

---

This is the **accepted version** of the article:

Munson, Seth M.; Reed, Sasha C.; Peñuelas, Josep; [et al.]. «Ecosystem thresholds, tipping points, and critical transitions». *New phytologist*, Vol. 218, issue 4 (June 2018), p. 1315-1317. DOI 10.1111/nph.15145

---

This version is available at <https://ddd.uab.cat/record/218318>

under the terms of the  **CC BY** COPYRIGHT license

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24

**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*

Seth M. Munson<sup>1,\*</sup>, Sasha C. Reed<sup>2</sup>, Josep Peñuelas<sup>3</sup>, Nathan G. McDowell<sup>4</sup>, Osvaldo E. Sala<sup>5</sup>

<sup>1</sup>US Geological Survey, Southwest Biological Science Center, 2255 N Gemini Dr., Flagstaff, AZ 86001, USA

<sup>2</sup>US Geological Survey, Southwest Biological Science Center, 2290 SW Resource Blvd., Moab, UT 84532, USA

<sup>3</sup>Global Ecology Unit CREAM-CSIC-UAB, CSIC, Bellaterra (Catalonia) E-08193, Spain

<sup>4</sup>Pacific Northwest National Laboratory, Richland, WA 99352, USA

<sup>5</sup>Global Drylands Center, School of Life Sciences and School of Sustainability, Arizona State University, Tempe, AZ 85287, USA

\*Corresponding author email: smunson@usgs.gov, Tel: 1-928-523-7740, Fax: 1-928-556-9111

Key words: climate change, drought, early warning sign, global change, human disturbance, terrestrial ecosystem structure and function

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

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

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

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

### 57 **Environmental Drivers of Ecosystem Thresholds**

58 Oral presentations in the session largely addressed the consequences of increased aridity  
59 on plant performance. Ted Hogg (Natural Resources Canada, Edmonton, Canada) and Kelly  
60 Heilman (University of Notre Dame, USA) defined a hydrological “tipping point” between forest  
61 and prairie in western Canada and midwestern USA, respectively, and related the climatic  
62 conditions at these ecotones to tree growth and mortality. Several presentations pointed out how  
63 multiple aspects of the abiotic and biotic environment interact and need to be considered to  
64 improve predictions of drought stress and thresholds. The negative impact of drought on tree  
65 growth was accentuated by insect defoliation (Malcolm Itter, Michigan State University, USA)  
66 but buffered by elevated CO<sub>2</sub> (Kelly Heilman); and topo-edaphic properties modified drought  
67 constraints on tree regeneration (Winslow Hansen, University of Wisconsin Madison). The  
68 research presented largely focused on forests, but presentations on drylands (Seth Munson, U.S.  
69 Geological Survey, USA; Esther Bochet, CSIC, Spain) demonstrated similar non-linear  
70 vegetation responses, and often greater sensitivity, at lower amounts of water availability. Future

71 research can expand our understanding of when and where thresholds occur by examining cross-  
72 ecosystem responses across broader gradients of environmental conditions. Many of the poster  
73 presentations focused on other agents of change, including nitrogen deposition (Jessica Moore,  
74 University of New Hampshire, USA), ice-melt (Shaleen Jain, University of Maine, USA), anoxia  
75 (Yang Lin, University of California Berkeley, USA), and human disturbance (Peter Guy  
76 Langdon, University of Southampton, England; Esther Bochet, CSIC, Spain).

### 77 **Indicators of Ecosystem Performance**

78 Ecosystem performance was commonly measured by changes in plant growth, with  
79 metrics that ranged from foliar cover to tree ring growth. Adam Moreno (NASA Ames, USA)  
80 pointed out that different aspects of plant structure have independent responses to shifts in  
81 precipitation and temperature, thereby creating unique tipping points that need to be identified.  
82 Independent responses among species and functional types can portend large shifts in community  
83 composition. Most presentations addressed aboveground plant structure, but several speakers  
84 broadened knowledge of critical ecosystem shifts by focusing on belowground performance in  
85 plants (Scott Mackay, University of Buffalo, USA; Alexis Wilson, Cornell University, USA) and  
86 microbes (Jessica Moore, Yang Lin). Scott Mackay demonstrated that deep roots and high root-  
87 to-leaf areas reduced the risk of catastrophic hydraulic failure. Jessica Moore showed that  
88 increasing nitrogen deposition decreased carbon mineralization and led to a shift toward a stress-  
89 tolerant microbial community. Close linkages among vegetation structure, microbial activity, and  
90 biogeochemical cycles have made it possible to identify thresholds in carbon cycling and storage.  
91 Chris Gough (Virginia Commonwealth University, USA) found that intermediate levels of  
92 disturbance can increase forest complexity and stimulate carbon storage, whereas severe  
93 disturbances beyond thresholds can simplify structure and lead to declines in carbon storage. A

94 couple of poster presentations added perspective to tipping points by highlighting threshold  
95 responses attributable to nutrient loading and radiative heating in aquatic ecosystems, which can  
96 cascade into social systems (Peter Langdon, Shaleen Jain). Many of the session participants  
97 raised awareness that the interconnectedness of ecosystem properties can generate feedback  
98 loops that further enhance threshold responses and degradation.

### 99 **Approaches to Understanding and Predicting Ecosystem Thresholds**

100 A diverse set of observations, experiments, and models used to study ecosystem  
101 thresholds were presented during the session. Those that combined multiple approaches to derive  
102 a tipping point were among the most convincing. For example, Scott Mackay used results from a  
103 seasonal drought, an unusually protracted drought, and an experimental drought (with and  
104 without warming) to define thresholds across North American woodlands. The definition of a  
105 critical transition required a means to discriminate ecosystem stress from an abrupt threshold,  
106 which was difficult or impossible to reverse. Interestingly, a majority of presentations did not  
107 find proof of an alternative ecosystem state or irreversibility to a previous state by restoring  
108 environmental conditions that existed before the threshold as defined by Scheffer *et al.* (2001).  
109 Failure to detect bifurcations in ecosystem state may be due to the limitations in the temporal and  
110 spatial extent, and lack of environmental extremes, in many of the datasets. Several presentations  
111 highlighted the growing occurrence of environmental extremes, which may enhance ecosystem  
112 thresholds in the future and the need for early warning signs to detect them. Brendan Rogers  
113 (Woods Hole Research Center, USA) and Yanlan Liu (Duke University, USA) demonstrated  
114 how threshold forest mortality events can be predicted by indices of the spatial and temporal  
115 dynamics of satellite-imaged vegetation, suggesting that environmental conditions do not have to  
116 be explicitly considered in threshold frameworks. The coupling of field measurements to

117 satellite-based vegetation indices and ecosystem models greatly broadened the assessments of  
118 early warning signs in space and time (Stephan Pietsch, IISA, Austria; Xiuchen Wu, Beijing  
119 Normal University, China). The inclusion of ecosystem memory to past environmental  
120 conditions was a particularly novel approach for defining ecosystem thresholds. Results  
121 demonstrated how the temporal persistence of plant response varied with ecosystem and location  
122 (Malcolm Itter, Seth Munson).

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

### 131 **Acknowledgements**

132  
133         The authors offer their sincerest thanks to all the presenters that contributed to the  
134 organized oral and poster session. We are also grateful to the New Phytologist Trust for their  
135 sponsorship. Any use of trade, firm, or product names is for descriptive purposes only and does  
136 not imply endorsement by the U.S. Government.

### 137 **References**

138 Allen CR, Fontaine JJ, Pope KL, Garmestani AS. 2011. Adaptive management for a turbulent  
139 future. *Journal of Environmental Management* **92**: 1339–1345.

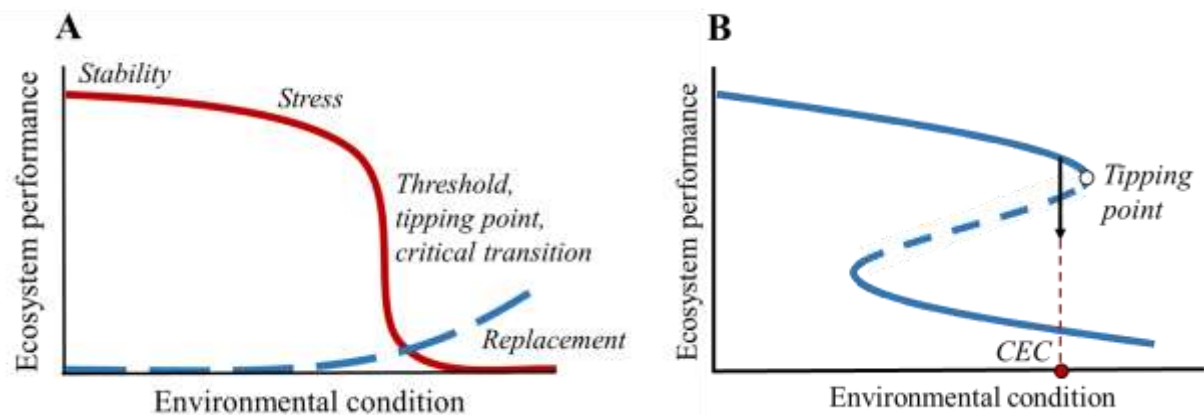
140  
141 Glick P, Stein B, Edelson NA. 2010. *Scanning the conservation horizon: A guide to climate*  
142 *change vulnerability assessment*. Washington, DC: National Wildlife Federation.

143

- 144 Holling CS. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and*  
145 *Systematics* **4**: 1–23.  
146
- 147 May RM. 1977. Thresholds and breakpoints in ecosystems with a multiplicity of stable states.  
148 *Nature* **269**: 471–477.  
149
- 150 McDowell NG, Beerling DJ, Breshears DD, Fisher RA, Raffa KF, Stitt M. 2011. The  
151 interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in*  
152 *Ecology & Evolution* **26**: 52–532.  
153
- 154 Munson SM. 2013. Plant responses, climate pivot points, and trade-offs in water-limited  
155 ecosystems. *Ecosphere* **4**: 109.  
156
- 157 Peñuelas J, Filella I. 2001. Responses to a warming world. *Science* **294**: 793–795.  
158
- 159 Peters DP, Sala OE, Allen CD, Covich A, Brunson M. 2007. Cascading events in linked  
160 ecological and socioeconomic systems. *Frontiers in Ecology and the Environment* **5**: 221–224.  
161
- 162 Reed SC, Maestre FT, Ochoa-Hueso R, *et al.* 2016. Biocrusts in the context of global change. In:  
163 Weber B, Budel B, Belnap J, eds. *Biological soil crusts: an organizing principle in drylands.*  
164 *Ecological Studies vol. 226.* Switzerland: Springer.  
165
- 166 Scheffer M, Carpenter S, Foley JA, Walker B. 2001. Catastrophic shifts in ecosystems. *Nature*  
167 **413**: 591–596.  
168
- 169 Schwinning S, Sala OE, Loik ME, Ehleringer JR. 2004. Thresholds, memory, and seasonality:  
170 understanding pulse dynamics in arid/semi-arid ecosystems. *Oecologia* **141**: 191–193.  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187



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



199  
 200