Early warning signals for catastrophic soil degradation

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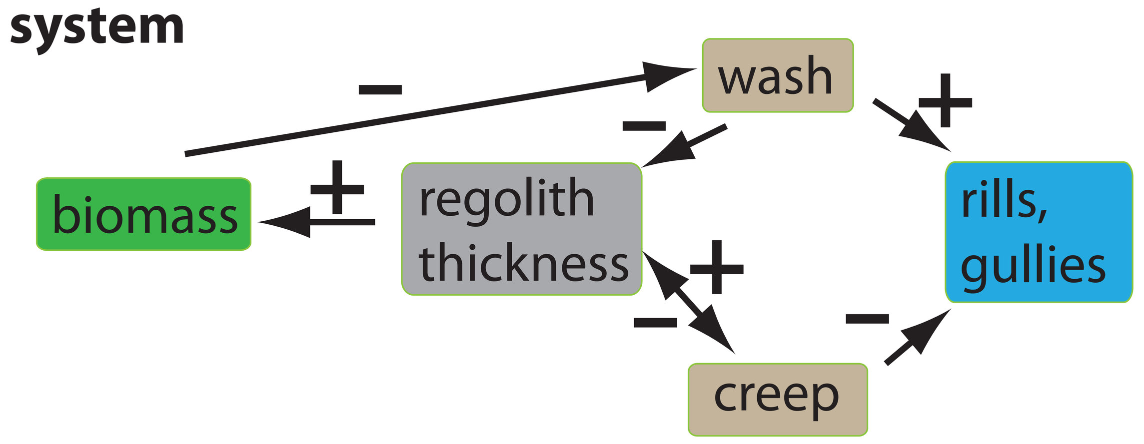
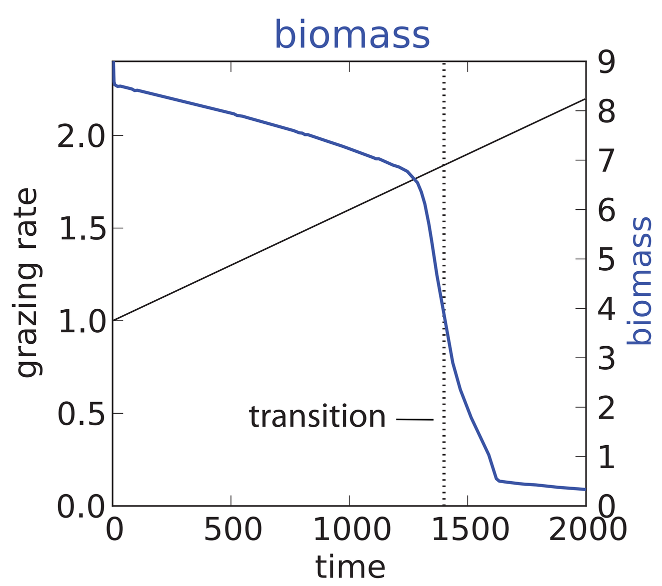
Introduction

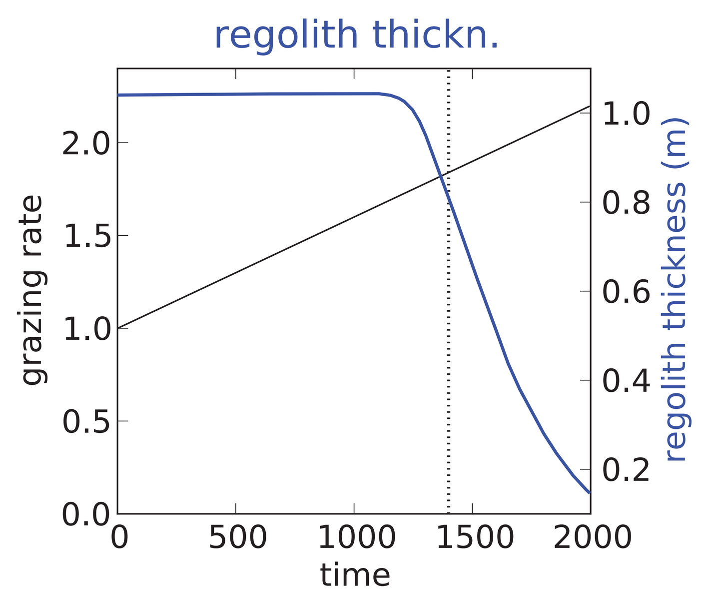
Complex dynamical systems may have critical thresholds at which the system shifts abruptly from one state to another. It is notably difficult to predict the timing of a transition, because the state variables of the system show little change before the threshold is reached. A possible solution is the use of spatio-temporal patterns in state variables as leading indicators of a transition. It is becoming clear that the critically slowing down of a system causes spatio-temporal autocorrelation and variance to increase before the transition (Scheffer et al, 2009). In this research we show that these early-warning signals also exist in geomorphological systems.

The system

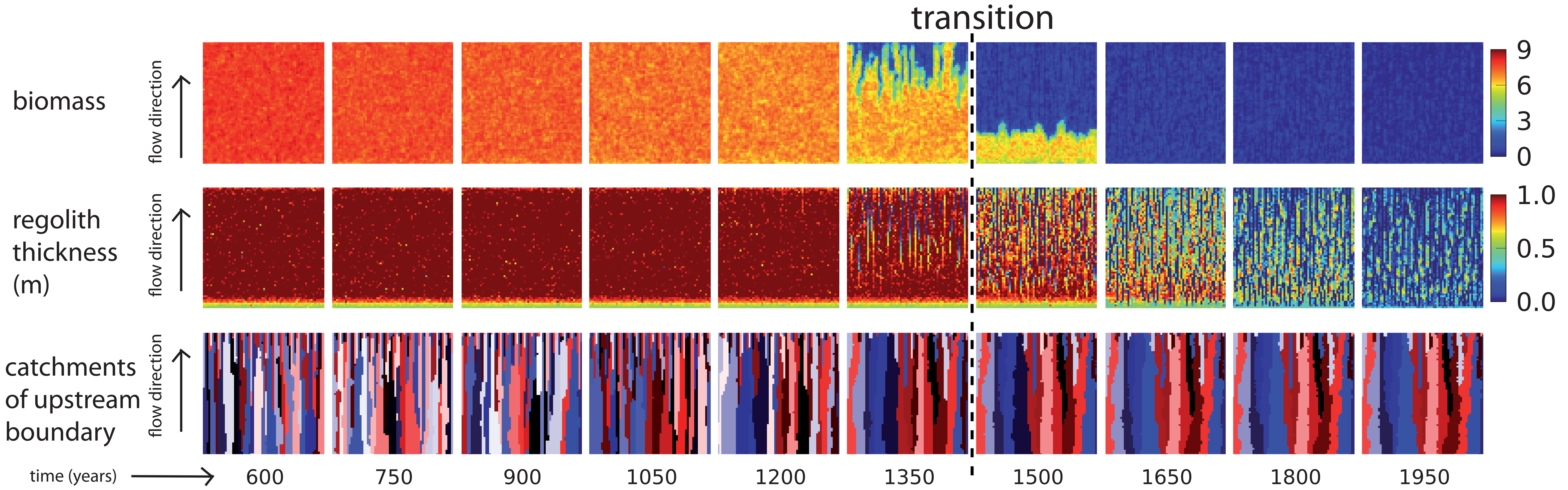


We consider the evolution over hundreds of years of a modelled hillslope system, with spatially distributed processes. The figure above shows key positive (+) and negative effects (-). Biomass is logistically growing including spatial diffusion of biomass. Soil wash and creep determine regolith thickness. The soil and biomass system are coupled: 1) increase in biomass increases interception, reducing wash, 2) decrease in regolith thickness reduces biomass growth. Wash results in concentrated flow, creating gullies.





Grazing rate is linearly increased (above). A critical threshold occurs at 1400 years, causing catastropic degradation of vegetation and soil. Note that biomass and regolith thickness show very little change before the threshold is reached. See also the timeseries of map at the top right side of the poster.



Spatio-temporal patterns in biomass as early warning signals

The mean biomass (see time series above) shows little change before the threshold is reached. However, the spatio-temporal correlation in biomass does change, and is an important early warning signal, similar to Dakos et al (2009, Theoretical Ecology).

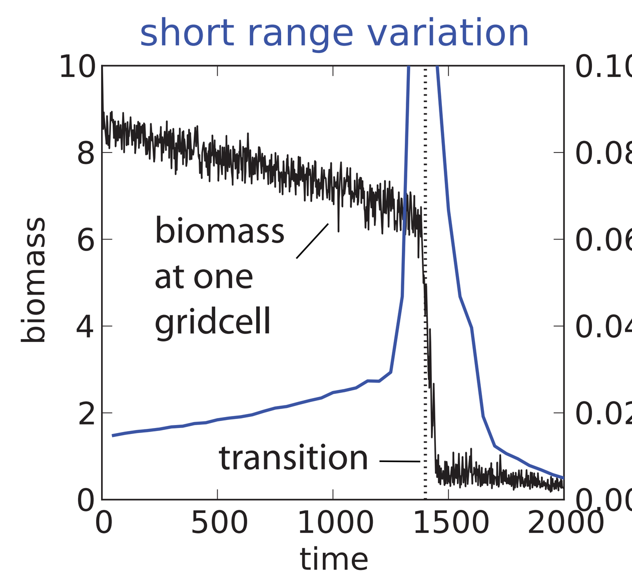
Spatial or temporal correlation is quantified as

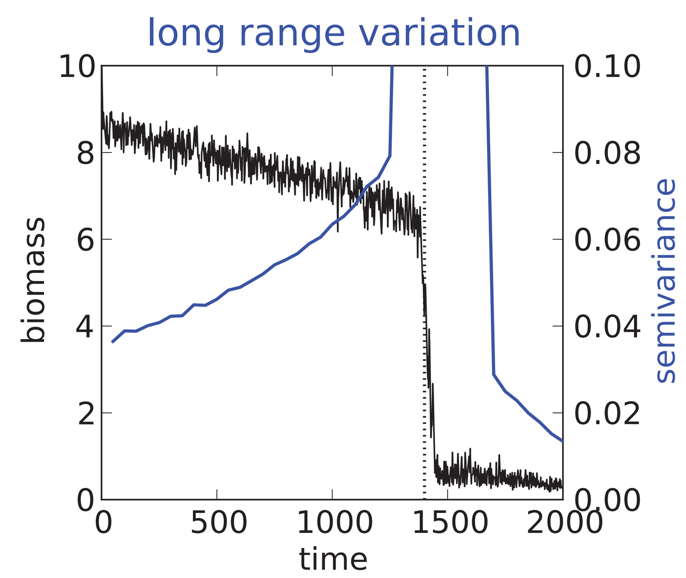
$$\gamma(h)=\frac{1}{N(h)}\sum(X(\mathbf{s})-X(\mathbf{s}+h))^2$$

$\gamma(h)$ semivariance at separation distance h

$N(h)$ number of sample pairs with separation distance h

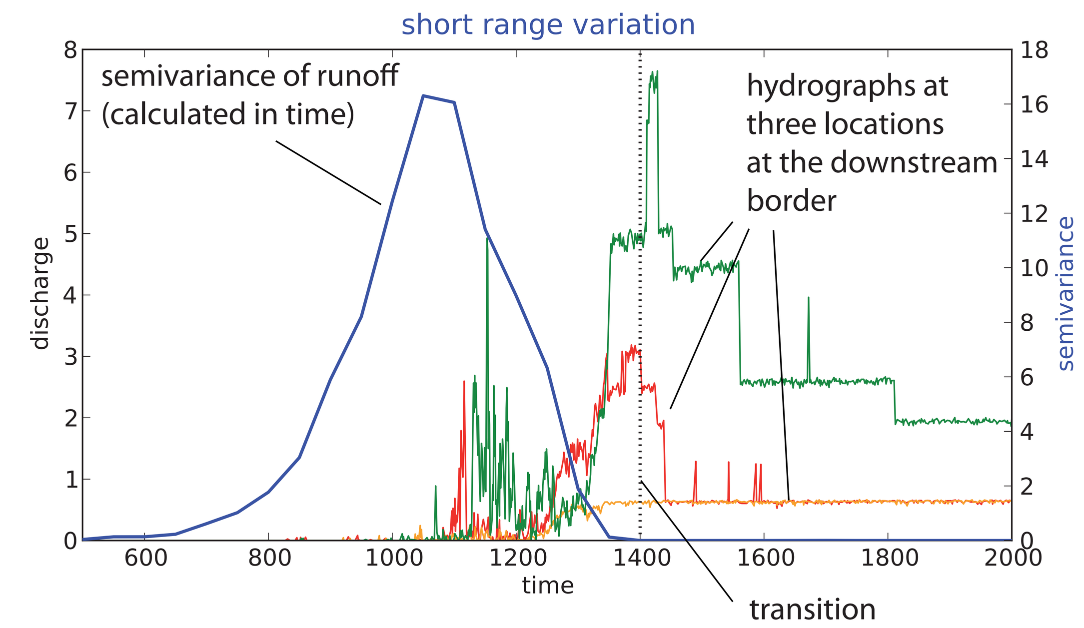
$X(\mathbf{s})$ the state variable, $\mathbf{s}$ is spatial index





The panels above show a marked increase in semivariance, representing short distance (left) and large distance variation (right). Thus, an increase in spatio-temporal variation in biomass can serve as warning signal for degradation of the soil at 1400 years.

Temporal patterns in runoff as early warning signal



Three fases with different spatio-temporal patterns of runoff occur. From 0-600 years, no runoff occurs as a result of high biomass. From 600-1400 years, wash processes initiate the creation of small gullies resulting in small amounts of runoff. However, gullies are small, with small catchments (see catchment timeseries above). Gully creation and removal occurs frequently, resulting in a large variation in the runoff pattern and large temporal variation in runoff (see the timeseries above). Thus, variance in runoff is an early warning for soil degradation. In the third phase, 1400 - 2000 years, runoff is constant and high due to absence of vegetation and fixed positions of catchments on the hillslope (see timeseries above).

Main finding

Increase in variance of biomass and runoff are leading indicators for soil degradation and can thus be used for forecasting.

References

Scheffer et al., 2009. Early warning signals for critical transitions. Nature 461 (7260): 53-59.