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Slow or rapid collapse? Transients between stable states as a source of uncertainty in predicting ecosystem shifts

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Abstract: In this study I explore the rate of change during the collapse of a vegetation-soil system on a hillslope from a vegetated state to an unvegetated, bare-soil, state. From a distributed, stochastic model coupling hydrology, vegetation, weathering and wash erosion, I derive two differential equations describing the interaction between the vegetation and the soil. Two stable states – vegetated and bare – are identified by means of analytical investigation, and it is shown that the change between these two states is a critical transition as indicated by hysteresis. Surprisingly, transitions between these states can either unfold rapidly, over a few years, or gradually, occurring over decennia up to millennia, depending on unforeseen soil parameters. This result emphasizes the considerable uncertainty associated with forecasting critical transitions, which is due to both the timing of the transition and the rate of change after the tipping point has been reached.

Keywords: critical transition, model simplification, vegetation, soil.

1 INTRODUCTION

Complex systems may switch between contrasting stable states under gradual change of a driver (Scheffer et al., 2012). In environmental systems, such critical transitions often result in considerable long-term damage because strong hysteresis impedes reversion. Critical transitions largely reduce our capability of forecasting future system states because it is hard to predict their occurrence (Karssenberg and Bierkens, 2012). Moreover, for many systems it is unknown how rapidly the critical transition unfolds. This is crucial information because the rate of change during the transition determines the time available to take action to reverse a shift (Hughes et al., 2013).

A first step in analysing critical transitions in a dynamical system is a stability analysis. Such an analysis enables finding equilibriums of the system, which are defined as the system states where the rate of change in all system variables is zero. At least two types of equilibriums can be distinguished (c.f., Scheffer, 2009). If the system is in a stable equilibrium state, a small push away from the equilibrium will result in an oscillation around the equilibrium, which is damped, finally resulting in a return of the system to its stable state. This could be compared to movement of a ball in a valley, which will finally result in a position of the ball in the lowest point of the valley. In the case of an unstable equilibrium state, a small change in the system will push the system away from the stable state. This could be compared to a ball resting at the top of a hill, where the top of the hill is the unstable equilibrium.

When gradually changing system drivers (inputs), the position of equilibriums will change, or a stable equilibrium may disappear or may be changed into an unstable equilibrium. The latter results in a considerable change in the system, where the system changes into another state that is completely different regarding the value of state variables and the magnitude of relations between state variables. This is called a critical transition and could be compared to the movement of a ball from one valley to another valley.

Stability analysis of an environmental system is mostly done using a description of the system provided as a simple lumped model, consisting of one or a small number of differential equations. This enables analysing the system through function analysis, i.e. analysis of the differential equations describing the rate of change in system variables, in particular by finding the equilibrium where the rate of change is zero. Such simple models, however, have the disadvantage that they often oversimplify the system studied. In this study, I propose an alternative procedure, which derives from a process-based, fully distributed, model of the system a multidimensional differential equation, including its parameters. The stability analysis is performed on the differential equation like in other studies. This approach has the advantage of a full understanding of the system through the process-based distributed model, while still enabling stability analysis on the lumped model (multidimensional differential equation). To the author's knowledge this approach of analysing equilibriums in a fully distributed model using a simplified model fitted to the distributed model has not been used so far.

The approach is applied in the case study of a semi-arid vegetation-soil system on a hillslope. In this system, we use as main driver the grazing rate, which, when increased, results in a decrease in vegetation cover and soil thickness. These both decrease because they are coupled: an increase in biomass decreases throughfall and runoff, which decreases wash erosion resulting in a net increase in soil depth due to weathering of bedrock; this increase in soil depth increases water availability during dry periods increasing biomass. It is generally known that when increasing grazing rate, soil erosion increases resulting in gullies and removal of vegetation, ultimately leading to a bare soil state with negligible vegetation and soil. Such vegetation-soil systems are currently mainly studied by analysing transient states using distributed models, which – as I argue – does not provide fundamental understanding of the system. To overcome this lack of understanding I address here the following research questions 1) Is the change of a semi-arid vegetation-soil system from vegetated to bare under an increase in grazing pressure a critical transition? 2) If so, how quickly unfolds the transition when the grazing threshold is reached?

2 METHODS

A distributed model of an 80 by 40 m hillslope running at a spatial resolution of 2 m and a time step of one week describes the semi-arid vegetation-soil system. Each week zero or one rainfall events occur by drawing from a discrete probability distribution. For each grid cell, rainfall is partitioned in interception, runoff to the steepest downstream neighbour cell, and infiltration into a one layer unsaturated zone. Interception is a function of the biomass at the cell. Infiltration occurs up to a maximum infiltration capacity or until the soil gets saturated. Evapotranspiration is modelled as function of biomass. Vegetation growth is limited by water availability in the unsaturated zone using a water use efficiency coefficient, and taking into account a maintenance rate, reduction of biomass by damage due to overland flow, and grazing rate. Spatial dispersal of vegetation is modelled by spatial diffusion of biomass. The change in the soil depth over time is a function of weathering of bedrock material, soil creep, and water erosion. The weathering of rate of bedrock asymptotically decreases with increasing soil depth, soil creep is modelled by a two-dimensional diffusion on the hillslope. Soil water erosion includes soil detachment by overland flow and raindrop impact, limiting transport by the effective streampower of overland flow, combining existing model approaches (De Roo et al., 1996; Govers, 1990; Morgan and Duzant, 2008). The geomorphological system has zero soil flux boundaries at all sides, except the bottom side of the hillslope, where the baselevel falls slowly.

In transient runs, the distributed model was driven by a very slow increase in grazing rate, starting with a zero grazing rate, using a model run time of millennia. At the start of the run, this results in a hillslope that is convex up in shape due to creep denudational transport. With increasing grazing rate, biomass gradually decreases, up to a point where runoff starts to occur, resulting in gullies and increased erosion. This erosion amplifies vegetation collapse resulting in a relatively fast reduction in soil depth and vegetation biomass. As this transition is a transient state, these simulations do not allow a stability analysis, because rates of net biomass or net soil depth change cannot be calculated for a steady situation. Therefore, we derive a two dimensional lumped model from the distributed model. This is done by fixing the state variables of the distributed model over a long period of time (multiple decennia) calculating average net biomass growth and water erosion for these fixed states. This is done for multiple combinations of biomass and soil depth, resulting in a table with vegetation growth and erosion for multiple combinations of soil depth and biomass. Two differential equations, one for net change in biomass and one for net change in soil depth are defined such that their shape corresponds with the rate of changes found by the distributed model. By fitting the parameters of these differential equations to the tabulated net vegetation growth and soil depth change, the parameters are found for the differential equations.

A stability analysis on the differential equations is executed to analyse the existence of a critical shift. In addition, this lumped model is used to analyse how quickly the critical transition unfolds.

3 RESULTS

3.1 Identification of lumped model

The lumped model is defined by two coupled differential equations representing the soil subsystem and the vegetation subsystem. The change in the soil depth *D* (m) is:

$$\frac{dD}{dt} = W_0 e^{-aD} - e^{-B/b}\left(E_t + e^{-cD}(E_0 - E_t)\right) - C$$

The first term represents weathering, with W_0, the soil production rate as a result of bedrock weathering (m/y) for bedrock without a soil cover (D = 0) and *a*, the weathering exponent (m^{-1}). The second term represents soil erosion, with E_0, the erosion rate (m/y) for soils with without soil cover, E_t, the erosion rate (m/y) for soils with infinite soil cover, *b* (m^{-1}), the exponent related to the effect of biomass on erosion, and *c* (m^{-1}), the exponent related to the effect of soil depth on erosion. The third term, *C* (m/y) is the soil loss by creep (m/y).

The change in biomass *B* (kg/m^2) is:

$$\frac{dB}{dt} = \left(1 - (1 - i)e^{-D/d}\right)\left(rB\left(1 - \frac{B}{c}\right)\right) - g\left(\frac{B}{s + B}\right)$$

The first term is the grow back term and the second term is grazing. The second part of the first term corresponds to Noy-Meir's overharvesting model (Noy-Meir, 1975), with *r*, the growth rate (y-1) and *c*, the carrying capacity (kg/m^2). The first part models reduction in growth when the soil depth decreases, with the exponent *d* (m^{-1}) and the intercept *i* (-, [0,1]). The grazing term uses *g*, the grazing pressure ($kg^1 m^{-2} y^{-1}$) and *s* (kg/m^2), the vegetation density where the grazing is 0.5g.

The parameters in both differential equations were found by manual calibration, focussing on good fits for rates of change at which critical transitions might occur resulting in an acceptable fit between the distributed and lumped model, using 100 combinations of soil thickness and biomass (Figure 1). At lower erosion values (Figure 1 A), the lumped model overestimates erosion, which is possibly due to the highly simplified process description. A better fit would require a larger number of parameters, which has the disadvantage that the lumped model becomes untractable.

3.2 Stability analysis

A stability analysis indicates that both differential equations have stable and unstable equilibriums, represented by the lines in Figure 2. The stable system equilibrium is found where both differential equations (rate of change) are zero, in the plot, this is the location where the stable equilibrium line of the soil system and the vegetation system cross, shown by the black circle in the figure. For the grazing rate used to create Figure 2, the equilibrium state is represented by a biomass of 1.8 kg/m^2 and soil thickness of 0.38 m.

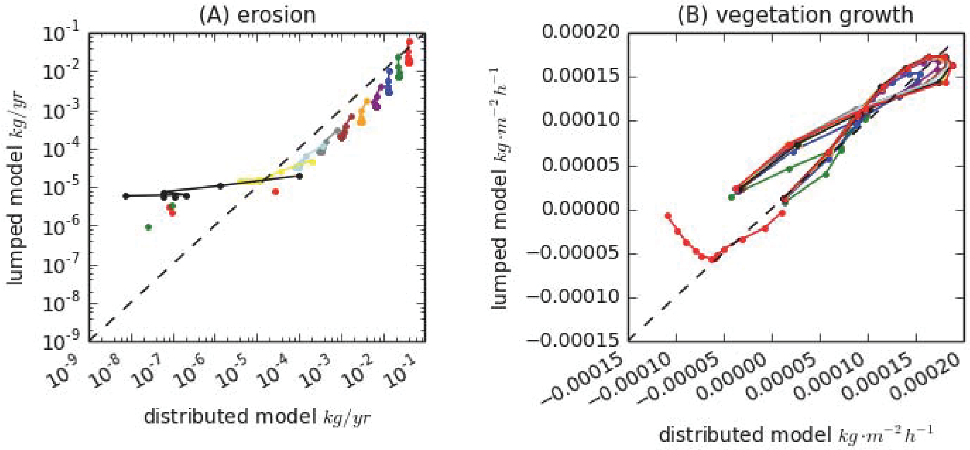

Figure 1. Lumped model results vs distributed model results. (A) Erosion rate, (B) vegetation growth rate. Each series of points connected by a line in a particular color refers to distributed model runs with the same soil thickness but variable biomass.

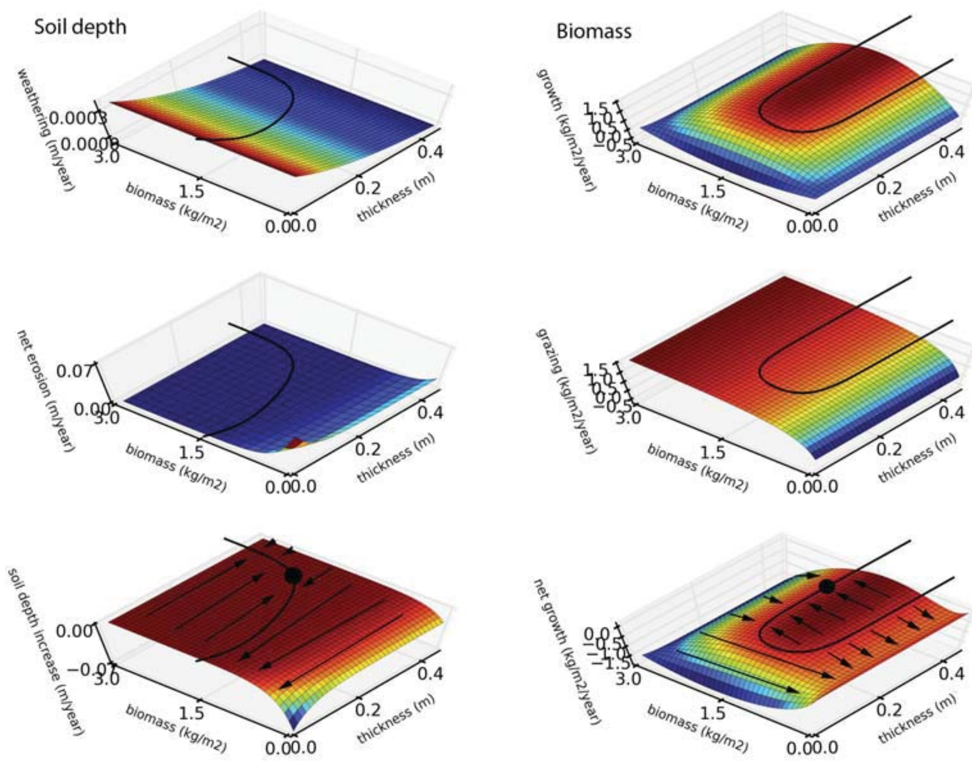

Figure 2. Stability analysis. Left, soil depth, with from top to bottom the component of the differential equation resulting in increase in soil depth (weathering rate), the component reducing the soil depth (erosion rate) and the net increase in soil depth (weathering minus erosion). Right, vegetation, with vegetation growth rate, grazing rate and net growth (growth minus grazing). The black lines indicate equilibrium; arrows show direction of change for each subsystem. Equilibrium lines with arrows pointing towards the line are a stable equilibrium, otherwise the equilibrium is unstable. The black circle shows the stable equilibrium.

3.3 Rate of change when the transition unfolds

When grazing rate increases, the position of the equilibrium line of the vegetation system changes in the stability plot. As long as both stable equilibrium lines cross, the system stays in a stable equilibrium. However, when the grazing rate continues to increase, the equilibrium lines become separated and do not cross anymore. This results in a critical transition towards a different system state: both biomass and soil depth decrease until a new stable state is reached, corresponding to zero soil depth and biomass. Figure 3 shows the stability plot for a situation with a grazing rate just above the point where the critical transition occurs. The blue line shows the transient between the two stable states.

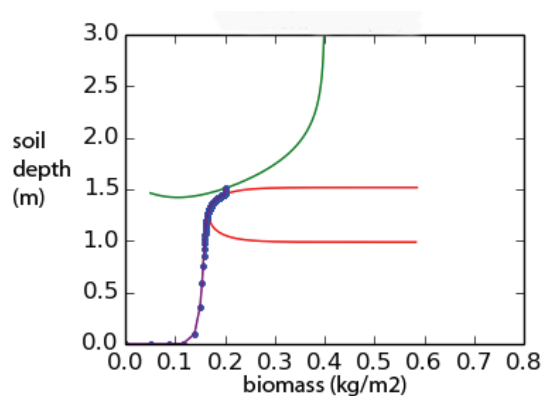

Figure 3. Critical transition. Green line represents equilibrium of soil system (left part of line is unstable, right part is stable), red line is equilibrium for vegetation system (upper part: stable, lower part: unstable). Blue line shows how the transition unfolds over time, each dot represents one year. The direction of change represented by the blue line is from higher biomass to lower biomass (and high soil depth to low soil depth).

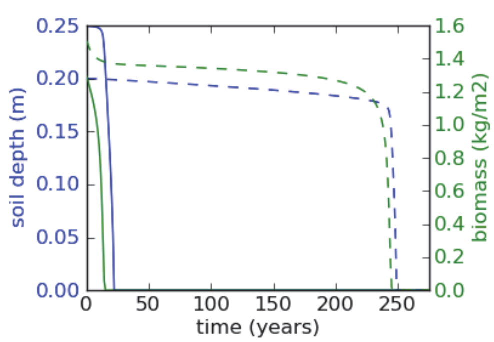

Figure 4. Unfolding of a critical transition: transient between a healthy system with large biomass and soil depth and a degraded system with zero soil depth and biomass. Biomass, green line; soil depth, blue line. Solid line, W_0 = 0.002 m/yr, a = 7.49; dashed line W_0 = 0.0004, a = 3.47.

A scenario analysis shows a surprisingly strong impact of soil parameters on how quickly the transition unfolds. Figure 4 shows two example runs created both with an equilibrium soil depth at zero grazing pressure of 0.4 m, but using different W_0 and a parameters. When the bedrock-weathering rate W_0 at zero soil depth is high, the transition unfolds within a few years, while at low values of W_0, it takes up to hundreds of years for the critical shift to unfold. This is because the equilibrium lines for both the soil and vegetation system change in position when these soil parameters change. Intuitively it can be understood as a critical transition that mainly unfolds as a result of vegetation collapse (i.e., vegetation collapse first, then relatively rapid soil collapse of a bare soil) in the case of a high value of W_0, or for low values of W_0, a transition which unfolds first by a slow decrease in soil depth of a soil with vegetation, followed by a rapid decrease in vegetation.

4 DISCUSSION AND CONCLUSIONS

In this study I showed how high-resolution process-based ecosystem models can be used to find simple models enabling analytical investigation of critical transitions. It was shown that arid vegetation-soil hillslope systems undergo a critical transition when grazing pressure is gradually increased. This is a real critical transition, which is indicated by hysteresis and the existence of a tipping point. The system is surprisingly sensitive to changes in the soil parameters, which has considerable effect on the rate of change of the system when a critical transition unfolds. At low bare bedrock weathering rates, the critical transition unfolds very slowly, and over a period of time that is much longer than changes in system drivers typically occur. It is concluded that such transitions may occur unnoticed for a long time, as suggested by (Hughes et al., 2013), because changes in the state of the system occur slowly, even at a grazing pressure above the tipping point.

It is expected that the model results mimic the fundamental behaviour of the system studied. An interesting future step however would be to compare model results with field observations. This requires overcoming the challenge of observing vegetation biomass and soil depth at multiple locations, and preferably reconstructing changes over time.

I followed a two-step approach consisting of the development of a distributed process-based model of the system, which is converted to a lumped model consisting of two differential equations. This approach is advantageous because it gives the deep understanding of the system provided through the (spatial) network of interactions simulated by the distributed model, while enabling analytical analysis using the lumped model. It is expected that a similar approach can be used for understanding other systems, particularly those including multiple interactions, e.g. coupled field-agent systems. In future studies, the fitting of the lumped model to the distributed model results could be done using an automated scheme, for instance a least squares fitting procedure.

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