Ecological Resilience

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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

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Overview and Objectives

Overview - What Will You Learn In This Lesson?

This lesson discusses what resilience is and how it relates to understanding and interpreting natural phenomena.

Objectives

This lesson covers the concept of ecological resilience. At the end of this module you should be able to:

1. Define ecological resilience and related terminology
2. Outline a brief history of the origin of the concept
3. Explain the ball-in-cup model of resilience and its dynamics
4. Demonstrate reasons why this concept may be used to make ecological management decisions

Correct answers to all questions are highlighted

Introduction - What Is Resilience?

Have you ever wondered how some systems, such as ecosystems or societies, can undergo massive changes, like forest fire or foreign invasion, and somehow recover to a similar state as before? Perhaps one forest burns and recovers in a few years, while a similar forest instead regrows as a different kind of forest, or as a mix of forest and grass. Why do some cities fall permanently to the first invading army, and others are rebuilt many times? Why do destructive forces affect forests and cities so differently? The concepts of ecological resilience help us understand why some complex systems like forests and cities stay the same and why others transform completely.

Ecological resilience is defined as the amount of disturbance that a system can withstand without altering self-organized processes and structures (Gunderson 2000). This concept can be applied to help explain why some communities continue to thrive following a natural disturbance and why other communities are devastated.

Ecological resilience was introduced as a concept in 1973 by C.S. Holling, who attempted to provide insight into three “reactions” ecosystems have to an external disturbance such as fire or climate change:

1. Persistence of the relationships among components of a system in the face of change; for example, the ability of an ecosystem’s members (like animals and plants) to continue their daily interactions despite a disturbance

2. The capacity of a system to absorb disturbances and continue functioning; for example, the ability of an ecosystem to continue providing the same ecosystem services (such as water purification, carbon sequestration, etc.) despite having been disturbed

3. The sudden and discontinuous change ecosystems undergo following a disturbance that cannot be absorbed; for example, a quick and significant change in ecosystem services or plant/animal interactions as the ecosystem becomes fundamentally different than it was before the disturbance

One example of resilience can be found in grasslands. A problem many grasslands around the world face is the encroachment of woody plants (Walker and Salt 2012). Woody encroachment occurs when the processes that limit woody plants in grasslands are altered. As woody plants expand they block sunlight from reaching the herbaceous plants below the canopy, like grasses and forbs, leading to the loss of herbaceous biomass. As herbaceous plants die off due to lack of sunlight, the woody plants fill in the gaps until the only thing left is a dense, woody thicket with little to no understory (Walker and Salt 2012).

Now let's look at this example through a resilience lens. In the early stages of encroachment, there were woody species within the grassland but the system still functioned as a grassland. As time progressed, the woody species grew denser and the grasses died off. Its resilience was overcome as the ability of the system to resist the invasion of woody species was reduced. Once the original grassland structures were gone, the system no longer functioned as a grassland. The structure, functions, and relationships of a grassland disappeared and were replaced by the structure, functions, and relationships of a forest. This is an example of the third reaction above.

Description - How Can We Visualize Resilience in the Real World?

The concept of resilience is often illustrated through the "ball-in-cup" model as illustrated in Figure 1. The balls in each diagram represent the current condition of the system (Gunderson 2000). Each cup or "basin of attraction" represents potential states or "regimes" in which the system can exist (for example, a desert, grassland, or forest). The ecological resilience concept recognizes that there is more than one basin of attraction (known as "alternative states") to which the system may transition. The peak that divides two alternative states is known as the "threshold". Ecological resilience is focused on quantifying how much "perturbation" the system can undergo before moving to an alternative state.

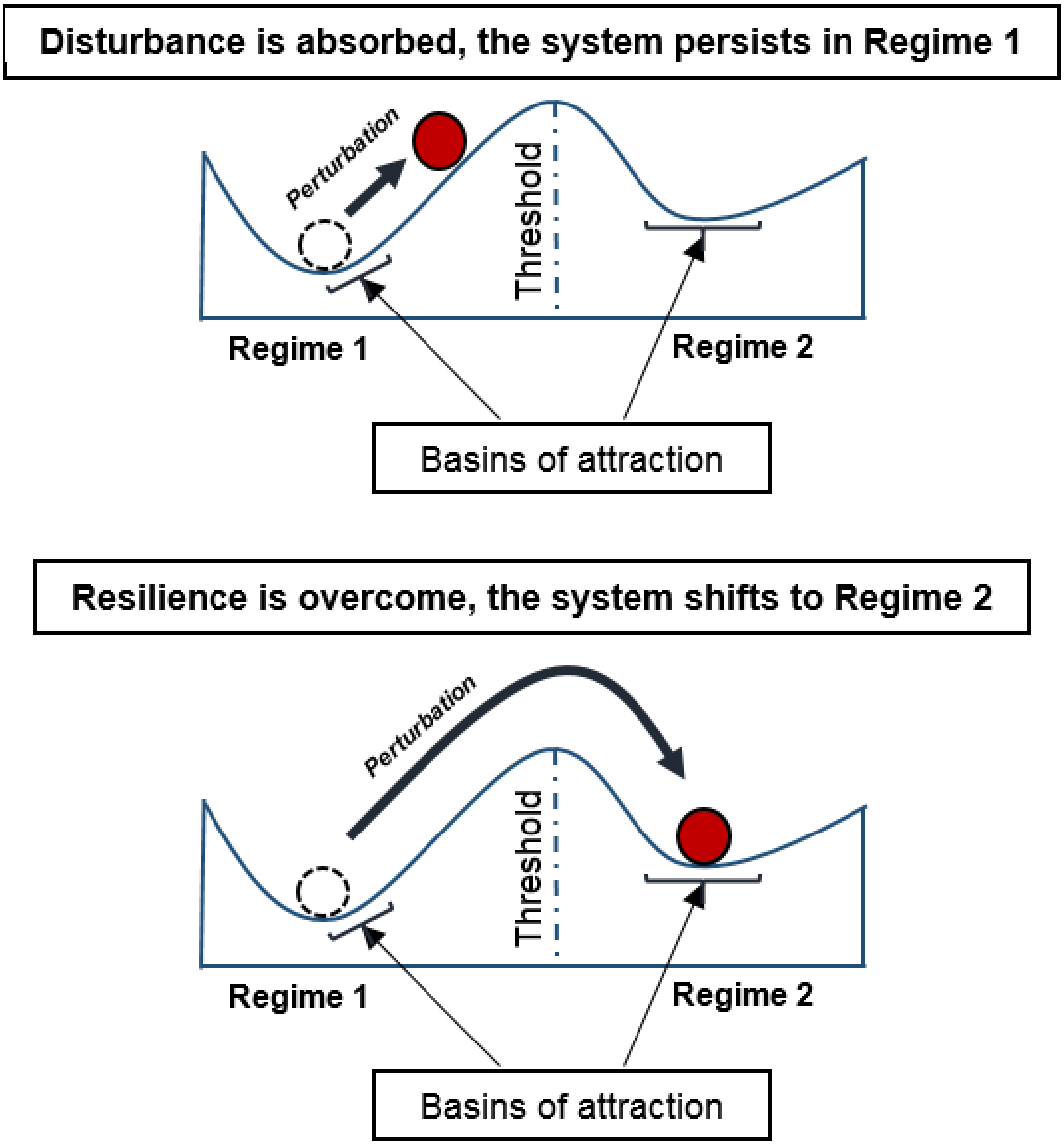
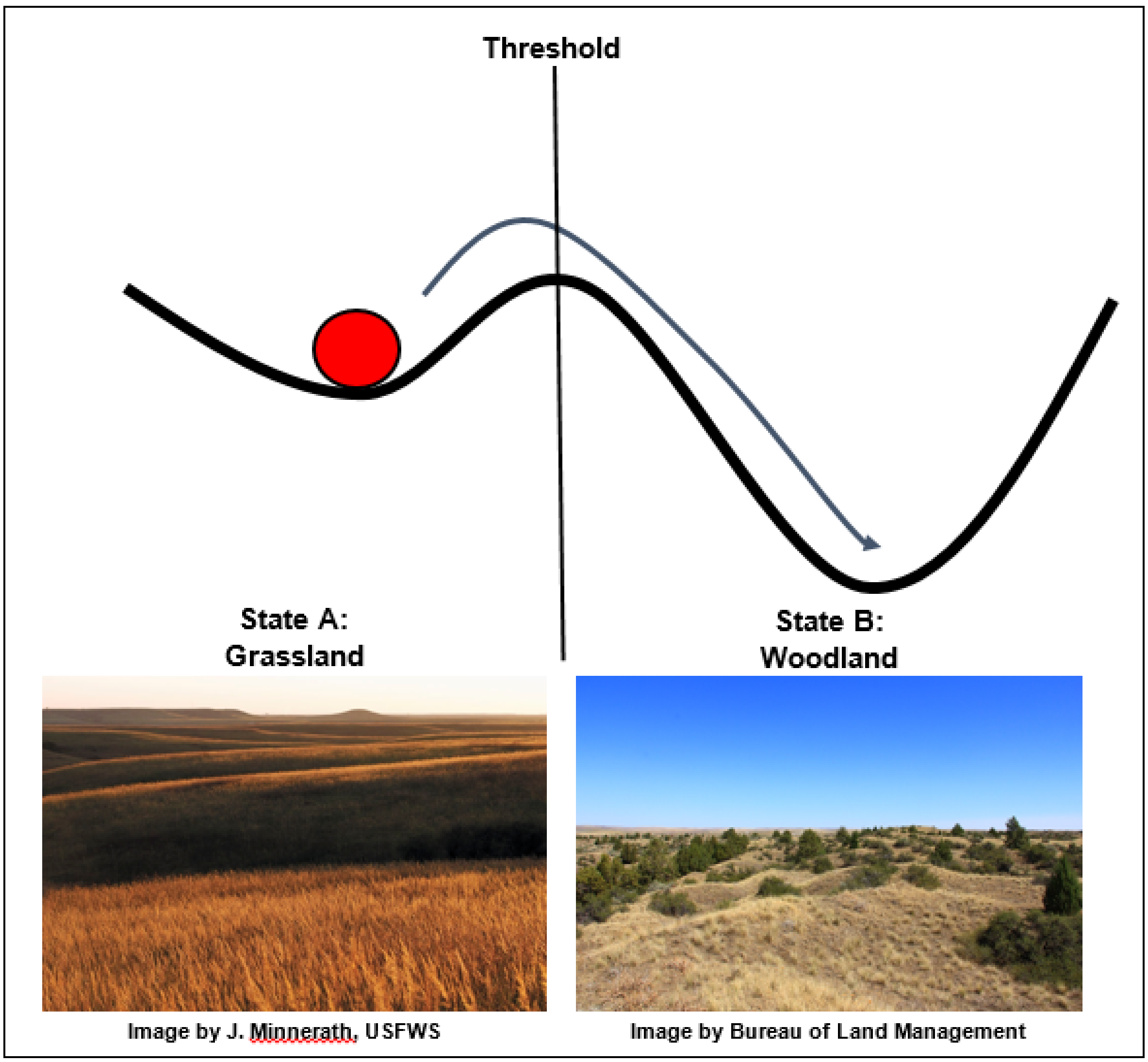


Figure 1. Ball-in-cup model. Figure created by Alison Ludwig.

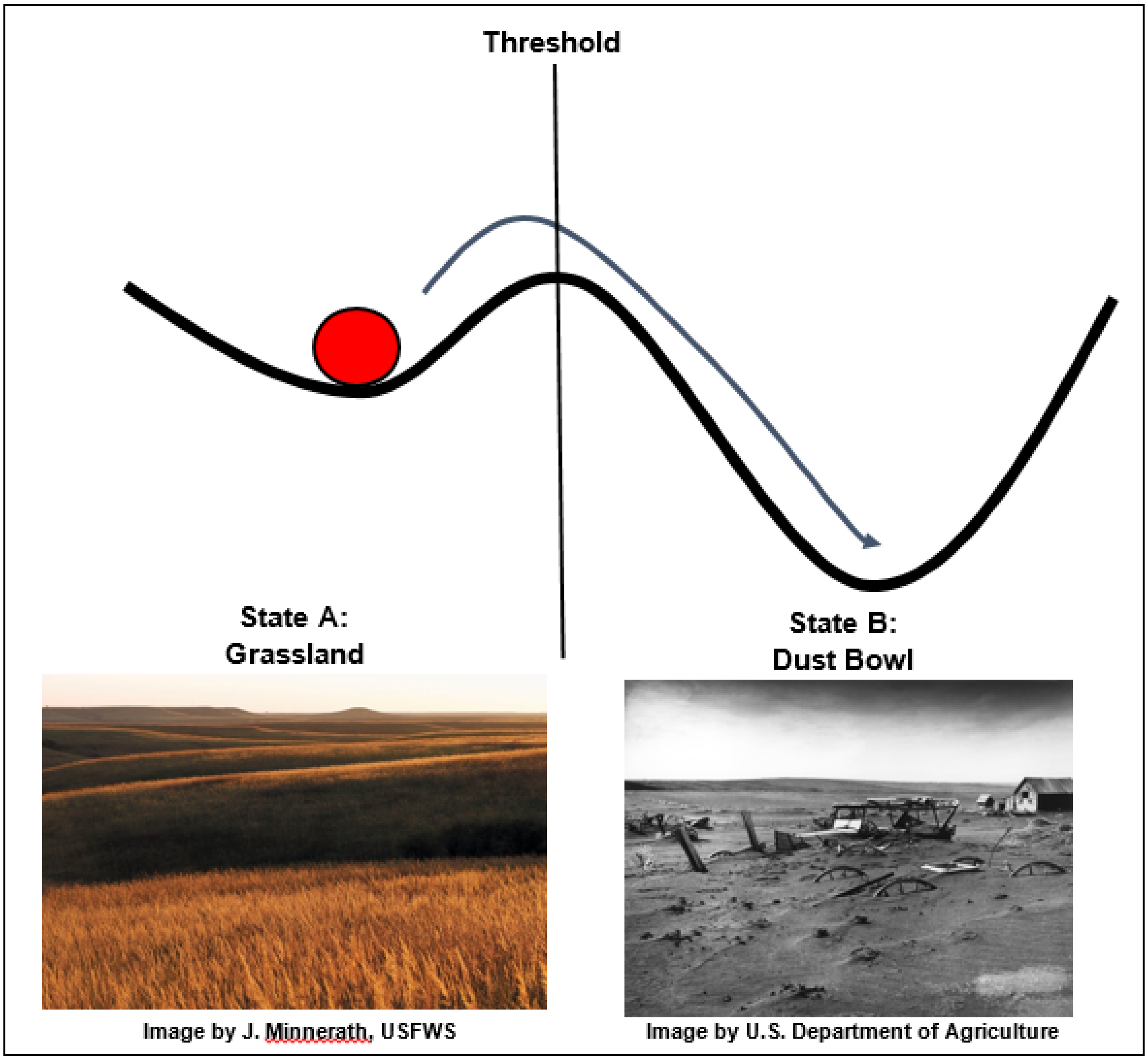
Figure 2 shows two examples of the ball-in-cup model as a grassland transitions to two possible alternative states.

Over half of the world's grassy ecosystems are considered "disturbance-dependent" ecosystems, in that they require disturbance to persist long term and will transition to a woody alternative state in the absence of disturbances (Bond et al. 2005). In the Great Plains, fire suppression and introduction of Juniperus propagules in grasslands has led to regime shifts from grassland to a Juniperus woodland alternative state (Twidwell et al. 2013).

Grassland resilience is supported by stabilizing feedbacks between herbaceous fuels, fuel continuity, and ignitions (Ratajczak et al. 2014). Continuous herbaceous fuels facilitate the spread of fire across grasslands that limit the distribution and abundance of Juniperus trees. Interruption of stabilizing feedbacks in grasslands reduces the resilience (i.e., shrinks the grassland cup in the ball-in-cup heuristic) of grasslands to Juniperus woodland regime shifts while supporting feedbacks that promote the Juniperus woodland state. For example, removing/suppressing ignitions, fragmenting herbaceous fuels, or reducing fuel loads can suppress stabilizing feedbacks in grasslands, increasing the likelihood of Juniperus establishment and further fragmentation and reduction of herbaceous fuels. Thus, high fire occurrence and intensity supports grassland resilience while low fire occurrence and intensity supports Juniperus woodland resilience (Fuhlendorf et al. 2008).



An example of a current **grassland state** with weak self-organizing feedbacks and low resilience (shallow cup), compared to an alternative **woodland state** with stronger self-organizing feedbacks (deeper cup).



An example of a current **grassland state** with weak self-organizing feedbacks and low resilience (shallow cup), compared to an alternative **eroded state** with stronger self-organizing feedbacks (deeper cup).

Figure 2. Examples of the ball-in-cup model in real world scenarios, the transition of a grassland ecosystem to a woodland ecosystem and the transition of a grassland ecosystem to an eroded ecosystem such as in the Dust Bowl. Figure created by Alison Ludwig.

Concept Use in Management - Lake Eutrophication

Studying the eutrophication of lakes provides a real-world example of a system's resilience being overcome and subsequently shifting to an alternative state (Scheffer et al. 2001; Wilkinson et al. 2018). Eutrophication occurs when increasing nutrient concentrations in a body of water cause a transition from a clear-water state to a turbid-water state with reduced water quality. Many shallow lakes have clear water and diverse underwater vegetation. Nutrients such as nitrogen and phosphorus enter the lake from various sources and atler stabilizing feedbacks in the clear-water lake (Wilkinson et al. 2018). If too many nutrients enter the lake, the resilience of the established regime can be overcome and the system suddenly flips from the clear, vegetated state to a cloudy, turbid state which kills off much of the underwater vegetation (Scheffer et al. 2001). In some cases, it can be very difficult to return to the previous clear state once eutrophication has occurred (Figure 3).

Figure 3. An example of two side-by-side lakes where one has transitioned to a turbid, cyanobacteria-dominated state (left) while the other remains in a clear-water state (right). Photo Credit: Dr. Stephen R. Carpenter (used with permission)

We can use the ball-in-cup model to help conceptualize this example. However, there is an alternative way to use this model (Figure 4). Up until now, we considered an example in which a disturbance moves the ball from one basin to another. This is easy to think about since we often view systems as static, unchanging, and at equilibrium until a disturbance shocks the system. But this is not the only way a system transitions to an alternative state; systems are dynamic and changing. Instead of disturbances that move the ball from one state to another, disturbances that alter the stabilizing feedbacks of an alternative state can change the shape of the cup itself (Beisner et al. 2003).

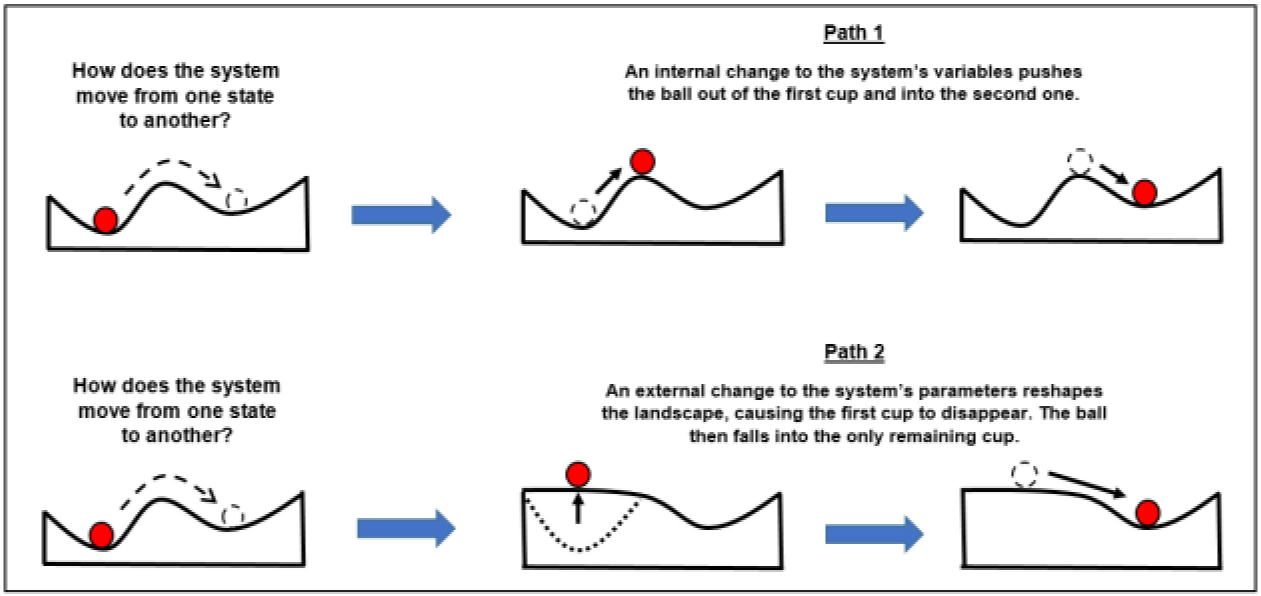


Figure 4. An alternative view of the ball-and-cup model in which changing system structures affects the movement of the ball. Adapted from Beisner et al. 2003.

Now let's reconsider the example of lake eutrophication (Figure 5). The lake starts in the first cup of the model, before nutrients have been added to the system and its water is clear. Over time, as more and more nutrients enter the system, the first cup starts to become shallower as the nutrients increase. Eventually, the cup becomes so shallow that the ball can easily be pushed to the other cup representing the turbid state; the resilience of the lake's clear-water state has been overcome and a transition to a turbid state becomes imminent. Although the switch may happen suddenly, it took a long time to reach that threshold in the first place. The lake's resilience allowed it to absorb the disturbance for quite a while until a threshold was crossed. After that, resilience was overcome and the lake quickly shifted to an alternative state.

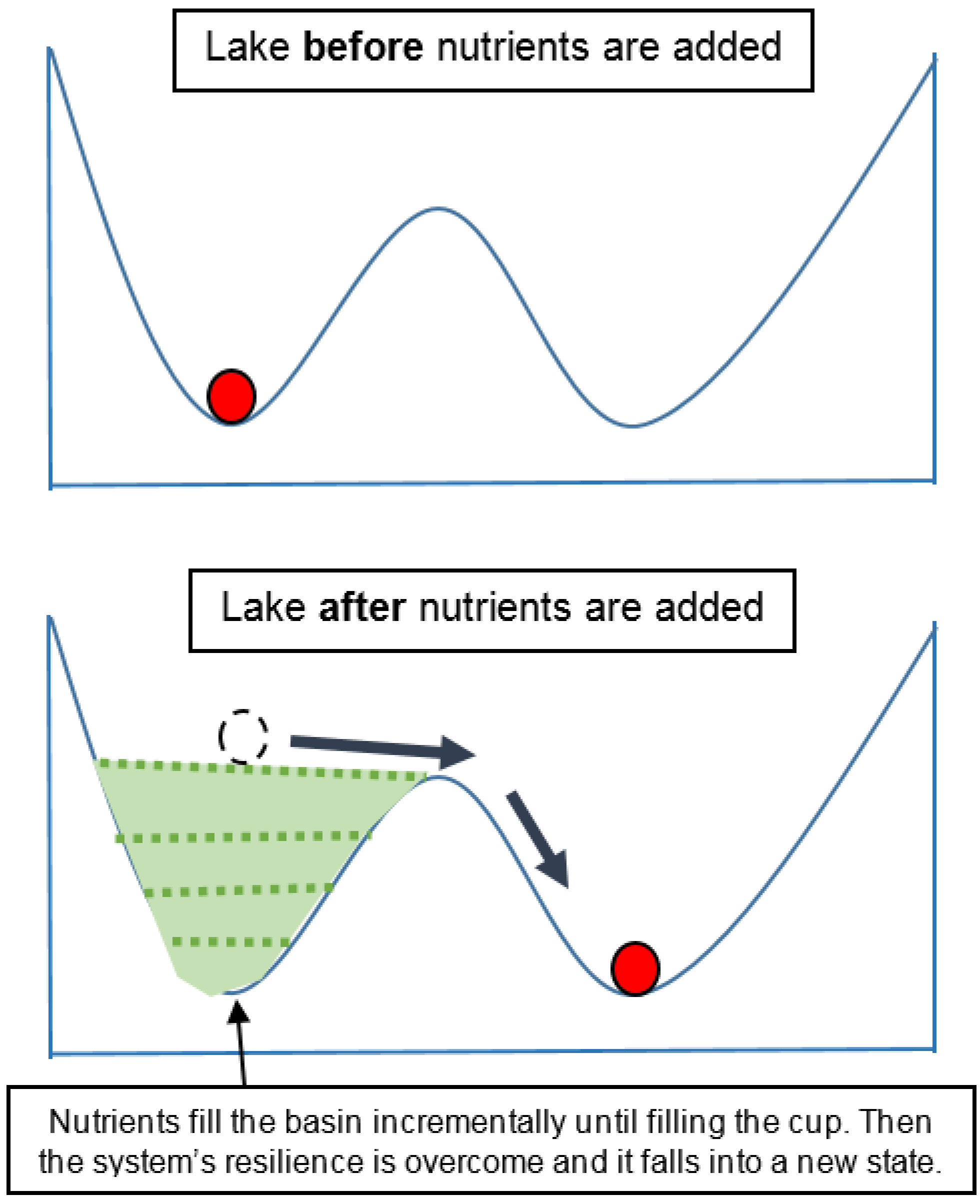


Figure 5. An example of a system's structures changing as more nutrients are added into the lake. Nutrients fill the basin incrementally until filling the cup. Then the system's resilience is overcome and it falls into a new state. Figure created by Alison Ludwig.

There are several methods to manage eutrophication and attempt to return a lake to a clear state. It is important to reduce the amount of nutrients entering the lake from outside the system (Sondergaard et al. 2001). Additionally, managers can add chemical compounds such as iron and alum to increase the lake's capacity to absorb nutrients, dredge the sediment to remove absorbed nutrients, or add algaecides to remove excess algae (Sondergaard et al. 2001; Moss 1990; Wilkinson et al. 2018). However, the eutrophic regime itself can have high resilience. Although some eutrophic lakes can be reversed to their previous state by a proportional reduction of nutrient content, other lakes exhibit hysteretic behavior, in which extreme reduction of nutrient levels must occur in order to return to the previous state (Carpenter et al. 1999, Scheffer et al. 2001). In these cases, a manager may need to reduce the nutrient load to a level far below what even the original clear lake had when the transition occurred (Figure 6). The concept of hysteresis is important to understand for those managing complex systems and will be covered in a subsequent module.

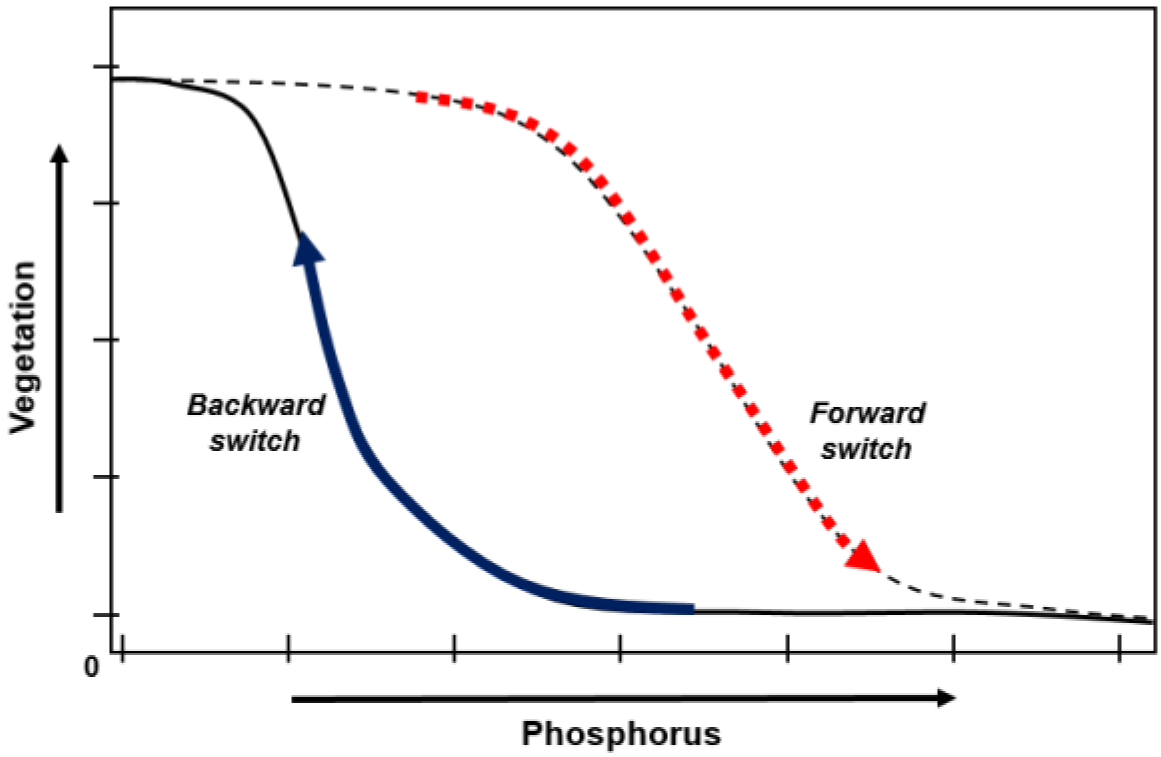


Figure 6. An example of a hysteretic curve. As phosphorus increases, vegetation decreases (dashed line). As phosphorus is removed from the lake, vegetation levels do not increase proportionally (solid line). Much more phosphorus must be removed in order to return to previous levels of vegetation. Adapted from Scheffer et al. 2001.

Example - Cities and Hurricanes

Cities and heavily-urbanized areas in the path of hurricanes can demonstrate two different forms of resilience. Hurricanes regularly flood urban areas with water, only for the urban areas to be rebuilt. In theory, urban areas are rebuilt after the disturbance of each hurricane to be better protected against powerful hurricanes, however that may not always be the case. Applying ecological resilience to hurricane management policy, we assume hurricanes to be a persistent, inevitable occurrence and design our cities and hurricane response plans accordingly. Unfortunately, hurricane damage has actually been exacerbated by the policy we have implemented from the mid-20th century to now. This policy is to build higher, stronger levees to keep floodwaters out and storm damage to a minimum.

New Orleans illustrates an overreliance on engineering solutions and the consequences of failing to apply resilience thinking. A hundred years ago, New Orleans was hit by a series of hurricanes, after which it decided to invest in structural upgrades to prevent future flooding (Colten and Giancarlo 2011). The structures' effectiveness was tested in the 1940s and though it did reduce damage to the city center, the suburbs that had grown beyond the seawall and levees were still heavily impacted by the storm. Post-storm analysis determined that although the suburbs could also be protected from heavy flooding through a more extensive levee system, other factors can play a role in mitigating storm damage. For example, one of the worst affected areas to the east of the city did not have any residential or commercial development and effectively functioned as a buffer. Traditional housing construction methods, which put houses up on raised tiers two or more feet above ground, also contributed to flood prevention (Colten and Giancarlo 2011).

The city nonetheless went all-in on levee construction while simultaneously expanding into low-lying wetlands and other flood-prone areas. With levees in place, housing construction switched to cheaper and more popular methods. City officials, confident that the new levees could withstand anything matching the force of previous hurricanes, largely discounted the threats posed by flooding. They have been repeatedly proven wrong, notably by the flooding done by Hurricanes Betsy, Camille, and Katrina (Figure 7).

Even as hurricanes struck and overcame the levees again and again, the philosophy of rebuilding stronger and better has remained. Instead of changing our tactics, we simply shift the baseline for protection upwards to the strongest hurricane in recent societal memory, only for that baseline to be overcome by future hurricanes.

This philosophy epitomizes engineering resilience, where the metric is how quickly the collapsed system can return, or "bounce back" to its prior state (Angeler and Allen 2016). In this example, a city "bounces back" when it is rebuilt to be the same as it was before the flooding. Although this is an example of "bounce back" resilience, there are downsides to this approach. The city has returned to the vulnerable state it was in pre-flood. Another weather event of sufficient severity would collapse the city once again. On the other hand, ecological resilience requires an understanding of the adaptive cycle as well as a holistic approach: how can policy, science, and engineering use the phases of collapse and reorganization to minimize the consequences of persistent, inevitable hurricanes? Ecological resilience can take other factors into account when protecting our cities from flooding, and can be the key to defending coastal cities from the increasing threats of climate change.

Figure 7: Photographs before and after Hurricane Katrina in Bay St. Louis, Mississippi show the destruction of the coastal structure on the border of the city, as well as massive damage to the city itself. Photo Credits: U.S. National Oceanic and Atmospheric Administration, available under the public domain

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Example – Resilience in Ancient Cities: The Eight-Year Siege of Constantinople

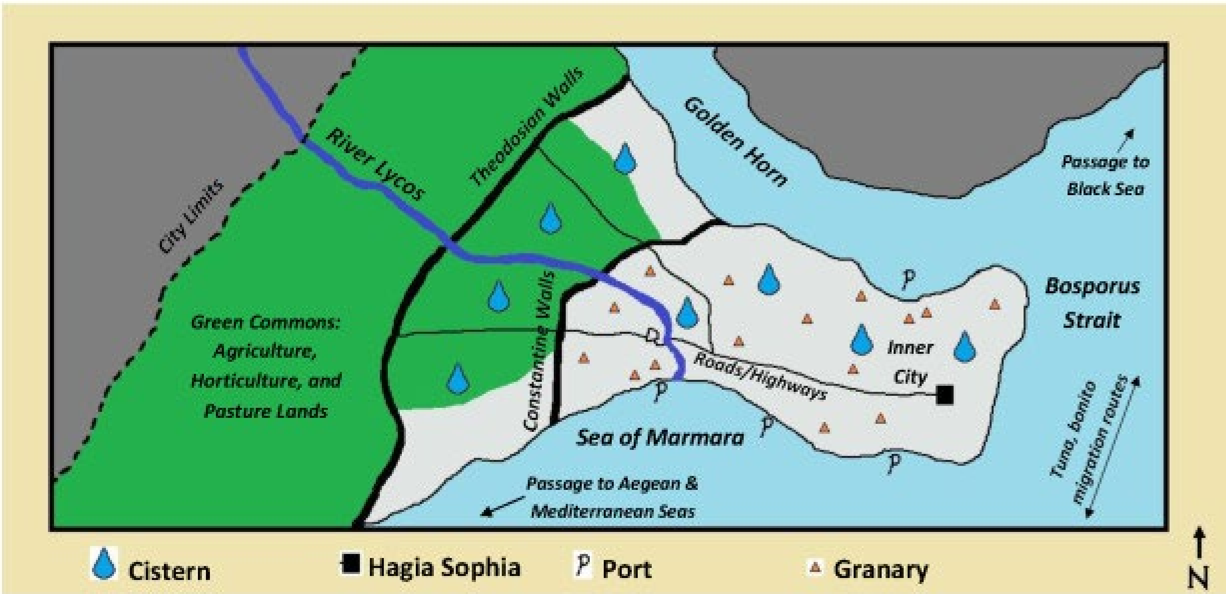

Figure 8: Map of Constantinople during the 8-year siege. Adapted from Barthel and Isendahl, 2013.

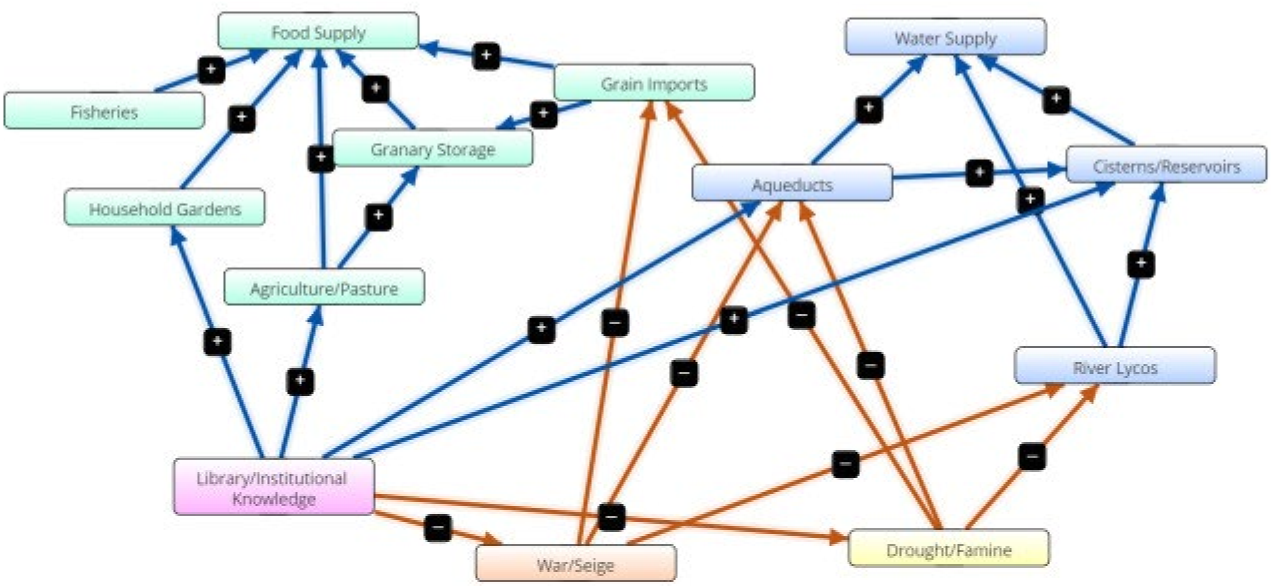

Figure 9: A concept map showing the resilience of Constantinople's food and water systems. War, siege, drought, and famine can negatively impact some—but not all—of the city's infrastructure. The protected infrastructure ensures the city's resilience. Institutional knowledge and library records give benefits to the food and water supplies and also reduce the impacts of war, siege, drought, and famine. Figure created by Alison Ludwig using Mental Modeler (Gray et al., 2013).

From 1394 to 1402 AD, the Turkish army led by Bayezid I besieged Constantinople, the capital of the Byzantine Empire. The city is strategically placed at one end of the Bosporus Strait, which connects the Black Sea and the Mediterranean (Figure 8). As such, it was of vital importance to the Byzantines. It had been besieged by many armies before then, including in the years 674-678, 714, 813, 1191, and 1204. The eight-year siege by Bayezid was the toughest test of the city's resilience up to that date.

Constantinople survived the siege by Bayezid, which ended in 1402. How can a city containing tens of thousands of people survive a blockade for eight years, cut off from the outside world and living only on what they can produce on their own? A city needs more than strong fortifications to survive such an ordeal. It must foster complex and resilient food systems and water storage, building diverse sources into the system to ensure that it does not fail (Figure 9). How many modern cities could survive for eight years if all outside food supplies were cut off? The persistence of Constantinople in the face of so great a challenge is a true testament to its resilience.

Lastly, no city can withstand a siege without fresh water. Although its supply lines were cut off, Constantinople survived for eight years. How did the people have enough water to drink and grow crops? The River Lycos runs through the city, but that river alone was not sufficient to provide for the city as it grew. Several major aqueducts were built over the centuries to bring in water from nearby mountains and augment the water supply. In addition, cisterns and reservoirs were constructed within the city's walls for long-term storage and protection of the water supply. During the eight-year siege, the city's water supply never ran out—proof of its resilient design.

Not only did Constantinople have a complex system of food production in place by the time of the eight-year siege, it retained institutional knowledge gained from centuries of learning. The city held a repository of historical records that documented the agronomical history of the region, including texts describing what crops to grow and how to grow them, information on the seasons and movements of celestial bodies, manuals for animal husbandry, and other resources. Access to such an extensive library of knowledge was a valuable addition to the resilience of the city, as it documented the historic highs and lows the city had experienced and the adaptations of the populace to outside pressures. This allowed the citizens to learn and adapt from past triumphs and failures.

First, many granaries were constructed throughout the city. Excess grain was stored in these granaries so that the city could rely on them in lean times or when supply lines were cut off. Second, utilization of nearby fishing grounds helped supplement the city's diet. Its close proximity to the Golden Horn—a prime fishery along the migration route of many species of nutritious fish such as tuna and bonito—meant that even poor townspeople could acquire high-quality sources of protein. Third, by increasing its control over agricultural lands and pasturage, Constantinople began to produce its own staples, such as wheat, instead of relying on distant suppliers. Vast tracts of land outside the mighty Constantine and Theodosian Walls were utilized over the years as pasture and farming fields. In addition, household gardens were widespread within the city and even the poorest citizens could grow some food by tending their own kitchen garden.

Although a prime target for invading armies, the city's persistence in repelling attackers helped to strengthen it, not weaken it. For example, grain imports from Egypt were a staple of Constantinople's diet. However, when supply lines were disturbed or cut off during times of war, drought, or famine, these imports were no longer reliable. Such disturbances occurred throughout the city's history. As a means of coping with such problems, the people of Constantinople devised multiple strategies to enhance food and water production.

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Example – Video Games: World of Warcraft

Figure 10: A screenshot of World of Warcraft gameplay. Blizzard Entertainment, 2020.

The online game World of Warcraft or WoW (Blizzard Entertainment 2020) started in 2004 and is one of the most popular games on the internet, with millions of subscribers (Ducheneaut et al. 2006, Bainbridge 2007, Braithwaite 2018) (Figure 10). Because of WoW's popularity, scientists globally use it to study topics ranging from social and behavioral sciences to economics and computer science (Bainbridge 2007), and its gameplay allows for a virtual example of ecological resilience concepts.

Early versions of WoW explicitly included resilience, where players had a character attribute called "Resilience", later changed to "PvP Resilience" (https://wow.gamepedia.com/PvP_Resilience). The resilience of a character is a measure of the amount of damage a character can withstand when under attack, i.e. how much total damage it takes to kill a character. Increasing this attribute reduces the amount of damage that a character can receive from another player. This parallels the concept of ecological resilience, where increasing a system's (character's) resilience increases its ability to absorb disturbances (e.g. enemy player attacks) and resist changing to an alternative state (e.g. character death).

If resilience can be measured and applied in video games, it can also be applied to complex, real-world problems.

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Summary - Why Is Resilience Important?

Ecological resilience, the ability of a system to maintain structure, function, and relationships while undergoing pressure to change, was introduced by C.S. Holling in 1973. It is a concept that focuses on how a system reacts to changes and disturbance. Research since Holling's foundational 1973 paper has applied resilience theory to many complex systems such as human societies, economies, cybersecurity, the human brain, and many more. Persistence and absorption are responses of a system faced with change. If a system can no longer absorb disturbance then it will shift to an alternative state with new structure, functions, and relationships. The ball-in-cup model can help us visualize a system undergoing change as its resilience is overcome and it transitions to a new regime. Concepts from ecological resilience give us the ability to characterize diverse, complex systems as dynamic, self-organizing systems that can absorb change or transition to an alternative state. In an era of global unprecedented change, concepts of ecological resilience are applied across the globe to maintain and conserve our life support systems provided by nature.

Quiz Questions

Question

Ecological resilience is the amount of disturbance an ecosystem can absorb before altering ________.

A. Self-organized processes and structures
B. Types of disturbance
C. Soil types
D. Hysteresis

Question

Ecological resilience originated by C.S. Holling is the idea that ________.

A. Ecosystems oscillate between healthy and unhealthy over time.
B. Ecosystems undergo sudden and discontinuous change following a disturbance that cannot be absorbed.
C. Ecosystems at their peak do not undergo long-term change since they can absorb disturbance and remain in optimal condition forever.
D. Ecosystems may undergo short-term change but will always return to their original state if left alone.

Question

From the ball-in-cup model, what are the two paths a system may take to change states?

A. Regimes 1 and 2 are the basins of attraction.
B. Thresholds and alternative stable states.
C. Internal change within the system and external change outside the system.
D. The way out is different from the way in.

Question

Ecological resilience can be applied to the management of ecosystems because ________.

A. There is a balance of nature.
B. Ecosystems are always predictable.
C. Ecosystems must be fully understood so that humans will not have any impacts on them.

D. It helps us understand the complexity and dynamics of self-organizing systems as they absorb change or change states.

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Glossary

Absorption

The capacity of a system to withstand disturbances without changing function.

Alternative Stable State

Alternative Stable State or 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.

Basin of Attraction

Part of the ball-in-cup model. Represents a stable state in which a system can exist. The system can move from one basin of attraction to another, which represents a system shifting from one state to another. See regime shift

Ecological Resilience

The capacity of an ecosystem 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”.

Ecosystem Services

Services and products that humans receive from ecosystems. For example, water filtration by wetlands, air purification by forests, food production by croplands, pollination by pollinators, etc.

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.

Persistence

The ability for components of a system to maintain relationships in the face of outside forces that cause change.

Perturbation

Perturbation (or 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

A state in which a system exists. Consider it as the status quo, which can be altered by forces that cause regime shifts.

Regime Shift

Regime Shift (or 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.

Threshold of Change

Threshold of Change (Tipping Point): The point at which a system shifts from one state to an alternative state.