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Original Research Article

Vegetation patterns generated by a wind driven sand-vegetation system in arid and semi-arid areas

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ABSTRACT

Wind has been proposed as a driving factor in determining vegetation patterns, but there are few dynamic models that include both vegetation and wind. In this paper, we present a dynamic model to investigate how a vegetation pattern is generated and affected by wind. In the model, the effects of prevailing wind and non-prevailing wind on sand and vegetation are modeled respectively as advection terms and diffusion terms. With these considerations and proper parameter values that satisfy Turing bifurcation conditions, labyrinth and banded vegetation patterns are obtained in two situations of wind. By changing wind transportation capacity, we simulate the adaptation process from one vegetation pattern to another. With environmental changes of large amplitude, the width of vegetation bands varies while the wavelength can increase but does not decrease in our simulation. Then we describe the difference between simulated patterns and real patterns. And in the discussion, we explain the mechanism that forming patterns and the consistency of this research with other studies.

1. Introduction

Striking patterns in vegetation have been observed in arid and semiarid areas (Klausmeier, 1999), and these vegetation patterns are reported widely in the world, particularly in Africa (Deblauwe et al., 2012; Muller, 2013), Australia (Berg and Dunkerley, 2004; Moreno-de las Heras et al., 2012) and North America (Deblauwe et al., 2012; Montana, 1992; McDonald et al., 2009). Recorded patterns in vegetation include regular isolated spots of trees and shrubs in savannah grasslands (Lejeune et al., 2002; Ben Wu and Archer, 2005), banded patterns of tree lines ('ribbon forests') in the Rocky Mountains (Hiemstra et al., 2006; Bekker et al., 2009), and spots, bands and labyrinths of vegetation in semiarid environments (Klausmeier, 1999; Galvin et al., 2007; Scanlon et al., 2007). The diversity and the widespread occurrence of vegetation patterns have attracted great interest from a number of researchers especially in the past decades. On the one hand, many studies have been carried out to explore the mathematical mechanisms that might generate vegetation patterns (HilleRisLambers et al., 2001; Rietkerk et al., 2002; van de Koppel et al., 2002; Lefever and Lejeune, 1997; D'Odorico et al., 2006a, 2007; Sherratt, 2005), and on the other hand studies are finding more ecosystems that show vegetation patterns (Lejeune et al., 2002; van de Koppel et al., 2005; van de Koppel and Crain, 2006; Hiemstra et al., 2006; Galvin et al., 2007). These two fields enhance the understanding of vegetation competition when resources are limited and the process by which robust land is converted to desert as a result of climate change or anthropogenic disturbances (van de Koppel et al., 2002; D'Odorico et al., 2006b). Therefore more situations, types and mechanisms of pattern formation need to be explored.

In order to investigate the physical mechanisms of vegetation pattern formation, mathematical models have been used widely (Borgogno et al., 2009), which have used partial differential equations (PDE) (HilleRisLambers et al., 2001; Rietkerk et al., 2002; Meron et al., 2004), simple cellular automata (Thiéry et al., 1995; Dunkerley, 1997) and complex lattice models (Ludwig et al., 1999). Among these methods, PDEs are now established as the dominant modeling framework (Dagbovie and Sherratt, 2014). The most well known model on vegetation pattern formation was proposed by Klausmeier (1999). In Klausmeier's model, soil water and vegetation biomass are considered as the main components that generate banded vegetation pattern on hill slopes. Many subsequent models divided water into soil water and surface water but remain based on 'water redistribution hypothesis' (von Hardenberg et al., 2001; HilleRisLambers et al., 2001; Rietkerk et al., 2002;

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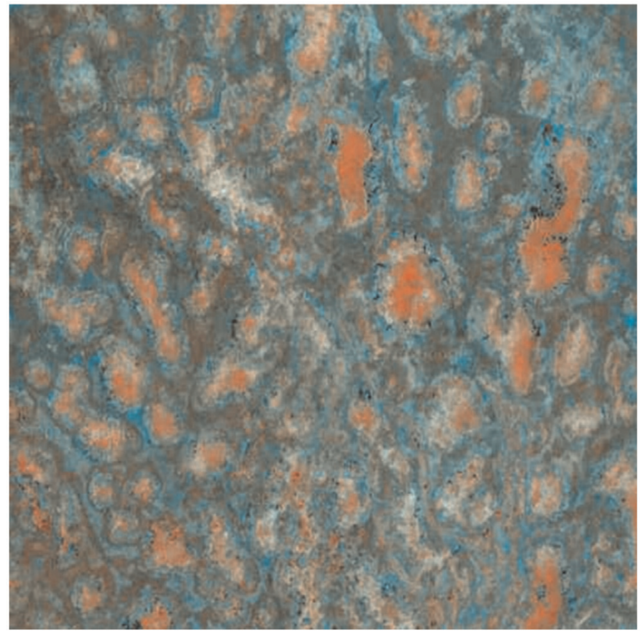
Ursino, 2007, 2009). Rain water falling onto bare ground mostly runs off to nearby vegetated areas. There the infiltration capacity of the soil is higher because of the presence of organic matter and roots (Hills 1971; Callaway, 1995; Valentin et al., 1999; Rietkerk et al., 2000), and thus the rain water can infiltrate. The resulting positive feedback in plant growth provides a potential mechanism for patterning. There are also another hypothesis on the causes of pattern formation, and most of them are based on the 'short-distance activation, long-distance inhibition' mechanism (Lefever and Lejeune 1997; Barbier et al., 2008; Lefever et al., 2009). Borgogno et al. (2009) proved that although these models are based on two different hypotheses patterns are all induced by symmetry-breaking instability in activation-inhibition systems. And the major causes and components of the vegetation patterns are mostly recognized as soil water and vegetation.

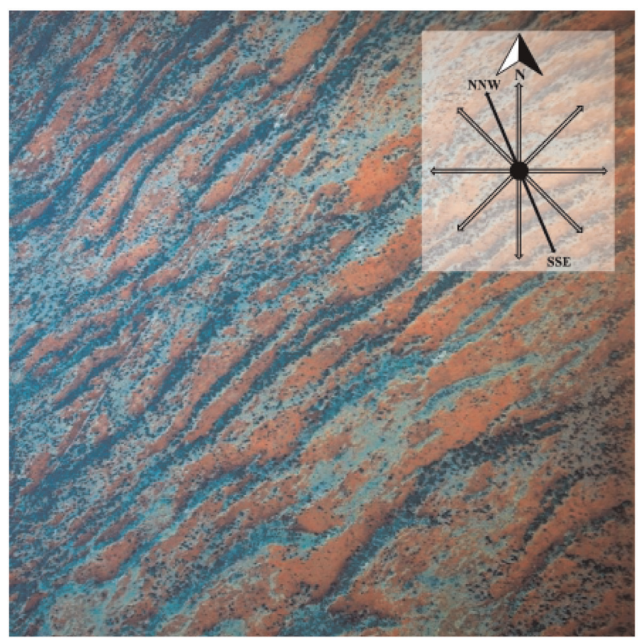
Apart from the above, which typically assume windless situations (or at least that wind was not involved as the driving force in the model), there is another group of studies on windy sandy situations. Vegetation patterns can also be generated when the driving force is wind. Banded vegetation patterns have been observed perpendicular to the direction of the dominant wind on windy sandy land in arid and semiarid areas, like in Mauritania by Audry and Rossetti (1962), in Mali by Leprun (1992, 1999), and in Australia by Mabbut and Fanning (1987). Different from vegetation patterns in windless situations, vegetation is alternated with micro-dunes instead of bare ground. White (1969, 1971) suggested that in Jordan wind might be the initiating and driving factor of banded patterns, and the accumulation of wind-blown material around isolated plants might act as a nucleus for the development of vegetation arcs. But until now mathematical models that consider wind as the driving force in the formation of vegetation patterns have been rare. We know that there are interactions between vegetation and sand deposition (Okin et al., 2001; Eldridge and Leys, 2003; Yan et al., 2011; Zhao et al., 2007; Zhang et al., 2012). When wind is also considered the processes and interactions become even more complicated. However, quantitative investigations of windy sandy areas are needed to understand how vegetation patterns are formed, and these could build on methods that developed in previous studies of windless situations.

Vegetation bands that lie perpendicular to the prevailing wind direction have been observed, showing that dying trees in the windward edge and a seedling regrowth on the leeward edge of each band (Clayton, 1966, 1969; Zonneveld, 1999). And in this research, we find two types of vegetation patterns in central Pilbara, Western Australia (around −22°425′N, 117°695′E), as shown in Fig. 1: labyrinth-type vegetation pattern in Fig. 1a and banded vegetation pattern in Fig. 1b. In this area, annual mean precipitation is around 300 mm, and vegetation cover has been maintained by native xerophytes. The altitude of the area is between 610 m and 630m. The slope angles are less than 0.2% and the orientation of these slopes is irregular. Prevailing winds are *NNW* (North Northwest) in summer and *SSE* (South Southeast) in winter. The annual mean wind velocity is 3.7 m/s, and the annual sand deposition has been reported as 31.4–43.8 t/km^2 (McTainsh and Lynch, 1996). And note that in Fig. 1b, the orientation of vegetation bands are almost uniform and it is perpendicular to the prevailing wind directions. Thus we infer that wind and sand have played very important roles in forming the patterns in Fig. 1. It seems that wind is not very strong and the sand deposition rate is moderate in global terms (Hesse, 2003), but possibly when sand movement is stronger vegetation goes extinct rather than forming patterns.

In this paper, we consider the brief processes in a windy sandy environment, and establish a sand-vegetation model using partial differential equations. We first simulate the formation of vegetation patterns, including the type, generation time and orientation.



(a)



(b)

Fig. 1. Two real vegetation patterns in Pilbara, Western Australia.
The green area is vegetated land (dark green and light green shows the different density of vegetation), while the orange area is sandy land. Fig. 1a is captured by Google Earth Pro on March 21st, 2006 (Ver. 7.1.4.1529). Fig. 1b was taken by a photographer (Gray, 2013) on March 13th, 2014. Both areas are about 1500 × 1500 m^2. The location of the places is around −22°425′N, 117°695′E. The prevailing wind direction in this area is *NNW* in summer and *SSE* in winter. The altitude of the area is between 610 m and 630 m. The slope angles are less than 0.2% and the orientation of these slopes is irregular. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As most of the studies concluded by simply demonstrating that vegetation patterns could be obtained. Only recently has research proposed the importance of investigations after getting the vegetation patterns (Siteur et al., 2014). Therefore further