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Modeling the impact of overgrazing on evolution process of grassland desertification

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In this study, the evolution process of aeolian dune fields in grassland is numerically investigated. The influence of overgrazing on vegetation coverage, wind erosion of soil and vegetation burial are considered. Results show that evolution time, grazing area and grazing intensity per unit area have significant impacts on grassland desertification. A formula describing the desertification intensity with respect to grazing area and grazing intensity per unit area is given.

1. Introduction

Grasslands cover about one-quarter of the earth's land surface (Ojima et al., 1993) and span a range of climate conditions from arid to humid. Most of grasslands are used for the production of animals for consumption, including for meat, milk, and any major animal products (Asner et al., 2004). They also play an important role in carbon storage (Gill et al., 2002), nitrogen fixation (Huss-Danell et al., 2007) and conservation of water and soil. Therefore, the sustainability is expectant due to the environmental, economical and social importance of grasslands. But, with the increase of population, pressure of food supply leads to the overload of most kinds of land including the grassland, and overgrazing becomes a worldwide problem. In China, it has been reported there are serious overgrazing on the grasslands of Inner Mongolian and Tibetan Plateau (Zhao et al., 2005; Xin, 2008). Long-term overgrazing not only results in decrease of biomass, but also causes the loss of vegetation coverage which can influence the climate and soil stability of the grassland or the nearby region (Bounoua et al., 2000), that is, once the vegetation is reduced or lost, the soil will be exposed to the air, which makes soil more vulnerable to erosion including water erosion (Hill and Peart, 1998) and wind erosion (Shi et al., 2004), and therefore leads to grassland desertification.

Overgrazing has attracted many researchers' interest (Noy-Meir, 1975; Van De Koppel and Rietkerk, 2000; Van Langevelde et al., 2003). Despite the consensus that overgrazing causes enormous harm or damage to the grassland such as a fall in production (Rusch and Oesterheld, 1997), the development of vegetation patches (Kéfi et al., 2007) and degradation or desertification (Zhao et al., 2005), controversy remains as to the influence of overgrazing (or grazing) on the grassland vegetation coverage. Previous researches provided various conclusions: overgrazing would decrease the grassland coverage (Mwendera et al., 1997; Zhao et al., 2005; Gao et al., 2007; Wu et al., 2009; Schönbach et al., 2011); it has no significant influence on the coverage (Mwendera et al., 1997); and it sometimes even increases the coverage (Biondini et al., 1998). For this problem, Fu et al. (2012) modified Noy-Meir's model of stability in grazing systems by modeling vegetation coverage instead of biomass, and the relationship between coverage change and the overgrazing sheep units was discussed. Their results revealed that the variation of coverage is determined corporately by grazing intensity, natural conditions and property of grassland.

Although overgrazing has been studied for a long time, the influence of overgrazing on the degradation or desertification of grassland is not well understood. Existing researches show that the desertification of grassland induced by overgrazing has seriously affected people's production and living. For example, Qi et al. (2006) pointed that about 90% of grassland in Maqu County, which is located on the eastern Tibetan Plateau, has occurred desertification in different degrees, and the length of dune belt along Yellow River has been up to 220 km. The study of Yao et al. (2007) shows that the water supply capacity of Maqu section

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of Yellow River has reduced about 15%, which directly results in cutoff at the downriver of Yellow River and hundreds of billions' economic losses. So, we need to deeply study the desertification of grassland with the action of overgrazing.

Due to the extremely large spatial and temporal scales involved in the evolution of aeolian dune fields, existing observational facilities and schemes have not achieved a panoramic survey of the whole process of dune fields in grassland. However, theoretical modeling and numerical simulations have provided important insights to the evolution of dune fields in grassland (Nishimori and Ouchi, 1993; Werner, 1995; Momiji et al., 2000; Sauermann et al., 2001; Schwammle and Herrmann, 2003; Parteli et al., 2007; Narteau et al., 2009; Baas, 2002; Luna et al., 2011; Pelletier et al., 2009). Cellular automaton and continuum models have simulated parabolic dune formation and furthered our quantitative knowledge of the barchan-parabolic transition. The cellular model of Nishimori and Tanaka (2001) partially succeeded in capturing the transition. In their simulation, barchan dunes temporarily gave rise to parabolic forms that were unstable. A cellular model by Nield and Baas (2008), which simulated the development of parabolic dunes from blowouts rather than barchans, produced stable parabolic dunes by incorporating two plant species requiring different growth environments. The continuum model that simulates the barchan-parabolic transition is that of Durán et al. (Durán and Herrmann, 2006; Luna et al., 2009), which uses a set of differential equations relating the relative timescales of vegetation growth and dune surface erosion/deposition. Their simulation succeeds in qualitatively reproducing the transition process and predicts a critical ratio θ_c of total surface change to vegetation growth rate, above which a barchan is stable and below which vegetation takes hold and a parabolic dune forms. Durán et al. (2008) compare the vegetation cover on a dune blowout in Brazil to a simulated blowout with an arbitrarily selected fixation index and find qualitative similarity.

From above, existing simulations can be found on the impact of vegetation on the dune or dune field which focuses on dune field morphology, the dune stability, and the barchan-parabolic transition process, but there has been little focus on the impact of vegetation cover on the evolution process of grassland desertification. The resolution of this problem is not only beneficial to the ecologists for understanding how grazing impacts on ecosystems, but also to the environmental scientists and land managers who can give constructive advices on the grassland management from the perspective of environment protection. In this paper, we established a comprehensive scale-coupled model of dune field in grassland on the basis of the variation law of the vegetation coverage with overgrazing intensity, and then, analyzed the process of grassland desertification as well as the influence of some factors.

2. Materials and methods

Recently, Zheng and co-workers (Zheng, 2009; Zheng et al., 2009; Bo and Zheng, 2011a,b) developed a scale-coupled model of dune fields (CSCDUNE), in which the 'sand body element' concept is proposed to bridge the multi-scales involved in the underlying processes, ranging from the motion of sand particles to the evolution of dunes as the representative element used to analyze the spallation in solids (Aidun et al., 1999). The size of the eroded 'sand body element' in the model is determined by the basic processes of wind-blown sand movements, including erosion, deposition, wind-blown sand flux and the wind intensity at various locations. The motion of the eroded 'sand body element' is determined by the transportation and deposition of the wind-blown sand flux, as well as the 'avalanche' behavior of sand particles (Zheng, 2009; Zheng et al., 2009; Bo and Zheng, 2011a,b). The relationship between the average saltation length of sand particles and the transportation length of the eroded 'sand body element' was established. Consequently, a correspondence between simulation results and the actual evolution of a dune field is obtained in both the spatial and temporal scales. The temporal and spatial scales in the model which have a span of 8–9 orders of magnitude, from the motion of a single particle (the size and saltation time of sand particles are 10^{-4} m and 10^{-2}–10^{-1} s, respectively) to the formation and evolution of the whole dune field (the size and evolution time of dune field are 10^{0}–10^{4} m and 10^{4}–10^{8} s, respectively), can be established. It has shown that the morphology (the relation between width, length and height) and change law (the relation between average dune height and sand supply, and the relation between dune speed and dune height) of a dune field obtained by the CSCDUNE scheme are consistent with observation results. Not only that, the model also has good scalability, for example, through considering the non-uniformity of sand supply on bed surface, the influence of some humans factors, such as straw checkerboard and vegetation, to realize the quantitative simulation of the evolution and propagation of aeolian dune fields toward a desert-oasis zone (Bo and Zheng, 2012).

The special status of grassland desertification in grassland makes the simulation of process of grassland desertification different from dune field in desert. For example, the difference involving deposition, vegetation coverage and the non-uniformity of sand supply on bed surface should be considered. Therefore, when the CSCDUNE model was used to simulate the process of grassland desertification, some special treatments need to be done. Details show as follow:

(1) Discretization of the sand bed. In which, the real local wind speed is calculated according to the significantly varying surface configuration and the incoming wind speed. The whole field is divided into 'sand body elements' which has a thickness of $H_{n,ij}$ determined by the real local wind speed. The actual frictional wind velocity blowing over every single "sand body element" is thereby deemed as almost uniform. And due to the sand supply, which lies under soil layer and vegetation cover, is not exposed to the wind field, as shown in Fig. 1. So, when we simulate dune field in grassland, two state variables, i.e., vegetation coverage $\text{veg}_{n,ij}$ and soil thickness $H^s_{n,ij}$, were given to each "sand body element". At the beginning, $H_{n,ij}$, $H^s_{n,ij}$ and $\text{veg}_{n,ij}$ is determined by actual situation, where n is time step, and ij denotes spatial location. Different from the simulation of dune field in desert, two state variables, i.e., the vegetation cover and soil thickness, are added in the simulation of dune field in grassland.

(2) The variation of vegetation coverage and soil thickness. Only soil layer was eroded out by wind action, the sand supply can be exposed to wind field. So the degradation process of vegetation and erosion process of soil, which were caused by overgrazing, must be considered, that is, (I) Randomly selecting α_{stock} "sand body element" from bed surface as grazing location. The variation of vegetation coverage in grazing area was determined by

$$\text{veg}_{n,ij} = \text{veg}_{n-1,ij} - p_{\text{graze}} \tag{1}$$

That is, the vegetation coverage $\text{veg}_{n,ij}$ during ΔT_n is determined as the differential between the vegetation coverage $\text{veg}_{n-1,ij}$ during ΔT_{n-1} and the increment of vegetation coverage p_{graze} during ΔT_n. Here, p_{graze} is increment of vegetation coverage, which can be expressed by initial vegetation coverage $\text{veg}_{n,ij}$ and overgrazing intensity per unit area P_{overG}, namely,