A Model Analysis for the Regime Shift under Climate Change in Alpine Vegetation

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EXTENDED ABSTRACT

Using a dynamic mean field model formulated by us (T.Yabuki), the regime shift of vegetation change in alpine ecosystem owing to climate change is theoretically analyzed in this work. Our analysis is developed on the basis of long terms observation data accumulated by one of us (G. Kudo) in the Daisetsuzan National Park in Hokkaido of Northern Japan.

In alpine ecosystem warm temperature in spring should accelerate the snowmelt, which shortens the duration of snowmelt water supply. As a result, soil moisture conditions might be insufficient for the growth of alpine plants inhabiting moist habitat.

In the model, the effect that dwarf bamboo suppress soil moisture content by its high transpiration ability and a positive feedback effect by dry soil condition favorable to dwarf bamboo are formulated. The feedback mechanism between dwarf bamboo coverage ($\boldsymbol{B}$) and soil moisture content ($\boldsymbol{W}$) is input as two equations. The effect of $\boldsymbol{B}$ on $\boldsymbol{W}$ is represented by a differential equation in which a decreasing duration of snowmelt water supply caused by an increase in air temperature ($\boldsymbol{T}$) is contained. The effect of $\boldsymbol{W}$ on $\boldsymbol{B}$ is represented by a function $\boldsymbol{B} = \boldsymbol{B}(\boldsymbol{W}, \boldsymbol{T})$, which is based on the empirical photosynthesis curves of dwarf bamboo (*Sasa kurilensis*) with reference to $\boldsymbol{W}$ and $\boldsymbol{T}$. The former is a direct effect of $\boldsymbol{T}$ on $\boldsymbol{B}$ and the latter is an indirect effect of $\boldsymbol{T}$ on $\boldsymbol{B}$. We analyzed numerically the regime shift in this system in various parameter regions. As a result, we found that a regime shift can occur through the indirect effect of $\boldsymbol{T}$ on $\boldsymbol{B}$.

The present model analysis predicts that a regime shift has already occurred in the model site, Goshikigahara area in the Daisetsuzan National Park, alpine snow-meadow vegetation is facing a critical state in which many herbaceous species is replaced by dwarf bamboo shrub irreversibly. Because the interval of two threshold temperature $\Delta\boldsymbol{T}$ seems to be small and very sensitive in this regime shift, extensive vegetation change may be accelerated in alpine ecosystem by global change. Therefore, governmental trials for conservative management of National Park are urgent to protect the biodiversity in alpine ecosystems.

Keywords: regime shift, climate change, alpine vegetation, dynamic mean field model, hysteresis

1. Introduction

Recently, a significance of regime shift, or an event of catastrophic change from one stable phase to another phase (May et al. 1977), has been concerned in various fields of ecology and environmental sciences, especially in lake and savannah ecosystems (Scheffer et al. 2001, Scheffer and Carpenter 2003, Sternberg 2001). When a change in a system satisfies the following three conditions, it is called a regime shift.

(1) A Great change in a system, such as a drastic change in species composition within community, happens suddenly.
(2) The changes in environmental conditions progress not suddenly but slowly.
(3) There is a hysteresis in the sense that a threshold value for recovering process is more severe than that for changing process.

A long-term observation of alpine vegetation in the Daisetsuzan National Park in Hokkaido of Northern Japan revealed that alpine snow-meadow, which is composed of various herbaceous species has been decreased the area and replaced by dwarf bamboo (*Sasa kurilensis*) during last 20 years (personal observation by G. Kudo). Furthermore, our preliminary research using GIS (Geographical Information System) and remote sensing technique has ascertained this vegetation change quantitatively (Hoshino et al. 2009). This abrupt change from snow-meadow to dwarf bamboo shrub-land may have been caused by a climate change. Warm temperature in spring should accelerate the snowmelt, which shortens the duration of snowmelt water supply. As a result, soil moisture conditions might be insufficient for the growth of alpine plants inhabiting moist habitat. This environmental change might in turn lead to an invasion of dwarf bamboo that had inhabited drier habitat with smaller snow accumulation. The high transpiration ability of dwarf bamboo, because of evergreen leaf habit and huge aboveground biomass, may accelerate the decrease in soil moisture and promote this situation as a feedback system.

In this report, we propose a mathematical model that predicts a regime shift of vegetation change in alpine ecosystem owing to climate change. We selected Goshikigahara area in the Daisetsuzan National Park as a model site in which invasion of dwarf bamboo (*Sasa kurilensis*) is most prominent. We have developed theoretical analysis on the basis of long terms observation data accumulated by one of us (G. Kudo). The model analysis postulates a hysteresis between dwarf bamboo phase (one stable state) and snow-meadow phase (the other stable state) as a function of air temperature in the field.

2. Formulation and results of analysis

We develop a dynamic mean field model in which spatial interactions are ignored, and the ecosystem composed of soil moisture, dwarf bamboos and snow-meadow vegetations are supposed to be homogeneous or well-mixed. In the model, the effect that dwarf bamboo suppress soil moisture by its high transpiration ability and a positive feedback effect by dry soil condition favorable to dwarf bamboo are formulated. The feedback mechanism between dwarf bamboo coverage ($\boldsymbol{B}$) and soil moisture content ($\boldsymbol{W}$) is input as two equations, one of which represents the effect of $\boldsymbol{B}$ on $\boldsymbol{W}$ and the other represents the effect of $\boldsymbol{W}$ on $\boldsymbol{B}$. The effect of $\boldsymbol{B}$ on $\boldsymbol{W}$ is represented by a differential equation in which a decreasing duration of snowmelt water supply caused by an increase in air temperature ($\boldsymbol{T}$) is contained. The effect of $\boldsymbol{W}$ on $\boldsymbol{B}$ is represented by a function $\boldsymbol{B} = \boldsymbol{B}(\boldsymbol{W}, \boldsymbol{T})$, which is based on the empirical photosynthesis curves of dwarf bamboo (*Sasa kurilensis*) with reference to $\boldsymbol{W}$ and $\boldsymbol{T}$.

In the model, both of a direct effect (in the first equation) and an indirect effect (in the second equation) of air temperature on snow-meadow vegetation are contained.

1) Effect of B on W

In our model, the effect of B on W within a growing season is represented by the following differential equation;

$$\frac{dW}{dt} = u(t) - \{\lambda B + \eta(1-B)\}W(t), \qquad (1)$$

where individual parameters are given by the following definition.

W : soil moisture content [ton]
B : coverage of dwarf bamboo ($0 \le B \le 1$)
t : time [day]
$u(t)$: inflow of snowmelt to the area [ton·day^{-1}] (2)
λ : transpiration rate of dwarf bamboo [day^{-1}]
η : transpiration rate of snow-meadow vegetation and evaporation rate [day^{-1}]

The inflow of snowmelt to the region, $u(t)$, is given as following formula:

$$u(t) = -at(t - b(\Delta T)) \ , \qquad (3)$$

where the term $b(\Delta T)$ represents the effect of increasing temperature on the duration of snowmelt water supply that is given by following formula:

$$b(\Delta T) = D(1 - k_1 \Delta T) \ , \qquad (4)$$

where D [day] is the initial period of inflow of snowmelt, ΔT [ºC] is the increase in air temperature of the area and k_1 [ºC] is the rate of deceasing period of inflow. It is supposed that total quantity of inflow within a growing season is fixed as SW [ton], so the coefficient a in eq.3 is given by the following numerical formula:

$$a = \frac{6SW}{\{b(\Delta T)\}^3}, \qquad (5)$$

The pattern of $u(t)$ is shown in Figure 1 in which right figure shows $u(t)$ after the increase in temperature (ΔT > 0).

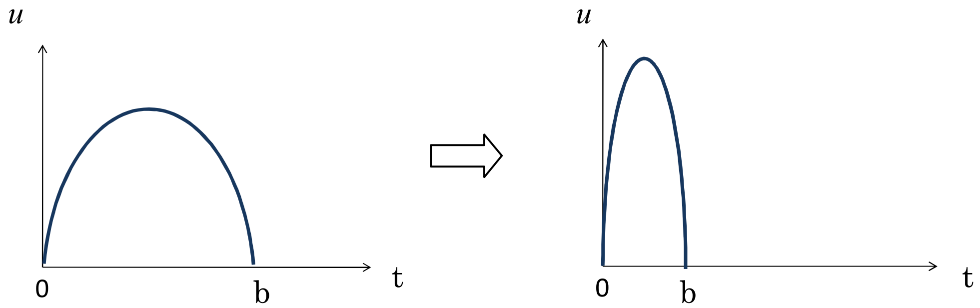

Figure 1: Temporal pattern of inflow of snowmelt $u(t)$ before (left) and after warming

Since dwarf bamboo increases the distribution range via vegetative growth by spreading the rhizome system, $\boldsymbol{B}$ is supposed to be constant in eq.1 given within a growing season.

By a brief analytic calculation, the solution of differential eq.1 is obtained as follows;

$$W(B,t_S) = e^{-\{\lambda B+\eta(1-\beta)\}t_S} \frac{a}{(\lambda B+\eta(1-B))^3}\{b(\lambda B+\eta(1-B))(e^{(\lambda B+\eta(1-B))b}+1)-$$

$$-2(e^{(\lambda B+\eta(1-B))b}-1)\} + W_0 e^{-(\lambda B+\eta(1-B))t_S} \tag{6}$$

where W_0 is initial soil moisture content.

In eq.6, t_s [day] is set as reference time, and it is supposed that the soil moisture at the reference time t_s, $W(t_s) = W_S$, decides $\boldsymbol{B}$ of next season.

A graph of the dependence of W_S on $\boldsymbol{B}$ after fitting several parameters in eq.6 is shown in Figure 2.

2) Effect of $\boldsymbol{W}$ on $\boldsymbol{B}$

Previous studies on the photosynthesis of dwarf bamboo provided several kinds of photosynthesis parameters. Two kinds of photosynthesis curves (Jarvis type function), one thing is given as a function of temperature and the other is given as a function of moisture, are used in our model.

$$B(T,W) = f(T)\left(\frac{\beta}{\alpha \cdot e}\right)^{-\beta} e^{-\alpha W} W^{\beta} \tag{7}$$

where $f(T)$ is a temperature dependent part and is given by following formula:

$$f(T) = -\frac{4}{(T_{MAX}-T_{MIN})^2}(T-T_{MAX})(T-T_{MIN}) \tag{8}$$

The relation between $\boldsymbol{B}$ and W_S is obtained according to eq.7 and eq.8 as shown in Figure 3.

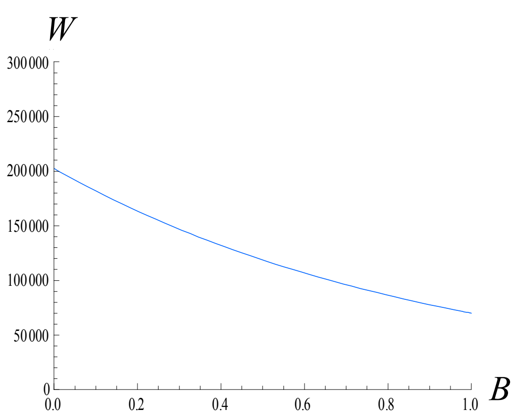

Figure 2: Effect of the coverage of dwarf bamboo $\boldsymbol{B}$ on soil

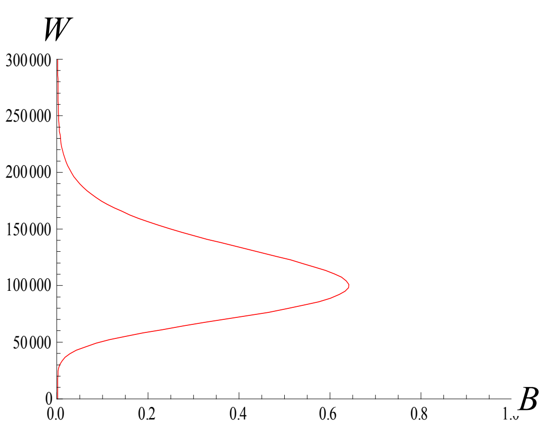

Figure 3: Effect of soil moisture $\boldsymbol{W}$ on the coverage of dwarf bamboo $\boldsymbol{B}$.

3) A feedback process between $\boldsymbol{B}$ and $\boldsymbol{W}$

Both curves generated by eq.6 (W_S at time t_s as a function of B) and eq.7 (B as a function of W_S) give us understanding of a feedback process between B and W. The Figure 4 is obtained by superimposing Figure 2 and Figure 3 and shows a step-stair sequence for two processes having different initial soil moisture content. From this graph a feedback effect between B and W can be seen. In Figure 4, the vertical arrows indicate the soil moisture content in the area that may be suppressed by much dwarf bamboo coverage, whereas the horizontal arrows indicate the dwarf bamboo coverage that may be suppressed by much soil moisture content. Consider the first process in which the region has a little more initial soil moisture content W_1 than that in the unstable state U. In this case B cannot suppress W_1, so W will increase (vertical arrow). This in turn will decrease B (horizontal arrow), which will subsequently suppress even less W. As a result, the positive feedback generated here will lead to the eventual disappearance of B. Consider the second process in which the region has a little less initial soil moisture content $\mathbf{W}_2$ than that in the unstable state U. In this case B can suppress W, so W will decrease (vertical arrow). This in turn will increase B (horizontal arrow), which will subsequently suppress even more W. The region will undergo a positive feedback leading to greater B.

These processes mean that this system composed of W and B has two alternative stable states, S_1 in which B is almost zero and S_2 in which B is much greater. A stable state S_1 can be regarded as a state of herbaceous species.

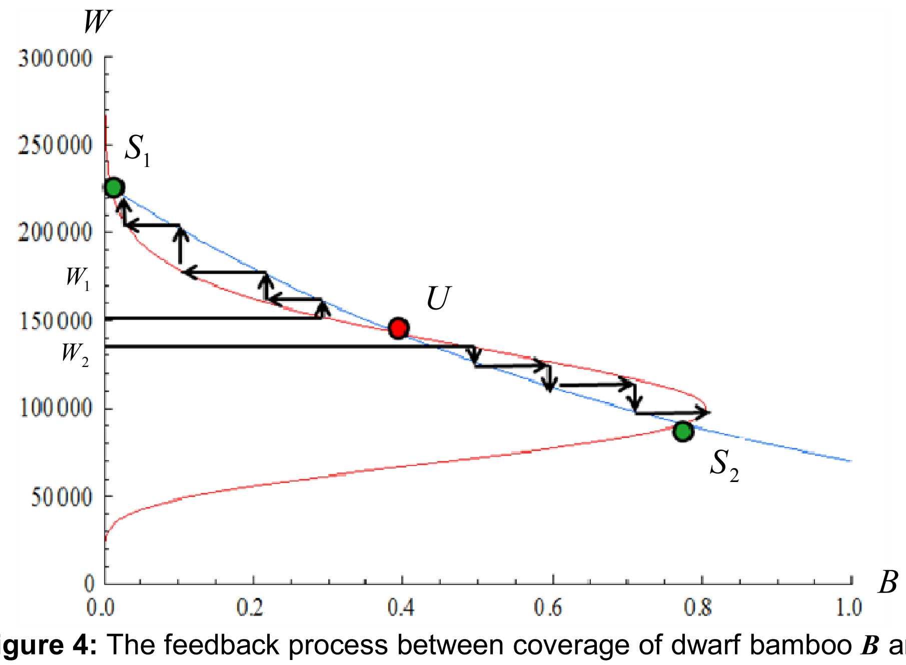

Figure 4: The feedback process between coverage of dwarf bamboo B and soil moisture W.

4) Regime sift caused by disappearance of one stable state of two alternative stable states

In eq.6, the coefficient b is a function of T, which is given by eq.4, and the blue curve in Figure 2 is shifted by the change of T. The red curve in Figure 3 is also shifted by the change of T through eq.8 in eq.7. As a result the both blue and red curves in Figure 4 are shifted with T. Therefore, temperature change has two kinds of effects on a system in our model. A direct effect of air temperature change is a shift of red curve and an indirect effect of air temperature is a shift of blue curve in Figure 4, and the both effects can make one stable state of two alternative stable states disappear. When one stable state disappears, strictly a little while before then, a regime shift between snow-meadow phase and dwarf bamboo phase occurs in a system.

A shift of stable state with changes in air temperature is shown in Figure 5. At T_1 (lower temperature), a system has only one stable state S_1 (snow-meadow phase). At T_2 (higher temperature), a system has only one stable state S_2 (dwarf bamboo phase). At $T = T^*$, the system undergoes a sudden shift from the snow-meadow phase to the dwarf bamboo phase, and the system cannot recover at the same temperature T^*. This means the existence of a hysteresis in this system, resulting in an occurrence of regime shift.

In our model we have analyzed how large temperature change can cause the regime sift of vegetation change in the alpine ecosystem owing to climate change.

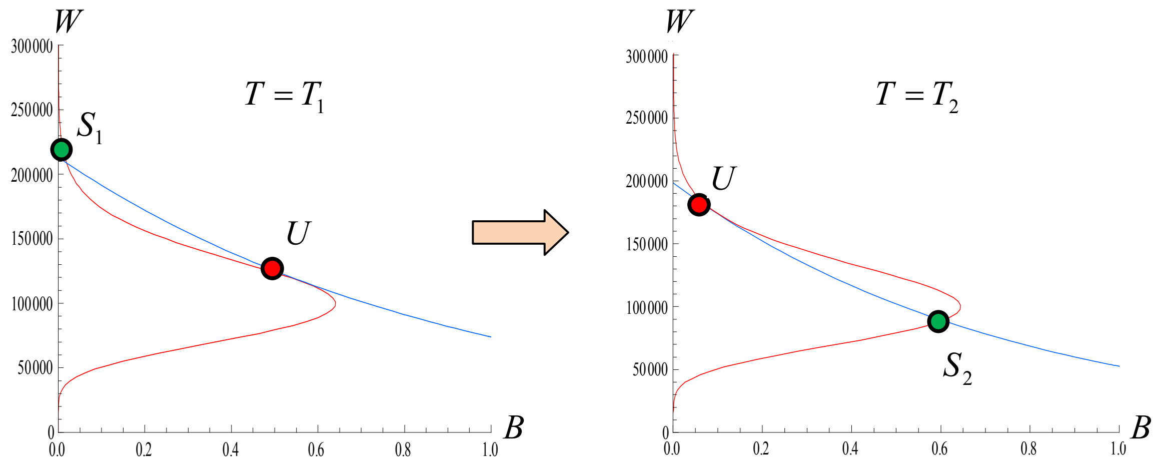

Figure 5: Temperature dependent regime shift predicted by the model.

3. Numerical results

In our mathematical model, we have analyzed how large temperature change $\Delta T = T_2 - T_1$ can cause the shift from one stable state S_1 (snow-meadow phase) to the other stable state S_2 (dwarf bamboo phase) in some parameter regions, using Masamatica software. We report several results in our analysis as follows;

・The parameter k_1 [day °C^{-1}] represents of the decreasing period of snowmelt water supply per 1°C increase that is defined as $b(\Delta T) = D(1 - k_1 \Delta T)$.

・The parameter k_2 represents how many times the transpiration rate of snow-meadow vegetation and evaporation rate is as much as the transpiration rate of dwarf bamboo that is defined as $\eta = k_2 \lambda$.

・The parameter k_4 represents how many times the total quantity of inflow of snowmelt within a growing season as much as the initial soil moisture content that is defined as $SW = k_4 W_0$.

For example, in the case of the parameter setting, k_1 = 15, k_2 = 0.1, k_4 = 4.75, λ = 1/70, the value of $\Delta T = T_2 - T_1$ = 0.058°C is obtained when the both of direct and indirect effect of air temperature increase, ΔT = 3.5°C is obtained when only a direct effect is contained, and ΔT =

0.06ºC is obtained when only an indirect effect is contained. This result means that larger value of temperature increase is necessary for regime shift to occur through a direct effect, whereas much smaller temperature increase can lead to a regime shift through an indirect effect. The same results have been obtained in the several different parameter settings. From these results we can see that the direct effect is essential for a regime shift. Since the value of temperature increase in the past 20 years near the Daisetsuzan National Park was 0.328ºC, which is larger than ΔT in our mathematical model, it is likely that a regime shift is already possible.

4. Conclusion

The present model analysis predicts that a regime shift has already occurred in the model site, Goshikigahara area in the Daisetsuzan National Park. Alpine snow-meadow vegetation is facing a critical state in which many herbaceous species is replaced by dwarf bamboo shrub irreversibly. Because the interval of two threshold temperature ΔT seems to be small and very sensitive in this regime shift, extensive vegetation change may be accelerated in alpine ecosystem by global change. Therefore, governmental trials for conservative management of National Park are urgent to protect the biodiversity in alpine ecosystems.

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