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Coffee, Cacao, and Chacras — Examining Sustainable Agroecosystems

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Introduction and Rationale

"Essentially, we have to farm the way nature farms" – Wes Jackson, The Land Institute[1]

In June of 2023, I was standing in a row of coffee bushes on a hillside in Costa Rica. Planted among the coffee bushes were banana palms, rainbow eucalyptus trees, and various citrus fruit trees. As I walked through the rows of plants, I couldn't help but notice the incessant chirping of several different bird species, matched only in volume by the continuous buzzing of insects. At my feet there was dark, rich, and fragrant soil. I couldn't help but contrast this with the dominant type of farm in my home state of Delaware: row after row of corn or soybeans, the sounds of irrigation pumps and combine tractors, maybe some vultures flying overhead, and pale dusty dirt. This experience also reminded me of June of 2022 when I spent some time in a chacra in northeastern Peru learning about Indigenous agricultural practices that raised yuca (also known as cassava), banana, plantain, sugarcane, and cacao all in one space. Contrasting coffee fields in Costa Rica and chacras in Peru with cornfields in Delaware might seem obvious – these are very different locations and different crops. But what I observed in those places was more than just a different agricultural system from the ones in Delaware; what I observed was an *agroecosystem*. The coffee bushes and cacao trees and yuca plants were *part of* the ecosystem, not *apart fromthe* ecosystem. I left the coffee field with Wes Jackson's quote resonating even more deeply than it had the first time I read it.

This experience also got me thinking about how my students view the foods and drinks they consume and the agricultural systems that produce those foods and drinks. If I were to ask them about coffee's origins, most would probably say Starbucks, or Dunkin. Maybe someone has read a label and would (mistakenly) say Arabica. Similarly, If I were to ask my students where chocolate comes from, most of them would probably give one of the following responses: the grocery store, the Hershey plant, or somewhere near the equator. And if were to ask them about yuca, they would probably say "what's that?". Since chocolate and coffee (especially iced coffee with a lot of sugar and sweeteners) have become ever-present in my students' lives, I feel they should learn more about their origins, and how farmers in Costa Rica and other regions are working to grow them more sustainably. Similarly, students should know more about traditional Indigenous farming (such as the methods that produce yuca) that has not been subjected to the same level of industrialization that traditional Western staple crops have been.

These agricultural systems that produce coffee, cacao, and yuca are vastly different from modern industrial agriculture, which more resembles an assembly line in a manufacturing plant than it does the growing of crops or raising of animals. This shift to industrial agriculture has had a profound environmental impact on the United States and the rest of the planet. The impacts include the clearing of forested lands, the whole-scale decimation of prairies and grasslands in favor of miles and miles of monocultures of corn, wheat, and soybean, the extermination of predator species to protect livestock, as well as on-going impacts related to the application of synthetic fertilizers and pesticides and the use of large-scale machinery run on fossil fuels.[2]

School Demographics

Students at William Penn High School are uniquely positioned to tackle the issues of modern industrial agriculture because we have a well-developed agricultural science program, a four-acre farm and full-time farm manager, two greenhouses, a small aquaculture facility, a wildflower patch, and a willingness to try out new educational models. WPHS 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. In addition to offering students a traditional education, WPHS offers courses within numerous Career and Technical Education programs, as well as 25 Advanced Placement courses.

AP Environmental Science sits on the border between the CTE and AP worlds, as it serves as the capstone course for students in the Environmental Science and Natural Resources career pathway and is also open to any student who meets the prerequisites. Students in this pathway take coursework in foundational ecology, natural resource management, and environmental science issues before coming to AP-ES. By the time students enter the course, they should have a solid base of environmental science knowledge and skills. However, in my seven years teaching this course, I haven't necessarily known this to be true. This year, I have been tasked with teaching all three levels of environmental science in hopes of streamlining and strengthening the pathway. My overarching goal is to provide students in the introductory and intermediate classes an experience that encourages them to continue studying the subject and to provide them with the foundational knowledge necessary to dive right into rich and rigorous content upon reaching AP-ES. This unit is one of the first steps in this process. While my intention is to develop an advanced level unit, I plan to teach elements of the unit in the introductory and intermediate courses.

Content Objectives

This one-week unit, developed for AP Environmental Science with elements that can be adapted for introductory and intermediate level students, focuses first on the environmental consequences of the Green Revolution and the industrialization of agriculture. Students then learn about more sustainable alternatives, including the overarching concept of agroecosystems, and more specific examples of polycultures, integrated pest management, and Indigenous agricultural practices. Finally, students are tasked with investigating the agroecosystems that produce coffee, cacao, and yuca and other locally relevant crops, and identifying specific sustainable practices within them. Students' ultimate goal is to better understand Wes Jackson's quote about farming the way nature farms.

The Environmental Impacts of the (Not So) Green Revolution

The Green Revolution is not the focus of this unit, as it is covered as part of a larger period of instruction on agriculture. But, the environmental impacts of the Green Revolution and the alternative methods with lower environmental impacts are the focus of this unit, so it is important to at least define and provide context for this term. The Green Revolution is most simply defined as the large increase in crop production across the world, but mostly in developing countries.[3] Historically it is considered the result of the following developments: the hybridization of corn, the nine-fold increase in fertilizer use and the tripling of irrigation post World War II, the rapid spread of new high-yield wheat and rice varieties in developing countries, and the adoption of chemical insecticides, herbicides, rodenticides, and fungicides as the primary tool for pest management.[4] The negative environmental consequences most related to this unit are the increase in fertilizer use, irrigation, and chemical pesticide use. Each of these are discussed in limited detail below. Other environmental consequences include biodiversity loss due to the clearing of forests and conversion of prairies into farmland, and the extermination of predator species to protect livestock.[5]

The Green Revolution and the resulting intensification of agriculture exponentially increased the productive capacity of the world's farms, in part due to the development of synthetic fertilizer. This helped farmers overcome the natural limits of the biogeochemical cycles within their soil. Natural processes only fix so much nitrogen and release limited amounts of available phosphorous for plants to take up, acting as a major limitation on yields. Additionally, the removal of biomass at harvest time limits the amount of carbon that gets recycled back into the soil. But the development of synthetic fertilizers ushered in a new era of nutrient management. Natural fluctuations in nutrient loads lead to inconsistent yields, which are not tolerated in modern agricultural systems. As such, modern management strategies deliver soluble and inorganic nutrients directly to crops in a way that leaves them in a permanent state of nutrient saturation. In addition to this, the previously coupled biogeochemical cycles of nutrients have been uncoupled over both space and time. And while it dramatically increased yields, it also led to the degradation of soil and water resources and the alteration of biogeochemical cycles.[6] The sustainable alternatives presented below aim to reduce the reliance on this practice to restore natural biogeochemical cycles.

Worldwide, agriculture accounts for roughly two-thirds of all water use.[7] Irrigation has been used to turn many low-rainfall areas into agricultural powerhouses; about thirty percent of all the food grown worldwide comes from irrigated land. In several regions, agricultural water use is depleting groundwater at rates hundreds to thousands of times faster than it can be recharged. This excessive water use has severe environmental consequences, including waterlogging and salinization. Waterlogging occurs when soil is saturated to the point where gas exchange between soil and atmosphere is inhibited. This depletes oxygen in the soil and leads to nutrient deficiencies, root death, and reduced growth or even death in plants.[8] Salinization occurs as irrigation water evaporates, leaving behind salts that slowly accumulate over time, diminishing soil productivity.[9] Irrigation is also incredibly inefficient: less than half the water delivered in irrigated systems gets used by plants. The rest runs off, infiltrates, or evaporates. Irrigation isn't just a problem in crop agriculture; in fact, water usage in livestock raising is even more problematic because of wild inefficiencies. Beef production requires about 100 times more water for an equivalent amount of grain.[10]

The impacts of chemical pesticides (which includes herbicides, insecticides, fungicides, and rodenticides)[11] have been well known since at least the 1970s, yet their use has only continued to increase. These environmental impacts include die offs of both target and non-target species which is especially concerning for pollinating and other beneficial insects, contamination of drinking water, the bioaccumulation and biomagnification of persistent organic pollutants through various ecosystems, and links to several types of cancers. Perhaps the most (in)famous environmental legacy of chemical pesticide use was the decline in bird populations caused by DDT chronicled by Rachel Carson in *Silent Spring*.[12] Another lesser-known impact is the development of pesticide resistant target species that leads to what has been termed a pesticide treadmill. More technically speaking, the "exposure to pesticides has led to genetic selection for individuals with the biochemistry or behavior necessary to nullify their toxic effects."[13] The modern industrial agriculture industry has responded not by rethinking the approach to pest management, but by increasing pesticide doses and developing novel pesticides that only continue the selection for genetically resistant pest populations. This leads to further negative environmental impacts but also threatens the economic security of smaller farmers whose margins don't allow for a never-ending increase to their pest management costs, which accelerates the shift toward industrial-scale agriculture that favors this method of pest control over more environmentally friendly approaches.[14]

Sustainable Alternatives to Modern Industrial Agriculture

The primary benefit of sustainable agriculture practices is that instead of working against nature, they use features of nature to their benefit. A shift towards more sustainable agricultural systems should emphasize the restoration of natural ecosystem functioning, including biogeochemical cycling and pest control/management. Each of the following practices favors and fosters these natural ecological processes over human intervention, though such measures are often incorporated as part of the system. Agroecosystems are perhaps the best examples of such sustainable practices, since they often involve one or more of the other examples relevant to this unit.

Agroecosystems

One way of improving the sustainability of agricultural systems is to view them not as a series of inputs (seeds, soil, fertilizer, pesticides) and outputs (crops), but as ecosystems that happen to produce food, fiber, and/or other agricultural products, called agroecosystems.[15] [16] Such systems function somewhere between highly managed modern industrial agriculture (crops, pests, weeds, etc.) and natural ecosystems (a wide variety of wildlife).[17] Figure 1 demonstrates the basic differences between modern industrial agricultural systems and agroecosystems.

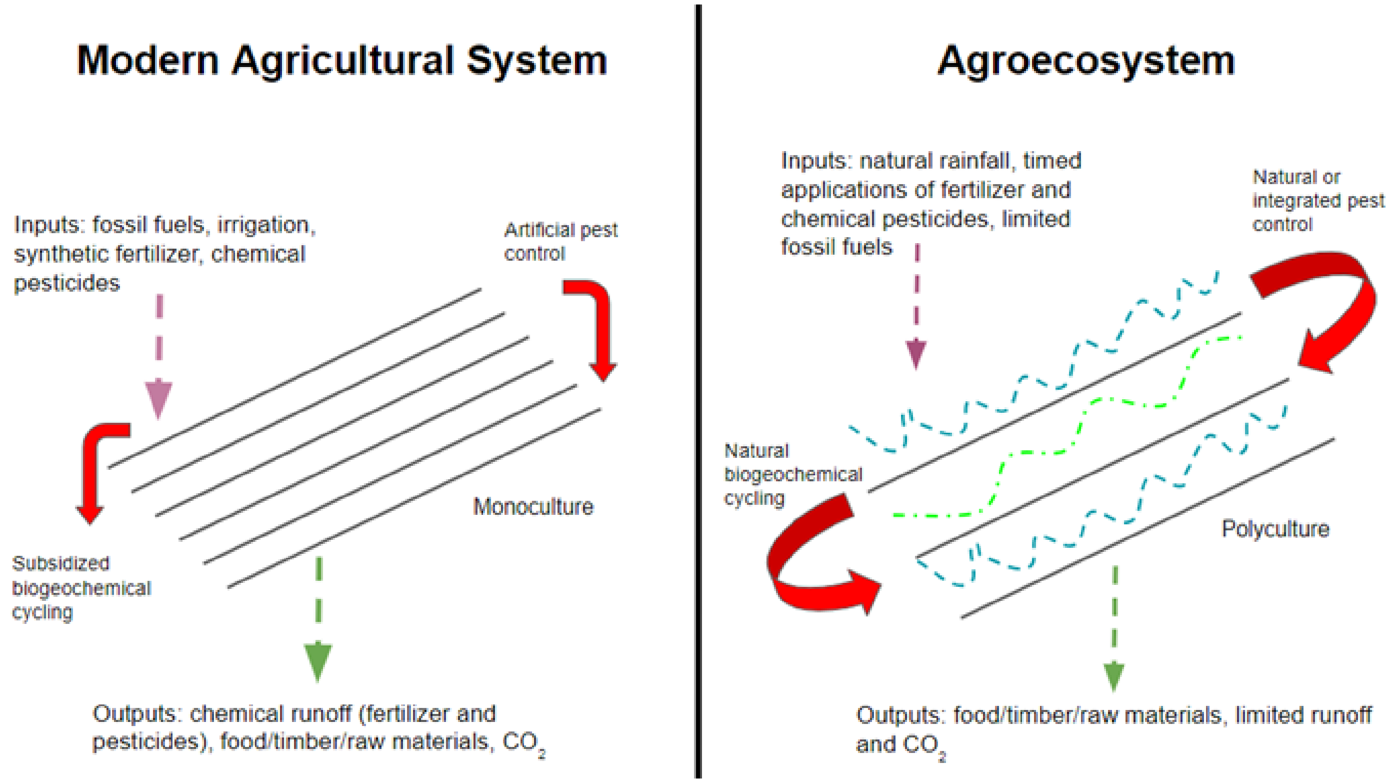

Figure 1: Modern agricultural systems versus agroecosystems.

An easy way of explaining the differences between these two systems is that "one is the expression of imposed will, the other the expression of the land's will."[18] Expressing the land's will in a way that produces food or timber or other raw materials is not an easy task, but through careful design and management, such systems can be productive, stable, and sustainable. Productivity is best expressed in terms of agricultural yield (weight or volume per acre or hectare). Stability in this application is best defined as the consistency of productivity and is subject to disturbance by fluctuations and cycles in the supporting and surrounding environments, such as changes in climate or market demand. Sustainability is the ability of the system to maintain productivity when subjected to a major disturbing force, such as a rare drought, flood, or the emergence of a new pest. A key feature of productive, stable, and sustainable agroecosystems is the ability to withstand stresses or shocks in ways that modern industrial agricultural systems cannot.[19] For example, an agricultural system that relies heavily on synthetic fertilizer cannot maintain its productivity if the price of that fertilizer skyrockets without passing along costs to the consumer. In contrast, a well-designed agroecosystem that relies more on natural biogeochemical cycling and the thoughtful planting of crops with different nutrient demands will be relatively unaffected by more expensive fertilizer. Like their more natural counterparts, agroecosystems are more resilient than industrial agriculture systems.

A critical aspect of the sustainability feature of agroecosystems lies within their nutrient management systems. This is done very differently than modern industrial agricultural systems; instead of oversaturating crops with a synthetic cocktail of soluble inorganic nutrients, an agroecosystem emphasizes organic and mineral nutrient reservoirs that rely on natural microbial and plant-mediated processes. Agroecosystems don't abandon the use of fertilizers all-together, they just get used more strategically. Fertilizer sources are varied and paired with a diverse system of plants that expands the functional roles of plants within the ecosystem.[20] For example, a nitrogen fertilizer might be used to supplement nitrogen demands in a crop system that includes a high-N crop and a N-fixing plant that may or may not be harvested.

In practice, an agroecosystem approach to nutrient management should have the following parameters: the strategic use of a variety of nutrient resources, the ability to maintain reservoirs with long residence times that can be accessed by both microbes and plants, promote the exchange of carbon (C), nitrogen (N), and phosphorous (P) between producers and decomposers, mix inorganic and organic N and P, maximize C-fixation and N and P assimilation over space and time through plant diversity, reduce the overall size of nutrient pools, and promote natural mediation of cycles through plant and microbe activity.[21] This natural approach to nutrient management has shown promise: in systems where natural biogeochemical cycling was restored, yields were maintained, runoff of excess nutrients was decreased, and nutrient uptake by plants and storage in soil microbial pools was more efficient than modern industrial agriculture.[22]

Most of this is not novel – farmers were planting crops in specific rotations or in pairs long before modern industrial agriculture opted for efficiency and increasing yields over ecosystem function. However, much has been learned about the interplay between certain species, and the successful restoration of ecosystem functioning will require more than planting crops in their traditional rotations. In this way, the same push for technological innovation that led to the Green Revolution and all its negative environmental consequences can be applied to develop advances in technology that support the agroecosystem approach.

The concept of agroecosystems is intentionally broad and vague, in part because the development of such systems requires local/regional concerns regarding crop selection. These include economic considerations of demand for products, and environmental considerations of sunlight, water, nutrient availability, soil, and more. As such, the effective design of agroecosystems must consider smaller, more concrete examples of sustainable agriculture, such as integrated pest management, multiple cropping/intercropping, crop-livestock polycultures, agroforestry, and communal resource use.[23] But when designed properly, agroecosystems are able to remain resilient in the face of disturbances, yielding generously and without the depletion and degradation typical of modern industrial agriculture. [24]

Polycultures

Polycultures are simply mixtures of multiple crops planted in the same space at the same time.[25] This is in direct conflict with modern agriculture, which emphasizes monocultures (one-crop systems such as corn, soy, or wheat) for their efficiencies of planting and harvesting. In general, polycultures align well with the core premise of agroecology, and thus have significant environmental benefits, including enhancing soil fertility, soil retention and accretion, climate regulation, natural pollination, pest and weed control, and better aesthetic appeal.[26] Through the intentional planting of crops with different nutrient requirements and the promotion of soil health and natural biogeochemical cycling, polycultures reduce the need for synthetic fertilizer applications. The dense root structures and shading provided by above-ground biomass reduce the growth of nutrient-sapping and light-grabbing weeds, therefore reducing the need for herbicide applications. Those same root structures physically bind soil, holding it in place against wind and water. Rain is more likely to fall on plants’ leaves than exposed soil, promoting infiltration and reducing runoff, even in intense rainfall events. Polycultures are more resistant to pests than their modern industrial agricultural systems for two reasons: first, they offer pests more than one plant to eat, and second, the involve the intentional planting of non-harvested species to attract pests would otherwise feed on the desired crop species.[27] In this way, several different crops may experience some damage, but no single crop will be decimated.

Like with agroecosystems, this practice must be tailored to the local environment. The types of crops grown in polyculture in Delaware must differ from those grown in Kansas and from those grown in Costa Rica or Peru.

Polycultures must be place-based: the species grown in polyculture must fit the biotic and abiotic conditions of their geography. Though this is a challenge (especially for the economic side of agriculture), it is a feature not a bug. Careful observation of natural processes within each of those locations provides the necessary information for effective polyculture design.

For example, a polyculture in Cape Cod includes this use of fish ponds, ground cover provided by vegetable and forage crops, livestock that graze on the groundcover, and several tree species that produce fruit, nuts, timber, and fodder to supplement the livestock's diet. In Costa Rica, some polycultures intentionally change over time. Following a natural clearing of rainforest, ecological succession takes over to begin restoring ecosystem function. Farmers here have closely observed the different stages and began using this knowledge to design crop systems that mimic natural succession. They start with grasses and legumes that grow well in full sun, then add in shrubs and eventually fruit and nut trees. The process starts again once another natural clearing occurs. Meanwhile, the maturing plot can be used to grow shade tolerant crops in polyculture with timber-producing hardwoods. A similar model has been developed for New England, which prior to contact, colonization, and clearing by Europeans starting the 1600s, was a hardwood forest. Successful polycultures here make use of the well-known succession models, and include a tree crop in the overstory, a stable understory that helps retain soil and regulate nutrient loads, a nitrogen source (typically a legume), and livestock to graze/browse and promote nutrient cycling.[28] These specific polycultures reflect the natural environment in which they are located, and the amount of human input necessary to sustain yields is minimized.

Integrated Pest Management

Integrated pest management (IPM) is the "careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment…[It] promotes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms."[29] This emphasis on natural processes makes it an excellent example of the agroecosystem approach.

A good IPM plan has the following goals: reduce pest status, conserve environmental quality, accept tolerable pest densities, and improve net profits from production. In practice, this is done by reducing pest numbers, reducing the susceptibility of the host plant, or some combination of the two. Tactics for achieving these outcomes include preventive practices as a first line of offense and therapeutic practices as a last line of defense. Figure 2 provides a basic visual for an IPM plan.

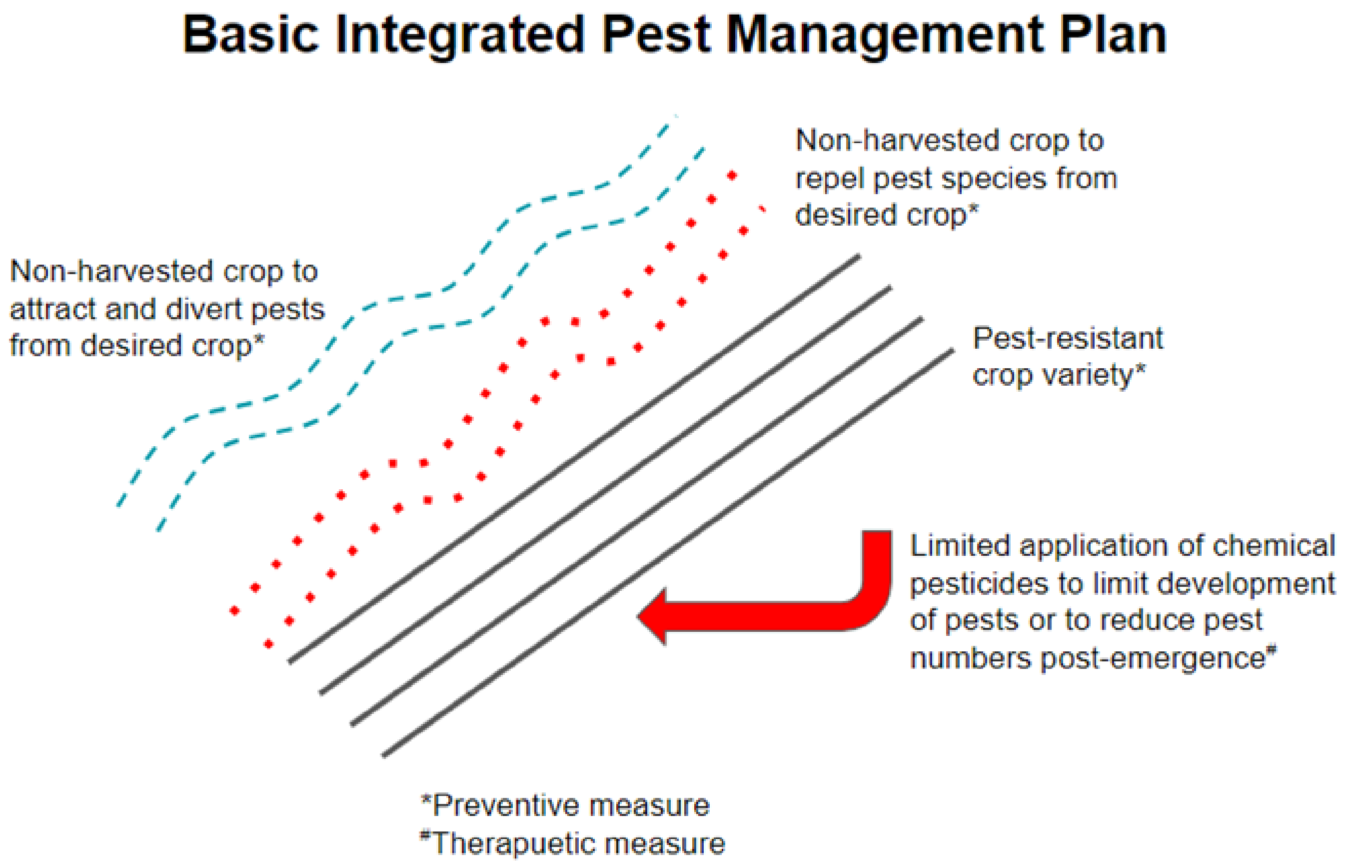

Figure 2: Basic IPM Plan

Preventive practices include biological control, crop rotation, staggered planting dates, trap cropping, spatial arrangement of crops and non-harvested plant species, and the planting of insect-resistant crop varieties. Therapeutic practices include the use of pesticides to kill or disrupt the mating/reproductive cycles. Preventive practices are the foundation of effective IPM plans, and since they don't rely on the use of chemical pest control measures, are what makes IPM sustainable.[30] Therapeutic practices should be used only when preventive practices have failed to reduce pest density or the susceptibility of the host species. However, in practice, most IPM plans have become overly reliant on the use of chemical control measures and thus fail to live up to their sustainable promises.[31] A more thorough investigation into this trend is beyond the scope of this unit, but it is a trend that is worth discussing with students.

An example of an IPM strategy relevant to Delaware is in the management of aphids and hornworms, commonly found in homeowners' backyard gardens. While these pests can be eliminated with chemical pesticides, they can also be managed using biological controls. Planting flowering native plants in proximity provides resources for beneficial insects, including wasps or flies that help control the population of aphids and hornworms. The use of chemical pesticides then becomes a supplementary step if biological control fails to reduce the pest population to acceptable levels.[32] On a larger scale, corn farmers can reduce the impact of aphids by creating edge habitats along their fields where native plants flourish and provide habitat for those same beneficial insects, and by *reducing* their insecticide use since their use also kills the aphids' natural enemies and contributes to the selection for pesticide resistance within the aphid population that survives.[33]

Case Studies of Sustainable Agriculture

The technical information presented above means very little to students without context. Therefore, it is appropriate to provide examples of how these practices function in the real world. Connecting these practices to agroecosystems that students have interest in (coffee and cacao) is an excellent way of increasing student engagement and showing them that Indigenous knowledge that makes chacras productive agroecosystems can be a powerful learning experience because it demonstrates that knowledge exists outside Western institutions and experiences. My passion and interest in this area will hopefully inspire students to learn about them more deeply and promote long-term knowledge retention.

Coffee

Coffee is an excellent polyculture crop because of its unique abiotic and biotic growth conditions. The basics of how coffee functions in such an agroecosystem are represented in an oversimplified manner in Figure 3 and are discussed more deeply below.

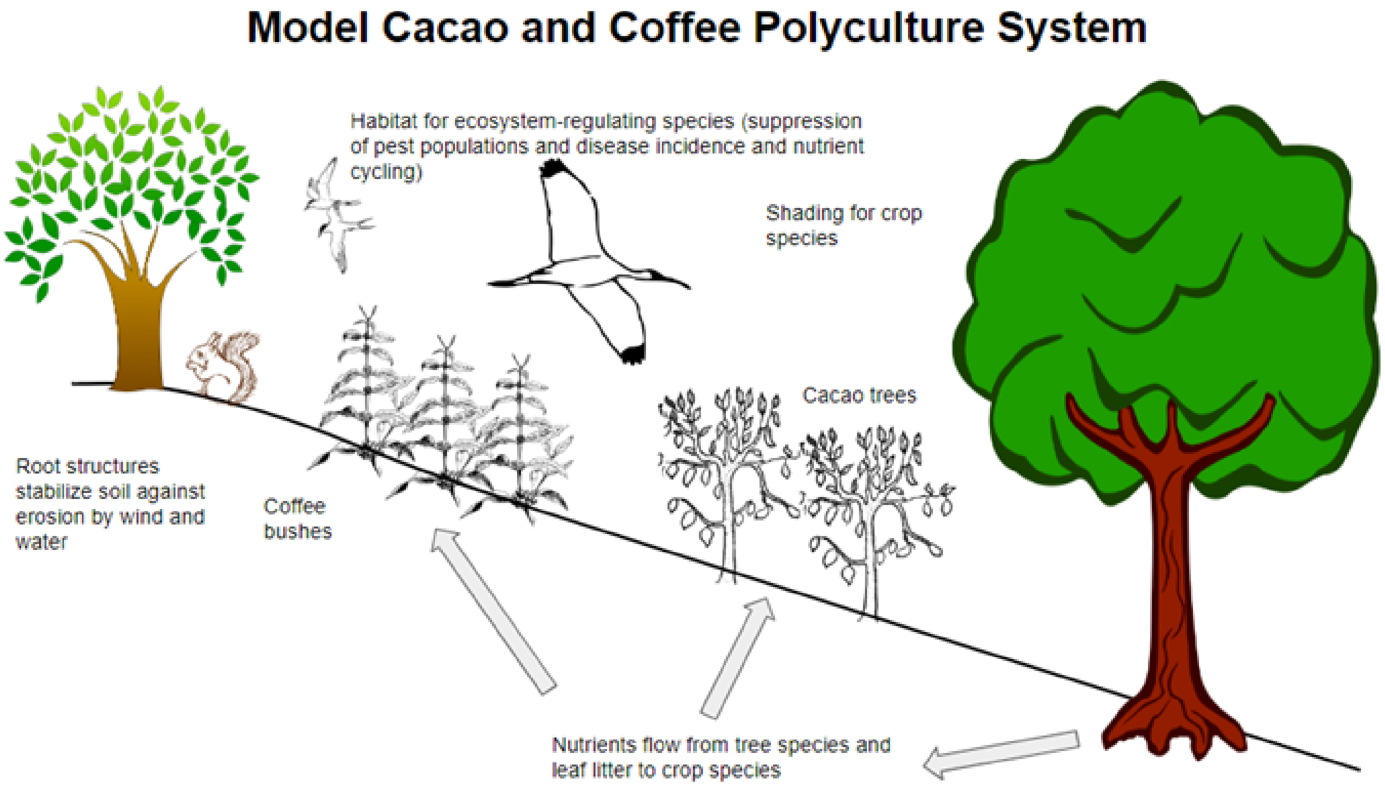

Figure 3: Coffee/cacao polyculture with coffee bushes, cacao trees, and miscellaneous hardwood/citrus trees and regulating services.

Coffee bushes require shade from the intense tropical sun. The growing of fruit and timber species as part of an agroforestry system provides the coffee bush the shade it needs. Additionally, coffee polycultures also benefit from pollination, pest control, and nutrients from decaying leaf litter. Research has shown that the presence of bird species in coffee agroecosystems reduces the incidence of yield-reducing pests. Other complex interactions within the coffee agroecosystem include the suppression of coffee rust, a serious fungal infection that resembles rust on the leaves of the coffee bush. This happens via a mutualistic relationship between ants and other insects.[34] These natural pest control measures highlight the resiliency of well-developed and managed coffee agroecosystems that emphasize natural ecosystem function and regulation over human intervention.

Additionally, coffee agroecosystems benefit from the presence of nitrogen-fixing plants, including *Cordia alliodora* (commonly known as Spanish elm or Ecuador laurel) and several *Erythrina* species (a genus of plants in the pea family). The consistent litterfall provided by these trees and symbioses with soil-dwelling bacteria provide natural sources of nitrogen. This reduces the amount of nitrogen losses to leaching. The soil organic material that develops over time provides nutrients, including carbon, nitrogen, potassium, calcium, and magnesium, in the correct proportion. In addition to providing shade and nutrients, the presence of these tree species also provides a potential income source through the sale of timber products.[35] Successful coffee polycultures integrate traditional knowledge and biodiversity conservation initiatives and protect local farmers' autonomy.[36]

Cacao

Cacao is an excellent crop to grow in polyculture as a part of a larger agroecosystem, as it is an under-story tree that requires shade and shelter from the intense rainfall typical of the tropics, as well as nutrients from leaf litter on the forest floor. This is represented in Figure 3 above. Growing cacao in this way also helps attract beneficial insects (for pollination and pest control) and provides a diverse habitat for many different species. This also minimizes traditional agricultural inputs, including synthetic fertilizers and fossil fuels. Other crops that can be grown in this agroecosystem include fruits, spices, root crops, timber, and medicinal plants, which sustains cash flow for cacao farmers.[37] Like coffee, cacao agroecosystems benefit from the presence of *C. alliodora* and *Erythrina* species in numerous ways, including the shade they provide and their delivery of balanced nutrient loads.[38] Research has shown that cacao agroecosystems that rely on natural ecosystem functioning perform on par with those that are intensively managed with pesticides and fertilizers but are more resilient in the face of ecological pressures like pest infestations.[39] As with coffee agroecosystems, the success of cacao-producing systems based on natural ecological function should serve as a model for the effective design of other agroecosystems.

Chacras

Farming in the Amazon rainforest has a well-studied legacy of environmental damage and disruption. At the forefront of this legacy are shifting cultivation and slash-and burn agriculture, both of which threaten the preservation of the rainforest and the health of the local environment.[40] Although there is an abundance of plant and microbial life in the rainforest ecosystems, their soil is quite nutrient-deficient. Because of this, farming in the region often involves the clearing of forest, burning the remaining vegetation, raising crops or livestock until the soil is too depleted to continue, and then moving on to the next plot of land and repeating. These practices cause and accelerate deforestation, biodiversity loss, soil erosion, changes to local hydrology, and decreased food security for local populations.[41]

However, Indigenous people have been successfully farming in this ecosystem for thousands of years without causing such widespread environmental damage. This is in part due to the small scale of their operations, but also because they embrace the agroecosystem approach (and were doing so long before this was a term). In northeastern Peru in the Amazon Rainforest, Maijuna people have been successfully cultivating yuca, sugarcane, banana, plantain, and even cacao in small clearings in the forest called "chacras," an Andean term meaning farm or agricultural field. These chacras are even better embodiments of agroecosystems than cacao or coffee because they operate on smaller scales and are typically family operated. They are most often located near primary or secondary forests, forming a productive and ecologically friendly landscape that works within the biodiversity of the area. Chacras are true polycultures, as they combine the cultivation of local staple crops with medicinal plants and timber species. This agroecosystem requires no additional inputs – just sunlight and rainfall. It functions as part of the forest ecosystem, not separate from it.[42]

These chacras are essential to Indigenous people because they provide food security, medicine, and building materials to the community, and in some cases allow for trading and export (as is the case with cacao).[43, 44] This example of sustainable agriculture holds special importance to me because I was lucky enough to visit a chacra in the Sucusari region of the Amazon rainforest in Peru, where I learned from members of the local Maijuna community. Sharing and elevating Indigenous knowledge is a goal of mine as I continue to develop the environmental science program at my school, especially in the introductory and intermediate courses.

Teaching Strategies

My teaching philosophy is grounded in helping students see the world as scientists. I have found that this requires reframing students' views of science not simply as a body of isolated facts, but as a systematic way of making observations, explaining phenomena, and acquiring new knowledge. The National Research Council (NRC) lays out a framework that ensures students have authentic scientific experiences in their classrooms even as they learn content-specific information. This framework "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."[45] This dual focus on process and content improves upon previous practices that reduced scientific procedures to isolated aims of instruction, rather than a vehicle for developing a meaningful understanding of true scientific concepts.

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 aligned with pedagogical best practices on marrying process and content in science classrooms. These new 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 which time allowed. However, since the redesign I have begun using strategies that better engage students in specific Science Practices. This allows them to hone their scientific skills while simultaneously covering a great deal of content. In this unit, students use several different Science Practices to study how treating agricultural systems as ecosystems can help lessen the environmental impacts of the agricultural industry and restore ecosystem functioning and health. Additionally, the content of this unit can be easily scaffolded to meet the standards of the introductory and intermediate environmental science courses we offer at WPHS.

Hands on Learning through AP-ES Science Practices

My role as a teacher is closer to that of a facilitator than that of a provider of information and correct answers.

Throughout my career I have developed a teaching toolkit full of strategies that get students doing science rather than simply learning it, and that toolkit now contains several Science Practice-aligned strategies. In this specific unit, I ask students to explain environmental concepts, processes, and models through written expression, identify a testable hypothesis or scientific questions for an investigation, describe environmental problems and potential responses/approaches to those problems, and propose, evaluate, and justify solutions to environmental issues. The strategies presented below foster the use and development of these skills in students.

Modelling Scientific Processes

Perhaps my most-used teacher strategy across all my classes is model development. It is not uncommon for me to ask students to model a process or phenomenon on the day it gets introduced. Doing this early gives students an opportunity to establish a baseline of knowledge and then start to identify gaps in their understandings, ask questions about the process, and design investigation to answer those questions and develop a more comprehensive understanding of the process in question. As students obtain new information through reading, investigating, collecting data, etc., they return to their model and update it. Fostering this iterative approach starts by stressing to students that their models need not be works of art. I alleviate a lot of their concern by showing them my sketches and drawings and encouraging them to simply focus on the science being communicated by the model. Early in the school year I provide students with a significant amount of scaffolding for models. I steadily reduce the amount of support as the year progresses. In the context of this unit, if we were tackling the concept of polyculture in coffee/cacao systems early in the year, I might provide students with a template of Figure 3 that includes the trees, crops, soil, and organisms and simply ask them to fill in the text and draw some arrows. But since this unit occurs later in the year, students are responsible for creating the entire model themselves.

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 the development of higher 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 timely feedback. Working collaboratively has the added benefit of exposing students to diverse perspectives and prepares them for real life social and employment scenarios. Two ways that I plan to foster collaborative learning in this unit is through guided inquiry activities and the use of case studies where students must present their findings as a team.

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 - 20 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 and post them to our learning management system for students to review later.

Class Discussions: Connecting Science to the Human Experience

A new strategy that I am excited to try out as part of this unit is to connect science with the student experience. The primary goal of this discussion-based strategy is to develop some empathy by connecting the science of agroecosystems with the farmers who use agroecology to produce food, medicine, and other raw materials for use around the world. Using this strategy effectively requires students to come prepared after having read relevant text or watched relevant content, a dynamic plan with some overarching questions and/or goals, a willingness to let student interests drive the discussion forward, a cohesive classroom community, and a commitment to some discomfort. Allowing for debrief time is critical to connecting discussion content back to specific science concepts.

Classroom Activities

Students are introduced to this unit with an overview of the Green Revolution and its impact on the environment. This is done via textbook readings and direct instruction. Students then explore the concept of agroecosystems through a variety of more interactive activities.

Driving Question Board (Day 1)

Students are first introduced to the concept of modern industrial agriculture and agroecosystem alternatives by being shown side-by-side pictures. They record what they notice and wonder about the images they see. The goal is for students to recognize, independent of teacher input, that the agroecosystem approach is more in line with natural systems. Keen students will recognize that modern industrial agriculture systems have very little natural biogeochemical cycling and pest control measures, while agroecosystems embrace and harness those natural processes. My role as a teacher is to honor all observations and questions at first, then to steer the conversation towards those key differences. This is done by thoughtful probing of student responses. For example, a student may observe that “there is only one crop planted in a modern industrial agriculture system compared to several in the agroecosystem.” A probing question to that student would be “why might an agroecosystem be designed around multiple plants?” or “what benefits does the modern agriculture system have by just being one crop?” This goes on until students reach a certain level of understanding of the differences.

Once enough of the students have at least a basic understanding, they can begin asking testable questions about what they see - this means no yes-or-no questions. Guiding this activity takes a great deal of patience, and if done early in the year, a lot of scaffolding and modeling. However, students will be well-versed in the activity by the time they reach this unit. They start by writing as many testable questions as they can over three minutes. Students then turn to share with a neighbor and add to their list of questions: partner A records partner B’s questions and partner B records partner A’s questions. Then through thoughtful discussion, partners A and B decide on their top three questions they want answers to. These questions are transferred to a public space in the classroom such as the chalkboard, chart paper, or a shared Google Slide. As a class, we organize and categorize questions by common themes. In this case, questions should fall into categories on nutrient management, pest control, and yield/economic considerations. These categories then become larger testable questions that students can investigate.

Student Inquiry and Model Development (Days 2 and 3)

Once students have established testable questions, they are tasked with finding answers to those questions. In this way, students in my classroom are “doing science,” not just learning science. Students work in small groups to answer individual questions, then share information with the group to build a collective understanding. It is best to have multiple groups working on overlapping questions. This serves two purposes: first, it lowers the chance that inaccurate information gets incorporated into the class’s common understanding of the phenomenon, and second, it fosters discourse between groups that arrive at different conclusions. This helps students practice the art of disagreement, which in addition to being a valuable skill in science is a good skill to have in life. In this case, student groups focus on questions of nutrient management, pest control, and yield/economic considerations. They have access to specific resources posted in our learning management system, including excerpts and the case studies from the Content Objectives section above, the resources cited in this unit, and other relevant internet resources. Students mine and annotate these resources for information related to their specific questions.

As students collect information related to their specific scientific question, they are gaining a piece of the larger puzzle that helps explain, citing evidence, why agroecosystems are more sustainable than modern industrial agriculture. They may also encounter contrary information, especially when it comes to yield and economic considerations. Such information is an important part of the puzzle since many phenomena have multiple facets and cannot be presented one “correct” way. Once students have enough information related to their specific question, they share it first with any other groups focusing on the same question, then the larger class community. After information has been shared, students are tasked with creating a detailed model demonstrating the differences between modern industrial agriculture and agroecosystems (like the ones presented in Figures 1 and 3). Students start by drawing an initial model in their notebook. Students then discuss their model in small groups. This gives them the opportunity to ask questions of one another and seek out additional information where needed. Then they revise/update their model to include any new information or components they may have been missing and write an explanatory caption.

Recommending Agroecosystem Approaches on Penn Farm (Days 4 and 5)

Once students understand the sustainable aspects of agroecosystems, the goal is for them to transfer/apply them to a portion of the school’s farm. This starts with a walking tour of the farm where students make careful observations of elements of either modern industrial agriculture or the agroecosystems we just learned about. Then, after discussing the farm’s operations with the farm manager, students work to identify areas of need that they can address using principles of agroecosystem. The goal is to pitch these improvements to the farm manager and plant science program and then implement any feasible and low-cost sustainable practices. Students can also put together a plan to present to the school board to raise funding for the implementation of any higher cost practices they identified. While the recommendations students make are ultimately up to them and their observations, I anticipate recommendations around improving the farm’s IPM plan and planting more polycultures.

Enrichment Activity (Day 6)

In addition to the environmental benefits of agroecosystem approaches to agriculture, I want students to see that such systems produce high quality food products and sustain local economies in a way that modern industrial agriculture does not. This activity is broken down into two parts. First, students will research the concept of fair-trade coffee and cacao agriculture and its impacts on local economies. They will compare this to the systems that produce typical coffee and cacao products. Activities such as this provide a human connection to science – we aren’t just working to reduce the impacts of humans on the planet, but to improve the living and working conditions for people all over the planet.

The second part of this activity includes blind taste-tests of coffee and cacao products from sustainable and fair-trade agroecosystems in Costa Rica with modern brands. I expect students to initially favor the sugar-laden modern brands over the less processed Costa Rican varieties. However, I hope to use this activity to open a dialogue about the nature of modern food systems and its impact on food quality and consumption behaviors, which will lead us into a separate unit on ecological footprints.

Appendix on Implementing District Standards

This unit satisfies AP-ES standards EIN-2 (when humans use natural resources, they alter natural systems) and STB-1 (humans can mitigate their impact on land and water resources through sustainable use). Standard EIN-2 is satisfied when students read and take interactive lecture notes on the impacts of the Green Revolution. Standard STB-1 is satisfied when students complete the Driving Question Board and conduct their research and develop models on agroecosystems. Additionally, students use the following Science Practices as described in the Course and Exam Description: 1.C (explain environmental concepts, processes, or models in applied contexts), 4.A (identify a testable hypothesis or scientific questions for an investigation), 7.A (describe environmental problems), 7.B (describe potential responses/approaches to those problems), and 7.E (make a claim that proposes an environmental problem in an applied context). Practice 1.C is used as students develop, share, and refine their models of agroecosystems. Practice 4.A is used as students conduct research on the sustainable aspects of agroecosystems. Practice 7.A is used as students read and discuss the Green Revolution. Practice 7.B is used as students conduct and share their research on agroecosystems. Practice 7.E is used when students work to propose sustainability improvements to Penn Farm.

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This is a good teacher resource with information on ecosystem functioning within coffee agroecosystems.

Arevalo, V, J Grijalva, R Limongi, R Vera, and A Yumbo. 2011. “Chacras Nativas: Alernativa de Sistema Integrado Para Seguridad Alimentaria, Biodiversidad y La Gestion Sostenible de Bosques En La Amazonia Ecuatoriana.” Quito. http://181.112.143.123/bitstream/41000/2827/1/iniapsc322est.pdf.

This is an excellent teacher resource for learning more about chacras from an ecological and cultural perspective. Originally published in Spanish.

Arias Gutierrez, R, T Carpio Arias, A Herrera Sorzano, and R Gonzalez Sousa. 2016. “SISTEMA INDÍGENA

DIVERSIFICADO DE CULTIVOS Y DESARROLLO LOCAL EN LA AMAZONIA ECUATORIANA.” *Cultivos Tropicales* 37 (2): 7–14. https://www.redalyc.org/journal/1932/193246554001/movil/.

This is another excellent teacher resource for learning about chacras. Also originally published in Spanish.

Beer, John. 1988. “Litter Production and Nutrient Cycling in Coffee (Coffea Arabica) or Cacao (Theobroma Cacao) Plantations with Shade Trees.” *Agroforestry Systems* 7 (2): 103–14. https://doi.org/10.1007/BF00046846.

Good teacher resource on learning about the biogeochemical cycling within coffee and cacao plantations. Certain excerpts can be modified for student use.

Benyus, JM. 1997. *Biomimicry: Innovation Inspired by Nature*. 1st ed. New York: William Morrow.

Seminal reading on all things biomimicry. This is a good teacher and student resource, though certain passages will likely need to be modified for student use.

Carson, R. 1962. *Silent Spring*. Boston, MA: Houghton Mifflin.

Widely regarded as one of the best, or at least most influential, science books of the twentieth century. The book documents the environmental impacts of the widespread use of chemical pesticides. Its publication is considered by many to be a pivotal moment in the environmental movement.

Conway, Gordon R. 1987. “The Properties of Agroecosystems.” *Agricultural Systems* 24 (2): 95–117. https://doi.org/10.1016/0308-521X(87)90056-4.

Good teacher and student resource for a foundational understanding of what agroecosystems are.

Drinkwater, L. E., and S. S. Snapp. 2007. “Nutrients in Agroecosystems: Rethinking the Management Paradigm.” *Advances in Agronomy* 92 (04): 163–86. https://doi.org/10.1016/S0065-2113(04)92003-2.

Good resource for teachers and students when learning about the impacts of the Green Revolution on soil and soil fertility, as well as how the agroecosystem approach restores some natural functions and features of soil.

FAO. 2023a. “Integrated Pest Management.” Agriculture. 2023. https://www.fao.org/agriculture/crops/thematic-sitemap/theme/pests/ipm/en/.

Good student resource for being introduced to the IPM concept.

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Felsot, A. 2018. “Integrated Pest Management: Strategies for Pollinator Habitat Promotion and Conservation in Agricultural Areas.” US EPA Pollinator Protection. 2018. https://www.epa.gov/pollinator-protection/integrated-pest-management-strategies-pollinator-habitat-promotion-and.

Excellent teacher resource for learning about IPM. Some slides/images/diagrams can be used with students.

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

Course textbook - this serves as students' introductions to concepts that we cover in class. It is also good resource for teachers when considering planning and pacing.

Graber, David R., Walter J. Jones, and James A. Johnson. 2005. “Human and Ecosystem Health: The Environment-Agriculture Connection in Developing Countries.” *Journal of Agromedicine* 9 (2): 129–46. https://doi.org/10.1300/J096v09n02_08.

Good teacher resource with easily adaptable sections for student use when learning about the environmental impacts of the Green Revolution and modern industrial agriculture.

Horrigan, Leo, Robert S. Lawrence, and Polly Walker. 2002. “How Sustainable Agriculture Can Address the Environmental and Human Health Harms of Industrial Agriculture.” *Environmental Health Perspectives* 110 (5): 445–56. https://doi.org/10.1289/ehp.02110445.

Good teacher resource for an introduction to how sustainable agriculture and the agroecosystem approach can alleviate the impacts of modern industrial agriculture.

Knight, Alan L, and George W Norton. 1989. “Economics of Agricultural Pesticide Resistance in Arthropods” 34: 293–313.

Good teacher resource for understanding the pesticide treadmill and the dangers it poses. While not necessarily student-friendly, showing students the date may help drive home the idea that this issue is widely recognized in the agricultural world and should command more policy attention.

McDonald, G. 2021. “Waterlogging – the Science.” Managing Soils. 2021. https://www.agric.wa.gov.au/waterlogging/waterlogging-–-science.

Clear and concise teacher and student resource for understanding waterlogging and its environmental consequences.

McSorley, R. 2008. “Polyculture.” *Encyclopedia of Entomology*. https://doi.org/10.1007/978-1-4020-6359-6_3039.

Clear and concise teacher and student resource for a basic understanding of polycultures.

Moura, Emanoel Gomes de, Christoph Gehring, Heder Braun, Altamiro de Souza Lima Ferraz Junior, Fabricio de Oliveira Reis, and Alana das Chagas Ferreira Aguiar. 2016. “Improving Farming Practices for Sustainable Soil Use in the Humid Tropics and Rainforest Ecosystem Health.” *Sustainability (Switzerland)* 8 (9): 1–22. https://doi.org/10.3390/su8090841. 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 Acadmies Press. https://doi.org/10.17226/13165.

Excellent resource for teachers new to NGSS or wanting to understand more about the pedagogy behind

NGSS-aligned instruction. This is a must read for science teachers of all levels and contents.

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Another excellent teacher resource for understanding ecosystem functioning with coffee agroecosystems. Sections could be adapted for student use.

Sabatier, Rodolphe, Kerstin Wiegand, and Katrin Meyer. 2013. “Production and Robustness of a Cacao Agroecosystem: Effects of Two Contrasting Types of Management Strategies.” *PLoS ONE* 8 (12): 1–10. https://doi.org/10.1371/journal.pone.0080352.

Excellent teacher resource for understanding ecosystem functioning within cacao agroecosystems. Sections could be adapted for student use.

University of California IPM Program. 2008. “Aphids.” Agriculture: Corn Pest Management Guidelines. 2008. https://ipm.ucanr.edu/agriculture/corn/aphids/.

Excellent website for teachers and students to understand the level of specificity required when developing a tailored IPM plan.

University of Delaware Cooperative Extension. 2023. “Beneficial Insects.” Pest Management for Homeowners. 2023. https://www.udel.edu/academics/colleges/canr/cooperative-extension/environmental-stewardship/pest-management-homeowner/benefcial-insects/.

Another excellent websire for teachers and students when learning about IPM. Cooperative extension services such as this one are an underutilized resource for homeowners and property managers, but well-recognized in the agricultural community.

Weißhuhn, Peter, Moritz Reckling, Ulrich Stachow, and Hubert Wiggering. 2017. “Supporting Agricultural Ecosystem Services through the Integration of Perennial Polycultures into Crop Rotations.” *Sustainability (Switzerland)* 9 (12). https://doi.org/10.3390/su9122267.

Good teacher resource with information about the basics of agroecosystems and polycultures. This resource pairs well with Chapter 2 of the Biomimicry book.

Whinney, J. n.d. “Considerations for the Sustainable Production of Cocoa.” Smithsonian Migratory Bird Center. Accessed July 16, 2023. https://nationalzoo.si.edu/scbi/migratorybirds/research/cacao/whinney.cfm.

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Endnotes

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[1] (Benyus 1997)

[2] (Friedland and Relyea 2019)

[3] (Friedland and Relyea 2019)

[4] (Graber, Jones, and Johnson 2005)

[5] (Friedland and Relyea 2019)

[6] (Drinkwater and Snapp 2007)

[7] (Horrigan, Lawrence, and Walker 2002)

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[9] (Horrigan, Lawrence, and Walker 2002)

[10] (Horrigan, Lawrence, and Walker 2002)

[11] (Friedland and Relyea 2019)

[12] (Carson 1962)

[13] (Knight and Norton 1989)

[14] (Friedland and Relyea 2019)

[15] (Benyus 1997)

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[33] (University of California IPM Program 2008)

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