Synopsis

Ecosystems can exhibit multiple stable states at similar external conditions. Such systems shift from one stable state to another abruptly and discontinuously, when they cross certain threshold parameters. Some examples of such abrupt shifts include coral bleaching, woodland encroachment of grasslands and desertification in semi-arid ecosystems. These transitions in ecosystems are often associated with loss of biodiversity and economic impacts, therefore are important to predict. These systems with multiple stable states, in some cases, can be understood as systems with a free energy functional having multiple local minima. In this theoretical framework, these abrupt transitions in ecosystems are similar to the discontinuous or first order phase transitions. In this thesis, we use the tools from the theory of non-equilibrium phase transitions to understand the mechanisms that cause abrupt transitions in spatially extended ecosystems and the statistical properties of these systems which can help us predict them.

Previous studies have shown that strong local positive feedback among individuals is an important mechanism for systems to have multiple stable states. In our study, we use a lattice based model of vegetation dynamics with basic processes as birth, death and positive feedback among individuals. In its simple version, this model is in the same universality class as directed percolation which is well known to exhibit a continuous phase transition from an active state to an absorbing state. Using master equation expansion for finite sized systems, we construct stochastic differential equations for our discrete state lattice model. We analytically show that systems with finite size can have multiple stable states even in the absence of positive feedbacks. Our numerical simulations of the spatial models confirm these results. Small sized ecological systems, therefore, can undergo discontinuous transition from an active high density state to a bare state where larger ecosystems would have survived.

It is well-known that systems close to a continuous phase transition show slow recovery from the perturbations. This phenomenon is known as critical slowing down. Since ecological systems are finite in extent and rarely in steady states, signatures of critical slowing down are seen before the discontinuous transition as well. In spatial systems,

critical slowing down manifests as increase in spatial correlations and spatial variance in the system. Theoretical studies have shown that these signatures can be used as early warning signals for the imminent transitions. These spatial signals have been tested in microbial systems in lab, but few studies show their validity in the field. We hypothesize that above spatial metrics increase when a transition occurs along the gradient of driver in space. We first test this "space-for-time substitution" in a lattice model where driver changes along space. This model shows a transition from one state to another across space. We show that spatial metrics like variance and correlations show an increase even before the transition along the spatial gradient of driver. We, then, test these theoretical predictions in a savanna ecosystem using remotely-sensed and the ground-truthed data. In this ecosystem, grassland and woodland states co-occur at similar rainfall values and the abrupt transition occurs along the rainfall gradient in space. We show that critical slowing down based spatial indicators show theoretically expected trends before the transition. Therefore, we argue that simple spatial metrics can be used to anticipate the abrupt shifts in large-scale ecosystems.

In addition to the early warning signals, it is important to quantitatively estimate the threshold parameter at which the system is likely to shift to another state. To estimate this threshold, we use the property of phase transitions that systems show diverging correlations at the critical point. Therefore, in finite ecosystems showing alternative stable states, we hypothesize that the spatial location at which variance and correlation in the state variable are maximum will be closest to the transition. We used a spatially-explicit model of vegetation dynamics in which the driver value shows a gradient in space. We show that the point at which spatial variance and correlation in vegetation are maximum, is indeed the critical point of the system. We then test this method of finding the critical point in real ecosystems by analysing spatial data from regions of Africa and Australia that exhibit alternative vegetation biomes.

In summary, we employ a model from non-equilibrium statistical physics to understand abrupt transitions in ecological systems. We show that stochasticity caused by finite sized systems can lead to abrupt transitions in spatial ecosystems. We suggest simple spatial metrics to quantify critical points in real ecosystems, offering a significant advance from current studies that only proposed qualitative metrics of proximity to critical points. This thesis presents an elegant example of how principles of nonequilibrium phase transitions can be applied to a complex biological system, by modelling and testing their predictions with data from ecosystems.