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# Ecosystem thresholds, tipping points, and critical transitions

*Terrestrial ecosystems in a time of change: thresholds, tipping points, and critical transitions; an organized session at the American Geophysical Union Fall Meeting in New Orleans, Louisiana, USA, December 2017*

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Abrupt shifts in ecosystems are cause for concern and will likely intensify under global change (Scheffer *et al.* 2001). The terms “thresholds”, “tipping points”, and “critical transitions” have been used interchangeably to refer to sudden changes in the integrity or state of an ecosystem caused by environmental drivers (Holling 1973, May 1977). Threshold-based concepts have significantly aided our capacity to predict the controls over ecosystem structure and functioning (Schwinning *et al.* 2004, Peters *et al.* 2007) and have become a framework to guide the management of natural resources (Glick *et al.* 2010, Allen *et al.* 2011). Our understanding of how biotic and abiotic drivers interact to regulate ecosystem responses and of ways to forecast the impending responses, however, remain limited. Terrestrial ecosystems, in particular, are already responding to global change in ways that are both transformational and difficult to predict due to strong heterogeneity across temporal and spatial scales (Peñuelas & Filella 2001, McDowell *et al.* 2011, Munson 2013, Reed *et al.* 2016). Comparing approaches for measuring ecosystem performance in response to changing environmental conditions and for detecting stress and threshold responses can improve traditional tests of resilience and provide early warning signs of ecosystem transitions. Similarly, comparing responses across ecosystems can offer insight into the mechanisms that underlie variation in threshold responses.

Scientists and land managers have used the concepts of thresholds, tipping points, and critical transitions in different ways and associated with different phenomena. The more general use of these terms reflects an abrupt change in the slope of the relationship between ecosystem performance and environmental condition (Fig. 1A). The *sensu strictu* definition is when a bifurcation occurs at a critical environmental condition that shifts the ecosystem into a different state (Scheffer et al. 2001; Fig. 1B). A key point of the *sensu strictu* definition is that returning the environmental condition to the previous level does not result in the previous ecosystem state.

We emphasize that careful consideration of terms and definitions would help promote evaluation and comparison of patterns.

The organized session *Terrestrial ecosystems in a time of change: thresholds, tipping points, and critical transitions* at the 2017 American Geophysical Union Fall Meeting in New Orleans, Louisiana, USA, consisted of seven oral and ten poster presentations that displayed new methods, emergent patterns, and forthcoming challenges for understanding threshold patterns across ecosystems in North America, Europe, Asia, and Africa. Here, we highlight the diverse environmental drivers, indicators of ecosystem performance, and approaches for detecting ecosystem thresholds in space and time.

## Environmental Drivers of Ecosystem Thresholds

Oral presentations in the session largely addressed the consequences of increased aridity on plant performance. Ted Hogg (Natural Resources Canada, Edmonton, Canada) and Kelly Heilman (University of Notre Dame, USA) defined a hydrological “tipping point” between forest and prairie in western Canada and midwestern USA, respectively, and related the climatic conditions at these ecotones to tree growth and mortality. Several presentations pointed out how multiple aspects of the abiotic and biotic environment interact and need to be considered to improve predictions of drought stress and thresholds. The negative impact of drought on tree growth was accentuated by insect defoliation (Malcolm Itter, Michigan State University, USA) but buffered by elevated $CO_2$ (Kelly Heilman); and topo-edaphic properties modified drought constraints on tree regeneration (Winslow Hansen, University of Wisconsin Madison). The research presented largely focused on forests, but presentations on drylands (Seth Munson, U.S. Geological Survey, USA; Esther Bochet, CSIC, Spain) demonstrated similar non-linear vegetation responses, and often greater sensitivity, at lower amounts of water availability. Future research can expand our understanding of when and where thresholds occur by examining cross-ecosystem responses across broader gradients of environmental conditions. Many of the poster presentations focused on other agents of change, including nitrogen deposition (Jessica Moore, University of New Hampshire, USA), ice-melt (Shaleen Jain, University of Maine, USA), anoxia (Yang Lin, University of California Berkeley, USA), and human disturbance (Peter Guy Langdon, University of Southampton, England; Esther Bochet, CSIC, Spain).

## Indicators of Ecosystem Performance

Ecosystem performance was commonly measured by changes in plant growth, with metrics that ranged from foliar cover to tree ring growth. Adam Moreno (NASA Ames, USA) pointed out that different aspects of plant structure have independent responses to shifts in precipitation and temperature, thereby creating unique tipping points that need to be identified. Independent responses among species and functional types can portend large shifts in community composition. Most presentations addressed aboveground plant structure, but several speakers broadened knowledge of critical ecosystem shifts by focusing on belowground performance in plants (Scott Mackay, University of Buffalo, USA; Alexis Wilson, Cornell University, USA) and microbes (Jessica Moore, Yang Lin). Scott Mackay demonstrated that deep roots and high root-to-leaf areas reduced the risk of catastrophic hydraulic failure. Jessica Moore showed that increasing nitrogen deposition decreased carbon mineralization and led to a shift toward a stress-tolerant microbial community. Close linkages among vegetation structure, microbial activity, and biogeochemical cycles have made it possible to identify thresholds in carbon cycling and storage. Chris Gough (Virginia Commonwealth University, USA) found that intermediate levels of disturbance can increase forest complexity and stimulate carbon storage, whereas severe disturbances beyond thresholds can simplify structure and lead to declines in carbon storage. A couple of poster presentations added perspective to tipping points by highlighting threshold responses attributable to nutrient loading and radiative heating in aquatic ecosystems, which can cascade into social systems (Peter Langdon, Shaleen Jain). Many of the session participants raised awareness that the interconnectedness of ecosystem properties can generate feedback loops that further enhance threshold responses and degradation.

## Approaches to Understanding and Predicting Ecosystem Thresholds

A diverse set of observations, experiments, and models used to study ecosystem thresholds were presented during the session. Those that combined multiple approaches to derive a tipping point were among the most convincing. For example, Scott Mackay used results from a seasonal drought, an unusually protracted drought, and an experimental drought (with and without warming) to define thresholds across North American woodlands. The definition of a critical transition required a means to discriminate ecosystem stress from an abrupt threshold, which was difficult or impossible to reverse. Interestingly, a majority of presentations did not find proof of an alternative ecosystem state or irreversibility to a previous state by restoring environmental conditions that existed before the threshold as defined by Scheffer *et al.* (2001). Failure to detect bifurcations in ecosystem state may be due to the limitations in the temporal and spatial extent, and lack of environmental extremes, in many of the datasets. Several presentations highlighted the growing occurrence of environmental extremes, which may enhance ecosystem thresholds in the future and the need for early warning signs to detect them. Brendan Rogers (Woods Hole Research Center, USA) and Yanlan Liu (Duke University, USA) demonstrated how threshold forest mortality events can be predicted by indices of the spatial and temporal dynamics of satellite-imaged vegetation, suggesting that environmental conditions do not have to be explicitly considered in threshold frameworks. The coupling of field measurements to satellite-based vegetation indices and ecosystem models greatly broadened the assessments of early warning signs in space and time (Stephan Pietsch, IISA, Austria; Xiuchen Wu, Beijing Normal University, China). The inclusion of ecosystem memory to past environmental conditions was a particularly novel approach for defining ecosystem thresholds. Results demonstrated how the temporal persistence of plant response varied with ecosystem and location (Malcolm Itter, Seth Munson).

The overall breadth of approaches presented in the session bolstered conceptual constructs of ecosystem thresholds with empirical support and cutting-edge tools. In face of the interchangeable and general use of the terms “thresholds”, “tipping points”, and “critical transitions”, a promising path forward is to rigorously quantify the level of change that represents these transitions so that we can compare shifts and their environmental drivers across ecosystems. Additional evidence for alternative states of ecosystem performance and hysteresis in regenerating ecosystem performance prior to threshold responses can help refine measures to mitigate and prepare for future ecosystem transformations.

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Figure 1. There are multiple definitions of ecosystem thresholds, tipping points, and critical transitions. (A) A more general definition identifies a progression from ecosystem stability, to stress, to threshold response, and eventually to replacement by a novel ecosystem under changing environmental conditions. (B) A *sensu strictu* definition identifies alternative states of ecosystem performance, separated by an unstable equilibrium (dashed line) at a critical environmental condition (CEC; *sensu* Scheffer et al. 2001). Returning environmental conditions to a previous level does not always result in the previous state of ecosystem performance. This figure was recreated from Scheffer *et al. 2001* with permission from the Springer Nature Publishing Group.