



Tutorial 3: Understanding Socio-Environmental Systems- Thresholds, States, and Resilience

Learning Goals:

- Understand why S-E systems are **complex adaptive systems**.
- Be able to explain the following characteristics of S-E systems and why they are important to understand systems behavior:
 - **Feedback** structures and behavior in a system
 - **Nonlinearity** in systems behavior
 - Existence of alternative **states** or **regimes** in a system
 - Existence of **thresholds** in a system
 - Ability to **self-organize** and **adapt**
- Be able to define **resilience**
- Be able to identify and explain properties of resilient systems:
 - Redundancy
 - Diversity
 - Adaptive capacity

A critical component of understanding S-E systems is understanding the dynamics of the system, including interactions and feedbacks. While systems maps (or concept maps of systems) and other diagrams can help us understand and keep track of the connections between parts of systems, there are other useful ways of considering the complex behavior of systems.

Complex adaptive systems

Another useful way to think about the behavior of S-E systems comes from *Complexity Science*, which focuses on the study of **complex adaptive systems** (often referred to as *complex systems*). The study of complex adaptive systems (CAS) have revealed several characteristics that can help us understand behavior. Examples of such CASs include as are insect societies (ant colonies), the internet, and human immune systems, coral reefs, and other socio-environmental systems.

The word “complex” is familiar, so the meaning of a complex system seems intuitive: it is the opposite of simple. It is a system with many parts and interconnections. While this is true, there is much more to the meaning of *complex systems*:

A complex [adaptive] system is “a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution.” (Mitchell 2008)



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Some describe the **complex collective behavior** that are exhibited by complex adaptive systems as **emergent** behaviors or properties of complex systems. This definition also describes the **self-organizing** properties of complex adaptive systems: organized behavior that arises without a central controlling force.

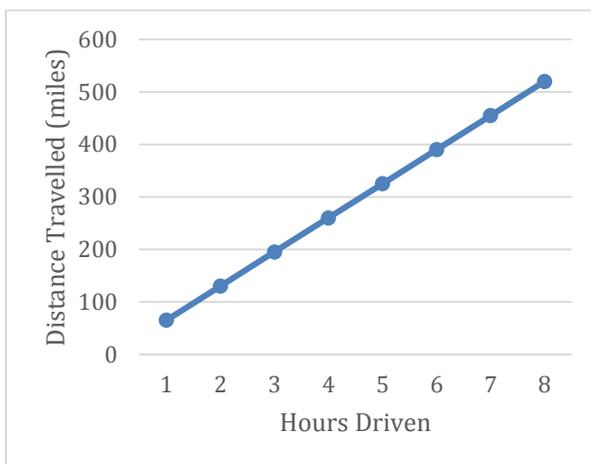
Others have characterized CASs as having the following features (Norberg and Cumming, 2008):

- Nonlinearity
- Feedbacks
- Thresholds
- The potential for alternative stable states
- Self-organization
- Ability to adapt via self-organization or learning

In the Tutorial 2, we discussed the feedbacks that are characteristic of S-E systems. Here, we describe the other features of CASs listed above.

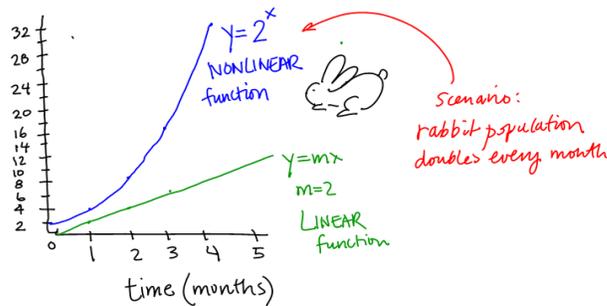
Nonlinearity

This might be summed up as “The whole is greater than the sum of its parts.” When we think of causal relationships, we often think about predictable, linear relationships. For example, if a car is travelling at 65 miles per hour, we can predict how many miles the car would have travelled after any number of hours, and a graph of this relationship would show a linear function as seen below.

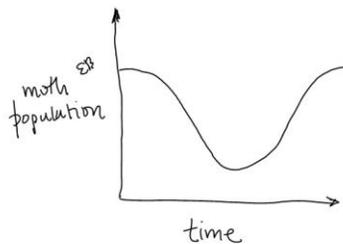


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A non-linear system does not change in linear, incremental, predictable ways. Nonlinear functions are common. For example, in the example of a rabbit population, population growth is nonlinear:



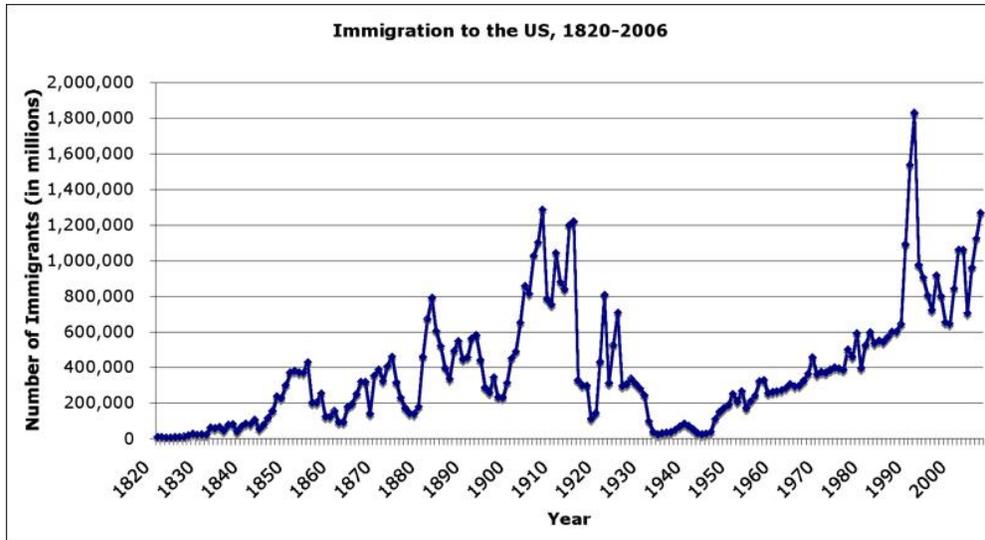
Other examples of nonlinear behavior include the pattern of moth population growth in cotton fields sprayed with pesticides. Initially, the population of moths decreases rapidly due to the application of the pesticides. However, as resistance to the pesticides developed in the moths, the population rebounds. Thus, the change in the moth population over time is nonlinear:



Another example of nonlinear patterns are immigration rates; the patterns here do not follow a predictable, linear path.



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Office of Immigration Statistics, US Department of Homeland Security 2006

As this example demonstrates, non-linear systems are often unpredictable. Furthermore, nonlinear behavior often leads to surprises.

Alternative Stable States and Thresholds

Another feature of complex adaptive systems and S-E systems is that they have the potential to exist in ***alternative stable states***, which are also referred to as ***regimes***. The state of a system is defined by the parts (or state variables) that constitute the system (e.g. in examples below, the sawgrass regime is characterized by the dominance of sawgrass in the ecosystem). A regime is a set of states that a system can exist in and still behave in the same way- still have the same identity (same function, structure, and feedbacks). Regimes in a natural sense refers to the characteristic behaviors of an ecosystem. Similarly, in a social context, regimes might be a mode of government.

State changes or regime shifts occur when S-E systems are pushed across a **threshold** from one state or regime to another, a change that is often surprising or unwelcome. When a system crosses a threshold to a new regime, the system has a different identity and the structure, function, and feedbacks of the system are no longer the same. Regime shifts or state changes can come in many forms as described in the following four examples:

Example: Regime Shift in the Great Barrier Reef

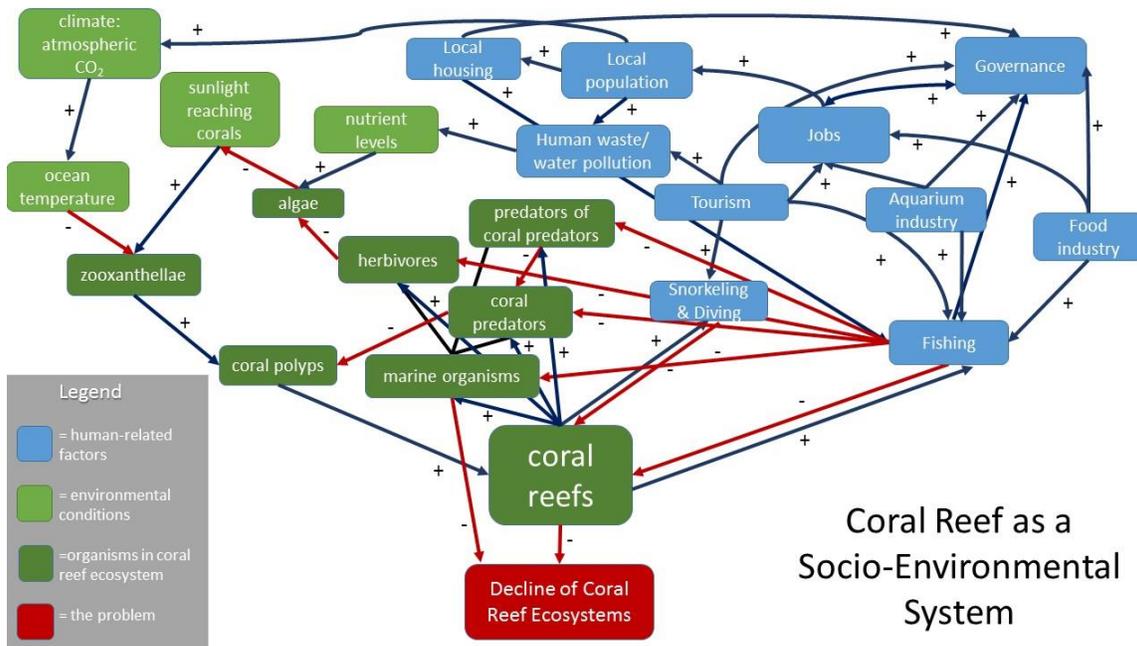
As discussed earlier, one of the major factors impacting coral reef health is ocean temperature. As temperatures in the ocean rise due to climate change, the range of



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temperatures where coral polyps can survive is exceeded and coral bleaching occurs. When that threshold is crossed for a certain amount of time, the zooxanthellae (symbiotic algae) in the polyps die and stop producing the essential nutrients needed by the coral. Thus, corals become bleached, and after some time, the corals also die. The duration and temperature threshold varies between coral polyp species, so the threshold has a range. But once this threshold is crossed, we see a regime shift from a healthy coral reef - full of marine life and benefits to humans- to a state of dead, bleached corals, an undesirable state that includes the loss of biodiversity and economic value. Sadly, several coral bleaching events have occurred in the Great Barrier Reef, and large portions of this system have shifted from a desirable regime- in this case coral reefs- to an undesirable one- bleached and possibly dead coral.

When corals die, the marine life in the coral reefs also disappear, and with that come significant changes to local communities and industries dependent on those reefs for food and livelihood. The feedbacks between the parts of the system are disrupted and the system no longer functions as it did. This shift in regimes is all the more problematic because it is one that cannot be reversed. More often than not, it is extremely difficult or impossible to return to the original state once a threshold has been crossed.





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Example: Regime Shift in the Florida Everglades

The iconic Florida Everglades are an internationally recognized natural treasure. These vast wetlands used to cover the vast majority of southern Florida. Nourished by fresh waters flowing from Lake Okeechobee, the Everglades ecosystem is a landscape of sawgrass, mangroves, orchids, periphyton (algae), and home to large populations of wading birds, alligators, panthers, and other iconic Florida wildlife. The Everglades are a place of subtle beauty “where wonders only whisper”¹.

The sawgrass that dominates this marshy landscape is the normal state of this socio-environmental system (sawgrass is the state variable or ecosystem component that defines the state). However, the northern section of the Everglades, the sawgrass community was replaced by invasive cattails. This shift from sawgrass to cattail regimes was caused primarily by nutrient enrichment in the wetlands: Sawgrass is adapted to the low nutrient environment that historically characterized the Everglades. However, in the northern part of the Everglades, agricultural run-off increased phosphorus levels in the soil in the 1960s and 70s. Cattails thrive when phosphorus levels are high, and soon they began outcompeting the sawgrass. The slow change in phosphorus levels moved the system across a threshold and caused the northern Everglades to shift from an ecosystem dominated by sawgrass, to one dominated by cattails.

Other changes followed. The habitat without the sawgrass was no longer suitable for wading birds to nest it, and as a result populations of several wading bird species declined significantly. Now, 90% of the bird populations have disappeared, and over a dozen native species of the Everglades are endangered, including manatees, wood storks, and Florida panthers. The structure, function, and feedbacks of the ecosystem are no longer the same in the cattail dominated system.

Example: Regime Shifts in Middle Eastern Governments

Regime shifts are not just ecological. In recent years, we’ve witness the Arab Spring, which resulted in shifts in political regimes across the Middle East. In many cases, stable governments were overthrown by populace protest and replaced by new governments, (e.g. Egypt, Tunisia, Libya, Yemen) while others have been plunged into civil war (e.g. Syria). While there are multiple causes of these regime shifts, political instability is often driven by a lack of water, food, and jobs. For example, in the years preceding the current crisis in Syria, four consecutive droughts forced over a million people to leave

¹ From the book “The Everglades: Where Wonders Only Whisper” by Bill Lea.



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home and plunged 2-3 million into extreme poverty. With these extreme conditions, a relatively small spark can trigger violence and unrest, and even regime change. As in Tunisia where the Arab Spring was sparked by when a street vendor set himself on fire in protest to the government, violence flared in Syria after an incident involving arrests of youths for writing political graffiti. In these examples, multiple drivers pushed the political regimes towards a threshold, and precipitating events pushed the regime over the threshold into a new state or regime, which is still being determined in several of these examples. As in ecological systems, once these thresholds have been crossed, returning to the original state is difficult or impossible.

While the consequences of regime shifts are often undesirable, this is not necessarily the case. Changes in governmental regimes can carry the hope of being better than the previous ones, and this is the hope embodied in the “Arab Spring” name. However, new regimes are often no better or even worse than the regimes they replaced. Furthermore, the process of regime change in governments often results in a tremendous toll of human suffering as recently seen in Syria.

Crossing the threshold

Given the often undesirable consequences of regime shifts, understanding what causes regime shifts is critical if we hope to prevent these changes in other similar systems or areas.

The question of what causes regime shifts is often a difficult one as there are often multiple processes that move a system towards the threshold. Furthermore, there may be multiple thresholds, and thresholds are most often not obvious and difficult to predict. More often, we discover where a threshold is in a system only after that threshold has been crossed. Thus, learning where the thresholds are in a system is a critical part of understanding the resilience of an S-E system and vital for developing solutions for managing the systems.

In the Great Barrier Reef example, we focused on one of the main drivers of regime change- rising ocean temperatures and coral bleaching. But as we discussed in the last lecture, there are multiple factors negatively impacting coral polyps, including human caused changes in water quality, which lead to algal blooms and decreased coral health. Thus, there are multiple processes driving the change in the state of the Great Barrier Reef and coral reefs around the world. However, not all processes have equal weight, and S-E systems are often controlled by a small subset of these factors, as illustrated in the examples just described.



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In the Everglades example, the shift from sawgrass communities to cattail communities was caused by multiple drivers. The change in phosphorus levels caused by agricultural run-off was a critical driver of change, but alone was not enough for the regime shift to occur. Natural events including fire, drought, and freeze- natural events that happen on different time scales- killed large portions of the dominant sawgrass community, which provided opportunity for the cattails to gain a foothold in the community. With the phosphorous rich environment, they quickly began to outcompete the remaining sawgrass. The balance had been tipped, slowly but surely.

Knowing that nutrient/phosphorus levels are a threshold between sawgrass and cattail regimes provides an opportunity for management of those nutrient levels in parts of the system that have not yet crossed that threshold (i.e. the southern part of the Everglades).

In the Arab Spring example, there were multiple drivers that caused the political instability leading to regime change. One major driver that has been hypothesized is drought, made more common and severe by climate change: extreme drought brings about water scarcity, food insecurity, and poverty, as seen in Syria. These factors combined with religious, political, and cultural tensions, create conditions ripe for violence and revolution. Here again, the threshold was difficult to predict, and the precipitating events that led to regime changes revealed these thresholds only after they had been crossed.

The process of regime shift can happen across different time scales. In the coral reef example, the time scale is on the order of days. In the Arab Spring, the process took months to years, and in the Everglades, the process was much slower- on the order of many years. This is because the processes that drive the changes in a system can work on *different scales across time and space*. This is an important point we'll return to later. Even for regime changes that are quick, the processes that factor into the change may be in motion long before the changes occur.

Resilience

We've just seen examples of how S-E systems have multiple states and how systems shift from one state to another when a threshold is crossed. But just how easy is it for a system to cross these thresholds and change regimes? This of course depends on the system and systems are dynamic and changing. The ability of a system to resist a change in regimes is called "**resilience**." A definition from the Resilience Alliance states that resilience is "the capacity of a system to absorb disturbance; to undergo change and still



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retain essentially the same function, structure, and feedbacks.” How far can you push a system before it stops being that system? The harder/further a system can be pushed before it crosses a threshold, the more resilient it is.

In chemistry, “buffering capacity” is the ability of a solution to absorb the addition of acids or bases without changing the pH of the solution. Similarly, resilience is like buffering capacity: it is the ability of the system to absorb disturbances without moving across a threshold into another state.

A more detailed definition of resilience (by Carpenter, Walker, Anderies, & Abel, 2001) includes 3 parts. Resilience consists of:

- 1) The amount of disturbance that a system can absorb while remaining within the same state
- 2) The degree to which the system is capable of self-organization
- 3) The degree to which the system can build and increase its capacity for learning and adaptation

Another definition of resilience is “the ability of the system to maintain its identity in the face of internal change and external perturbations” (Cumming & Collier, 2005)

In everyday usage, resilience carries a positive connotation. We want people to be resilient to the trials of life, and we want communities to be resilient to the impacts of climate change. But resilience does not necessarily imply a desired state- it refers to the ability to resist change, and in some circumstances, this is undesirable. For example, many corrupt governmental regimes may exhibit great degrees of resilience.

In many cases, we want to manage resilience to a specific disturbance that threatens the system. For example, we may want to manage phosphorus levels in the Everglades to increase the resiliency of the system against shifts to the cattail regime. In other instances, managing for resilience is meant more generally; rather than resilience of a particular aspect of a system to a specific factor, we often need to manage whole systems to be resilient to unknown disturbances and surprises.

A model for understanding resilience

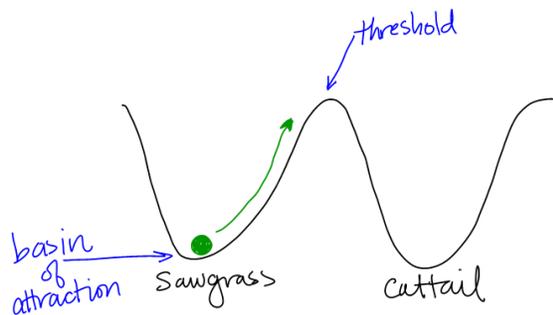
One common model for understanding resilience, thresholds, and regime shifts is the **Ball-in-a-Basin Model**. This model is a visual representation to help understand these rather abstract concepts. If you’re familiar with evolutionary biology, the model is similar to adaptive fitness landscapes.



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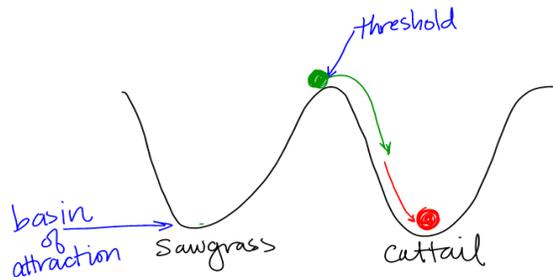
The Ball-in-a-Basin Model starts with the idea of “basins of attraction” for a regime. These are essentially the state towards which a system naturally gravitates within a regime. For example, people generally have a natural body weight towards which they tend. If you weigh more than your natural weight point, your body tends to do things to bring your weight back down. If you’re under that weight, your body tends to do things to bring your weight back up. There are of course ways to change this, but within the naturally self-organizing system of your body, this is how the system operates.

If we think about the example of the Everglades, there are two regimes and two “basins of attraction”; one we’ll label “sawgrass” and the other we’ll label “cattails”

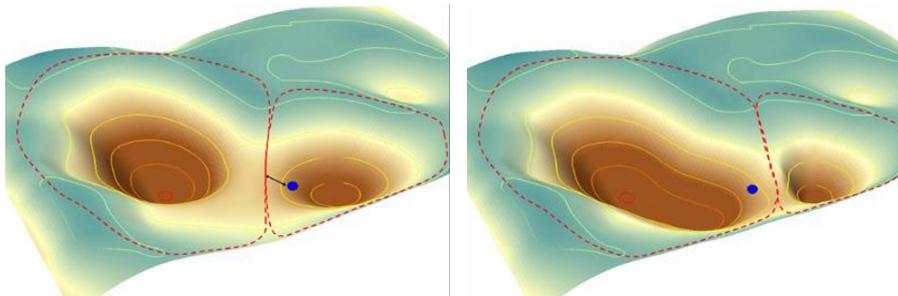


The Everglades have traditionally been in the “sawgrass” regime. However, a regime shift to the cattail regime can occur when the system experiences fire, flood and freezing, and rising phosphorus levels. This shift depicted in the diagram as a change in the slope or curvature between regimes. When the conditions favor a different regime, we characterize that in the diagram like this:

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Here is a 3-D model that provides a richer picture of how the “basin of attraction” can change as the conditions change. The ball in the picture is the state of the S-E system. [insert diagram from (Walker & Salt, 2006)].



Loss of Resilience in the Florida Everglades: A Case Study

Once a vast ecosystem teeming with wading birds and iconic wildlife, half of the Everglades are gone, and the other half is now on life support. This World Heritage site is now the focus of the largest environmental restoration project ever attempted, the Comprehensive Everglades Restoration Plan, a \$7.8 billion project funded by the US government and passed through a bi-partisan bill in Congress in 2000. This is testament to the importance of the Everglades region, and evidence of the tightly coupled interactions between the natural and social systems of the Everglades.

Despite its quiet beauty, the Everglades were once a scorned landscape, derided as worthless in its swampy state. But beneath the swamp is black gold: rich soil that is good for agriculture. In the early 1900s, as southern Florida began to grow in population, locals decided to drain the swamp and convert the area to farmland. This resulted in an

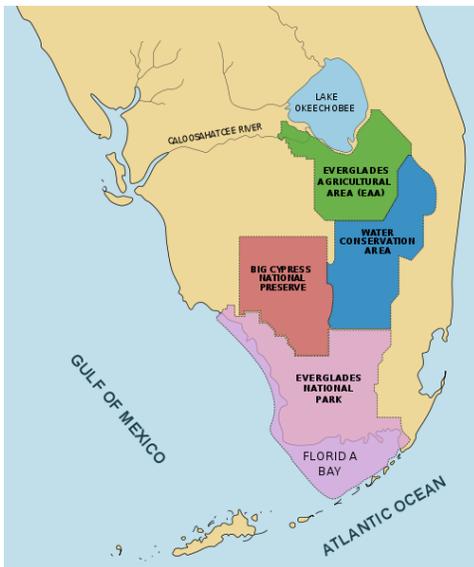


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agricultural region just south of Lake Okeechobee, which is the source of the agricultural run-off and phosphorus that has caused the shift to a cattail regime in the northern Everglades. It also resulted in reduced water flows into the southern Everglades.

As farming established in the Everglades agricultural area, and as the population of southern Florida began to grow, people demanded greater control of water into that region. The result of these demands was the building of a dike around Lake Okeechobee.

Where Lake Okeechobee used to provide an outlet for water overflow during storms and hurricanes, the dike now held that water. In 1926, one of the most devastating hurricanes in US history caused the dike on Lake Okeechobee to burst, killing over 2500 people (an event that inspired the novel, "Their Eyes Were Watching God.")



The response to this tragedy was build a bigger and better dike: The Hoover Dam. The dike was welcomed by the US Sugar industry, which took hold in southern Florida. However, the Hoover Dam prevented water from Lake Okeechobee from flowing into the Everglades, and the results were dry wetlands and droughts. A million acres burned each year, and with the life-giving water supply dwindling, wildlife in the Everglades suffered and began to disappear. These fires, combined with the phosphorus levels, are what enabled the cattail regime change in the northern Everglades.

Recognizing the peril that the Everglades were in, some federal scientists and environmental activities began to take action. Scientists from the USGS and USDA began providing critical information about the state of the Everglades, including estimates of



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how much water was needed to protect the water supply, data suggesting that the soil under the lower Everglades was not profitable for agriculture, and data on how many Everglades species were endangered. Other activists began to push for plans to establish the Everglades National Park, which finally became a reality in 1947, 24 years after the idea was first proposed.

Now, with water from Lake Okeechobee cut off from the lower Everglades by the Hoover Dike and the Tamiami trail, which cuts across the northern border of Everglades National Park, there is little hope of restoring the Everglades to its original state. Rather, the focus is on adapting water flows to maintain what is left of the Everglades.

Over the period of several decades and as the result of many interactions with the human communities that began to develop and thrive in southern Florida, the Everglades have been losing their resilience bit by bit.

What makes a system resilient?

If we define resilience as the ability to bounce back after a disturbance, what makes a system more springy, more elastic?

Looking at the definition presented earlier (Carpenter et al. 2001), what makes a system able to absorb disturbances, self-organize, and build capacity for learning and adaptation? What increases its **adaptive capacity**²?

There is no simple answer for this, and understanding what creates resiliency in an S-E system is the subject of intense research.

One characteristic of resilient systems is that they have many **feedback loops** that help to restore a system after a disturbance (Meadows 2008). Instead of one single feedback loop restoring a stock, a resilient system has many loops operating with different

² The concept of resilience overlaps with the concept of **adaptive capacity**, but the difference between these two terms is not very clear. Some use the terms interchangeably, while others consider adaptive capacity as a component of resilience that reflects the learning aspect of a systems behavior in response to a disturbance, Others define it as the ability of humans in an S-E system to manage resilience or as robustness to changes in system resilience (Gallopín, 2006)



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mechanisms across different time scales. Understanding these feedback loops that keep a system functioning is the key to understanding resilience.

Another characteristic is **redundancy**. If one of the feedback loops fails, there are other ways to restore the system. Interestingly, resilience is often lost when people- or organizations- eliminate redundancy in a push to increase efficiency or productivity.

Example of redundancy: pollination

For example, honeybees have been bred and cultivated to pollinate many crops (i.e. almonds, apples, cherries, broccoli, peaches, cranberries, melons, etc.). They are so good at pollination that they are relied upon to pollinate approximately 14.6 billion dollars worth of agricultural produce. However, honeybee populations have been declining under the threat of colony collapse disorder, and the agricultural system that is reliant on the honeybees' pollination services is also threatened. In the drive to maximize the efficiency of this system, honeybee management practices have increased stress on honeybee colonies and weakened their health, thus contributing to the problem of colony collapse. Agricultural producers are now paying attention to the idea of redundancy- they are asking now: what other ways can these crops be pollinated? They are now looking to ways to encourage native bees to fill some of the gaps in the system that the disappearing honeybees have left behind.

This system of honeybee-pollinated crop production would be more resilient if there were greater pollinator **diversity**. There are many other familiar situations where **diversity** is important for resilience. For example, investors are encouraged to diversify their stock portfolios in order to minimize risk: if certain stocks are not doing well, you have not put all your eggs in one basket, and the other stocks you have in your portfolio may function in helping you achieve your goal of increasing the overall value of your investments. In stock and flow terms, diversity increases the number of ways that you can influence the flow of a stock.

Self-organization in systems

Diversity is also critical for a system's ability to **self-organize**. Let's go back to the second part of the Carpenter definition of resilience:

Resilience consists of:

- 1) The amount of disturbance that a system can absorb while remaining within the same state
- 2) *The degree to which the system is capable of self-organization*



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- 3) The degree to which the system can build and increase its capacity for learning and adaptation

Previously, we mentioned that **self-organization** was a characteristic of complex adaptive systems, and that it is behavior organized without a central controlling force. We see examples of self-organization everywhere: snowflakes, our bodies, ant colonies, grassroots community groups, etc. Self-organization allows a system to change itself- sometimes by adding feedback loops, new rules, or structures. In biology, we see this in evolution. In societies, we see this in revolution. Self-organization also creates unpredictability and surprises, and requires freedom and experimentation.

It is this ability to change that makes self-organization an important component of resilience in a system:

“The ability to self-organize is the strongest form of system resilience.”
(Meadows, 2008)

Diversity is critical for self-organization as it provides more options for a system to change. Thinking from a biological context, evolution drives change by acting on variants. If all organisms were exactly the same, evolution would not occur; it is the variation created by changes in DNA that provide opportunities for change. This is true generally: having diversity in the system- whether it is diversity in knowledge, ideas, culture, structures, or rules- provides a system with more opportunities to change and adapt. And in an environment that changes, the ability to adapt is critical.

For example, think about agricultural systems. Modern agriculture has moved towards high productivity and efficiency such that farmers focus on a few crops, like corn. The agricultural system encourages monoculture. However, when there is a major disturbance to the system, such as a pest outbreak that affects corn production, farmers may have a hard time recovering because so much of their resources are devoted to corn production. The system hasn't provided much in the way of alternatives. A more resilient agricultural system would incorporate more diversity; if a farmer plants several different crops, he/she can more easily shift their resources towards the production of the non-corn crops and lessen the impacts of a problem with corn production.



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References

- Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? *Ecosystems*, 4(8), 765–781.
doi:10.1007/s10021-001-0045-9
- Cumming, G. S., & Collier, J. (2005). Change and Identity in Complex Systems, 10(1).
- Gallopín, G. C. (2006). Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change*, 16(3), 293–303.
doi:10.1016/j.gloenvcha.2006.02.004
- Grunwald, M. (2006). *The Swamp*. New York: Simon and Schuster.
- Meadows, D. (2008). *Thinking in Systems*. White River Junction, Vermont: Chelsea Green Publishing.
- Norberg, J. and Cumming, G.S. (2008). *Complexity Theory for a Sustainable Future*. New York: Columbia University Press.
- Walker, B., & Salt, D. (2006). *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Washington DC: Island Press.



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