Ecosystem Engineers and Keystone Species

Mike Doody | High School Science

Unit Description

This AP Environmental Science unit focuses on biodiversity and ecology, using the Amazon Rainforest as an anchor ecosystem and engages students in authentic science experiences. Students analyze biodiversity data, create and execute their own data collection plan, and compare the biodiversity of Sucusari to two local ecosystems. They also examine camera trap footage, investigate biodiversity hotspots, examine the role of the tapir in the rainforest ecosystem, and then apply what they have learned to construct case studies of other ecosystem engineers and keystone species, including peccaries, wolves, beavers, and otters.

Content Standards

1. Explain levels of biodiversity and their importance. (AP-ES ERT-2.A)
2. Describe ecosystem services and human impacts (AP-ES ERT-2.B and C)
3. Explain how human activities affect biodiversity and strategies to reduce those impacts. (AP-ES EIN-4.C)
4. Describe, explain, and model environmental concepts and processes (Science Practices).

Objectives and Outcomes

1. Describe the flow of matter and energy through an ecosystem.
2. Analyze biodiversity data.
3. Explain how ecosystem engineers impact their environment.
4. Develop a meaningful connection to our “case study” ecosystems.

Supporting Materials

1. **DTI 2022 Unit**
2. **Biodiversity Data Analysis**
3. **Ecosystem Engineers Case Study**
4. **Video**

Thank you to the Longwood Foundation for their support.

ACEER FOUNDATION

Delaware Teachers Institute

Title: Ecosystem Engineers – Teaching Ecology and Biodiversity Using Case Studies of Select Keystone Species in Various Ecosystems

Author: Michael A. Doody

"You won't save what you don't love" – Joel Sartore

Introduction/Rationale

Each year I start my AP Environmental Science course at William Penn High School with a simple question: why are you taking this course? Inevitably I get a wide range of answers, including "it was on my schedule", "I heard it was the easiest science AP class", and occasionally "I liked your Chemistry class so I figured why not?". But I also get responses such as "I want to know more about climate change", "I'm thinking of majoring in environmental science", and every now and then I get "I want to know how to save the planet." Whenever a student provides such a response, most of the class will nod in agreement or plead to change their answer to that one. So this year I pushed back on this response, asking my students to explain what about the planet needs saving. "Climate change" a student exclaims. "Plastic pollution" someone else chimes in. "Save the penguins and polar bears!" another student shouts. As the topics fly right and left, some more germane than others, I am trying to gauge just how much students know and care about the things they are saying. Because as Mr. Sartore says, you won't save what you don't love.

This quote speaks to me on a deep personal level. I spend my academic year trying to educate students on how humans interact with the world around them. Much of what we talk about is negative – plastic pollution, climate change, ozone depletion, deforestation, etc. Many of my students have asked the question "but why should we care [about xyz issue]?" My answer to this question is always grounded in a personal sense of adoration and appreciation for the earth and the natural environment. But often times students don't share my viewpoint. When it comes to the places like the Amazon Rainforest, Mid-Atlantic temperate forests, or kelp beds on the Pacific coast, students may feel a sense of wonder from some previous lesson, but they likely lack a real, deep appreciation for these ecosystems and all they hold. In this unit, I would like to foster a deeper connection to these threatened ecosystems that encourages students to seek solutions to the myriad environmental problems they face. This unit enhances and replaces parts of my existing curriculum on ecology and biodiversity, and takes approximately eight class periods to complete.

School Profile

William Penn High School is a public high school in the Colonial School District in New Castle County, DE. It is the only high school in the district and is the largest high school in the entire state, serving between 2,000 and 2,300 each year across grades 9-12. The district is considered suburban/urban fringe and serves a diverse population in terms of both race and income. Several years ago, William Penn began focusing on the growth of Career and Technical Education (CTE) programs that provide opportunities for students to experience a vocational-type education while still being provided with the traditional college preparatory education typical of public schools. Such a shift has allowed the school to retain students who may otherwise attend one of the four area Vo-Tech schools. Students entering William Penn chose a degree program to specialize in within one of three college academies: Business, Humanities, or STEM. Degree programs within the Business College Academy include Air Force JRTOC, Business Administration, Culinary Arts, Financial Services, and Accounting. Degree programs with the Humanities College Academy include Behavioral Sciences, Communications, Teacher Academy, Legal Studies, International Studies, and Visual and Performing Arts. The STEM College Academy offers degree programs in Agriculture, Allied Health, Computer Science, Construction, Engineering, Manufacturing, Mathematics, and Science. William Penn also offers 25 Advanced Placement courses, the largest number of any school in the state. This dual focus on college and career readiness has greatly improved the school culture and the school's image in the community, which has translated to the growth in student population.

This growth in student population and interest in the sciences helped me justify the need for adding Advanced Placement Environmental Science (AP-ES) to the course catalog in the 2016/17 school year. Students enrolled in the Agriculture degree program can specialize in the Environmental Science pathway, which requires them to take two years of on-level environmental science before enrolling in AP-ES as their capstone course. Since the course is officially part of a CTE program, students are expected to finish the course with some sort of job-applicable skill. To me, getting students to think critically about environmental problems and potential solutions is my primary goal, but I am always looking for ways to address those job skills as well. And for anyone planning on becoming an environmental scientist or scientist in a related field, being able to explain environmental concepts, processes, and models, analyze visual representation of environmental concepts and processes, analyze and interpret quantitative data, and propose and justify solutions to environmental problems are critical skills to develop.

Content Objectives

In this unit, students learn about relevant ecology and biodiversity principles through the lens of several case studies of organisms classified as either ecosystem engineers, or keystone species. My two goals for this unit are 1) for students to better understand the functions of ecosystems and the value of biodiversity, and 2) to develop a meaningful connection to these places and begin to think about solutions to the challenges they face.

Ecology and Biodiversity Background

This unit starts with some basic ecology and biodiversity principles, ones that students need to adequately analyze the case studies and eventually explain the outsize role some organisms play in their ecosystem. It then introduces the topics of ecosystem services and ecosystem resilience (two topics anchored in a solid ecology and biodiversity foundation).

Ecology Principles

While some students have been exposed to some level of ecology (either through their Biology or introductory-level Environmental Science courses), I find that many students are encountering the following principles for the very first time: energy flow, matter and nutrient flow/cycling, trophic interactions, species interactions, and biomes. Since the case studies require an integration of these principles, it is important to provide students a solid foundation on which to build.

The flow of energy and matter in/through ecosystems is a foundational principle in my course – not only for ecology and biodiversity, but for later units on land and water use, agriculture, and pollution. For this course, students need to know that in nearly all ecosystems, autotrophs use photosynthesis to convert solar energy and CO_2 into biomass. I briefly introduce the concept of chemosynthesis (the process by which organisms extract energy from the bonds of compounds like methane or hydrogen sulfide) but it is not tested so we don’t dive any deeper. Autotrophs, or primary producers, are consumed by primary consumers, who are consumed by secondary consumers, or who are consumed by tertiary consumers. This concept is best visualized in a food chain, a simplified diagram that shows the direction of energy flow from the sun through the various trophic levels. Each time energy moves from one level to next, only 10% actually gets transferred, meaning that if a photosynthetic organism has 1,000,000 units of solar energy available, it can only convert 100,000 units into biomass; a primary consumer would then be able to convert 10,000 units into biomass; a secondary consumer 1,000 units, and a tertiary consumer 100 units. The remaining 90% of energy in each transfer is lost to the environment according to the laws of thermodynamics. This concept is known as the 10% rule and though it is a generalization, it is an important concept in ecology. Since food chains are simplified models of real ecosystems, students also learn about more complex and complete food webs, which do a better job of showing how energy gets recycled by detritivores and decomposers. Students are always confused by the difference between the two, so clarifying and providing examples is critical. Detritivores, such as earthworms, are organisms that break down dead tissues and waste products into smaller particles. Decomposers, such as dung-beetles and fungi, convert organic matter into small elements and molecules that can be recycled back into the environment. In examining food chains, food webs, and trophic levels, students are introduced to the myriad of ecology vocabulary above, as well as terms like including herbivore, omnivore, carnivore.[1]

Matter/nutrient flow and cycling is another foundational concept of my course. We focus on the flow and cycling of water, carbon, nitrogen, and phosphorous. In addition to understanding the processes by which matter/nutrients flow through and cycle within ecosystems, students also learn how humans have impacted each cycle. Our textbook does a decent job of describing and showing the relationship between the various steps of each cycle, including excellent diagrams. Below is a brief description of each cycle adapted from the text.[2]

The water, or hydrologic cycle, is the one students come to me with the most knowledge about. In brief, water moves from the atmosphere to Earth's surface via precipitation. From there, some of it infiltrates into the ground, some runs off, some is taken up by plants. The cycle is completed by the return of this water to the atmosphere via evapotranspiration. Students should understand that solar energy is the driver of this cycle. Human impacts to this cycle include local changes to evapotranspiration due to land use changes and increased surface runoff in developed areas. Additionally, regional changes to the water cycle, including drought and more frequent intense rainfall events, have been observed recently due to the effects of climate change.

The carbon cycle is significantly more complex than the water cycle. It includes the following processes: photosynthesis, respiration, exchange, burial, sedimentation, extraction, and combustion. Photosynthesis removes carbon from the atmosphere and stores it in biomass, while respiration returns that carbon to the atmosphere. Exchange occurs in bodies of water where CO_2 is constantly moving back and forth between the atmosphere and water. Some carbon is buried in sediments through decomposition, while some dissolved CO_2 can precipitate out water as calcium carbonate in sedimentation. Humans extract carbon from the ground in the form of fossil fuels, and combust it where it ultimately ends up in the atmosphere as CO_2. Because of the last two processes, the carbon cycle has been massively disrupted by human activities. The extent of this impact is studied in a future unit on climate change.

The nitrogen cycle is perhaps the most complex and challenging for students to grasp, partly due to its moderation by microorganisms and partly due to the many different nitrogen-species involved. The nitrogen cycle is defined by the following processes: nitrogen fixation, nitrification, assimilation, mineralization, ammonification, and denitrification. Nitrogen fixation occurs when nitrogen gas in the atmosphere is converted into forms of biologically available nitrogen. It can happen abiotically through lightning strikes and biotically by cyanobacteria and root-associated bacteria. Nitrification is the process of converting ammonia into nitrite and nitrate. This process is also done by bacteria. Assimilation occurs when producers incorporate nitrite and nitrate into their tissues. Mineralization is the process by which decomposers break down organic nitrogen and convert it back to inorganic nitrogen. Ammonification is the process by which decomposers covert organic nitrogen into ammonium. Denitrification occurs as nitrate is converted, via several microbe-regulated processes, into nitrous oxide and nitrogen gas. Because nitrogen is usually a limiting nutrient, its widespread use in the form of synthetic fertilizers in agriculture has results in widespread disruptions to its natural cycle, especially in aquatic ecosystems where, along with phosphorous, can lead to algal blooms and eutrophication (the process by which dissolved oxygen levels are depleted by the aerobic decomposition of organic matter and leads to the decline in aquatic organism populations).

Aside from the water cycle, the phosphorus cycle is the most straightforward cycle for students. It is also the slowest of the all the cycles since it is mostly geologically controlled. Geological uplift exposes new phosphate-containing rocks, which weather and infiltrate into soil or runoff into water bodies where producers take them up. Phosphorous must be readily recycled by producers and decomposers within ecosystems since new phosphate is limited by slow geologic processes. Humans have altered the phosphorous cycle through the use of synthetic fertilizers that leach excess phosphate from soils into aquatic ecosystems, where, combined with excess nitrogen, can lead to eutrophication (described above).

Species interactions, including interspecies competition, predation, mutualism, commensalism, and parasitism, are fundamental concepts needed to understand the role species play in their ecosystem. Interspecies competition occurs between individuals from different space, such as when different species of birds compete for habitat within the forest. Predation occurs when one organism eats another species, such as when zooplankton feed on phytoplankton in the ocean. Mutualism is a symbiotic relationship between two or more species wherein both species benefit, such as in the Central American rainforest where acacia trees provide ants with habitat and shelter in exchange for protection from intruding insects and fast-growing vines. Commensalism is a relationship where one species benefits and the other is not impacted, such as when fish use coral reef structures to hide from predators; the fish receive the benefit of not being eaten but the reef receives no benefit or harm. Parasitism is an interaction where one organism benefits and the other is harmed, such as when the isopod *Cymothoa exigua* attaches to the tongue of various fish species. The isopod replaces the tongue of the host and feeds on its blood or mucus.[3] Another example of parasitism in the Amazon occurs when the fungus *Ophiocordyceps unilateralis* infects an ant and hijacks its body. Likened to a zombie, the ant initially appears normal until the infection drives it from the nest in search of higher humidity, where it eventually dies and the fungus sprouts a fruiting body from the base of the ant's head. The fruiting body will launch new spores out into the environment and infect new ants.[4]

The last topic within ecology that students are expected to be familiar with is how temperature, rainfall, latitude, and altitude impact terrestrial biomes and how light, temperature, and salinity impact aquatic biomes. We cover the following biomes: tundra, boreal forests, temperate grasslands, temperate seasonal forests, temperate rainforests, subtropical deserts, savannas, woodlands/shrublands, tropical rainforests, streams and rivers, lakes and ponds, freshwater wetlands, salt marshes, intertidal zones, coral reefs, mangrove swamps, and open oceans.[5] In addition to knowing what controls the biome type, students should know some characteristic organisms for each, critical ecosystem services provided by the biome, and has how human activity has impacted each. To explain the details of each biome is beyond the scope of this unit, but such descriptions are readily available in most environmental science textbooks.

Biodiversity Principles

Like with the ecology principles above, students in my class often come with a basic understanding of biodiversity. Most have something in the form of a definition and an inkling that it is important for the planet. But in order to analyze how ecosystem engineers impact biodiversity in their specific ecosystems, students need a more thorough understanding of the topic.

There are three levels to biodiversity: genetic, species, and ecosystem. Students are most familiar with species biodiversity, but should also understand that it only arises from genetic diversity. It follows that ecosystem diversity is based on species diversity (along with abiotic factors like temperature and rainfall).

Students are generally familiar with how to measure species biodiversity: count the number of different species in a given ecosystem. This is species richness, and is only one (relatively basic) measure of biodiversity. The Shannon index and evenness are two more advanced measures that provide more insight into the biodiversity of an ecosystem. Both are based on the relative proportion of species in a location. The drawback is that they require some advanced calculations (the details of which are beyond the scope of this unit). Nonetheless, students need to be familiar with these values and how to interpret them. What follows is a basic data set from an activity on wildlife living in Gorongosa National Park in Mozambique, adapted from HHMI Biointeractive.[6]

Vegetation Type	Richness	Shannon Index	Evenness
Floodplain grassland	33	2.046	0.5852
Limestone gorge	34	1.489	0.4221
Miombo woodland	25	2.297	0.7137
Mixed savanna and woodland	43	1.575	0.4187

Table 1: Biodiversity indicators for Gorongosa Park.

According to species richness, the mixed savanna and woodland ecosystem is the most biodiverse. However, if we use the Shannon index and/or evenness, the Miombo woodland is the most biodiverse ecosystem. This is because those metrics balance the abundance of each species. This discrepancy often launches an important discussion of which metric is the best one to use. Unfortunately, there isn't really a good answer for the purposes of this course – instead I encourage students to be able to justify their answer using appropriate evidence. What I try to stress is that each metric has its flaws. I tend to overplay the flaws of evenness to set up the idea that having an equal number of all species in an ecosystem is not a good thing considering the 10% rule. This also sets us up to focus on the importance of ecosystem engineers and keystone species.

Ecosystem Services and Resilience

Ecosystem services are the various benefits to humans provided by the natural environment. For our course's purpose, they are split into four major categories: provisioning services, regulating services, support services, and cultural services. Provisioning services are those that provide goods that humans use directly, like the lumber from trees or honey from bees. Regulating services are those that maintain environmental conditions within an acceptable range, such as nutrient cycles. Support services are those that allow for other ecosystem functions to operate naturally, such as pollination and water filtration. Cultural services are those that provide cultural and/or aesthetic benefits to many people.[7] This can take the form of tourism and recreation, such as in state and national parks, but it can also be seen in the deep connections communities have to their environment, including aesthetic appreciation, inspiration for art and design, and a source of spirituality and sense of place. Indigenous communities have robust connections to their ancestral lands that would be categorized as cultural services, and these connections can serve as models for fostering and entrenching environmental stewardship in other cultures.[8]

Ecosystem resilience ensures that ecosystems have the necessary genetic and species diversity to continue functioning healthily and providing ecosystem services. Resilient ecosystems are those that can withstand some degree of impact (whether human or otherwise) and still function, while less resilient ecosystems are unable to function within their normal bounds and cannot provide the same level of ecosystem services.[9]

Ecosystem Engineers, Keystone Species, and Trophic Cascades

Now that students have the requisite foundation in ecology and biodiversity, they can turn their attention to the phenomena of ecosystem engineers, keystone species, and trophic cascades.

Ecosystem engineers are organisms that create, modify, maintain, or even destroy habitats. Because of this, they have an oversized impact on the biodiversity of their ecosystems.[10] It is true that each organism within an ecosystem impacts it in some way, but ecosystem engineers' behavior is the dominant force within that ecosystem. This force is so dominant that they have been termed "keystone species", a reference to the keystone in an arch, without which the structure collapses. The presence of a keystone species helps regulate ecosystem function, keeping populations of various organisms at different trophic levels within healthy limits.[11] Given their place in the food web, apex predators such as wolves are often keystone species. But other organisms with different roles in ecosystems also serve as keystone species, including tapirs, termites, and beavers. The removal of a keystone species (or reintroduction of one) can lead to a trophic cascade; a series of mostly indirect ecological consequences that fundamentally alter how an ecosystem functions.[12] Trophic cascades are often described using terms like "direct", "indirect", "positive", and "negative." A direct effect is one that occurs between two organisms in adjacent trophic levels, like one organism eating another. An indirect effect is one that occurs between organisms in non-adjacent trophic levels. For example, by consuming an organism in one trophic level, a predator can have an indirect positive effect on whatever its prey eats. Positive effects are good for the organisms (typically meaning their population grows or remains stable), while negative effects are bad (their numbers decrease).

Case Studies of Select Ecosystem Engineers

The sections below highlight the role of specific organisms in their ecosystems and how they exert regulating pressures on them, as well as how their removal or reintroduction impacts the ecosystem.

Tapirs and Peccaries

Many of my students would be able to tell me that tropical rainforests, such as the ones found in the Amazon River Basin, are among the world's most biodiverse and productive ecosystems.[13] But I would bet that not many would be able to explain how these incredible ecosystems are regulated by the organisms that live there, or even identify those organisms by name. While there are several keystone species in different tropical rainforests, the scope of this unit is limited to the lowland tapir (*Tapirus terrestris*) and the white-lipped peccary (*Tayassu pecari*).

Tapirus terrestris is an ungulate species (mammals distinguished from other animals by the presence of hooves[14]) that lives in large swaths of tropical South America, including tropical lowland rainforests and seasonally dry savannas/grasslands. They are about six feet in length and weigh close to 500 pounds.[15] They have a broad diet, feeding on dozens of different plants and fruits and act as long-distance seed dispersers. This is because they ingest whole seeds and then drop them intact with their feces.[16] The seed dispersal behavior of the tapirs is so important to ecosystem functioning because it reduces competition with seed siblings, promotes local regeneration, and allows for colonization of vacant or low-density habitats.[17] This behavior has earned them the accurate title of "forest gardeners." They are mostly solitary, with limited overlap between individuals (except for at mineral licks or during mating season).[18] This means they have a broad range and that significant populations can only be sustained by large tracts of forest.

Tapirus terrestris also has a low reproductive rate, with gestational periods of thirteen to fourteen months for a single calf.[19]

Tayassu pecari is also an ungulate, though it is considerably smaller and much more social than *Tapirus terrestris*, averaging about four feet in length and about seventy pounds.[20] They form groups ranging in size from a dozen to several hundred. Like *Tapirus terrestris*, they play an incredibly important role in the forest ecosystem. They act as seed predators, destroying them through mastication or digestion. So while *Tapirus terrestris* helps ensure the distribution of seeds in their ecosystem, *Tayassu pecari* reduce the number of seeds and saplings through their feeding habits.[21] They also act as literal ecosystem engineers by creating and maintaining mineral licks and wallows, critical aquatic habitats for many species that are created by their trampling, rooting, and digging behavior.[22] This creates a depression which fills with water, creating microhabitats that are then inhabited or frequented by otters, small crabs, baby caiman, crab-eating raccoons, and snail-specialist snakes.

Because of their roles as ecosystem engineers, losses in either species' populations can lead to dramatic impacts on the forest ecosystem. Both species are prey for several large predators such as the puma and jaguar, and hold immense socio-economic importance for Indigenous communities.[23] Loss of both species would increase competition for other food sources for both cat species, and increase hunting pressures on other species. Without the seed dispersion of *Tapirus terrestris*, and the seed predation of *Tayassu pecari*, the very composition of the forest changes. The absence of *Tapirus terrestris* results in the loss of critical seed dispersal networks that promote widely-dispersed growth of tree species. This could result in clusters of trees instead of biodiverse forested habitats.[24] The absence of *Tayassu pecari* also promotes denser stands of the same species because seed predation has decreased. Localized proliferation of such tree species could be expected in their absence.[25] Additionally, species that rely on the wallows created by *Tayassu pecari* must find habitat or prey elsewhere.[26]

Red and Gray Wolves

Several different species of wolves play incredibly important roles in the health of forested ecosystems. As apex predators, they are classic examples of keystone species. It is important to note that though they are keystone species, wolves are not widely regarded as ecosystem engineers because their downstream impacts are relatively diffuse (as opposed to tapir or beaver who has a direct impact on the morphology or species distribution of an ecosystem). This unit highlights two species of wolves: the red wolf (*Canis rufus*) and the more familiar gray wolf (*Canis lupus*).

C. rufus is a canine species native to the southeastern US. It has been described as an intermediate between *C. lupus* and the coyote (*C. latrans*). They average about four feet in length and weigh between around sixty-five pounds. Their common name comes from their reddish hue. Historically *C. rufus* ranged from the Mid-Atlantic and southeastern US west to the Mississippi River, and were adapted to several different habitats, including coastal marshes and swamps, as well as temperate mixed forests and mixed woodland/ grasslands. Their diet consists of deer, rabbits and other small rodents. Today their range and habitat is limited to the forested wetlands of northeastern North Carolina, where they continue to prey on white-tailed deer, raccoons, and the nutria (an introduced species). Like other canine species, C. rufus is social by nature, living and hunting in close-knit family groups.[27] Their removal from their historical range was driven by habitat loss and hunting, as they were (mistakenly) perceived as threats to livestock and resulted in an explosion of white-tailed deer populations.[28] Overpopulated deer are problematic for two key reasons: increased grazing of tree saplings, which alters tree density and distribution in the forest, and in modern times, increased automobile accidents involving deer.[29] The reintroduction of c rufus to North Carolina shows promise in regulating deer populations in the region, as their predation of deer should lead to less grazing pressure on emergent vegetation.

C. lupus is a canine species like *C. rufus*. However, it is slightly larger, measuring about five feet in length, having much taller shoulder heights than their canine relatives, and weighing around eighty pounds. Their common name is also related to their dominant gray color. In North America, *C. lupus* has an historical range of nearly two-thirds of the US (mainly west of the Mississippi River and in the Great Lakes region) and almost all of Canada. Their present day range includes western Montana, northern Idaho, northwest Wyoming, northern Michigan, northern Wisconsin, northeast Oregon and Alaska in the US and much of interior Canada. Their diet consists mostly of large hoofed mammals, including deer, elk, moose, and bison. They are also more social than *C. rufus*, hunting and living in larger extra-familial packs. Their numbers declined as for several reasons, such as the overhunting of their prey, destruction and/or fragmentation of their habitat, or culling efforts by ranchers in order to protect their livestock. When *C. lupus* was driven out of Yellowstone National Park in the late 1800s/early 1900s, the population of elk increased. This in turn led to a decline in the aspen trees as the elk grazed on emerging aspen suckers. As wolves have been reintroduced into the ecosystem, the population of elk has decreased and their grazing behavior changed such that aspen stands have flourished.[30] These trees provide habitat to other organisms, stabilize soil (especially in steep-sloped forests), and help retain moisture. Riparian ecosystems have also experienced a comeback as insects, birds, small rodents, and even beavers have returned to the aspen groves that straddle streams and rivers.[31]

Beavers

Beavers (*Castor canadensis*) are semi-aquatic rodents that live in ponds, lakes, rivers, and streams. They range in length from two to three feet and typically weigh around fifty pounds. Their long, flat tail is perhaps their most defining characteristic, which helps is swim, communicate to others, and maintain balance. Their diet consists mainly of tree bark, leaves, roots, and wetland plants. *C. canadensis*' importance in an ecosystem is related to the construction of dams for habitat. Their historical range included almost all of North America before they were hunted to near extinction (for their prized fur or because they were considered a nuisance to farmers and landowners). However recent efforts have seen an incredible resurgence in beaver populations to almost all of their historical range.

In this unit, we focus on *C. canadensis*' impact on riparian zones, the intermediaries between land and a river or stream.[32] They have unique soil and vegetation characteristics due to the influence of the nearby water and are greatly impacted by the presence of *C. canadensis*. They play a critical role in the functioning of these zones by building dams. Their dams create extensive wetland habitats capable of supporting various types of plant species not found elsewhere in riparian zones. This has several outcomes for this ecosystem, including increased species richness. Not only do these created wetland habitats support plant species, they attract insects, birds, and other species (such as described above in the section on gray wolves). In this way, *C. canadensis* is a literal ecosystem engineer. Since beaver dams are semi-permanent structures, their direct impact on the ecosystem lasts for about 10 years. But after dams are abandoned an eventually breached by the stream/river, extensive meadows or shrubby swamps can form in the nutrient-rich soil once trapped by the dam and then deposited via regular flooding and river processes.[33] This has a great impact on the morphology and health of riparian zones, including promoting nutrient and water cycling, and regulating local hydrologic function.

Sea Otters

Sea otters, *Enhydra lutris*, are marine mammals that measure up to four feet in length and typically weigh between fifty and on-hundred pounds (southern sea otters are slightly smaller than their northern relatives). They eat a broad diet of crabs, snails, urchins, clams, abalone, mussels, and other invertebrates. Some otters may also eat various fish species. They inhabit kelp forests or beds, areas typical near the coastline with high densities of kelp.[34] Kelp is a type of marine algae that anchors into the sea floor. These kelp forests/beds are one of the most productive ecosystems on Earth.[35] *E. lutris* acts as ecosystem engineers because they control the sea urchin and other invertebrate herbivores that eat the kelp. As the otters were hunted to near extinction in the early 1900s, urchin populations were left unchecked, and over-grazed the kelp beds. Since then, some otter communities have recovered, leading to a resurgence in kelp coverage due to the regulation of the urchin community by otters.[36] This is similar to the regulating pressure exerted by wolves and other top predators on deer that allows for the regrowth of vegetation in areas previously overpopulated. Students should recognize this pattern of regulation by predators as a fundamental ecological principle.

Teaching Strategies

In order to instill in students that science is not merely a body of isolated facts but a systematic process for acquiring new knowledge, I always try to incorporate real aspects of the scientific process into the classroom. The National Research Council (NRC) lays out a framework for how to ensure that under NGSS students have authentic scientific experiences in their classrooms even as they learn the bodies of knowledge of the specific sciences. When implemented properly, this framework of "supports a better understanding of how scientific knowledge is produced and how engineering solutions are produced…help[ing] students become more critical consumers of scientific information."[37] This focus on process, according to the NRC, improves upon previous practices that reduced scientific procedures to isolated aims of instruction, rather than a vehicle for developing a meaningful understanding of the true scientific concept.

In 2019, the College Board did a soft redesign of the AP-ES curriculum to better align the course with the NRC philosophy and provide students with a better educational experience, improve their assessment performance, and promote college readiness. This included the development of a more specific set of standards that revolved more around process than product. To that end, the course standards are now split by Science Practices and Course Content. The idea is that teachers engage students in the Science Practices as a means of developing mastery of Course Content. For those familiar with the Next Generation Science Standards, it is similar to the use of Science and Engineering Practices and Cross Cutting Concepts as a means of covering Disciplinary Core Ideas. Because of this shift in curriculum structure, I have had to rethink my instructional approach to the AP-ES course. Previously I held the view that we needed to cover all the content to whatever degree of depth time would allow for. However, since the redesign I have begun using strategies that better engage students in the specific Science Practices. Several of them are outlined below.

Hands on Learning through AP-ES Science Practices

In my classroom, I act as more a facilitator of learning than a source of information and correct answers. To that end, my teaching toolkit is full of strategies that get students *doing* science rather than *learning* science. I use a wide range of the pf the Science Practices in my classroom. In this specific unit, I will ask students to explain environmental concepts, processes, and models through written expression, analyze sources of information about environmental issues, analyze and interpret quantitative data represented in tables, charts, and graphs, and propose, evaluate, and justify solutions to environmental issues. The biggest challenge I find when employing these practices is wanting to interject. But it is important to limit my interruptions and let students struggle and find solutions. Emphasizing the Science Practices as the main vehicle for student learning has to be carefully managed and not every student is going to be successful right away. This is especially true in this unit, as it is early in the school year and students are relatively inexperienced with this style of learning. I notice that students with previous AP and honors experience tend to struggle more because they are used to uncovering an answer or being given one quickly. But by not giving in to student demands and providing answers right away, I hope to train them to think creatively, work together, and develop their scientific "muscles" for use on the AP exam in May.

Collaborative Learning

I use collaborative learning for two reasons: to foster a sense of community in my classroom and because studies show that peers teaching and learning from one another to be highly effective. Collaboration and group work, whether in pairs, small groups, or more complicated jigsaw groups, is a staple in my classroom. It leads to development of high order thinking and communication, self-management, and leadership skills. It also allows me to meet with more students in less time to check for common misunderstandings and provide immediate feedback. Working collaboratively allows exposes students to diverse perspectives and prepares them for real life social and employment scenarios.

Direct Instruction

While most of my class time is spent engaging students in authentic science practices and thoughtful discussion, the nature of my course does require a certain amount of direction instruction. I try to limit myself to 15 minutes of direct instruction a class period and make it as interactive as possible by using guided notes, check in questions, turn-and-talks, quick-writes, and other progress checks. I prepare PowerPoint slides as a guide for my direct instruction. I then post those slides on our learning management system for students to review.

DIY Case Studies

Using case studies is a way of covering detailed and often technical information in a more engaging and time effective way than direct instruction can. Students engage in a deep study of some phenomenon (in this case ecosystem engineers) that helps them hit specific learning targets along the way. Using case studies also allows students to engage in the Science Practices and take ownership of their learning. As a teacher, my role is to help students progress through the material in a timely fashion while still hitting all the learning targets. I do this by having frequent progress checks, turn and talks, and other informal assessments of progress. In my opinion, case studies are even more effective when students have to create their own using what they know about a subject. In this way, they have even more ownership over their learning and allows them to more fully develop their understanding of critical concepts.

FRQ Notebooks

The AP-ES exam consists of eighty multiple choice questions and three Free Response Questions (FRQs). Students get plenty of multiple choice practice throughout the year on quizzes and unit exams. In order to prepare students for the FRQs, I combine frequent low-stakes practice and high-quality peer and teacher feedback through the use of FRQ notebooks. Students keep a notebook for the duration of the year with each FRQ prompt, their response, and a scored rubric. For students, this is beneficial because they can track their progress throughout the year and use it as a study tool at the end of each unit and before the AP Exam. For me, these notebooks serve as key benchmark data for determining how much exam preparation each student needs, as well as strong evidence of understanding. I use a combination of released exam questions from College Board, my own written questions, and in some cases, student-generated prompts. These questions ask students to integrate knowledge from different aspects of the course in order to assess their understanding of key course content. They require students to think critically, make determinations of cause and effect, identify patterns, analyze relationships, complete mathematical calculations, and propose and justify solutions.

Classroom Activities

This unit is designed to be implemented over eight 85-minute class periods, and replaces a portion of an existing unit on biodiversity. In advance of each day, students are expected to have read the appropriate module in their textbook so that they are prepared to discuss and engage meaningfully in activities that develop their understanding of those topics.

Days 1 to 3: Ecology Principles

To introduce the principles of ecology described above, I spend one class period on an interactive lecture that helps students make connections and develop their understanding of topics they read about in the textbook. Then we spend a day on a lab exploring how energy transfers through trophic levels. This lab involves students standing arms' length apart and attempting to transfer rice or seeds from the tallest person to the smallest person as fast as possible. This simulates the 10% rule and most of the rice or seeds end up on the ground. From here, students discuss the laws of thermodynamics and how they apply to trophic transfer. This activity also launches us into a discussion of food chains vs. food webs. The next day is spent exploring the various biogeochemical cycles, with special emphasis on carbon and nitrogen. To do this, I start with a brief lecture highlighting the processes of each cycle. Significant time is spent on nitrogen cycle and its various components. Then, students play a card game with the goal of satisfying the carbon, nitrogen, and phosphorous demands of a grassland ecosystem. It demonstrates the importance of soil microbial health and how C, N, and P accumulate in certain reservoirs while being depleted in other. This activity has been adapted from one created by HHMI Biointeractive to be played online instead of with physical cards.[38] Students complete the ecology portion of this unit by engaging in a "speed dating" activity wherein each student is responsible for researching a specific biome and creating a dating profile based on information such as rainfall, temperature, location, characteristic organisms, ecosystem services, and human impacts. This activity is often the highlight of the marking period and kids tend to have a lot of fun with it. To make sure that students maintain their focus on the assignment, they take a short quiz afterwards attempting to identify each biome based on the information they received during the activity.

Days 4 to 5: Biodiversity Principles

As with ecology, I start this section of the unit with a short interactive lecture on concepts related to biodiversity to reinforce the concepts students read about in the textbook. This includes an overview of the different levels of biodiversity and the different metrics. However, we don't go into too much detail because they are best learned in the context of real ecosystems. To that end, students spend the bulk of their time in this section of the unit exploring data from a collected from Sucusari and three locations in Delaware.

Throughout this activity, students formulate hypotheses about which ecosystem would be the most biodiverse and how humans impact biodiversity, ask questions about experimental design, analyze and interpret trail cam data, and construct explanations of biodiversity in the different ecosystems. This assignment is also an opportunity for students to learn a little about data manipulation using Google Sheets. I teach them how to use formulas to calculate their biodiversity indicators instead of having to tabulate them by hand. This activity usually takes one and half class periods as students work through the background material and are introduced to the data set on day one, and then spend the next class analyzing, manipulating, and interpreting the data. The Sucusari data comes from my time in Peru and focuses exclusively on birds in the region. I spent time collecting similar data in Brandywine Creek and Bellevue State Parks in Wilmington, Delaware. I also collected data on birds in the Herring Creek area of Lewes, Delaware. Students collectively create a data set for the New Castle area by spending a small amount of time each day for a week observing birds in and around their neighborhoods. This activity can be accessed using this link: https://docs.google.com/document/d/1bCXZ8daMDWh_VqvO8gC4KbabsYeiBY5T29pwiYPU0FI/edit?usp=sharing.

As a follow-up, students analyze trail camera images collected from the Sucusari area and identify species with my help. They read about the importance of each species in the ecosystem and to the Maijuna, an indigenous group who have immense knowledge about their rainforest ecosystem where they lived since time immemorial. This knowledge, referred to as Traditional Ecological Knowledge, or TEK, has been amassed over generations of people, including Maijuna, through their lived experiences in their local environments. TEK helps provide a new level of understanding about ecosystem functions and changes in the such functions beyond what scientists traditionally explore.[39] This TEK and trail camera data is an excellent lead in to the case studies of the tapir and peccary described below.

Day 6: Mid-Point Assessment and Miscellaneous Ecology and Biodiversity Principles

This day is split into two parts. The first is dedicated to a formative assessment on everything we’ve covered so far. At this point, students should have a solid, if still basic understanding of foundational ecology and biodiversity principles. They are assessed using questions from AP Classroom, a new-ish tool developed by the College Board to help teachers better prepare their students for success on the AP Exam. Questions are categorized by unit, topic, science practice, and skill. What is great about this tool is the reports it generates for both students and teachers about progress on material. After each assessment, teachers can see a breakdown of how students did on each question, which helps to identify areas of growth and call out areas of strength. For students, it can help them self-identify areas of growth that they will need to revisit in preparation for unit exams as well as the AP Exam. The second part of the day is dedicated to introducing the remaining ecology and biodiversity concepts that students need in order to complete the case study activity described below. This is done via interactive lecture, and includes material on ecosystem services, ecological resiliency, ecosystem engineers, and keystone species. I do not go into great detail on the last two so that students can investigate how/why some species have a greater influence on their ecosystem than others on their own.

Day 7: Case Studies

On this day, we spend our time analyzing and then creating case studies for each of the species detailed above. I start by presenting the case study of the tapir, modeling the same type of analysis required of students. This includes describing the organism, its habitat, food, behavior, ecological role, and consequences of removal. I also provide an example for students using resources on trophic cascades developed by HHMI Biointeractive.[40] Then, for each of the remaining species, students work in small groups and are tasked with creating a written description of the species, where it lives, and its role in the ecosystem. Students also create a diagram of all of the above information to connect the concept of keystone species and trophic cascades, students must also make evidence-based predictions of what would happen if that species were to be removed from the ecosystem. These predictions are then put to peer review before the class. The final aspect of this part of class is for students to identify and describe the role of any keystone species or ecosystem engineer in our own Delaware ecosystems. Since our ecosystems have been heavily impacted by human activities, students can really choose any species. What I am looking for is for them to be able to describe in detail why the species they chose is critical to ecosystem function. I expect students to pick common animals like squirrels and white-tailed deer given their prevalence in even the most altered ecosystems. I am interested to see if anyone picks the opossum for its incredible ability to control insect populations, specifically ticks that spread blood-borne diseases. In addition to helping students better understand the concepts of keystone species and trophic cascades, these case studies are designed to be a comprehensive review of all the ecology and biodiversity principles from earlier in the unit. This activity can be accessed using this link: https://docs.google.com/document/d/1w4xbUtXExskMbf786mD3fG80CZHgKtvYGrRK1oTNmz4/edit?usp=sharing.

Day 8: Wolves of Yellowstone Assessment Activity

In this activity, students apply their knowledge of ecology and biodiversity principles to the reintroduction of wolves to Yellowstone National Park. They watch video clips produced by National Geographic, examine data on wolves, elk, elm trees, and beavers to assess the possibility of a positive trophic cascade that occurred upon wolves being reintroduced to the region. I love this activity because it acts an "assessment before the assessment" in the sense that students have an opportunity to integrate information from throughout the unit before taking any sort of formal exam. This provides them an opportunity to self-assess and identify areas of strength and areas of growth. This activity was developed by The Nature Conservancy and PBS Learning Media.[41] I have adapted the document into an editable Google Slides presentation for students to use through our online learning platform.

Day 9: FRQ Notebook and Unit Reflection

On the last day of the unit, students demonstrate their learning by answering and scoring a previously released FRQ, and then engage in peer review. In addition to providing students with an opportunity to demonstrate their learning, frequently answering and scoring FRQs allows them to build familiarity and confidence with an otherwise daunting assessment tool. For this unit, students answer Question 4 from the 2013 AP-ES exam. This question asks students to: describe characteristics shared by ecosystems that have high biodiversity, identify specific human activities that result in a loss of biodiversity and explain how each activity lowers biodiversity, propose practical strategies to reduce the loss of biodiversity, describe factors that lead to losses of biodiversity, and describe the ecological benefits of high biodiversity. After answering the questions, students are provided with the rubric readers used to score the exam and have a chance to score themselves and a peer.

Something new that I am trying with this unit is collecting some student data on their experience with the unit. To that end I have developed a simple Google Forms survey that asks students the following questions: rate your *overall* experience in this unit on a scale of 1 – 5, rate your experience with the *textbook* sections related to this unit on a scale of 1 – 5, rate your experience with the *lecture* portion of this unit on a scale of 1 – 5, rate your experience with the *activities* portion of this unit on a scale of 1 – 5, what was your favorite part of this unit? what was your least favorite part of this unit? what is one thing we did in this unit you would like to see more of? what is one thing in this unit you would prefer not to see again? and did this unit foster a greater sense of connection to the ecosystems we studied?

Resources

Altrichter, Mariana, Andrew Taber, Harald Beck, Rafael Reyna-Hurtado, Leonidas Lizarraga, Alexine Keuroghlian, and Eric W. Sanderson. 2012. “Range-Wide Declines of a Key Neotropical Ecosystem Architect, the Near Threatened White-Lipped Peccary Tayassu Pecari.” *Oryx* 46 (1): 87–98. https://doi.org/10.1017/S0030605311000421.

Teacher resource for understanding role of peccaries in their ecosystem.

Basic Biology. 2015. “Ungulates.” 2015. https://basicbiology.net/animal/mammals/ungulate.

Good basic information about ungulates – I would recommend this site as a supplemental resource for students throughout the AP-ES course, especially if they are weak in ecology.

Escribano-Avila, Gema, Carlos Lara-Romero, Ruben Heleno, and Anna Traveset. 2018. “Tropical Seed Dispersal Networks: Emerging Patterns, Biases, and Keystone Species Traits.” *Ecological Networks in the Tropics*, 93–110. https://doi.org/10.1007/978-3-319-68228-0_7.

Good teacher resource explaining why seed dispersers can be keystone species.

Food and Agriculture Organization of the United Nations. 2021. “Cultural Services | Ecosystem Services & Biodiversity (ESB) | Food and Agriculture Organization of the United Nations.” FAO.Org. 2021. https://www.fao.org/ecosystem-services-biodiversity/background/cultural-services/en/

A good resource for understanding the cultural aspect of ecosystem services – definitely worth showing to students.

Friedland, Andrew, and Rick Relyea. 2019. *Environmental Science for the AP Course*. 3rd ed. New York: Bedford, Freeman, and Worth.

Course textbook – foundation of course.

HHMI. 2020a. “Nutrient Cycling in the Serengeti.” HHMI Biointeractive. 2020. https://www.biointeractive.org/classroom-resources/nutrient-cycling-serengeti.

Student-facing curriculum resource – has a teacher guide and supporting documents.

HHMI. 2020b. “Biodiversity Studies in Gorongosa.” HHMI Biointeractive. 2020. https://www.biointeractive.org/classroom-resources/biodiversity-studies-gorongosa.

Student-facing curriculum resource – has a teacher guide and supporting documents.

HHMI. 2021. “Modeling Trophic Cascades.” HHMI Biointeractive. 2021. https://www.biointeractive.org/classroom-resources/modeling-trophic-cascades.

Student-facing curriculum resource – has a teacher guide and supporting documents.

Huffman, Brent. 2017. “Tayassu Pecari.” Ultimate Ungulate. 2017. http://www.ultimateungulate.com/Artiodactyla/Tayassu_pecari.html.

Solid resource with background information on peccary – would be good for students during case study development.

Keuroghlian, Alexine, and Donald P. Eaton. 2009. “Removal of Palm Fruits and Ecosystem Engineering in Palm Stands by White-Lipped Peccaries (Tayassu Pecari) and Other Frugivores in an Isolated Atlantic Forest Fragment.” *Biodiversity and Conservation* 18 (7): 1733–50. https://doi.org/10.1007/s10531-008-9554-6.

Good teacher resource about the peccary.

Lu, Jennifer. 2019. “Cordyceps Zombie Fungus Takes over Ants’ Bodies.” National. 2019. https://www.nationalgeographic.com/animals/article/cordyceps-zombie-fungus-takes-over-ants.

Interesting article about the zombie fungus – would be a good video to show students.

Mann, K. H. 1973. “Seaweeds: Their Productivity and Strategy for Growth.” *Science* 182 (4116): 975–81. https://doi.org/10.1126/science.182.4116.975.

Teacher resource for understanding kelp forests.

Marris, Emma. 2014. “Where Peccaries Wallow, Other Animals Follow.” National Geographic. 2014. https://www.nationalgeographic.com/science/article/140927-peccary-wallow-amazon-rainforest-camera-trap-biodiversity-science.

Another peccary resource.

Monterey Bay Aquarium. 2021. “Sea Otter.” Animals A to Z. 2021. https://www.montereybayaquarium.org/animals/animals-a-to-z/sea-otter.

Excellent site for information about otters – useful for students during case study development.

Mulheisen, Michael, and Rebecca Ann Csomos. 2020. “ADW: Canis Rufus: INFORMATION.” Animal Diversity Web. 2020. https://animaldiversity.org/accounts/Canis_rufus/.

Excellent site for information about red wolves – useful for students during case study development.

National Research Council. 2012. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/13165.

This is a must read for any teacher who wants to learn about NGSS and the philosophy behind the sea change it brought about in science education.

National Wildlife Foundation. n.d. “Red Wolf.” NWF.Org. Accessed December 12, 2021. https://www.nwf.org/Educational-Resources/Wildlife-Guide/Mammals/Red-Wolf.

More information on the red wolf.

Paine, Robert T. 1995. “A Conservation on Refining the Concept of Keystone Species.” *Conservation Biology* 9 (4): 962–64.

Good teacher resource for understanding the keystone species concept.

PBS Learning Media. 2021. “Wolves of Yellowstone: Lesson Plan.” Earth: A New Wild. 2021. https://whyy.pbslearningmedia.org/resource/331db173-a528-46ae-985c-e2432ebc6dc2/wolves-of-yellowstone-teacher-guide/.

Excellent student-facing resources on the impacts wolves have had since their return to Yellowstone. Comes with a teacher guide.

Pursell, Allen, Troy Weldy, and Mark White. 2013. “Too Many Deer: A Bigger Threat to Eastern Forests than Climate Change.” Cool Green Science. August 22, 2013. https://blog.nature.org/science/2013/08/22/too-many-deer/

Good resource on why overpopulation of deer is a bad thing.

Ripple, William J, and Eric J Larsen. 2000. “Historic Aspen Recruitment, Elk, and Wolves in Northern Yellowstone National Park, USA.” *Biological Conservation* 95: 1–10.

Good resource on the roles of wolves in an ecosystem.

Robbins, Jim. 2018. “Native Knowledge: What Ecologists Are Learning from Indigenous People - Yale E360.” Yale Environment 360. April 26, 2018. https://e360.yale.edu/features/native-knowledge-what-ecologists-are-learning-from-indigenous-people

Good resource on Traditional Ecological Knowledge.

Silliman, Brian R, and Christine Angelini. 2012. “Trophic Cascades Across Diverse Plant Ecosystems.” *Nature Education Knowledge* 3 (10).

Good resource for learning about the trophic cascade concept.

Tapir Specialist Group. n.d. “Tapir Tracks: A Curriculum Guide for Educators.” http://tapirs.org/resources/educator-resources.

Good resource on the tapir – useful for students during case study development.
Tobler, Mathias W, John P Janovec, and Fernando Cornejo. 2017. “Frugivory and Seed Dispersal by the Lowland Tapir Tapirus Terrestris in the Peruvian Amazon.” *Biotropica* 42 (2): 215–22.

Good resource on the role of the tapir in an ecosystem.

Tobler, Mathias Werner. “The Ecology of the Lowland Tapir in Madre de Dios, Peru: Using New Technologies to Study Large Rainforest Mammals.” PhD Dissertation. (Texas A&M University, 2008).

Another good resource on the tapir.

USDA. 1996. "Riparian Areas Environmental Uniqueness, Functions, and Values | NRCS." NRCS. 1996. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/?cid=nrcs143_014199#what.

Good resource on understanding riparian areas and their value in ecosystems

Wright, Justin P, Clive G Jones, and Alexander A Flecker. 2002. "An Ecosystem Engineer, the Beaver, Increases Species Richness at the Landscape Scale." *Ecosystems Ecology* 132: 96–101. https://doi.org/10.1007/s00442-002-0929-1.

Good resource on the beaver – needs to be distilled down for student use.

Appendix: Implementing District Standards

This unit addresses several key learning objectives in Units 1 and 2 of the Course and Exam Description for AP Environmental Science, including broad coverage of the following: ERT-1.B-G, and ENG-1.B-D,. These standards collectively make up Unit 1 – The Living World: Ecosystems. The meat of the unit covers the following Unit 2 = The Living World: Biodiversity learning objectives in more significant detail: ERT-2.A (explain levels of biodiversity and their importance to ecosystems), ERT-2.B and C (describe ecosystem services and the results of human disruptions to them), ERT-2.F (describe ecological tolerance), EIN-4.C (explain how human activities affect biodiversity and strategies to combat the problem), and ERT-2.I (describe ecological succession, limited to role of keystone species).

The following AP-ES skills are covered in this unit: explain environmental concepts, processes, and models, analyze visual representation of environmental concepts and processes, and analyze and interpret quantitative data.

Students also fulfill Common Core State Standards on reading and writing in this unit, including CCSS.ELA-Literacy.RST.11-12.1 (cite specific textual evidence…), CCSS.ELA-Literacy.RST.11-12.9 (synthesize information from a range of sources…), and CCSS.ELA-Literact.WHST.11-12.1 (write arguments focused on discipline-specific content).

Endnotes

[1] Friedland, Andrew, and Rick Relyea. 2019. *Environmental Science for the AP Course*. 3rd ed. New York: Bedford, Freeman, and Worth.

[2] *Ibid*

[3] *Ibid*

[4] Lu, Jennifer. 2019. “Cordyceps Zombie Fungus Takes over Ants’ Bodies.” National. 2019. https://www.nationalgeographic.com/animals/article/cordyceps-zombie-fungus-takes-over-ants.

[5] (Friedland and Relyea 2019)

[6] HHMI. 2020a. “Nutrient Cycling in the Serengeti.” HHMI Biointeractive. 2020. https://www.biointeractive.org/classroom-resources/nutrient-cycling-serengeti.

[7] (Friedland and Relyea 2019)

[8] Food and Agriculture Organization of the United Nations. 2021. “Cultural Services | Ecosystem Services & Biodiversity (ESB) | Food and Agriculture Organization of the United Nations.” FAO.Org. 2021. https://www.fao.org/ecosystem-services-biodiversity/background/cultural-services/en/

[9] (Friedland and Relyea 2019)

[10] Wright, Justin P, Clive G Jones, and Alexander A Flecker. 2002. “An Ecosystem Engineer, the Beaver, Increases Species Richness at the Landscape Scale.” *Ecosystems Ecology* 132: 96–101. https://doi.org/10.1007/s00442-002-0929-1.

[11] Paine, Robert T. 1995. “A Conservation on Refining the Concept of Keystone Species.” *Conservation Biology* 9 (4): 962–64.

[12] Silliman, Brian R, and Christine Angelini. 2012. “Trophic Cascades Across Diverse Plant Ecosystems.” *Nature Education Knowledge* 3 (10).

[13] (Friedland and Relyea 2019)

[14] Basic Biology. 2015. “Ungulates.” 2015. https://basicbiology.net/animal/mammals/ungulate.

[15] Tapir Specialist Group. n.d. “Tapir Tracks: A Curriculum Guide for Educators.” http://tapirs.org/resources/educator-resources

[16] Tobler, Mathias Werner. “The Ecology of the Lowland Tapir in Madre de Dios, Peru: Using New Technologies to Study Large Rainforest Mammals.” PhD Dissertation. (Texas A&M University, 2008).

[17] Escribano-Avila, Gema, Carlos Lara-Romero, Ruben Heleno, and Anna Traveset. 2018. “Tropical Seed Dispersal Networks: Emerging Patterns, Biases, and Keystone Species Traits.” *Ecological Networks in the Tropics*, 93–110. https://doi.org/10.1007/978-3-319-68228-0_7.

[18] *Ibid*

[19] (Tapir Specialist Group, n.d.)

[20] Huffman, Brent. 2017. “Tayassu Pecari.” Ultimate Ungulate. 2017. http://www.ultimateungulate.com/Artiodactyla/Tayassu_pecari.html.

[21] (Tobler 2008)

[22] Marris, Emma. 2014. “Where Peccaries Wallow, Other Animals Follow.” National Geographic. 2014. https://www.nationalgeographic.com/science/article/140927-peccary-wallow-amazon-rainforest-camera-trap-biodiversity-science.

[23] Altrichter, Mariana, Andrew Taber, Harald Beck, Rafael Reyna-Hurtado, Leonidas Lizarraga, Alexine Keuroghlian, and Eric W. Sanderson. 2012. “Range-Wide Declines of a Key Neotropical Ecosystem Architect, the Near Threatened White-Lipped Peccary Tayassu Pecari.” *Oryx* 46 (1): 87–98. https://doi.org/10.1017/S0030605311000421.

[24] Tobler, Mathias W, John P Janovec, and Fernando Cornejo. 2017. “Frugivory and Seed Dispersal by the Lowland Tapir Tapirus Terrestris in the Peruvian Amazon.” *Biotropica* 42 (2): 215–22.

[25] Keuroghlian, Alexine, and Donald P. Eaton. 2009. “Removal of Palm Fruits and Ecosystem Engineering in Palm Stands by White-Lipped Peccaries (Tayassu Pecari) and Other Frugivores in an Isolated Atlantic Forest Fragment.” *Biodiversity and Conservation* 18 (7): 1733–50. https://doi.org/10.1007/s10531-008-9554-6.

[26] (Marris 2014)

[27] Mulheisen, Michael, and Rebecca Ann Csomos. 2020. “ADW: Canis Rufus: INFORMATION.” Animal Diversity Web. 2020. https://animaldiversity.org/accounts/Canis_rufus/.

[28] National Wildlife Foundation. n.d. “Red Wolf.” NWF.Org. Accessed December 12, 2021. https://www.nwf.org/Educational-Resources/Wildlife-Guide/Mammals/Red-Wolf.

[29] Pursell, Allen, Troy Weldy, and Mark White. 2013. “Too Many Deer: A Bigger Threat to Eastern Forests than Climate Change.” Cool Green Science. August 22, 2013. https://blog.nature.org/science/2013/08/22/too-many-deer/

[30] Ripple, William J, and Eric J Larsen. 2000. “Historic Aspen Recruitment, Elk, and Wolves in Northern Yellowstone National Park, USA.” *Biological Conservation* 95: 1–10.

[31] *Ibid*

[32] USDA. 1996. “Riparian Areas Environmental Uniqueness, Functions, and Values | NRCS.” NRCS. 1996. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/?cid=nrcs143_014199#what.

[33] Wright, Justin P, Clive G Jones, and Alexander A Flecker. 2002. “An Ecosystem Engineer, the Beaver, Increases Species Richness at the Landscape Scale.” *Ecosystems Ecology* 132: 96–101. https://doi.org/10.1007/s00442-002-0929-1.

[34] Monterey Bay Aquarium. 2021. “Sea Otter.” Animals A to Z. 2021. https://www.montereybayaquarium.org/animals/animals-a-to-z/sea-otter.

[35] Mann, K. H. 1973. “Seaweeds: Their Productivity and Strategy for Growth.” *Science* 182 (4116): 975–81. https://doi.org/10.1126/science.182.4116.975.

[36] (Silliman and Angelini 2012)

[37] National Research Council. 2012. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/13165.

[38] HHMI. 2020b. “Biodiversity Studies in Gorongosa.” HHMI Biointeractive. 2020. https://www.biointeractive.org/classroom-resources/biodiversity-studies-gorongosa.

[39] Robbins, Jim. 2018. “Native Knowledge: What Ecologists Are Learning from Indigenous People - Yale E360.” Yale Environment 360. April 26, 2018. https://e360.yale.edu/features/native-knowledge-what-ecologists-are-learning-from-indigenous-people

[40] HHMI. 2021. “Modeling Trophic Cascades.” HHMI Biointeractive. 2021. https://www.biointeractive.org/classroom-resources/modeling-trophic-cascades.

[41] PBS Learning Media. 2021. “Wolves of Yellowstone: Lesson Plan.” Earth: A New Wild. 2021. https://whyy.pbslearningmedia.org/resource/331db173-a528-46ae-985c-e2432ebc6dc2/wolves-of-yellowstone-teacher-guide/.