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Formation of Vegetation Patterns and Hysteresis Phenomena in Arid and Semiarid Zones *

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Ecosystems are exposed to all kinds of environmental changes. How ecosystems evolve with such environmental changes is one of the main frontiers in ecology and biophysics. It has been found that the environmental changes can lead to a sudden catastrophic shifts in the structure and function of ecosystems although the changes are slow and gradual.[1] Such catastrophes are commonly linked to the existence of two alternative stable states in ecosystems, which has been defined as bistability.[1,2] Many mean field model studies have proposed that an occurrence of many complex self-organized patterns of vegetation is associated with the bistability.[2–6] When resource decreases, the spatial self-organized patterns of plant and resource may be developed. Once resource scarcity is beyond a threshold, the system jumps to a desertification state with a little vegetation. Increasing resource again does not recover these localized structures, because the initial vegetation and resource distributions are different. This phenomenon is called the hysteresis, which denotes the importance of self-organized patterns for a better understanding of catastrophic shifts. Therefore, understanding the underlying mechanism of such patterns is considered as an important step toward a comprehension of the vegetation degeneration and the desertification process.

Vegetation patterns are regarded as a typical example of one species (plant) and one resource (water) system and field studies have discovered a wide variety of stable spontaneous self-organized patches in a limited resource condition.[7–13] Thiery et al.[14] have proposed a random model to simulate the formation of banded vegetation patterns. Recent several models of vegetation growth based on mean field reaction-diffusion equations[2,4,15,16] can yield stripes, spots, labyrinth, and other ordered arrangements attributed to two positive-feedback mechanisms, i.e., (1) vegetation increases surface-water infiltration, and (2) the longer the roots, the more soil-water they take up and the faster the plant grows. On the other hand, some studies proposed that the positive feedback of the plant in short range and negative competition of plant for resource in a long range are necessary conditions for the formation of the self-organized patterns.[5,17,18] The situation becomes more complicated if the interactions between the plant and resource admit spatial effects. Furthermore, the effects of the soil condition and stochastic feature of an ecological process takes a very important role in the plant birth and death. Therefore, in order to understand the mechanism of the pattern formation deeply, it is needed to further investigate the effect of complicated ecological processes and the local vegetation and spatial landscape.

In this Letter, we introduce a lattice gas model to investigate the pattern formation of the vegetation in a limited resource condition. There are two ingredients in our model, one is the introduction of the spatial effect of the complicated interactions between soil water and biomass including the effect of the soil condition. Another ingredient is that the stochastic character of a dynamical process in an ecosystem is considered very well. The model can reproduce a wide range of patterns observed in the arid and the semiarid regions and it is found that an increase of the competition of the plant for resource along the slope direction results in the regular stripes perpendicular to the hill slope.

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It provides an interesting mechanism to understand the formation of the complex vegetation stripes. Using this model, we also investigate the sequences of vegetation states with scanning two parameters, i.e., the precipitation parameter and the plant growth rate, and identify the parameter ranges where a hysteresis loop appears and two different stable states coexist.

**Model:** We employ an \( L \times L \) square lattice to model a surface. As shown in Fig. 1, the lattice site is called the plant position \( v(i, j) \), every site can be occupied by vegetation \( (v(i, j) = 1) \) or vacant \( (v(i, j) = 0) \). In order to describe the interactions between the water and biomass, we assume that the soil water is located in the centre hollow site surrounded by four lattice sites and the hollow site is called the water position \( w(i, j) \) \((w(i, j) = 1 \text{ or } 0\), it denotes that there is water or not on the water position\). Therefore, a plant position is also surrounded by four water positions. Our model takes into account of the complicated interactions between plant and soil water including the effect of the soil condition.

![Fig. 1.](image)

**Fig. 1.** Sketch of the square lattice surface. Solid lines indicate the links of the plant positions and dotted lines represent the links of the water positions.

The distribution of the soil water is changed due to the effect of the competition between the plants for resource, rainfall and evaporation. Firstly, due to the competition of the vegetation for the water resource in the surroundings, we assume that the soil water can diffuse to one of the four nearest neighbour (NN) water positions if the sum of the plants on the four NN plant positions around the new water position is larger than that around the initial one. Therefore, in our model, it is considered that a local aggregation of vegetation can increase the competition strength and lead to an exhaust of the resource at a short range position. On the other hand, rainfall and evaporation can lead to a redistribution of the soil water, these processes are related with the precipitation and the protection of vegetation for the soil water. We assume that due to the co-effect of rainfall and evaporation, a water position is occupied by water with a probability \( p_w = 1.0 - \exp[-b\Sigma v(i, j)] \), where \( \Sigma v(i, j) \) is the sum of plants on the four NN plant positions around the water position and it denotes a local positive feedback effect of the vegetation on the soil water, the dimensionless parameter \( b \) includes the rainfall strength and the protection of the soil water and \( v_0 \) describes the effect of the soil itself on the protection of the soil water. In our model, \( v_0 \) is regarded as a dimensionless constant for a homogeneous soil condition.

The distribution of the vegetation is changed due to the plant growth and death. For simplicity, we assume that a new plant can grow with a probability \( p = 1.0 - \exp[-b\Sigma v(i, j)] \) on a vacant plant position when one of the four water positions around the vacant plant position is occupied by water at least, where \( \Sigma v(i, j) \) is the sum of the plants on the four NN plant positions around the vacant plant position and constant \( b \) describes the growth ability of the vegetation.

On the other hand, a positive feedback between local soil water and vegetation survival is considered, we assume that a plant can be alive with a unit probability if the four NN water positions around the plant are occupied, otherwise a plant can survive with a probability \( p_c = 1.0 - \exp[-c\Sigma w(i, j)] \), where \( \Sigma w(i, j) \) is the sum of the soil water on the four NN water positions around the plant and \( c \) is a constant. In our model, we mainly hope to understand the effect of the change of environmental condition and vegetation growth ability on the evolutionary behaviour, then we can assume that the grazing effect is very light and can be neglected. If it is needed, it can be considered conveniently in the survival probability \( p_c \).

Before describing the simulation algorithm, we define several parameters for the simulation. Here \( q \) describes a relative change rate between soil water and plant because the soil water can change much rapidly than the plant growth and death. Here \( q_1 \) describes the relative effect of the plant competition for resource on the water redistribution.

**Simulation process** A random number \( \rho_0 (0 < \rho_0 < 1) \) is generated firstly. If \( \rho_0 \leq q \), a trial of soil water redistribution is taken following item (a), otherwise a corresponding step of plant change is carried out following item (b):

(a) A water position \( w(i, j) \) is selected randomly and a random number \( \rho_1 (0 < \rho_1 < 1) \) is chosen. (1) If \( \rho_1 \leq \rho_1 \), a water competition process is carried out. Then, if \( w(i, j) = 1 \), another NN water position is chosen randomly, if the second water position is occupied then trial ends, otherwise the water can diffuse to the second water position if the sum of plants on the four NN plant positions around the new water position is larger than that around the initial one. (2) If \( \rho_1 > \rho_1 \), the effect of rainfall and evaporation is carried out, then \( w(i, j) = 1 \) with a probability \( p_w \) or \( w(i, j) = 0 \) with a probability \( 1.0 - p_w \).

(b) A plant position \( v(i, j) \) is selected randomly, (1) if \( v(i, j) = 0 \) and if there is water on one of the
four NN water positions around the vacant plant position, a new plant grows on the plant position with a probability \( p_b \), if \( v(i,j) = 1 \) and the four NN water positions around the plant position are occupied by water, the plant can survive with an unit probability, otherwise the plant can survive only with a probability \( p_c \).

With Monte Carlo simulation, we can discuss the vegetation patterns under different conditions. We employ an \( L \times L \) \( (L = 200) \) square lattice under a periodic boundary condition. Under the initial condition, 30\% of water positions \( w(i,j) \) are chosen randomly and are occupied by water \( (w(i,j) = 1) \) and the corresponding \( v(i,j) = 1 \). In our simulation process, the evolution time uses the Monte Carlo step (MCS) (an MCS means \( L \times L \) Monte Carlo trials). In Fig.2, typical simulation results for a flat plain are present when the system enters into a steady state. With increase of parameter \( I \), the vegetation pattern changes from a spot pattern into a labyrinth stripe and then the surface is covered almost by the vegetation.

\[ \text{Fig. 2. Patterns of the vegetation on a plain by Monte Carlo simulations. The black place is covered by vegetation. (a) The irregular spot pattern, } I = 0.47; \text{ (b) the irregular stripe-spot pattern, } I = 0.50; \text{ (c) the labyrinth stripe pattern, } I = 0.53; \text{ (d) the surface is almost covered by the vegetation when } I = 0.56. \text{ The other parameter values used are } q = 0.75, q_1 = 0.99, v_0 = 0.00015, b = 1.1, c = 0.001. \]

Compared to the irregular patterns of the vegetation, the regular patterns, such as the regular stripes on a hillside, have attracted much more interesting. In the previous mean field models, a diffusion term of water only along the hill slope is introduced, it is very difficult to describe the competition of the plant for the resource along the hillside. On the other hand, there also exists a water competition between plants along the contour. Due to the hillside, once a place is bare, much more soil water can be soaked in by the next vegetation of the downhill than the neighbouring vegetation along the hill’s contours, the plants can aggregate much more rapidly and then causes an exhaust of the soil water in the next place along the hillside. The competition between vegetation along the hillside is increased. As a result, the slope increases the indirect interaction (through the competition for soil water) between the vegetation along the hillside.

\[ \text{Fig. 3. Regular stripe on a hill slope: (a) } p_1 = 0.75; \text{ (b) } p_1 = 0.85; \text{ (c) } p_1 = 0.95; \text{ (d) } p_1 = 0.99. \text{ The other parameters are the same as those in Fig. 2(c).} \]

In our simulation of the competition process for soil water on a hill slope, the second NN water position is chosen with a probability \( p_1 \) from the two NN sites randomly in the \( x \) direction which denotes the hillside direction and with a probability \( 1 - p_1 \) from the other two NN sites randomly. In Fig. 3, we show the simulation results with the increasing parameter \( p_1 \). Compared to the pattern in Fig. 2(c) where \( p_1 = 0.5 \), the vegetation pattern exhibits a gradual change from the complex labyrinth stripe into a regular stripe parallel to the \( y \) direction which denotes the parallel direction of the hill’s contours. Compared with the simulation patterns in Fig. 2, these simulation results show that an increase of the competition for resource along the slope direction leads to the orientation of the vegetation stripes. Therefore, we can understand the labyrinth stripe deeply and can predict other special patterns of vegetation stripes on different local landscapes, such as a ring stripe. In the simulation process of the competition of the vegetation for resource on a flat plain, the second site is chosen randomly from the four NN sites and then the competitions in two directions are equal, as a result, the direction of the stripe can change randomly to form a labyrinth pattern.

Based on our model, we can predict other com-
plex patterns of the vegetation under other disturbed factors which can change the source competition on different directions. For an example, under a desertification condition, soil is an important resource and wind can change the local soil distribution. Along the main wind direction, the competition for soil is increased and a regular stripe perpendicular to the main wind direction is formed.[19]

In some mean field models,[2,4,15,16] it is shown that the sequences of the nonequilibrium steady states of the vegetation with the change of precipitation parameter exhibits a bistability and then it predicts a catastrophic shift according to the vegetation structure. We discuss the effect of the parameter $I$ and $b$ by scanning two parameters with the decreasing parameter firstly and then with the increasing parameter. In Fig. 4, it is shown that the system exhibits a bistability state and hysteresis behaviour with the scanning of $I$ and $b$. Under different scanning rate, we can also obtain a hysteresis loop. Furthermore, in the decreasing process of the parameter, we find that the vegetation exhibits a series of complex patterns as shown in Fig. 2. However, the vegetation exhibits an aggregation pattern as those as the right inserts in Fig. 4 when the parameter increases.

In conclusion, we have introduced a lattice gas model to simulate the dynamical process considering the spatial feature of the complicated interactions between soil water and biomass. The model can reproduce a wide range of patterns observed in the arid and the semiarid regions. It is discovered that an increase of the indirect interactions between the vegetation along the slope direction leads to the formation of the regular stripes parallel to the hill’s contours. It provides an interesting mechanism to understand the formation of the complex vegetation patterns under a limited resource condition. We also investigate the sequences of vegetation states with scanning the precipitation parameter $I$, the plant growth rate $b$ and the soil condition parameter $v_0$ to identify the parameter ranges where a hysteresis loop appears and two different stable states coexist. The scanning simulation results denote that the complex structures occur when the two parameters decrease, but not when the two parameters increase.

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