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Transient trajectories in vegetation patterns spawning from non-equilibrium initial conditions and singular perturbations

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Vegetation self-organisation in water-limited ecosystems in semi-arid climates has been extensively studied by means of numerical simulation using a set of different reaction-diffusion-equations. Most of such models and studies have been concerned with the long-term steady ecohydrological steady states on domains with periodic boundary conditions and forced by steady rainfall. A vast majority of the modelling literature on vegetation self-organisation exists around near-equilibrium conditions. One of the clearest examples of this is that most of the published numerical results have been obtained by evolving near-equilibrium initial conditions to asymptotic steady states, since researchers have been historically interested in the resilience and stability of the systems to perturbation around converged, steady (equilibrium) states and little interest has been given to the transient states which lead to the equilibrium states. Nonetheless, ecohydrological theory recognises that dryland ecosystems can often be far-from-equilibrium systems, in quasi-permanent transient condition, exhibiting non-linear responses to boundary conditions and forcings. This prompts the question of how different the behaviour of the system can be when far-from equilibrium.

In this contribution we explore the role of far-from equilibrium initial hydrological conditions on both the transient and long-term asymptotically steady ecohydrological states. A simulation study was performed using the HilleRisLambers-Rietkerk ecohydrological model on a flatland varying the initial available water both near and far from equilibrium whilst also spanning the rainfall gradient (90 – 360 mm/year), performing simulations up to 200 years long. The results were assessed in terms of the evolution of total biomass yield and hydrological water balance, as well as a quantitative assessment of vegetation patterns.

The results show that equilibrium conditions always yield smooth system trajectories, with little over- or undershooting, converging to the well-established patterns in the literature. However, as initial conditions move further away from equilibrium, the patterns start to differ, both in their temporal trajectory as in their long-term stable states. Conditions closer to equilibrium generate patterns with quantitative differences when compared to equilibrium conditions (e.g., larger spots). Conditions far from equilibrium can result in an entirely different hybrid patterns, consisting of a mix of spots, arcs and spirals. We evaluate these differences both qualitatively (by observing the patterns) and quantitatively, through a set of geometric indicators which describe the patterns. The results show that the patterns are history dependent and suggest that published results so far are only a subset of possible patterns. Additionally, the quantitative assessment of pattern properties in time shows that although patterns appear steady, they may indeed be slowly changing over time, while the total biomass and vegetation cover are steady early on. This has implications on the definitions of ecohydrological steady states. We also show that the effects of the idealised initial conditions on model results can be analogous to singular hydrometeorological events, as even stable patterns can be shifted into hybrid patterns by single events. Furthermore, we also explore how the new hybrid patterns compare to the well-established ones in terms of resilience to hydrological perturbations.