetation feedback and root augmentation growth as driving mechanisms, yet patterns of sedimentation and erosion on the soil surface have a strong effect on hydrological processes, stressing the need to introduce a soil-vegetation and an annual-shrub feedback."

Gallart et al. [32] observed that banded vegetation patterns in high-mountain terracettes were common features on steep slopes between 1700 and 2700 asl in the central Pyrenees. As described by Gallart et al. [32],