# Quantitative Measures of Resilience and Vulnerability

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Resilience and vulnerability of co-evolving systems such as soils and vegetation, vegetation and climate, etc. are strongly dependent on the balance of the positive and negative feedbacks of interactions. Under stress, these feedbacks breakdown and result in runaway dynamics until new equilibrium is established. While these notions are now well-understood, quantitative characterization of both resilience and vulnerability remain elusive, or are only available for deterministic systems. We develop a probabilistic framework for quantifying resilience and vulnerability and develop a number of alternate measures and evaluate the behavior of these measures. We note that a given resilience measure yields different values when a system is subject to different disturbances. This disturbance may be related to changes in magnitude, timing, frequency, duration, or sequencing of external events. Our quantitative approach allows us to reveal that different measures may respond differently to the same disturbance. Under certain conditions disturbance and dynamics intertwine to create new dynamic regimes or exclude dynamical possibilities. This quantitative approach also allows us to develop the notion of iso-resilience curves that can be used for control and maintenance of systems exhibiting alternate dynamic regimes. Iso-resilience curves connect points that have identical resilience values and allow us to find an optimum path of travel in the resilience landscape for management of these systems. Application of these ideas to natural systems with co-evolutionary dynamics and alternate dynamic regimes will be presented.