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Modeling the impact of overgrazing on evolution process of grassland desertification

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ABSTRACT

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 $\mathrm{veg}_{n,ij}$ 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 $\mathrm{veg}_{n,ij}$ 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

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

That is, the vegetation coverage $\mathrm{veg}_{n,ij}$ during ΔT_n is determined as the differential between the vegetation coverage $\mathrm{veg}_{n-1,ij}$ 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 $\mathrm{veg}_{n,ij}$ and overgrazing intensity per unit area P_{overG}, namely,

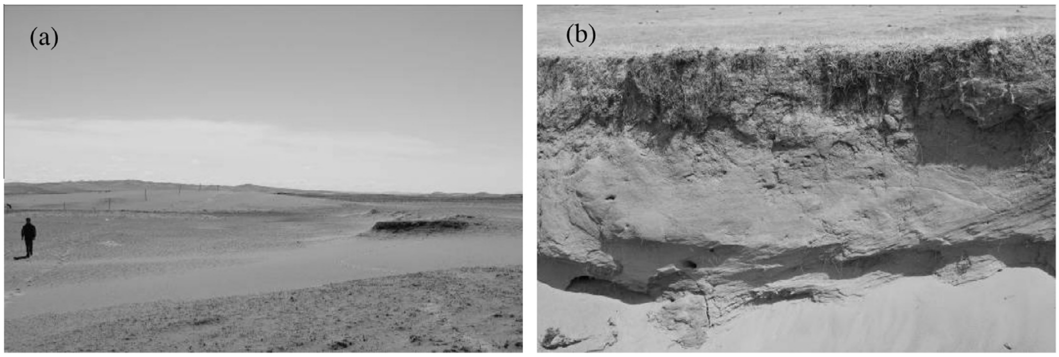

Fig. 1. Wind erosion sand pit (a) and its structure (b).

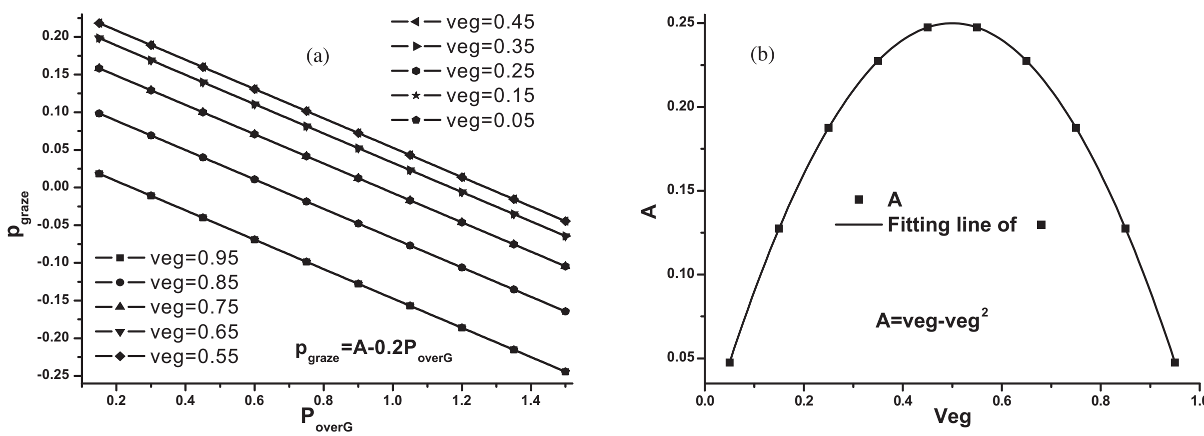

Fig. 2. The variation of vegetation coverage increment with overgrazing intensity per unit area (a) and the variation of parameter A with initial vegetation coverage (b).

$$P_{\text{graze}} = \text{veg}_{n,ij} - \text{veg}^2_{n,ij} - 0.2\left(\frac{\alpha_{\text{stock}}}{\alpha_{\text{veg}}}\right)P_{\text{over}G} \tag{2}$$

Here, α_{veg} is the number of vegetation elements. This relation was determined by the model proposed by Fu et al. (2012). On the basis of the work (Fu et al., 2012), the relation between the increment of vegetation coverage and overgrazing intensity per unit area can be obtained (Fig. 2a). From the figure we can see that the relationship between the increment of vegetation coverage and overgrazing intensity per unit area satisfies a linear function, which can be described by $p_{\text{graze}} = A - 0.2P_{\text{overG}}$. From Fig. 2b we can see parameter A increases first and then decreases with increasing $\text{veg}_{n,ij}$, which can be described by $A = \text{veg}_{n,ij} - \text{veg}^2_{n,ij}$, here actual overgrazing intensity per unit area is $(\alpha_{\text{stock}}/\alpha_{\text{veg}})P_{\text{overG}}$; (II) When the vegetation coverage of 'sand body element' is less than a threshold value, generally is 0.3, the soil which is on the top of sand supply will be blown away, then

$$H^s_{n,ij} = H^s_{n-1,ij} - H^s_{\text{de}} \tag{3}$$

That is, the soil thickness $H^s_{n,ij}$ during ΔT_n is equal to the differential between the soil thickness $H^s_{n-1,ij}$ during ΔT_{n-1} and the reduction of soil thickness H^s_{de} during ΔT_n, here, H^s_{de} is the reduction of soil thickness (Zheng, 2009); (III) In addition, windblown sand movement make the vegetation buried, namely, once the thickness of deposition sand on the soil is larger than the height of vegetation h_{veg}, the vegetation will die, thereby the vegetation coverage is zero,

$$\text{veg}_{n,ij} = 0(h_{s,ij} \geqslant h_{\text{veg}}) \tag{4}$$

Here, $h_{s,ij}$ is the thickness of sand supply on the soil. It should be noted that this step is not considered in the simulation of dune field in desert.

(3) Calculation of the windblown sand flux for the eroded 'sand body element'. The sand flux $q_{n,ij}$, the corresponding sand particles' average saltation length $\bar{l}_{n,ij}$, saltation time $\bar{t}_{n,ij}$, and the average velocities $\bar{v}_{n,ij}$ of impacting sand particles in steady-state windblown flux during ΔT_n for the eroded 'sand body element' where the soil thickness is zero are calculated (Huang et al., 2006). Different from the simulation of dune field in desert, only when the soil thickness of 'sand body element' is zero the calculation of these physical quantities is carried out in the simulation of dune field in grassland.

(4) Evaluation of the thickness and the transportation length of the eroded 'sand body element'. Firstly, the sand particles' deposition and ejection probability during ΔT_n are evaluated. Secondly, the covering coefficient and transportation factor matrix of the 'sand body element' are determined. Finally, the thickness $\eta_{n,ij}$ and the transport length $l_{n,ij}$ of the eroded 'sand body element' are calculated (see also Bo and Zheng, 2011b).

(5) Correction of the transportation and the relative position of the 'sand body element'. Firstly, it is necessary to judge whether $H_{n,ij} < \eta_{n,ij}$ during ΔT_n If so, the thickness of the eroded 'sand body element' is then set equal to $H_{n,ij}$. Secondly, an assessment is made to judge whether the 'sand body element' being moved from locations $i+1$ to $i+l_{n,ij}$

dropped into a 'protected area' where little deposition and erosion of sand happens (Frank and Kocurek, 1996; Walker and Nickling, 2002). If yes, the eroded 'sand body element' will deposit at the first location of the protected area. The area has a length of ζh, in which h is the dune height and the coefficient is commonly taken as $\zeta = 4$ (Werner, 1995). At the same time, the influence of vegetation also is considered. That is, an assessment is made to judge whether the 'sand body element' being moved from locations $i + 1$ to $i + l_{n,ij}$ drops into a 'vegetation area' where little transportation of sand happens (Buckley, 1996). If yes, the eroded 'sand body element' will deposit at the first location of the vegetation area where the vegetation coverage is not zero. If not, the transportation length of those eroded 'sand body elements' along with the wind direction is taken as $l_{n,ij}$. Thirdly, avalanche behavior is considered through moving sands at the higher position moves to the adjacent lower position when the topographic gradient of sand bed is larger than angle of repose of the sand particle. Different from the simulation of dune field in desert, the influence of vegetation on transportation of 'sand body element' is considered in the simulation of dune field in grassland.

(6) Judging whether $\sum \Delta T_n \geqslant T$ is satisfied. If yes, the simulation is over; if not the procedure returns to the first step and is repeated.

where, the 1st, 2nd, 3th and 5th steps are different from the simulation of dune field in desert (Zheng, 2009; Zheng et al., 2009; Bo and Zheng, 2011a). The calculation of the sand flux, the average saltation length and saltation time of corresponding sand particles, the particles' average impact velocities, the sand particles' deposition and ejection probability in the sand flux, the covering coefficient and transportation factor matrix of 'sand body element', as well as the thickness and the transport length of the eroded "sand body element" etc. can reference to CSCDUNE (Zheng, 2009; Zheng et al., 2009; Bo and Zheng, 2011a).

3. Results and analysis

Based on the numerical scheme presented in Section 2, quantitative simulations are conducted of the evolution of dune field in grassland. The simulation box is 5 km in length and 5 km in width ($S = 5 \times 5$ km). The incoming frictional wind speed is 0.5 m/s, sand diameter is 0.3 mm, and the thickness of sand supply, soil thickness and the height of vegetation are, respectively 1.0, 0.5 and 0.2 m, which were estimated from field observation (see in Fig. 1b). Fig. 3 shows the formation and development process of dune field in grassland where grazing area (A_G) is $8e^{-5}$ S and $P_{\mathrm{overG}} = 1.38$. It shows that sand dune appears at 36th year in the grassland, in the 40th year there are many sand dunes in grassland and in the 60th year there are a large area of grassland desertification. And the main dune morphology of grassland is barchans, which is consistent with the results of Liu et al. (2012) obtained from the analysis of satellite imagery. Meanwhile, we found that the arm of barchans in grassland is larger than that in desert (Fig. 4), which is mainly caused by the influence of vegetation (Durán and Herrmann, 2006). That is, due to the action of vegetation the sand particles at the horns cannot be transported along wind direction. As a result, sand particles are left behind at the horns, which lead to the stretching of the arms of barchans.

Fig. 5 shows the variation of grassland desertification intensity with evolution time. The desertification intensity is defined as the ratio between desertification area and the sum area of grassland (P_A), or the ratio between sand amount of sand dunes and the sum sand supply amount of grassland (P_S), to characterize grassland desertification rate. For example, in a certain period of time, the larger desertification intensity means the faster desertification rate. Our results show that with evolution time increasing the desertification area and sand amount of sand dunes increase. Through comparing with field observation results (Sheng et al., 2007), as shown in Fig. 5b, we can see that the simulating results of grassland desertification not only agrees with observation results in quality, but also is close to observation results in quantity. The simulating result indicates that sand dunes appear in the grassland at 36th year, and the desertification intensity (P_A) reaches 0.52%, 0.59%, 0.72% and 0.89% at 45th, 49th, 54th and 58th year, respectively. Therefore, the increasing rate of P_A from 45th to 49th year is 0.07% which is close to that (0.1%) from 1990 to 1994; the increasing rate of P_A from 49th to 54th year is 0.13% which is close to that (0.13%) from 1994 to 1999; and the increasing rate of P_A from 54th to 58th year is 0.17% which is close to that (0.13%) from 1999 to 2003, as shown in Fig. 5b and Table 1.

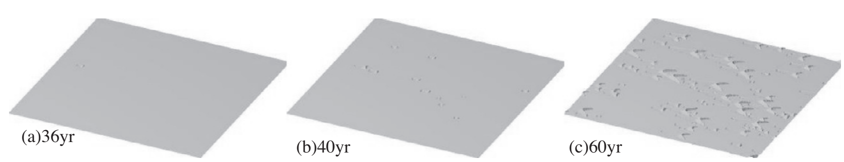

Fig. 3. The evolution of dune filed in grassland. Simulation area is 5×5 km, $u^* = 0.5$ m/s, $D_s = 0.3$ mm, $H = 1$ m, $h_{\mathrm{veg}} = 0.5$ m.

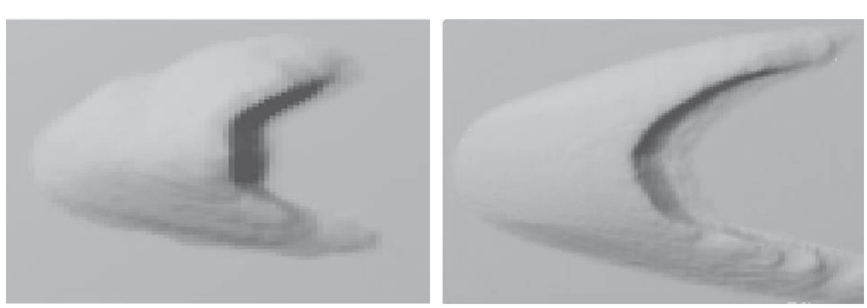

Fig. 4. The shape of simulated barchan in desert and grassland.

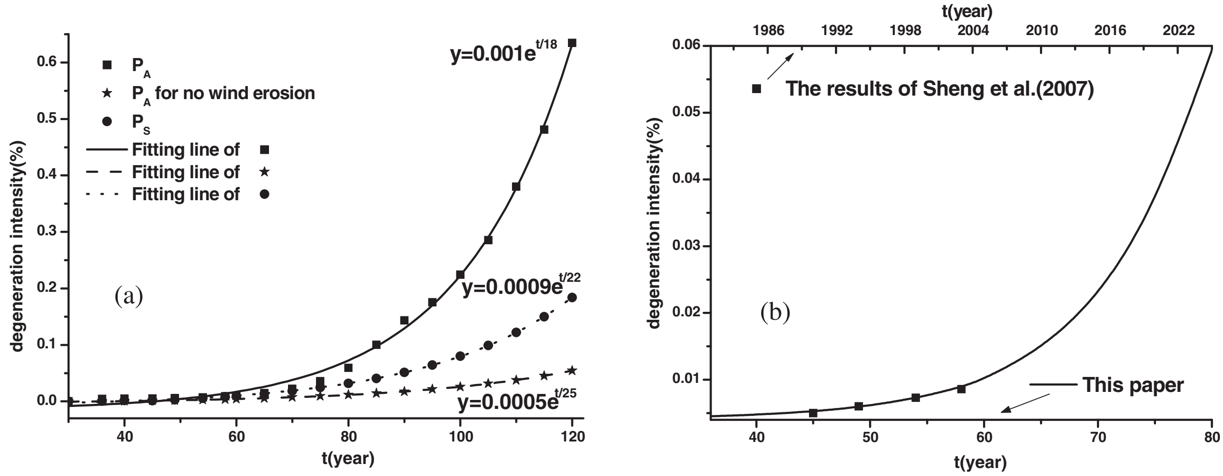

Fig. 5. The variation of desertification intensity with evolution time. Simulation area is 5 × 5 km, u^* = 0.5 m/s, D_s = 0.3 mm, H = 1 m, h_{veg} = 0.5 m.

Table 1
The variation of desertification area in Maqu (Sheng et al., 2007).

Time	1990	1994	1999	2003
Desertification area (hm^2)	3915	4798	6080	7136
Desertification intensity (%)	0.5	0.6	0.73	0.86

It indicated that this model can reflect the actual evolution of grassland desertification by considering the variation of vegetation coverage, wind erosion of soil and windblown sand movement.

Fig. 5 also shows that the grassland desertification is not a simple linear process, but satisfies an exponential function with evolution time. The ratio between current desertification area and sum grassland area of Maqu is small, which means grassland desertification of Maqu is still in the early stage. If not controlled timely, desertification will become serious in the near future.

Through comparing results of considering and those of no considering wind erosion, as shown in Fig. 5, we can found that with no consideration of the wind erosion of sand layer, the grassland desertification intensity is far less than that of considering wind erosion, which suggests that wind erosion is one of major reasons of grassland desertification, and the formation and migration of sand dunes will accelerate grassland desertification. That is grassland degradation makes sand supply exposed to wind field, consequently sand dunes formed under wind action. At the same times, the migration of sand dunes will bury vegetation, which results in the death of vegetation and conversely increases the degradation rate of grassland. It demonstrates that the appearance of sand dunes will accelerate the grassland desertification and the wind erosion needs to be considered in the research of grassland desertification.

In the process of grassland desertification, overgrazing intensity per unit area and grazing area have significant impacts on the grassland desertification, as shown in Figs. 6 and 7, which are the simulation results of 40th year. Fig. 6 is the pattern of dune field in grassland with different overgrazing intensities per unit area P_{overG} when grazing area is $8e^{-5}$ S. It shows that the number of sand dunes and desertification area increase with P_{overG}. For examples, when P_{overG} = 1.48 there is only one small sand dune, but when P_{overG} = 1.58 a lot of sand dunes and some sand dunes even link each other. Fig. 7 is the pattern of dune field in grassland with different grazing areas at certain intensity P_{overG} = 1.38. Also, we can see the number of sand dunes and desertification area increase with grazing area.

To further illustrate the influence of the grazing area and grazing intensity per unit area, the variations of desertification intensity with these two factors were given in Fig. 8. It shows that with overgrazing intensity per unit area or grazing area increasing the desertification intensity increase exponentially, which can be expressed by follow equation,

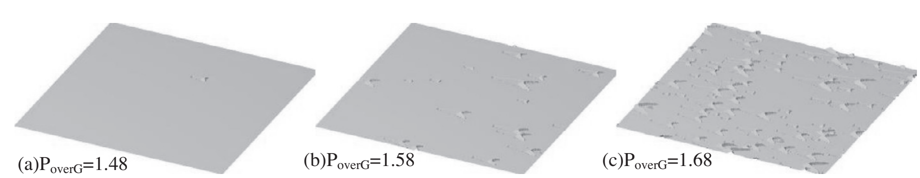

Fig. 6. The pattern of dune field in grassland at 40th year in cases of different overgrazing intensities. Simulation area is 5 × 5 km, u^* = 0.5 m/s, D_s = 0.3 mm, H = 1 m, h_{veg} = 0.5 m, $A_G = 8e^{-5}$ S. From a to c the P_{overG} are equal to 1.48, 1.58 and 1.68, respectively.

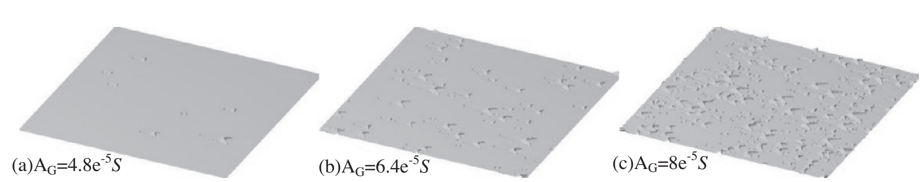

Fig. 7. The pattern of dune field in grassland at 40th year at various grazing area. Simulation area is 5 × 5 km, u^* = 0.5 m/s, D_s = 0.3 mm, H = 1 m, h_{veg} = 0.5 m, P_{overG} = 1.38. From a to c the grazing area are equal to $4.8e^{-5}$S, $6.4e^{-5}$ S and $8e^{-5}$ S, respectively.

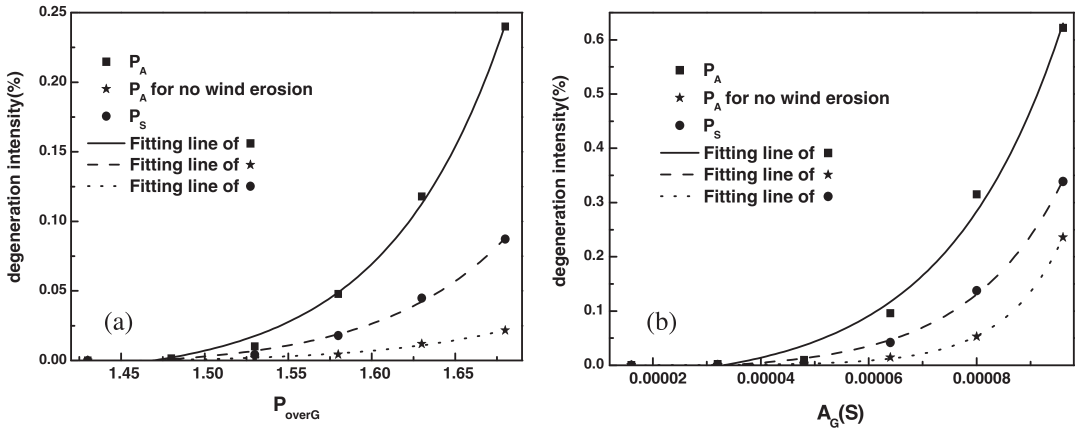

Fig. 8. The variation of desertification intensity with overgrazing intensity per unit area (a) and grazing area (b). Here, solid symbols are simulation results and lines are fitting curves of simulation results. Simulation area is 5 × 5 km, $u^* = 0.5$ m/s, $D_s = 0.3$ mm, $H = 1$ m, $h_{veg} = 0.5$ m.

$$P_A = 0.002e^{P_{overG}A_G/0.23}e^{t/6.7} \quad (5)$$

where, t is evolution time, P_{overG} is overgrazing intensity per unit area and AG is grazing area.

4. Conclusions

Quantitative simulations of dune fields in the grassland were achieved by considering the influence of overgrazing intensity on vegetation coverage, non-uniformity of sand supply on bed surface, wind erosion of soil and vegetation burial. The formation and development process of grassland desertification was analyzed, as well as the influence of overgrazing intensity per unit area and grazing area on the grassland desertification. The results show that with evolution time increasing the desertification area and sand amount of sand dunes increase exponentially; with overgrazing intensity per unit area or grazing area increasing the desertification intensity increases exponentially which can be described by Eq. (5). Further, simulation results suggest that the appearance of sand dunes will accelerate the grassland desertification.

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