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Early-warning signals (potentially) reduce uncertainty in forecasted timing of critical shifts in vegetation systems

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Non-linear systems may undergo abrupt transitions as a result of a gradual change in system drivers. Such regime shifts, or critical transitions, have been described for a large range of spatio-temporal systems, including those studied in the social sciences, ecology, geology, and climatology. Regime shifts are considered undesirable because they cause large changes in values of system variables and because such changes are often difficult to reverse or even irreversible. Thus, the ability to forecast the probability and timing of a shift may be essential for designing adaptation strategies to avoid shifts. However, it is hard to even detect upcoming regime shifts because mean values of observable system state variables show little change before a transition occurs. This problem has sparked much research focused on finding alternative properties of a system that show a more marked change before a transition is coming. It turns out that such properties exist, and include higher order statistics of state variables and patch size distribution.

Despite the identification of these early-warning signals, limited evidence exists that they can be used to forecast the actual timing of a critical shift. Here, we propose a probabilistic approach to forecast the timing of a shift by combining uncertain prior information about the ecosystem dynamics (parameters and drivers) and sampled spatial and temporal correlation and variance of ecosystem states, which are well known early-warning signals. In our approach, systematic and random sampling error is included in the calculation of the early-warning signals. These sources of information are combined with a sequential solution of Bayes' equation, solved using the Particle Filter data assimilation scheme. This scheme takes into account and balances the uncertainty in the system state and the uncertainty in the observed early-warning signals.

For a synthetic ecosystem of logistically growing vegetation under linear increase in grazing pressure, we show that the use of sampled early-warning signals results in a lower prediction uncertainty in forecasted timing of shifts compared to forecasts made with sampled mean state variables. In addition, we show that uncertainty in all ecosystem drivers and parameters decreases well ahead of a shift. An important conclusion of our study is that the use of early-warning signals in forecasting of shifts is promising, provided that a large number of samples is collected ($n \approx 10{,}000$ in our study). This would be feasible with large data sets of biomass that can be derived from remote sensing data. The large number of samples required explains the limited success of finding early warning signals from field studies of real world ecosystems because these mostly rely on small data sets from field sampling.