Alternative Stable State Theory and Regime Shifts

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A note from the authors: This version is static and as such has lost both formatting for viewing ease and important interactive elements like the ability to quiz oneself and click on key terms for hover-box definitions. We highly recommend using this module in it's interactive form by visiting the following link: https://passel2.unl.edu/view/lesson/ab491bda9f88

Authors

Julie A. Fowler, School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska

Conor D. Barnes, School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska

Dillon Fogarty, Department of Agronomy and Horticulture, University of Nebraska-Lincoln

Katharine F. E. Hogan, Nebraska Cooperative Fish and Wildlife Research Unit, and School of Natural Resources

Jessica E. Johnson, Biological Systems Engineering Department, University of Nebraska-Lincoln

Alison K. Ludwig, Department of Agronomy and Horticulture, University of Nebraska-Lincoln

Dirac Twidwell, Department of Agronomy and Horticulture, University of Nebraska-Lincoln

Overview and Objectives

Overview - What Will You Learn in this Lesson?

This lesson discusses what alternative stable states and regime shifts are and how they relate to understanding and interpreting natural phenomena.

Objectives

This lesson covers the concept of alternative stable state and regime shifts. At the completion of this lesson, you should be able to:

Describe the concepts of alternative states or regimes, thresholds, and regime shifts and how they come together under alternative state theory

Explain how scale, resilience, and hysteresis play a role in alternative stable state theory

Identify the management value of alternative stable state theory, its application to real world problems, and its role in global change

Correct answers to all questions are highlighted

Introduction - What Are Alternative Stable States? What Is a Regime Shift?

Example

Take a look at Figure 1. How can it be that two lakes side-by-side with similar conditions look so different from one another? The answer is that these two lakes are examples of alternative stable states. Systems can shift radically and suddenly into fundamentally different configurations (in this case, a clear-water lake and a turbid, cyanobacteria-dominated lake) depending on the type and magnitude of disturbances inflicted on the system. The theory of alternative stable states is related to the concept of hysteresis, the idea that sometimes the way to reverse a change is different than just reversing what caused the change in the first place. Excess nutrient pollution from sources such as agricultural runoff can lead to lake eutrophication, or the turbid appearance visible in Figure 1 (Wilkinson et al. 2018). However, returning to the clear-water lake (on the right below) may require the removal of more nutrients than originally led to the catastrophic shift from a clear to a turbid lake. Given these facts and the presence of hysteresis in the turbid lake, it is possible for the two lakes to have the same amount of nutrients present, yet be in different states. Clear-water states and turbid, algae- or cyanobacteria-dominated states in freshwater lakes are a common example of alternative stable states exhibited by complex systems.

Figure 1. An example of two lakes where one has transitioned to a turbid, cyanobacteria dominated state while the other remains in a clear-water state. Photo credit: Dr. Stephen R. Carpenter (used with permission)

What Are Alternative States and Regime Shifts?

The theory of alternative stable states utilizes three main concepts to explain the dynamic nature of ecosystems: 1) alternative stable states or regimes, 2) thresholds of change, and 3) regime shifts between these alternative stable states.

Alternative stable states are defined as differing arrangements of an ecosystem's characteristics, such as its functions, processes, components, and interrelationships. These differing arrangements are maintained through different stabilizing feedbacks with abrupt shifts between these arrangements. The arrangement of an ecosystem at a given time is its state. In the lakes example, one alternative stable state is the clear-water lake and the other alternative stable state is the turbid lake.

Thresholds of change are the borders between alternative stable states. If a disturbance pushes an ecosystem beyond that border line, then the ecosystem will switch into an alternative stable state. These are also referred to as "tipping points". In the lakes example this is the amount of nutrient loading, or the quantity of nutrients, that the clear lake must surpass to "tip" into the turbid lake alternative stable state.

Regime shifts are the transition from one alternative stable state to another through the passing of a threshold. It is caused by some form of internal feedback or external perturbation over timescales of varying length (Angeler and Allen 2016). In the lakes example this is the moment and process of shifting from the clear lake alternative stable state to the turbid lake alternative stable state.

Therefore, alternative stable state theory suggests that multiple states may exist for one ecosystem. Over time this ecosystem may transition from one state to another due to either external or internal influences, fundamentally altering the structure and function of the ecosystem.

Description of Theory

The ability to understand the range of alternative states one ecosystem may move between is crucial to understanding and managing ecosystems overall. The theory of alternative stable states and regime shifts predates the 1973 inception of ecological resilience by Holling, instead originating in 1969 with Dr. Richard Lewontin, an evolutionary biologist. Scheffer et al. (2001) describes three response curves an ecosystem may have as a result of changes in external conditions:

1. An ecosystem may respond in a “smooth, continuous” way
2. An ecosystem may be relatively static over a certain range of these changes, before responding in a more sudden and strong manner at a certain point
3. Or, an ecosystem’s response curve may be “folded” in on itself, demonstrating two alternative stable states that can exist for the same external conditions

These response curves and the feedback strength associated with them are further described in Figure 2, demonstrating how for a continuous, linear change in an external condition the three response curves may result, with the final one showing strong positive feedbacks that result in alternative stable states and increased hysteresis:

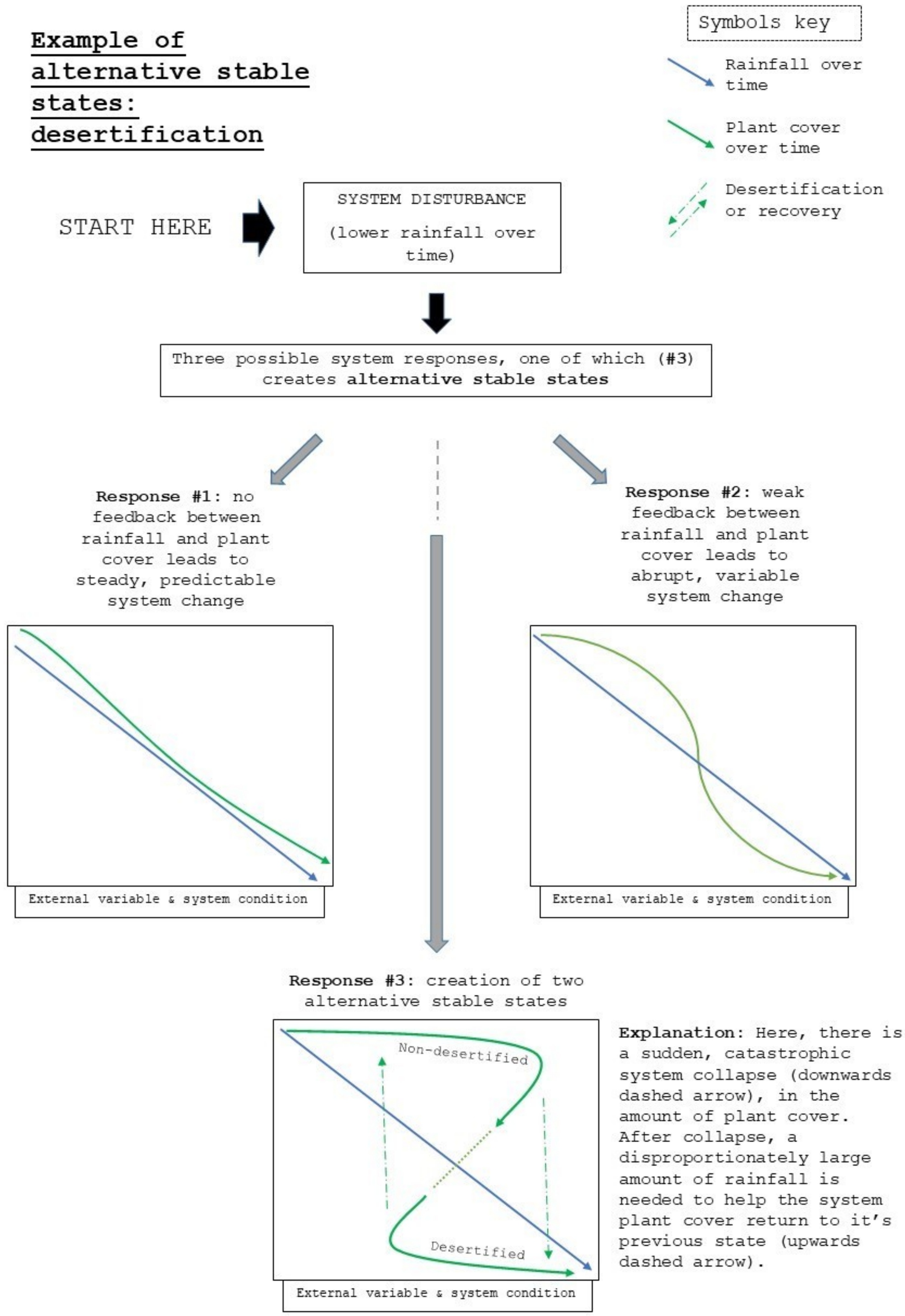

Figure 2. A demonstration of how systems may respond to the same disturbance in different manners, including the switch into an alternative stable state for which a larger force is required

to shift the system back to the previous state than was needed to push it into the alternative stable state. Figure adapted from Scheffer et al. (2001)

The shape of the third response curve, or the curve that demonstrates the theory of alternative stable states, is notable as it demonstrates how these regime shifts can occur rapidly and with little warning as they cross a threshold. The second notable feature of this response curve is the presence of hysteresis, i.e. the ecosystem cannot be returned to the previous regime by simply returning to the same external conditions. The third notable feature is that for the same conditions on the x-axis, two different ecosystems states could occur. This is the fundamental idea behind alternative stable states: fundamentally different ecosystem structures can occur under the same external conditions. Figure 3 demonstrates the two alternative stable states under changing external conditions, with the hill representing the threshold between these states.

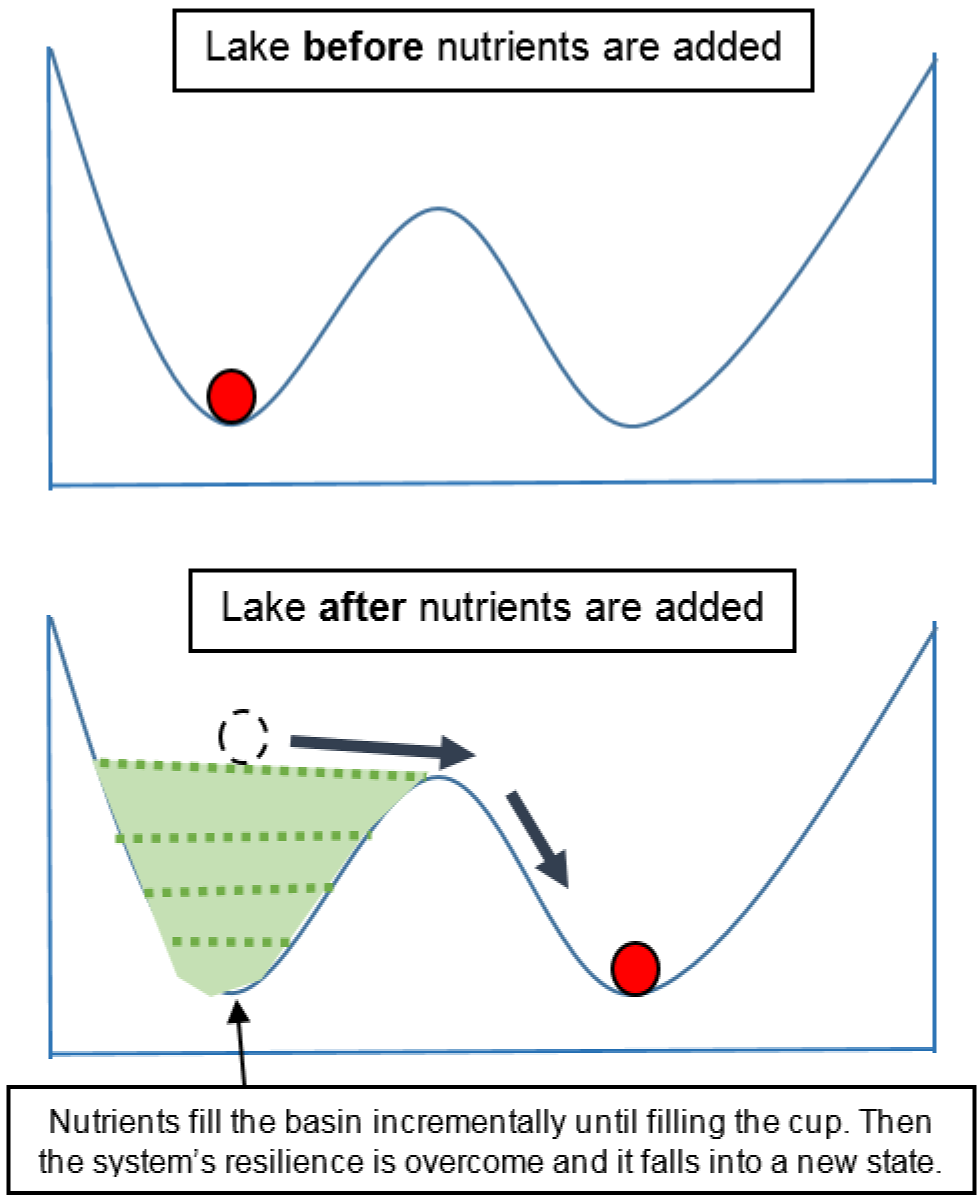

Figure 3. An example of a system's parameters changing as more nutrients are continually added into the lake. Nutrients fill the basin incrementally until filling the cup. Then the system's resilience is overcome and it falls into a new state. Figure created by Alison Ludwig.

Utility - Why Are These Ideas Useful?

The theory of alternative stable states and regime shifts is exceedingly important for scientists, land managers, and global citizens to understand. Fundamentally, this theory demonstrates that in natural systems even incremental changes over time to either the system's variables or parameters (that is, either the ball or the cup itself) can result in catastrophic and sudden shifts into alternate regimes with different ecosystem functions. Given the rapid and massive human impacts on Earth in the modern era, we must be aware of how actions may be approaching a threshold of change that threatens the stability and function of critical ecosystems. Understanding this possibility and managing for it is a crucial application of ecological resilience for human and ecosystem health. It is important to note that these regimes shifts can occur at a variety of spatial scales, from individual lakes up to the global scale.

Example - Bare vs. Vegetated Sand Dune Alternative Stable State and Regime Shift

Free-blowing sand dunes (blowouts) existing alongside vegetated sand dunes illustrate alternative stable states (Figure 4). Alternative stable states are different arrangements of an ecosystem's functions, processes, and relationships (Holling 1973, May 1977, Scheffer et al. 2001). Vegetated dunes and blowouts show how two stable states can exist side by side, each with their own reinforcing processes that contribute to their existence. Plants spread via roots and seeds into open sand, which stabilizes blowing sand over time and creates vegetated dunes. Simultaneously, wind erosion scours the edges of the blowouts, gradually weakening plants and eroding around their roots, creating a blowout (Hesp 2002). These two processes create a constantly changing landscape affected by many factors, but specific environmental changes such as dry or wet years that favor either vegetation or blowing sand can trigger a shift between states at any given point in space and time.

Figure 4. Bare and vegetated sand dunes. Photo on the left is from the U.S. Forest Service. Photo on the right is by Kay Williams, distributed under the CC BY-SA 2.0 license

References

Hesp P. 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology 48:245–268.

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics, 4, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

May RM. 1977. Thresholds and breakpoints in ecosystems with a multiplicity of stable states. Nature 269:471–477.

Summary - Why are Alternative State States and Regime Shifts Important?

The theory of alternative stables and regime shifts is the concept that systems are dynamic and may have multiple possible configurations in which they are able to exist. The example used here is of two lakes in the same location and under the same climate but yet fundamentally different. One has undergone a regime shift from a clear lake to a turbid lake as the result of having its resilience to nutrient overloading overcome and subsequently flipping into an alternative stable state from the clear lake. Looking back at the ball-and-cup model, some disturbances, some disturbances may move the ball while altering stabilizing feedbacks of a state cause the size and shape of the cup to change, overall these concepts allow us to understand that systems are dynamic and that even small disturbances may be the "last straw" that suddenly collapses a system, or breaks the camel's back. What is needed to change a system back into a previous state may be unclear, as systems pushed into alternative stable states may have to contend with hysteresis, or the fact that pushing the ball back over the hill from where it came may be much more difficult than pushing the ball into the new state in which it is now. Whether ecological systems or states of government, this theory prevents us from seeing systems as static, and is necessary to understand the full range of possible configurations for any system.

Quiz Questions

Question

What is another name for a threshold of change?

A. Alternative Stable State
B. Tipping Point
C. Basin of Attraction
D. Hysteresis

Question

What element of an ecosystem describes the amount of disturbance a system can absorb before it shifts into an alternative stable state?

A. Scale
B. Hysteresis
C. Resilience
D. Eutrophication

Question

Alternative stable states exist in systems other than ecosystems

A. True
B. False

References and Further Reading

References

Gunderson, L. H., Allen, C. R., and Holling, C. S. (2010). Foundations of Ecological Resilience. Island Press, Washington D.C. 466 pgs.

Holling, C. S. (1996). "Engineering Resilience versus Ecological Resilience", in Engineering Within Ecological Constraints pgs. 31–44. National Academy Press, Washington D.C. 224 pgs.

Liao, K. A. (2012). Theory on Urban Resilience to Floods—A Basis for Alternative Planning Practices. Ecology and Society, 17(4), 48

Resilience Alliance. (2012). "Resilience." https://www.resalliance.org/resilience. Accessed 17 Dec 2018.

Rocha, J., Biggs, R. O., Peterson, G., and Carpenter, S. "Freshwater Eutrophication." In: Regime Shifts Database, www.regimeshifts.org. Last revised 2017-01-23 08:58:21 GMT.

Turner, M. G., and Gardner, R. H. (2015). "Chapter 9: Landscape Dynamics in a Rapidly Changing World". Landscape Ecology in Theory and Practice: Pattern and Process. Springer, New York. 2nd ed. 482 pgs.

Walker, B., Holling, C. S., Carpenter, S. R., and Kinzig, A. (2004). Resilience, Adaptability and Transformability in Social–Ecological Systems. Ecology and Society, 9(2), 5

Further Reading

Angeler, D. G., & Allen, C. R. (2016). Quantifying resilience. Journal of Applied Ecology, 53(3), 617–624. https://doi.org/10.1111/1365-2664.12649

Beisner, B. E., Haydon, D. T., & Cuddington, K. (2003). Alternative Stable States in Ecology. Frontiers in Ecology and the Environment, 1(7), 376–382.

Hobbs, W. O., Hobbs, J. M. R., Lafrançois, T., Zimmer, K. D., Theissen, K. M., Edlund, M. B., Michelutti, N., Butler, M. G., Hanson, M. A., & Carlson, T. J. (2012). A 200-year perspective on alternative stable state theory and lake management from a biomanipulated shallow lake. Ecological Applications, 22(5), 1483–1496. https://doi.org/10.1890/11-1485.1

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. Nature, 413(6856), 591–596. https://doi.org/10.1038/35098000

Schröder, A., Persson, L., & De Roos, A. M. (2005). Direct experimental evidence for alternative stable states: a review. Oikos, 110(1), 3–19.

Turner, M. G., & R. H. Gardner. (2015). Introduction to landscape ecology and scale. J. Slobodien (Ed.), Landscape Ecology in Theory and Practice (pp. 1-32). New York, NY: Springer.

Walker, B., & Salt, D. (2006). Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Washington, D.C: Island Press.

Glossary

Alternative Stable State

Also known as "regime". One out of multiple different forms of existence or organization for a system; the system may transition to any of its alternative states if the appropriate environmental conditions are met.

Ball-and-Cup Model

A conceptual model used to visualize and understand ecological resilience. This is outlined in detail in another module, however the visualization is of a ball, representing the current state of a system, on a 3D plane that has different “basins” or points at which there is concavity. This visualization is meant to represent the states a system is drawn to (the ball being drawn into a basin) and the potential for shifting from one state, or basin, to another with movement of the ball caused by perturbation.

Ecological Resilience

The capacity of a system to withstand disturbances without altering established processes, functions, and structures. This concept can be applied to other systems such as economies, governments, or companies, despite the term “ecological”.

Feedback

When a change in one aspect of a system causes a change in an earlier aspect of the same system, whether positive or negative, and can be self-reinforcing. For example, rising temperatures can cause ice cover to decrease through melting. This exposes more land to the sun, which heats up the land near the ice and causes more melting, creating a positive feedback loop.

Hysteresis

The general idea that the path out of a situation is different from the path you took to get into the situation. This can occur in ecosystems. See lake eutrophication example in the resilience and hysteresis modules.

Perturbation

Also known as "Disturbance". An event or input to a system that causes a loss of the system's capital. It may cause a regime shift. For example, wildfire in a forest, ocean acidification and coral reefs, woody encroachment in a grassland.

Regime Shift

Also known as Regime Change. The transformation of a system from one stable state to another. These changes often occur in response to disturbances. For example, a volcanic eruption on a Hawaiian island can shift a tropical forest ecosystem into bare volcanic rock.

Scale

The spatial or temporal dimension of an object or process, characterized by both grain and extent (Turner & Gardner, 2015)

Threshold of Change

Also known as "tipping point". The point at which a system shifts from one state to an alternative state.