

CONCEPTS & SYNTHESIS

EMPHASIZING NEW IDEAS TO STIMULATE RESEARCH IN ECOLOGY

The interactive effects of press/pulse intensity and duration on regime shifts at multiple scales

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turbid freshwater lakes (Scheffer et al. 2001), and coral and macro-algal dominance (Mumby et al. 2007). The growing pace and extent of global environmental change could potentially force regime shifts at local to global scales (Barnosky et al. 2012). Therefore, it is critical to

variations of this model have been used to describe budworm outbreaks (Ludwig et al. 1978), deer browsing in forests (Augustine et al. 1998), grazing impacts in semiarid grasslands (van de Koppel et al. 1997), biomass loss due to fire (D'Odorico et al. 2012) and other systems (van Nes and Scheffer 2005). For simplicity, we focus on a system with two stable states, rather than models with more than two stable states. We also did not consider systems with only a single attractor. Single attractor versions of the model (by relaxing the exponent in Eq. 1) also show displacement during a press or pulse, but they will return to their original state after the press/pulse ends regardless of

ecosystems differ in their growth rate, due to variation in substrate, species composition, and other factors (Levin 1992, Frehlich and Reich 1999, Collins and Xia 2015, Chisholm et al. 2015). To evaluate how differences in growth rate might interact with press duration, we altered growth rate and kept press duration and intensity constant. In the model (Eq. 1), higher vegetation growth rates lead to higher potential equilibrium biomass for a given value of grazing pressure and also increase the grazing pressure needed to exceed a bifurcation point, because

in Fig. 4C). For both press intensities, the press duration needed to force a regime shift decreases non-linearly as vegetation growth rate decreases (Fig. 4B, C).

Local-scale model with temporal stochasticity

Most ecosystems are affected by stochastic events, such as disease, drought, and emigration/immigration (e.g., Holmgren and Scheffer 2001, Turner 2010, Ridolfi et al. 2011). We accounted for stochasticity by adding a white-noise term (dW) to the model

where notation follows Eq. 1 and σ denotes the strength of normally distributed perturbations. We considered noise $\sigma = 0.184$ (1 and 1 and

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In line with the base model (Eq. 1), the press duration needed to force a transition in all patches decreases as press intensity increases (Fig. 9). For instance, at the highest press intensity we considered, a press of 8 yr results in regime shifts to the low biomass state in nearly all the patches, whereas for the lower press intensity, a press duration >13 years is needed to force a regime shift across most patches. The press duration needed to result in regime shifts across most patches is a saturating function of press intensity, where at a certain point ($\sim \Delta c = 0.11$)

in spatial variance might be useful as an indicator that the duration of a press is reaching a threshold, beyond which large-scale regime shifts occur. In comparison, a press with an intensity too weak to initiate regime shifts (the lightest gray lines in Fig. 10) resulted in a slight increase in spatial variance and autocorrelation, and a slight decrease in skewness over the time frame we considered (Fig. 10; similar to Guttal and Jayaprakash 2009, Dakos et al. 2010).

between press duration and the eventual ecosystem state (sensu Briske et al. 2006, Groffman et al. 2006). These results are slightly affected by adding white noise (Fig. 5) and robust to using incremental driver presses, rather than discrete presses (Box 1 and Fig. 11). Moreover, these results were not specific to the model we chose, based on simulations of four other dynamical system models (see Box 2 and Fig. 12). Spatial heterogeneity smoothed out some of the threshold behavior (Fig. 13).

regime shifts to a shrubland state at this site in the early to mid 20th century (Bestelmeyer et al. 2011, 2013). After four years, the grazing treatments ended and large grazers were completely removed. Precipitation was variable over the experiment, but below average for all but one year of the grazing press (Bestelmeyer et al. 2013). Over the same time period, three additional paddocks were measured and received no grazing.

The experiment revealed surprising potential for recovery in a semiarid grassland that has experienced widespread regime shifts in the past (Bestelmeyer et al. 2013). Over the first 4 years of the experiment, cover of the dominant grass doubled to ~25% in the control

paddocks without grazers. Grazed paddocks followed the opposite trajectory, decreasing to between 1.5% and

(Wissel 1984). The lack of regime shifts is unlikely to be due to the lack of alternative stable states in the underlying dynamics, given the substantial evidence for bistability in this system (Gibbens et al. 2005, Yao et al. 2006, Bestelmeyer et

plots changed little, but invasive biomass started to increase because exotic species expanded from nearby experimental plots (see Isbell et al. 2013). In contrast to the controls, the high N-addition treatment quickly decreased to an average species richness of <6 species/0.3 m²

a mean inter-fire interval of 2.5 to 4 years (estimated over the last several hundred years; Desantis et al. 2010, Allen and Palmer 2011, Stambaugh et al. 2013). Ignitions in tallgrass prairie are now largely human controlled, making landscape fire frequency effectively an exogenous

et al. 2007, Mumby 2009, Suding and Hobbs 2009). We saw a similar effect of stochasticity, where simulations

fostering desired regime shifts. These tools are crucial as many ecosystems could be operating near or beyond their

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