What is a Complex Adaptive System?

Introduction

During the last three decades a leap has been made from the application of computing to help scientists 'do' science to the integration of computer science concepts, tools and theorems into the very fabric of science. The modeling of complex adaptive systems (CAS) is an example of such an integration of computer science into the very fabric of science; models of complex systems are used to understand, predict and prevent the most daunting problems we face today; issues such as climate change, loss of biodiversity, energy consumption and virulent disease affect us all. The study of complex adaptive systems, has come to be seen as a scientific frontier, and an increasing ability to interact systematically with highly complex systems that transcend separate disciplines will have a profound affect on future science, engineering and industry as well as in the management of our planet's resources (Emmott et al., 2006).

The name itself, "complex adaptive systems" conjures up images of complicated ideas that might be too difficult for a novice to understand. Instead, the study of CAS does exactly the opposite; it creates a unified method of studying disparate systems that elucidates the processes by which they operate.

A complex system is simply a system in which many independent elements or agents interact, leading to emergent outcomes that are often difficult (or impossible) to predict simply by looking at the individual interactions. The "complex" part of CAS refers in fact to the vast interconnectedness of these systems. Using the principles of CAS to study these topics as related disciplines that can be better understood through the application of models, rather than a disparate collection of facts can strengthen learners' understanding of these topics and prepare them to understand other systems by applying similar methods of analysis (Emmott et al., 2006).

About Complex Systems

What are Complex systems ?
(a.k.a. Complex Dynamic Systems or Complex Adaptive systems)

Complex = difficult-to-understand or difficult to predict
Dynamic = moving, changing
Adaptive = changing to adapt to an environment or condition

Complex systems are collections of simple units or agents interacting in a system. A complex system is a large-scale system whose behaviors may change, evolve, or adapt.

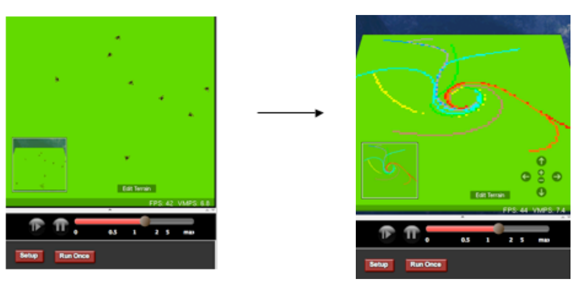
Some examples through activities:

1. Turn and Walk (10 minutes)

In this simulation, participants are asked to stand in a circle. They are told that they are "agents" in a simulation. As agents they will have a very specific set of instructions that they will follow. First, they will turn to face the person directly to the right. Second, they are to remain pointing in that direction as they take three steps forward. This set of instructions will be repeated each time the instructor says "go".
Discuss what the outcome might be. Next, try out the instructions.

Discuss what happened. What did you observe?
What would happen if the instructions were changed to 5 steps
Discuss what would happen if they started off in a different arrangement.





Some more examples through activities:

2. Swords and Shields (20 minutes)
In this simulation, participants are asked to select one person to be their "sword" and a different person to be their "shield". They are told that their objective is to always have their shield between them and their sword (thus protecting them from the sword.)

When I say "go", use your "Shield" to protect you from the "Sword." In other words, you must keep the person who is your "Shield" between you and your "Sword"

Ask for predictions on what might happen.
Try out the instructions. Discuss what happened and why.

Discussion

Discuss characteristics of complex systems:
1) Patterns emerge from simple interactions of its agents
What patterns emerged in the previous simulations?
2) There is no central control – it is a decentralized system
How is this seen in the previous simulations.
What would centralized control look like?
3) The system self-organizes – it spontaneously generates a well-defined entity by self-assembling from individual components.

In the simulations we just took part in, what patterns emerged? Ask for an example of each characteristic from the simulations, ask for an example in nature… What are some other examples of complex systems?

Some examples of Complex systems:
Global climate patterns, termite mounds, highway traffic patterns, the spread of a disease in a population, the internet, the evolution of ideas in a society, and a food web in an ecosystem.

References

Towards 2020 Science, Microsoft Research

Colella, V., Klopfer, E., & Resnick, M. (2001). *Adventures in modeling: Exploring complex, dynamic systems with StarLogo*. New York: Teachers College Press.

Characteristics of Complex Adaptive Systems

Complex Adaptive Systems

- A complex adaptive system is a system made up of many individual parts or agents.
- The individual parts, or agents, in a complex adaptive system follow simple rules.
- There is no leader or individual who is coordinating the action of others.
- Through the interactions of the agents emergent patterns are generated.
- If elements of the system are altered, the system adapts or reacts.

Definitions:

Leaderless –

- Without a leader.

Emergent patterns -

- Patterns that form even though the agents were not "directed" to make a pattern.

Non-linear -

- System level data as seen in graphs and plots are not linear (do not form straight lines). Often feedback loops cause systems to display non-linearity.

Self-organizing –

- A system in which a pattern emerges as a result of the agents following simple rules without external control or a leader is called a "self-organizing" system.

Feedback loop –

- A closed system that contains a circular process in which the system's output is returned or "fed back" to the system as input.

Adaptive –

- Reacts to changes.

Chaotic behavior of a system –

- Small changes in initial conditions can generate large changes in the system's outcome.

Stochastic -

- Governed by chance. The behavior of a complex adaptive system can be inherently stochastic as elements of the system, the agents, can have randomness in their movement, and thus, in their interactions.

Feedback Loops

Background

Feedback loops are an important feature of complex adaptive systems. Examples of feedback can be found in most complex systems in biology, physics, economics, social systems, and engineering. In some cases, the interaction of individual agents can create feedback loops drive the emergence of patterns at the global level.

Definitions:

Feedback is a circular process in which a system's output is returned or "fed back" into the system as input. There are two kinds of feedback: **reinforcing** (or positive) and **balancing** (or negative).

A feedback loop is a closed system that has feedback. Often, when talking about feedback in layman's terms, we use the words "positive" and "negative" to describe how we feel about an outcome, or to describe whether or not a certain outcome is desirable or not. For example, people say "my boss gave me positive feedback on a new idea". **This is not to be confused with the technical terms "positive feedback" and "negative feedback".**

In the technical definition, reinforcing or positive feedback is feedback that amplifies or accelerates a change away from a starting point or equilibrium point whereas balancing or negative feedback is feedback that dampens, slows down or corrects a change in a system that is moving away from the starting point.

Here's one way to remember it:

In reinforcing (or positive) feedback loops
"More leads to more" OR "Less leads to less"

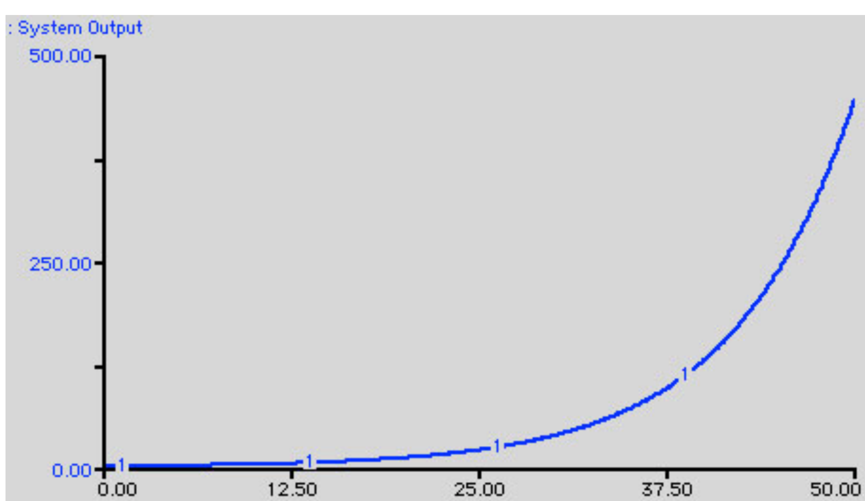
In balancing (or negative) feedback loops
"More leads to less" OR "Less leads to more"

Some concrete examples:

Let's look at some concrete examples with simple systems comprised of two parts.

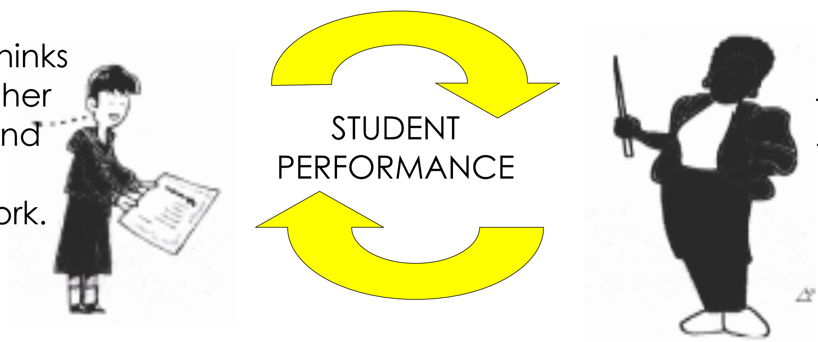
Example 1:
A classic example of feedback is audio feedback. In this system there are two parts: a speaker and a microphone. What happens when we close the loop by turning the speaker and the microphone so they are aimed at each other? The microphone takes in some sound and sends it out louder through the speaker. Then that sound goes back in again, comes out louder, then back in again and before you know it you have a loop, a vicious circle, producing a high-pitched screeEEEEch!

This is an example of positive feedback (though we may think of the outcome as negative to our ears!) Luckily, eventually one of the mechanical parts will fail which breaks the loop. In this example "more (louder sound) leads to more (louder sound)". A graph of the amplitude of the sound might look like this.



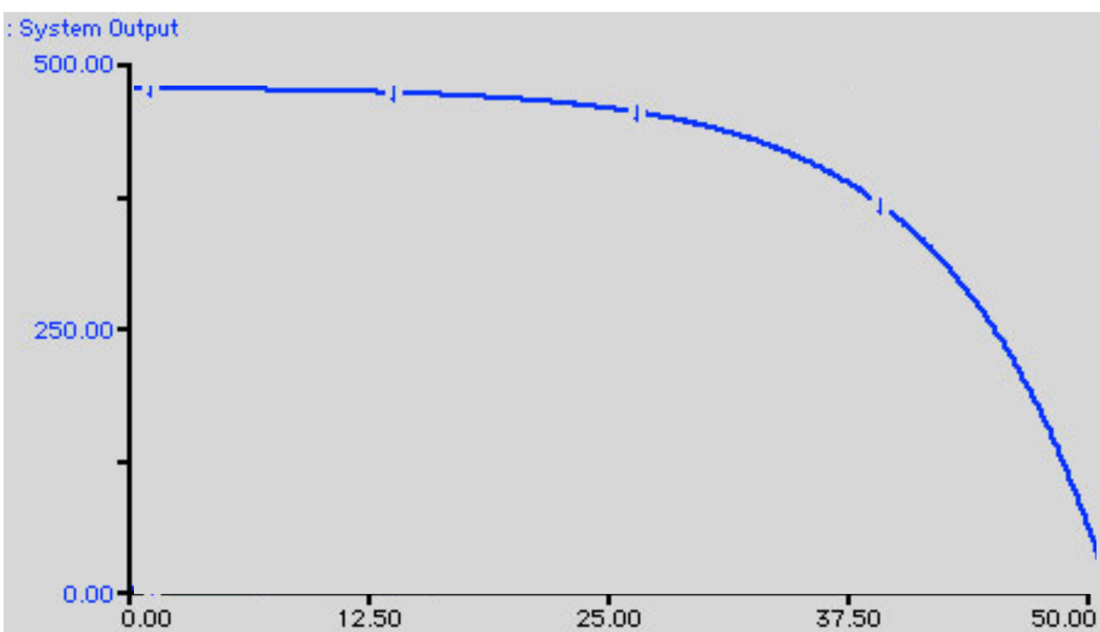
Example 2:
Here's another example, a system made up of a teacher and a student. In this hypothetical situation, let's say the student turns in some sloppy work. The teacher takes a look at the work and gives the student a bad grade. In response, the student thinks poorly of him/herself and puts in even less effort on the next assignment. Is this an example of "positive" or "negative" feedback? Remember that in reinforcing (or positive) feedback loops "More leads to more" OR "Less leads to less" while in balancing (or negative) feedback loops "More leads to less" OR "Less leads to more".

Student thinks poorly of her abilities and turns in sloppy work.



Teacher gives the student a poor grade.

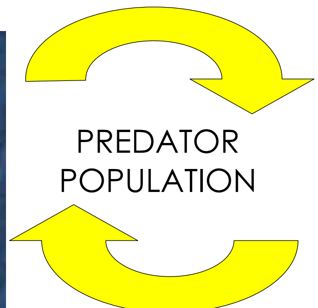
Even though the outcome is perceived as negative - the student is in a downward spiral, by definition, the feedback loop is a "**positive**" or self-reinforcing feedback loop. A graph of the student's performance might look like this. In this scenario "less (academic success) leads to less (academic success)"



Example 3:
Let's look at a simple ecosystem with two populations: predators and prey. As the population of predators increases, the population of prey usually decreases as the predators eat more of the prey. But, at some point, the prey get scarce and some predators die of hunger. When most of the predators have died off (and a few wily prey remain) then the prey population can regenerate over time. When the prey population booms, plenty of food becomes available for the remaining predators and they thrive and reproduce. This cycle of predator and prey population variation repeats over time.

Increase in predators leads to decrease in prey.

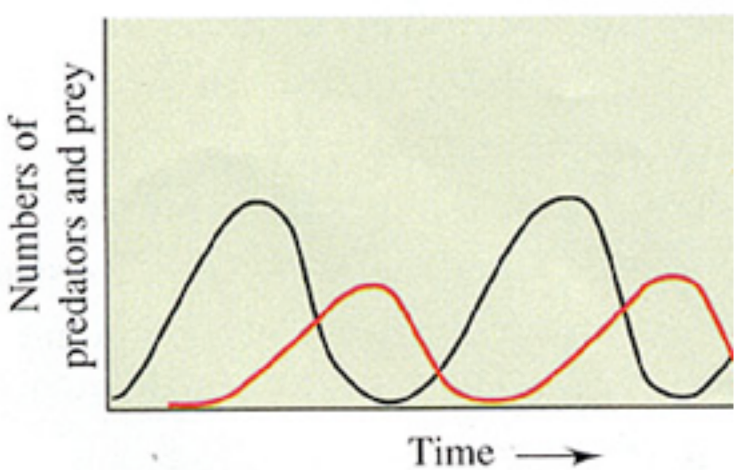
Increase in prey leads to increase in predators.



Decrease in prey leads to decrease in predators.

Decrease in predators leads to increase in prey.

This is a classic example of "balancing" or "negative" feedback. The population of prey acts as a balancing force against the exponential growth (positive feedback) that could occur if the wolf population grew unchecked. (and visa versa.) Generally negative feedback works to re-establish equilibrium or balance in systems. In this example we see "More (predators) lead to less (prey)" and "less (predators) lead to more (prey)."



Here are some examples to discuss. Are they examples of positive or negative feedback?

Nuclear fission
Thermostat
The Swords and Shields activity
Termite forming mounds

In the real world, positive feedback loops are controlled eventually by negative feedback of some sort; a microphone will break or a resource limitation will cap runaway growth. Resource limitation may also serve to dampen a runaway positive feedback process.   A variety of negative feedback controls can be used to modulate the effect of a positive feedback loop.

Ecosystems as Complex Systems

Background

Every living organism is complicated, impressive – and sometimes confusing – in its own way. A scientist may spend his or her entire career (and build on the work of countless scientists that went before) in learning as much as possible about how one type of organism functions. This problem only becomes more challenging when we look at the relationships between multiple organisms, or between an organisms and its environment. Fortunately, we usually don't need to know all of the details about the internal functions of an organism, to observe and begin to understand its interaction with other organisms and its environment.

When we talk about a specific area, all of the organisms in that area, and the environment of that area in which the organisms live, we are talking about that area's *ecosystem*. In practice, even a very small area may contain so many different kinds of organisms, and variations in the details of the environment, that trying to understand the entire ecosystem of the area is practically impossible. So we usually focus on a relatively small number of organisms (which may still seem very large, at first glance), and the key environmental factors that most affect that subset of organisms. However, even with a few organisms, there may be complex interactions between them, and rich areas for exploration and experimentation.

Goals for Student Learning

The primary goal of this unit is to engage students in the use of simple interactive activities to explore ecosystems concepts, and in the use and creation of agent-based models to conduct experiments on simple ecosystems.

Interactions Define Complex Ecosystems

If there were no interaction at all between organisms, then each organism would live in its own ecosystem. There would be no need to study them together, since doing so would not improve our understanding of the individual organisms, or of the whole. But in fact, even when organisms don't interact directly, they do so indirectly. For example, all biological organisms take up some amount of space. All organisms take in nourishment from their surroundings, reducing the amount available to other organisms of the same type – and possibly other types, as well. All organisms excrete waste products, that modify the environment of the ecosystem. Organisms may modify the environment in other ways as well – adding heat to it, for example. All of these, and more, result in indirect interaction between organisms.

Besides indirect interaction (including some types of competition), most organisms have some direct interaction with other organisms as well. But whether direct or indirect, these interactions allow changes which might at first seem to affect only a single type of organism to ripple through the organisms and environment of an ecosystem, to affect many others types of organisms.

Primary Interactions

Predation

Predation occurs when one organism (the *predator*) feeds on another (the *prey*), ultimately reducing the population of the second (though that may not be an immediate effect), and increasing the likelihood of survival of the first.

There are a number of different kinds of *predation*; one way of classifying them is to look at whether the prey is always killed, and how closely (and for how long) the predator and prey interact.

When the predator kills and eats the prey, the interaction is sometimes called *true predation*. This is generally observed between carnivores and their prey, where the prey is either killed before being consumed (partially or completely), or dies after being ingested by the predator.

But most herbivores (for example) eat their food sources without necessarily killing them; this is called *grazing*. For example, while excessive grazing by livestock may eventually kill the grass it feeds on, more often the livestock eats a portion of the grass and moves on, allowing the grass to grow back.

Finally there interactions where the prey must generally stay alive for a much longer time for the predator to benefit, and where the predator and prey generally have to stay in close proximity for that time; this type of interaction is called *parasitism*, and the predator and prey are generally referred to as the *parasite* and the *host*, respectively. Parasitism is sometimes considered to be a form of *symbiosis* (see below), but it is usually distinguished by the interaction being ultimately detrimental to the host – even if it doesn't always lead to the death of the host. In fact, some parasites that live on or in the host organism cannot survive for very long after the host dies.

Or course, there are many types of predation which don't fit neatly into simply one of the above categories. For example, does a mosquito graze? Or is it a parasite, even though it moves from one animal to another?

Competition
When the presence of one organism reduces the likelihood of survival or reproduction of another, the interaction is called *competition*. Competition can be direct, where aggression by one organism reduces the other's access to mating partners, food, or other resources. This is called *interference competition*.

The interaction can also be indirect. One form of this is *exploitation competition*, where the two organisms consume the same resource(s) from the environment. In that case, since no resource is unlimited, consumption of that resource by one organism decreases (even if only for a short time) it availability for consumption by another organism in the vicinity.

Another interesting form of indirect competition, called *apparent competition*, is not manifest through consumption of a shared resource.
Instead, two organisms may have a common predator. The effects of this type of competition are not always obvious in advance. For example, an increase in the rabbit population might lead to an increase in the number of coyotes in the vicinity, which may then decrease the number of prairie dogs.

Symbiosis

Taken literally, *symbiosis* simply means "living together"; from a biological perspective, it is used to describe a long-term interaction between different species. In that sense, it includes parasitism (described above). However, it is most commonly used to refer to the phenomenon more descriptively called *mutualistic symbiosis*, or *mutualism*. In mutualistic symbiosis, the long-term interaction of two different organisms increases the likelihood of survival and/or reproduction of both organisms. Another common form of symbiosis is one where one organism benefits, and the other is not significantly impacted (positively or negatively); this is called *commensal* symbiosis.

Intra-species Interaction

When talking about interactions in ecosystems, we are usually talking about interactions between species. However, sometimes the interaction between members of the same species is also important to examine. One clear intra-species interaction is competition: members of virtually any species compete with other members of the same species. For example, predation by one species (for example) produces competitive pressure within the prey species: those who are better able to elude or otherwise resist the predator are more likely to survive and produce offspring.

Nonetheless, as noted above, when we are looking at several species, we often choose not to address intra-species interactions. A common exception is the case where the effects of cannibalism – i.e. predation by members of one species on others of the same species – are significant in the ecosystem as a whole.

Food Chains and Webs

When there are two or more species with predator-prey relationships in an ecosystem, we often look at the chain of such relationships. For example, rabbits graze on grass and other plants, and are in turn eaten by coyotes.
These chained sequences of relationships are called *food chains*.

However, a linear chain is generally insufficient to describe the interactions of even a handful of species in a real-world ecosystem. For example (a very simple example), a single species might prey on two others, and those two might compete to consume the same type of plant. At this point, it is not really a food chain anymore. Instead, it is a *food web* – a network of interactions between species. However, the term "food chain" is still widely used in describing relationships in even large ecosystems – particularly when talking about a mostly linear subset of those relationships.

Energy: Producers, Consumers, and Trophic Levels

When studying or describing the food web of an ecosystem, we often use the concept of *energy* as a key quantity – in fact, we can view the food web as a kind of economy, in which energy is produced and consumed by the different species.

For example, most ecosystems have at their base one or more plant species that converts sunlight and other basic resources into *biomass* (an accumulation of living matter – we often use this term as a species-neutral way to talk about the quantities of the different species in an ecosystem). These species are *primary producers* – they are not consuming other members of the ecosystem (at least, not at the level of detail we are studying), and the biomass of these species represents energy that can be consumed by other species in the ecosystem. These other species are therefore *consumers* of the energy produced by the primary producers; in turn, these consumers are producers to the species that prey on them.

However, there's a catch: just as an engine can't convert all of the potential energy in its fuel to kinetic (moving) energy, the same is true in an ecosystem – when a consumer eats some of the biomass of a producer, it can only convert a fraction of that energy into biomass of its own species. At each step along the chain of producers and consumers, less energy is available – and the biomass gets smaller and smaller.

If we represent an ecosystem's food web as a network of consumers and producers (both included as nodes in the network), and the interactions between them (the edges or links in the network), and then arrange the network so that the primary producers are located at the bottom, and each successive consumer is higher up, we are producing a picture of the *trophic levels* of the food web. At the lowest levels are the primary producers – usually plants. At the next trophic level, we have the *primary consumers*, the *herbivores* (plant eaters).

At the next trophic level, we have the *secondary consumers*; here we find the first carnivores in our ecosystem. We can have additional consumers at higher trophic levels, preying on the lower levels (many predators consume prey from multiple trophic levels – for example, mountain lions sometimes prey on coyotes (which are secondary consumers), as well as rabbits (primary consumers).

Keep in mind that as we move to higher trophic levels, we take more steps, with each step losing a lot of the energy that can be converted to biomass. Thus, the total biomass at higher levels will be less than that at lower levels. If we include that concept in our visual arrangement of the food web, by sizing and spacing the nodes according to biomass, our food web starts to look like a pyramid: a lot of biomass (and probably many species) at the bottom, less and less biomass (and usually fewer species) as we move upward.

An Ecosystem as a Complex System

As noted above, in discussing apparent competition, the overall effect of some interaction might not be obvious from a description of the basic form of the interaction. In fact, this is one of the main characteristics of a complex system: the behavior of some aspect of the system, seen as a whole, doesn't necessarily follow directly from an understanding of how the individual "parts" of the system work (more on this below).

Another characteristic of most complex systems is feedback: as the system changes, the new state of the system affects the way in which the system changes in the future. For example, if we look at the ecosystem of fish in a pond, where the fish are not being consumed by predators (our penny growth or papercatchers ecosystem was a rough analogue of this), we see that as the population approaches the carrying capacity of the pond, the rate of eggs hatching and maturing to adulthood decreases. This is often through increased cannibalism, as other food sources become scarce; it also happens via limits in other required resources (e.g. oxygen in the water). So the increase in the fish population leads to a reduction in the necessary resources available to each member of the population, which in turn leads to moderation in the rate of increase in the population. (This type of feedback is called negative, or *damping* feedback.) This results in the flattening out of the population growth curve, similar to that observed with the penny growth or papercatchers ecosystem simulation.

Another important feature of complex systems is that relationships are non-linear: small changes in one moment may result in disproportionately large changes later on. Ecosystems often demonstrate this feature: we might have relative stability in the populations of a number of species, but then a brief spike or dip in one can produce a chain reaction of changes in the other populations, sometimes with serious results.

Possibly most important, ecosystems often demonstrate *emergent behavior*. This is related to the first point, where the overall behavior turns out not to be obvious from the component behavior. In a high desert ecosystem, simply knowing that rabbits eat grass, coyotes eat rabbits, and mountain lions eat rabbits and coyotes, doesn't tell us much (beyond giving us a general sense) about the patterns in the respective populations over time – we really need to study the ecosystem as a whole.

From the above, we can see that ecosystems are usually complex systems, as well.