VISION AND APPROACH

In the last 50 years, the doubling of the production of coffee (*Coffea arabica*), the world's most traded tropical agricultural commodity[1], through intensification and expansion into previously forested areas[2] has led to severe environmental degradation, economic hardship, and social crises. Conversion of forest to coffee causes loss of biodiversity, increases in carbon emissions, soil erosion, runoff, and severe regional water shortages. Processing pollutes water from coffee pulp waste[3] and causes further deforestation from harvesting of fuel wood to dry beans[4]. Coffee yields are susceptible to pest outbreaks and weather, and the global market price of coffee fluctuates wildly often dropping below production costs[5]. About 70% of the world's coffee is produced by small-scale farmers in low- and middle-income countries[6], whose vulnerability to volatility in price and yield results in social and economic hardships including poverty, poor health, and child labor; problems that are exacerbated by gender inequality and often lead to emigration and unstable rural communities[7]. The coffee sector's extractive model of production, in fact, relies on rural poverty, devalued labor, continued depletion of natural resources and marginalization of producers[8]. Demand for coffee is expected to at least double again over the next 30 years while climate change is predicted to reduce the area suitable for coffee cultivation, and negatively impact yields through bolstering coffee pests, drought, and intense rain events[9]. The coffee sector has acknowledged the problem and Conservation International initiated a "Sustainable Coffee Challenge" where many major resellers have pledged to expand their sustainable sourcing of coffee[10]. Solutions, however, remain elusive[8]. Interventions to produce coffee in a more sustainable way generally focus at the farm scale and do not influence the sustainability of other links in the value chain, like processing, trade and consumption or address regional- and global-scale sustainability[8]. Achieving sustainability in the coffee sector will require participatory and multidisciplinary approaches[11] that apply systems-thinking to coffee production to design, integrate, and evaluate the potentially complementary and dynamic effects of social, technological, economic, and environmental interventions at multiple scales.

More generally, there is a pressing societal need for food systems that are sustainable in all dimensions: profitable for producers (economic sustainability), beneficial to local communities and global society (social sustainability) and have a positive or neutral impact on the natural environment (environmental sustainability)[12]. The development of sustainable food systems is a challenge that requires convergence research with participation from all stakeholders and innovations at multiple scales (local, national, regional and global) and on multiple fronts including agriculture, engineering and technological innovation, trade, policy, health, environment, gender norms, education, transport, and infrastructure[12]. Our long term goal is to develop a unifying framework for convergence research, based on socio-ecosystems modeling, to integrate the goals of a diverse group of stakeholders and researchers. Our objective in this proposal is to use this framework to design and assess the dynamics of a coffee production system that will be environmentally, economically, and socially sustainable at multiple scales and resilient to climate change. A systems model will allow for ex-ante identification of synergies, tradeoffs, and vulnerabilities that will facilitate adaptations of the system prior to and during implementation.

We use the theory and infrastructure of socio-ecological systems[13] within a recently developed Multi-Scale Ecosystem Framework[14], which employs ecosystem principles to integrate across sustainability dimensions and multiple scales. Our approach will consist of a set of steps with adaptive feedback in which we: (1) Assemble a core team of researchers and stakeholders; (2) Identify a set of goals for the system that span all dimensions of sustainability: economic, social, and environmental; (3) With full participation of the stakeholders, construct a multi-scale conceptual socio-ecological model of the food production system. This requires identifying the necessary structural elements at all relevant scales, the inter- and intra- scale interactions among those elements, and ecosystem and social services at multiple scales; (4) Develop a set of quantitative indicators at multiple scales that represent the different components of sustainability; (5) Measure baseline values and establish the functional relationships between elements of the system; and (6) Construct and parameterize an empirical, multi-scale, ecosystem model and use the model through scenario testing and optimization to identify tradeoffs, synergies and critical points among sustainability indicators at different scales and dimensions (Fig. 1).

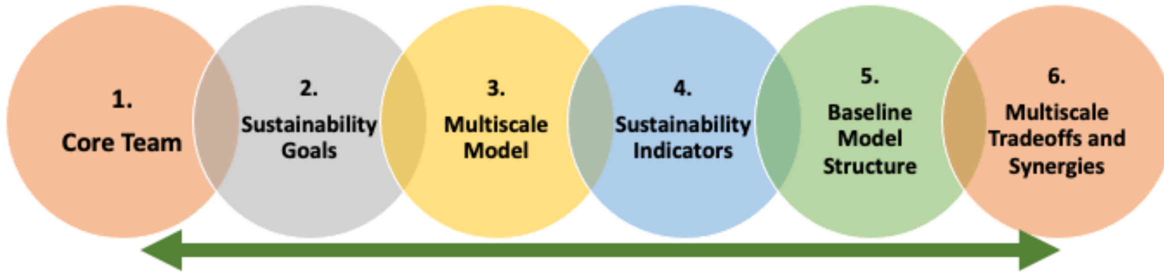

Figure 1. Ecosystems Approach to Designing Sustainable Food Systems

We have formed the core of our convergence research team and made considerable progress towards initial design of a sustainable coffee production system. In phase one of this research, our goal is to evaluate how regional and global conditions affect the social, economic, and environmental sustainability at the scale of an individual farm that uses our design. At the same time, we will use the research as a vehicle for two-way interaction in which we incorporate more farms and local stakeholders into the system and modify the system design based on ideas, feedback and research results. Our goal in phase two is to, through synthesis, study inter-scale and emergent properties of sustainable coffee systems and evaluate system resilience to exogenous changes in climate and markets. During this phase, we will be designing, testing, and implementing new technological and social components of the system.

Appropriateness for GCR: Sustainability of food systems is emerging as a pressing societal issue that is too complex to address using traditional approaches. This complexity is due to multiple scales and interactions of the dynamic system. Convergence research is required to identify innovative approaches that often lie at the interface of agriculture, ecology, economics, engineering, social sciences, and management disciplines. Traditional approaches to food sustainability have failed in attempts to find comprehensive solutions as there is a need for deep integration of multiple disciplines and participation from all stakeholders. Our research goes beyond the normal interdisciplinary problems that might be funded by other NSF programs as we will use the tools of Socio-Ecological Systems, extended to a Multiscale Ecosystem Framework to grow a convergence research community of conservation biologists, ecologists, agronomists, farmers, indigenous peoples, economists, social scientists, land managers, and engineers who will collaborate and co-design a coffee system that will enhance biodiversity conservation and promote sustainable livelihoods.

EXPECTED SIGNIFICANCE

The sustainability of smallholder agroforestry is critical to addressing global environmental challenges. Sustainable agroforestry practices can reduce poverty[16], create carbon sinks, enhance the environment[17], and improve community welfare and women empowerment[18,19]. There is a critical need to harmonize agriculture and natural ecosystem interactions with economics, technology, and social conditions to create opportunities that capture synergies among sustainable development goals and address trade-offs[20]. This need requires convergence research - a deep integration of scientific and engineering disciplines as well as participation by all stakeholders[11]. One fundamental challenge is providing a framework to facilitate convergence, and another is to account for disparities between scales of management and scales of ecological processes. Failure to account for multiple scales results in decreased resilience, mismanagement, and reduced well-being[21,22]. Socio-ecological systems[13] have been effective in conceptualizing multiple interactions and in evaluation of governance regimes. Research into addressing emerging issues in sustainable agriculture is constrained by lack of consideration for multiple scales[23] and evaluation of impacts from external stressors. Further, much of the research in sustainable agroecosystems has focused on existing systems rather than on development of new and innovative systems that recognize interdependencies between scales and global stressors, especially globalization[14] and climate change[24]. A multiscale approach that connects ecosystem processes with governance is vital to addressing key problems facing agroecosystems[14]. The understanding of scale in scientific assessment of these socio-ecological systems[25] remains limited as these form complex adaptive systems[26] that require convergence of multiple research strands and disciplines. PI Randhir has developed a Multi-Scale Ecosystem Framework, an extension to socio-ecological systems, which uses ecosystem principles to integrate across sustainability dimensions and multiple scales[14,15]. This proposal will address a fundamental challenge in sustaining food systems by developing a multidisciplinary framework to grow a convergence research community around designing a solution to a multiscale, multi-dimensional, complex societal problem. Our proposal is unique in incorporating multiple dimensions of both sustainability and scale that are vital to achieving sustainable outcomes in food production. The overall significance of this proposed work is twofold. First, we will address a critical societal problem and design a system for sustainable production of coffee using conceptual and empirical modeling as a means to converge researchers and stakeholders. Second, we will fill a gap in sustainability science by promoting this framework - the use of a multi-scale socio-ecosystems modeling - as a tool to organize and structure the convergence research necessary to design sustainable food systems.

Individual project components will also have significant impacts. We will develop a new framework for evaluating landscape scale environmental sustainability that integrates biodiversity and water conservation, and we will examine the effects of multiple ecosystem services, including water availability, pollination by native bees, insect pest control by birds, and a novel hypothesized service that forest may act as a physical buffer, mitigating the spread and incidence of fungal pathogens on coffee. Through choice experiments, we will parameterize links between marginal changes in quality of life, and the probability of adopting sustainable production methods and learn how coffee and carbon offset markets respond to adoption of sustainable practices. We will develop and design novel environmentally friendly technologies for coffee processing and an innovative and cost-effective methodology for verification of carbon offsets.

BACKGROUND AND PRIOR WORK

The problem: About 70% of the world's coffee is produced on working landscapes at high altitudes on formerly forested land, primarily by small-scale, family farms in low- and middle-income countries[6]. In many of these places, coffee production is the principal source of economic activity, yet conventional methods of coffee production combined with yield and market volatility have resulted in interlinked problems of environmental degradation, economic hardship, and social crises. Forest ecosystem services at multiple scales have been compromised by deforestation due to land clearing for coffee plantations and forest degradation due to harvesting of wood to fuel drying of coffee[4]. At the global scale, deforestation reduces carbon sequestration and threatens biodiversity as much of the tropical forest that is being displaced and fragmented by coffee is located in biodiversity hotspots. At a regional or watershed scale, clean abundant water is a key ecosystem service provided by forests to towns and cities that is compromised by conventional coffee production. As forests are converted to coffee plantations, water holding potential is lost, resulting in increased runoff and erosion during rainy periods and water shortages during dry periods[27–29]. Increased runoff leads to lower water quality from increased sediment load and turbidity[30], which is compounded by contamination from conventional coffee processing. The conventional coffee de-pulping process, as well as being water intensive, generates organic waste which, when dumped into waterways, causes nutrient loading, eutrophication, and pathogen growth[3]. Water shortages affect coffee yield causing fruit to wither and low water quality leads to poor health in low-income countries where the cost of drinking-water treatment systems can be prohibitive[30]. Annual coffee yields are highly variable and vulnerable to climate fluctuations (e.g., drought) and pests, particularly insects such as the coffee borer beetle (*Hypothenemus hampei*)[31] and coffee leaf rust disease (hereafter "rust"), caused by the fungus *Hemileia vastatrix*[32,33]. At a local or farm scale, forest is habitat for native bees and birds which provide important ecosystem services to coffee farmers in the form of enhanced yield due to pollination and insect pest control, respectively[34]. There is some evidence that suggests the presence of forest on a landscape may act as a windbreak and reduce the spread of rust spores[35].

Because of the fluctuations in yield and a continued rise in supply of lower quality coffee from Brazil and Vietnam, the price of coffee (C-price) determined by the commodity markets is highly volatile. In recent years, the C-price has frequently dropped below production costs for many farmers of high grown, high quality coffee[5,36,37]. Unless protected by instruments such as Fair Trade[38], low prices and volatility mean that poor farmers are unable or unwilling to invest in their farms or pay workers livable wages. Low and unstable income, lack of employment opportunities, and regional water shortages are contributing causal factors to mass emigration from coffee growing regions in Central America[39]. Gender inequality also contributes to unsustainability of coffee communities. In many coffee growing regions, women do not have the same access to resources as men, including credit and processing facilities. Consequently, fewer farms are owned or managed by women and those that are women-managed produce less and sell coffee at lower prices[7]. Increasing gender equality leads to healthier, better educated, and more sustainable communities as 90% of a woman's income, on average will be invested back into families, farms, and communities compared to only 30-40% of men's income[40].

Climate change is expected to exacerbate the myriad problems in the coffee industry. Coffee pests and diseases, already serious, are aggravated by higher temperatures. Crop yields will be impacted by changing weather patterns, including droughts and extreme rain events and climate-driven changes to land suitability for coffee production is increasingly driving deforestation especially of critical high-elevation forest near headwaters[8,36,41].

Previous solutions: Interventions to produce coffee in a more sustainable way generally focus only at the farm-scale and include the traditional cultivation method of growing coffee under shade trees (hereafter "shade coffee")[42], development of certifications that provide price premiums for shade coffee, and protection from price volatility through price insurance certifications such as Fair Trade[43]. Shade coffee supports higher levels of native biodiversity than open canopy or "sun coffee"[44–46] but some forest-dependent species are absent[47,48] and shade coffee is unlikely to protect water resources to the same degree as forest[49]. In many areas, shade coffee is particularly susceptible to leaf rust which often thrives under dense shade and can devastate coffee plantations[33,50]. Some research has suggested that, if premiums are high and yields are consistent, shade coffee can be economically viable at the farm scale[51-53] but such investigations often do not take into account the cost of obtaining and maintaining certifications, which can be prohibitive[54]. Sets of indicators to assess multiple dimensions of sustainability at the farm scale have been developed[55] but a widespread strategy for achieving sustainable coffee remains elusive[8].

Our solution: Our team has identified six sustainability goals and associated indicators related to coffee production. For <u>environmental sustainability</u>, the agroecosystem should support **biodiversity**, provide abundant **clean fresh water**, continue to **sequester carbon**, and use **renewable energy** for processing. For <u>economic sustainability</u>, producers must receive **sufficient and stable income** and there must be **training** and **employment** opportunities, especially in good-paying skilled jobs. For <u>social sustainability</u>, the goals are improved **quality of life** and **gender equality**. To meet these goals, we are designing a sustainable coffee system with four types of interventions. Our key *Environmental Intervention* is the adoption of **Integrated Open Canopy (IOC)** where a farm conserves an area of forest of equal or greater in size to the area of cultivated coffee. This allows farmers to adjust shade levels to optimize yields and control coffee leaf rust[51,53] . Forest conserved on IOC farms provides regional ecosystem services in the form watershed protection and habitat for forest dependent wildlife[47,48] and farm-scale services of pollination and pest control that enhance coffee yield, partially compensating farmers for relinquishing productive land. To further compensate farmers, our key *Economic Intervention* is to use **payments for ecosystem services** to generate additional income for IOC farmers. We are currently pursuing payments from sales of carbon offsets, and payments for other ecosystem services such as payments from hydroelectric utilities for water conservation are feasible. Using payments for ecosystem services means that the farmer is not completely economically dependent on coffee premiums via certification, which is an inefficient mechanism for channelling value from consumer to producer[8]. Our *Technological Interventions* are aimed at improving the processing of coffee. First, we have designed facilities that provide **carbon-neutral industrial coffee drying** using novel hybrid solar/biofuel technology that eliminates the use of firewood. The planned scale-up of carbon-neutral processing is a necessary investment that allows carbon on IOC farms to be verified and sold on global markets. A second technological intervention will be to research and develop standardized technologies (“**clean wet mills**”) to improve water efficiency when de-pulping coffee and convert the waste pulp to fertilizer thus providing a useful product and removing contaminants from processing water before releasing to streams and rivers. We have identified *Social Interventions* to improve gender equality including **training and outreach** programs to increase production, through participation of women farmers and development of local **microcredit** programs especially for women-managed farms. The multi-scale conceptual model of this system is shown in Figure 2. IOC Farms contain forest and coffee. Forest supports local biodiversity, sequesters carbon, and through various ecosystem services increases coffee yield. At the regional scale, water conservation and biodiversity depend on the spatial distribution of forest in farms in relation to other forest patches, elevation, and waterways. Coffee is de-pulped at clean mills and then aggregated and processed (dried and sorted) at the regional scale using resource-efficient, renewable-energy facilities which increases the value of the carbon for IOC farms. Coffee and carbon, also aggregated, is then sold to global markets. Regional training programs and instruments to provide access to microcredit, designed to be inclusive of women, increase the productivity of the farms and the quality of the coffee. Higher incomes, water protection and employment opportunities incentivize non- IOC farmers to adopt IOC, providing feedback to the farm scale. Global benefits from farm-scale and regional implementation are enhanced biodiversity, including improved habitat for biodiversity, reduced human-water footprint, enhanced carbon sequestration, reduced emigration, increased participation of women and sustainably produced coffee with verifiable attributes that will be marketed to institutional buyers and coffee consumers.

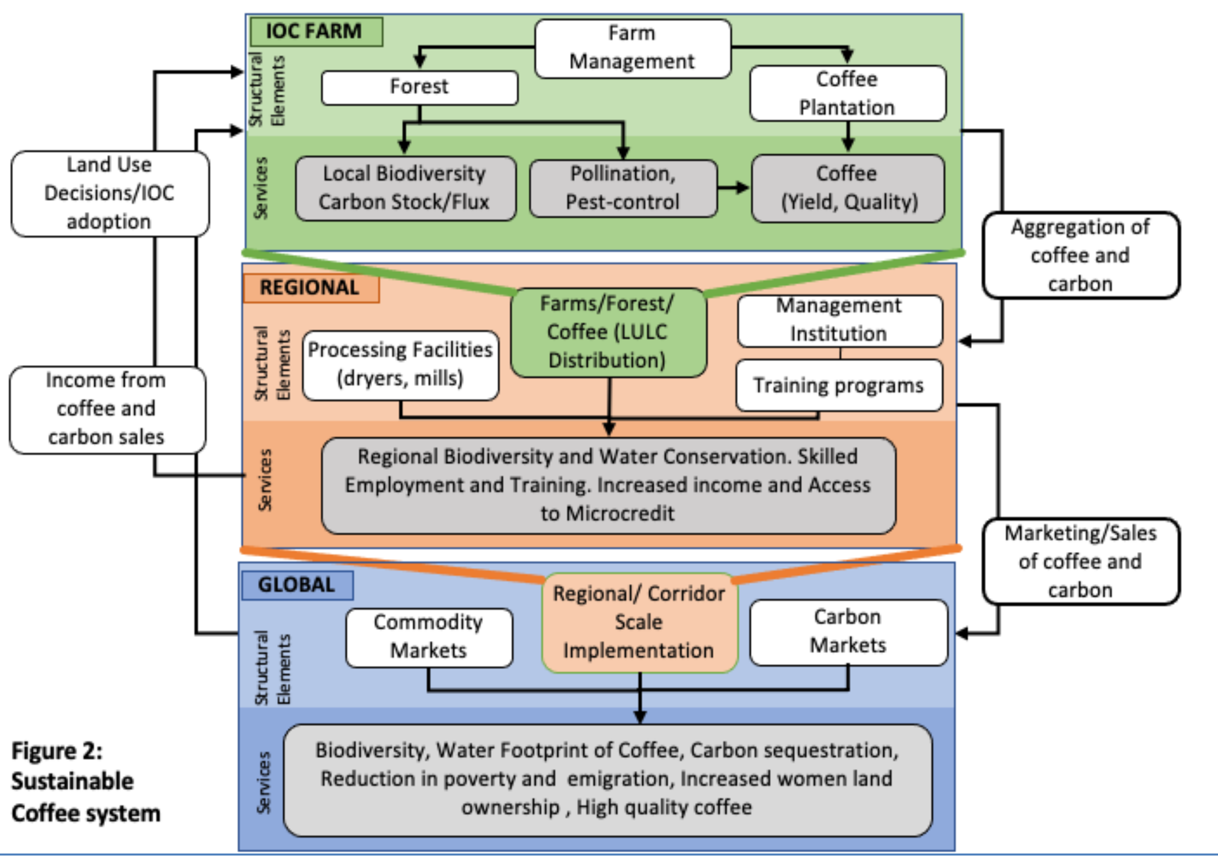

Figure 2: Sustainable Coffee system

RESEARCH PLAN

Goals

During phase one of the research, our goal is to evaluate how regional and global conditions affect the social, economic, and environmental sustainability at the scale of an individual farm. Our overall hypothesis is that the interventions will be environmentally, economically, and socially sustainable at the farm scale under achievable carbon and coffee prices. During this phase, we will be using the research as a vehicle for outreach to expand our convergence team, assess needs of the community, and develop modifications and additions to the sustainable system design. Our specific aims are to:

1.1 Evaluate Farm-scale Ecosystem Services from IOC forest. Our working hypothesis is that IOC farms have higher levels of ecosystem services than conventional farms and higher per-hectare yield of coffee.

1.2 Explore the carbon and coffee market conditions under which IOC farms are economically sustainable by integrating results from aim 1.1. Our working hypothesis is that IOC coffee farms will be economically sustainable at regular carbon prices and a moderate coffee price premium over baseline prices.

1.3 Explore the economic and environmental conditions under which the IOC model is socially sustainable. Our working hypothesis is that human decisions on land use are influenced by socioeconomic and environmental conditions.

During phase two, our goal is to use the foundational work and results from phase one to collaboratively design a sustainable coffee system and evaluate system resilience to exogenous changes in climate and market forces (before and during the implementation). Our overall hypothesis is that multi-scale processes and regional interventions are critical to achieve social, economic, and environmental sustainability. Our specific aims are to study:

2.1 Regional Environmental Processes and Services. Our working hypothesis is that interventions in the extent and distribution of IOC forest cover will improve water resources and biodiversity.

2.2 Economic Processes and Services. Our working hypothesis is that carbon value and coffee prices are determined by production attributes and scale of aggregation.

2.3 Engineering Innovations: Our working hypothesis is that these new technologies will improve energy efficiency, reduce pollution and enhance the value of carbon offsets.

2.4 Social Dimensions. Our working hypothesis is that training and access to microcredit will improve farm productivity, income, gender equality and overall sustainability.

2.5 The Multi-Scale Socio-Agro-Ecological System. We will construct a dynamic, multi-scale, empirical systems model under the multi-scale ecosystems framework to evaluate changes to sustainability under scenarios of climate change and land use and land-cover. Our working hypothesis is that adaptive interventions that take into account dynamic conditions such as climate change and market fluctuations can lead to long term sustainability.

Study Region

We are working in the region of Yoro, Honduras. Honduras is the fifth largest coffee producer in the world and the largest coffee producer in Central America[56]. Coffee production provides the principal source of income for more than 100,000 Honduran families, and employment for ~1 million. 95% of Honduran coffee is produced on family farms less than 7 ha[32]. Poor rural communities are vulnerable to downturns in the coffee market and to crop failure. Widespread emigration from coffee-growing areas has led to unstable communities[39]. Honduras has one of the highest rates of deforestation in the world, driven largely by expanding coffee production. Deforestation causes shortages of drinking water and reduces electricity output of the main hydro-utility. The Municipality of Yoro declared a state of water emergency in September 2019. Regional climate has tended toward drought, heavier rainfalls and higher temperatures, suggesting that the effects of deforestation on water supplies may be exacerbated by climate change[32].

PIs Raudales and Trubey founded the MesoAmerican Development Institute (MDI) in 1995. MDI co-manages Pico Pijol National Park and Montaña de Yoro National Park and is working with the Honduran government to legally establish the Yoro Biological Corridor which will encompass five threatened national parks with IOC farms providing forest landscape connectivity. MDI conducts outreach and training in Yoro, and through MDI's efforts, twenty farms have adopted IOC and conserved 171 ha of forest and offset 6,955 mt of CO2 annually. Several, one-time "boutique" carbon sales have been enacted, totaling $100,000. An industrial hybrid solar/biomass coffee dryer facility (designed and patented by MDI) has been in operation for six years. This dryer uses diesel for electricity and thermal solar/biomass (using pellets from coffee husks) for drying. Land has been purchased to construct a new dryer facility with an improved, carbon-neutral, patented design that also uses photovoltaic-solar and liquid biofuel (from a locally grown source: *Jatropha curcas*) to generate electricity. Coffee produced in the region is exported under the Cafe Solar® brand. Since 2011, our team has been conducting environmental research in the region including (1) Avian point count surveys. (2) Ecological studies have focused on the habitat use, habitat selection, habitat-specific survival[57], and habitat segregation of Neotropical migratory bird species of conservation concern. (4) An evaluation of birds as agents of pest control. (5) A water quality assessment of four stream transects using physical, chemical, and biotic indices making use of aquatic macroinvertebrates. All of this work has been conducted by students and local collaborators.

Using watershed boundaries, we have delineated a study region of ~40,000 ha that contains several hundred coffee farms and encompasses the area where ecological research has taken place as well as the existing solar-hybrid processing center and all 20 existing IOC farms. We will identify a subset of 40 farms (20 IOC, and 20 non-IOC, with varying levels of shade) as experimental study farms to conduct our research activities. For regional scale analysis, we use 10 m resolution Land Use/Land Cover (LULC) maps derived from 2019, 2014, 2009, 2003, and 1965 satellite images[58]. From these we will create maps representing a range of potential land-use and land-cover (LULC) scenarios from (1) Maximal forest loss: all forest in suitable coffee habitat converted to coffee, (2) Business as usual: Projected changes of conversion of forest elements to coffee, based on extrapolating observed changes from 2014 (or earlier) to 2019, (3) Status quo: no further deforestation, (4) Optimistic: scenarios where secondary vegetation on private land is restored to forest and existing forest is conserved. We will also employ 8 climate GIS layers[59] for this region at 1 km^2 resolution representing the following climate variables: monthly precipitation, monthly minimum, maximum, and mean temperature, diurnal temperature range, solar radiation, and mean wind speed. Future projections of the 8 climate variables were produced (by downscaling 18 General Circulation Models) for four emission scenarios (Representative Concentration Pathways 2.6, 4.5, 6.0, and 8.5; IPCC 2013) and three future periods named as the 2030s (2021 to 2050), 2050s (2041-2070) and 2080s (2071 to 2100). We will analyze combinations of climate projections with the scenarios of LULC change to assess the future suitability of the study region for coffee.

Phase one : Investigating Farm scale Sustainability

Integrated Open Canopy (IOC) is a new model for cultivation of coffee and similar crops and an alternative to shade coffee. Landholders hold back at least 50% of their productive land to protect the natural forest ecosystem and receive payments for ecosystem services, i.e., carbon offsets. Farmers can decide to retain shade trees in the coffee plantation or not, allowing yields to be optimized for local conditions. Our hypothesis that IOC plus carbon offsets model will be environmentally, economically, and socially sustainable at the farm scale under achievable carbon and coffee prices. We will quantify forest ecosystem services at the farm scale (Aim 1.1) and use the results to model and assess the economic sustainability of IOC farms under a range of coffee and carbon prices (Aim 1.2). Finally, we will assess how environmental and economic conditions affect the willingness to adopt IOC (Aim 1.3; Fig. 3). Our expected outcomes from phase one are an integrated farm-scale model that predicts local biodiversity, carbon stock, coffee yield, and revenue of an IOC farm given exogenous carbon and coffee prices and an understanding of the levels of revenue and other conditions necessary to incentivize farmers to adopt IOC. Our findings will assist efforts to set best practices for IOC, such as minimum forest area. We will use the research as a vehicle to scale up IOC adoption in the region and to better understand needs and constraints and improve the design of the sustainable coffee system.

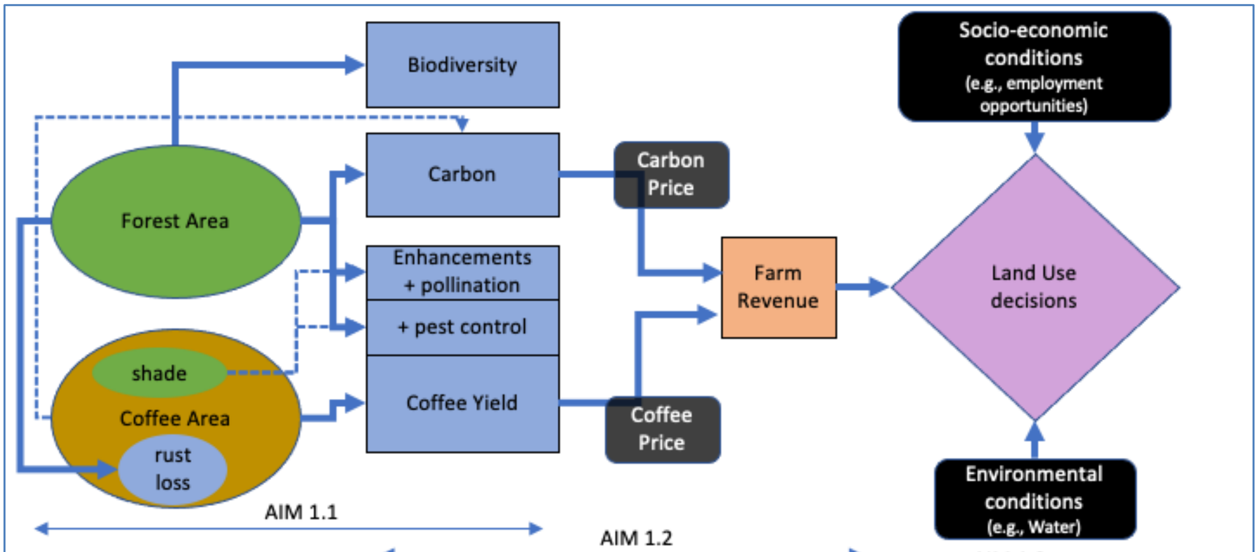

Figure 3: Farm-scale Model

Aim 1.1. FARM-SCALE ECOSYSTEM SERVICES

Biodiversity: Based on previous studies[47,60], we hypothesize that biodiversity on IOC farms will be similar to shade coffee farms in the region but will support a higher number of forest-dependent species and that diversity will increase with forest patch area with steep drops below a threshold. We rely on bird diversity as birds have been shown to perform well as a surrogate for overall diversity when they are specious[61] as in our study region. Additionally, many avian species are considered a priority for conservation[62], particularly migratory songbirds for which our study region provides critical over-wintering habitat[63]. To test our hypotheses, we will analyze data from prior avian counts conducted at 50 sites in 3 winter seasons. We will measure the species richness and abundances for migrants, residents, and other avian groups of elevated conservation concern or vulnerability and estimate the relationship between richness and abundance with habitat characteristics and forest patch size[65,66].

Carbon sequestration: We hypothesize that carbon sequestered in vegetation and soils will increase with forest area and other farm characteristics. Above-ground carbon stocks have been quantified on the 20 IOC farms from vegetation sampling using standard models[67]. To measure belowground carbon, we will collect and analyze soil core samples. By calculating soil carbon, we assess the incentive for organic certification as, under MDI's protocol, soil carbon offsets are only saleable if the farm is certified organic.

Insect Pest Control: A direct and important service is provided by forest-dwelling insectivorous birds in the form of depredation of coffee pests, especially larvae of the devastating coffee-borer beetle (*Hypothenemus hampei*)[31,44,68–74]. We hypothesize that coffee yield on IOC farms will be enhanced by depredation of pest insects by forest-dwelling birds and positively associated with abundance and diversity of predators. To test this, we will: (1) Gauge the potential of bird species as predators of coffee pests and establish the association of individual bird species with IOC farms; and (2) Conduct an experiment in which we exclude birds, but not pests, from focal coffee plants. The model derived from integration of (1) and (2) will explain the variation in coffee yield due to insect pests as a function of farm characteristics[70,71]. For (1), we will use data and samples collected in the study region as part of a biodiversity assessment in 2018-2020[75] when we collected and preserved 153 fecal samples from 29 species and conducted standardized point counts in 15 IOC and 30 non-IOC farms. We will supplement these data with finer-scale transect surveys[76]. Potential coffee insect predator species will be identified based on observed foraging height and substrate[69,71] and actual predator species will be identified by amplifying insect DNA from genomic material extracted from preserved fecal samples. The relationship between abundance of potential predator species, distance from forest, and foraging substrate (coffee plant or "other") will be analyzed using N-mixture models and GLMMs[77,78]. For (2), at 40 study farms, mesh exclosures will be placed over randomly selected coffee plants near and far from forest just after flowering when berries are forming and vulnerable to pests. Just before harvest, mesh will be removed and a sample of coffee berries will be inspected for coffee-borer damage using standard industry techniques.

Pollination is another important service provided by forest that increases coffee yield. Coffee is both self- and wind-pollinated, but multiple studies have shown that pollination by bees greatly increases fruit set and yield[34] and that bee abundance and visitation rates decline with distance of coffee from forest[79]. Some pollination services may be provided by non-forest dependent solitary bees[80] and naturalized honey bees, *Apis melliflora*[81,82]. We hypothesize that coffee yield will be enhanced by forest and shade due to pollination services from native bees and that pollinator diversity, visitation rates, and fruit set will decline as a function of distance from forest. To test these hypotheses, we will conduct a pollination experiment using field methods from similar studies[34,83–85]. At each study farm we will select two coffee plants, and assess fruit set on selected branches for three treatments: (1) open pollination treatment, to measure yield under conditions of ambient pollination; (2) hand cross-pollination to measure maximal yield; and (3) control bagged flower treatment to measure the effect of no insect pollination[83,84]. Comparisons between hand cross-pollinated and open pollinated treatments will determine pollination deficiencies and between control and open-pollinated will determine the effect of insect pollination. Statistical analysis will reveal the effect of distance from forest and other site variables (shade, elevation) on insect pollination. To quantify pollinator visitation rates and diversity/abundance, we will conduct standardized pollinator visitation surveys on open pollination treatment branches, identifying visitors to morphospecies[83,85,86] and passive surveys along walking transects analyzed with hierarchical distance models[87] to estimate how abundance varies with distance from forest[88].

Disease buffer: Outbreaks of coffee leaf rust disease have had a devastating effect[33,50]. At a regional scale, rust outbreaks are affected by climate[33]. At a farm scale, shade coffee is more susceptible to rust than open-canopy coffee due to microclimatic conditions[35,50] and this was a major motivator in the development of IOC. Fungicides can reduce rust incidence but are costly, and if used inappropriately can cause rust expansion[33]. New coffee varieties, developed to be resistant to rust, are in use in some farms in our study region but emergence of new rust strains have reduced resistance[33]. Land cover surrounding coffee farms affects the spread of fungal pathogens since vegetation impedes the dispersal of wind-borne spores[33,89–91]. We hypothesize that IOC coffee will have lower incidence of leaf rust than sun or shade coffee because forest in IOC attenuates spread by spores and open canopy provides less hospitable microclimatic and soil conditions than shaded coffee for fungal development. To test this, we will conduct monthly surveys for 18 months at all study farms, estimating the incidence of leaf rust and other diseases, microclimate data, degree of shade, soil pH and metrics, and coffee varieties and test for correlation between the disease incidence and surrounding land cover, climate, site variables, and coffee variety[35].

Aim 1.2 ECOLOGICAL ECONOMICS of INTEGRATED OPEN CANOPY FARMS
Because proximate forest cover may affect two sources of revenue on IOC farms - coffee yields and carbon offset credits - we hypothesize that IOC coffee farms will be economically sustainable at regular carbon prices and a moderate coffee price premium over baseline prices. To test this, we will construct a stochastic, empirical model of carbon sequestration, coffee yield and revenue (Fig. 3). Results from Aim 1.1 along with baseline data collected from the questionnaire in Aim 1.3 will be used to estimate the enhancement of coffee yield due pollination and pest control, while accounting for the expected area of coffee lost due to leaf rust. The farm model will be used to simulate how expected revenue varies with different farm arrangements of forest, coffee, and shade and varying prices of coffee and carbon. For this farm-scale analysis, we treat the prices of coffee and carbon as exogenous inputs to the system.

Aim 1.3 SOCIAL CONDITIONS and HUMAN BEHAVIOR

The willingness of landowners to adopt sustainable coffee production practices is essential for the realization of improvements in environmental quality and human wellbeing. An *a priori* understanding of the factors that contribute to the decision to adopt sustainable farm practices will help policy makers identify and design incentive mechanisms to facilitate the transition toward broad scale sustainable production and will provide critical links between human behavior and natural systems in our multiscale model. We hypothesize that landowner decisions to adopt sustainable coffee production practices will be a function of economic factors such as the magnitude and variability of revenue from sales of coffee and carbon credits, start-up costs and subsidies, as well as quality of life factors such as the availability of clean water and community stability. To measure sustainability indicators as a baseline for measuring the effectiveness of interventions during and after the life of the project, we will administer questionnaires to farm families. Questionnaires will collect socioeconomic and demographic variables, including family size, age, gender education, detailed cost and revenue information (e.g. price and availability of capital and labor inputs). Medical students on the survey teams will measure the Body Mass Index of children in the household, an indicator of health and nutrition[92]. We will assess proportion of decisions made by women and information regarding farm owner preferences for, and perceptions of, opportunities for healthcare, housing and education. To gain insights into the relative importance of factors that affect the decision to adopt sustainable coffee production practices, we will conduct a choice experiment (CE) as part of the questionnaire. Grounded in Lancasterian preference theory[93] and used in multiple disciplines[94], choice experiments are a method for understanding human preferences and decision-making in the context of multi-attribute alternatives. CE data are obtained from surveys that guide respondents through a series of hypothetical choices described in terms of different levels of attributes. Modeling choices as a function of attributes can be used to generate estimates of how changes in attribute levels affect the probability of a given choice. Small focus groups will be assembled to assist with the determination of appropriate attributes and levels and the CE will be pretested on 12-15 farmers and modified where necessary for improved exposition, clarity, accuracy and flow. Final CE surveys will be administered through face-to-face interviews administered to a random stratified sample of at least 100 farm families. Respondents will be presented with a series of scenarios involving the choice between adopting IOC practices and using traditional production methods. Attributes are expected to include income from coffee sales, income from sales of carbon, income volatility, start-up costs/time, co-op support, and community characteristics. Attribute levels will be centered on current conditions for non-IOC farms and data will be analyzed using multinomial logit regression of the discrete decisions with respondent characteristics as covariates. Expected outcomes of the CE include an understanding of the influence of marginal changes in economic and community factors on farmer decisions regarding the adoption of IOC practices. This information will serve as the foundation for policy advice regarding interventions that would increase the use of sustainable practices, and the expected impacts on economic viability in the region. To synthesize the findings from this goal we will derive models that estimate probabilities of adopting sustainable practices as a function of quality of life factors and economic and community returns to adopting sustainable practices.

Phase two : Multi -Scale Sustainable Coffee System

During phase two, our goal is to build on the farm-scale work and collaboratively identify missing interventions or modifications needed and refine the design of the sustainable coffee system (Figure 2). We know that regional interventions are needed. Obtaining high coffee premiums and sale of carbon offsets require regional aggregation and marketing of coffee and carbon as well as carbon verification. Environmentally, watershed protection and regional biodiversity needs forest distributed across a landscape, including around headwaters with forest patches close enough together to provide landscape connectivity. Processing and sales must be aggregated to achieve efficiencies of scale. Dryers process coffee from 500 - 800 farms and each clean wet mill will serve 50 - 100 farms in a 10 km to 20 km radius. Training and microcredit programs are only viable at a regional or larger scale. An entire region will be affected by global climate and market changes.

We will collaboratively construct an empirical systems model to evaluate trade-offs and synergies at multiple scales across multiple dimensions of sustainability as well as resilience to exogenous changes in climate and markets. Our overall hypothesis is that multi-scale processes and regional interventions are critical to achieve social, economic, and environmental sustainability. We will evaluate how the distribution of forest at a watershed scale affects water quality, water yield, and biodiversity, and produce an integrated, generalized environmental model that can provide an estimate of how water conservation and biodiversity indicators are affected by forest distribution, which will be useful for planning tropical forest conservation beyond our study region (Aim 2.1). We will determine how scale of aggregation and environmentally friendly cultivation and processing practices affect prices of coffee and carbon and develop a new carbon verification methodology (Aim 2.2). We will develop green processing technology by (1) evaluating the efficiency of newly constructed novel carbon-neutral drying facilities and (2) developing a mechanical and biological system for de-pulping coffee berries that will use water efficiently, recycle waste pulp into organic fertilizer, and remove this major source of water pollution (Aim 2.3). We will create and assess microcredit and training programs, especially directed at women (Aim 2.4). Finally, we will synthesize our findings by creating a multi-scale systems model to identify trade-offs and synergies and evaluate sustainability and resilience under projected climate change (Aim 2.5). The systems model will be used to modify and identify new interventions and will be maintained beyond the timeline of this project as the coffee production system continues to evolve. Our project will develop a convergence community, with leadership in Honduras, that will have created a system for production of coffee that is environmentally, economically, and socially sustainable. We will be presenting our Multi-Scale Ecosystem Framework approach for growing convergence research to interested parties in the larger sustainable agriculture research community.

Aim 2.1 REGIONAL ECOSYSTEM SERVICES

Forests enhance water infiltration, reduce runoff, maintain soil moisture, and influence water quality[28]. Water deficit limits coffee yield[95] and results in farmers selling unprocessed berries for lower prices[96]. More forest cover in watersheds minimizes fluctuation in hydrologic processes, which is critical for climate adaptation. However, the spatial distribution of forest within a watershed is important and not all potential conservation or restoration opportunities will be equally effective. Forests also support biodiversity and our studies show that IOC forest supports forest-associated bird species that would otherwise be absent from the landscape[47,60]. Nevertheless, IOC forest is distributed in patches rather than a large contiguous area, so at the landscape scale, biodiversity value will be determined by how well the forest patches function as a network that allows animals to move between patches. Our hypothesis is that forest configuration and forest quantity interact to influence indicators of biodiversity and water conservation in a similar way creating synergies between aspects of environmental sustainability.

To test this, we will create a spatially explicit simulation of the watershed using the Soil and Water Assessment Tool (SWAT) and apply the model to predict future water yield and quality changes under different land-use and climate change scenarios[97]. SWAT, a continuous-time, semi-distributed, process-based, river basin model[98,99], will model streamflow, sediment yield and nutrients load[97,100–105]. The model requires several datasets including a Digital Elevation Map (DEM), a watershed delineation, LULC maps, soils data from the UN Food and Agricultural Organization, and monthly monitoring of streams. We will use precipitation and regional water flow data for 40 years to model the watershed process over time. Calibration, sensitivity analysis, and validation will follow documented procedures[106–108]. Outputs from the simulation model will be used to construct a generalized model that describes how the distributions of forest and waterways in a landscape as well as climate affect water quantity and quality. To assess how landscape-scale biodiversity varies with forest configuration, we will use a metric shown to be related to a likelihood of a species' persistence called "metapopulation capacity" (MC) that can be calculated from data on forest patch distribution, average dispersal capability and likelihood of occurrence in a given patch[109,110]. For a subset of avian species (selected to span different guilds and dispersal potential based on work from phase one), we will calculate MC for existing and projected LULC/climate scenarios and calculate a summed MC metric to represent an indicator of landscape-scale biodiversity. We will create a generalized model that can be used to predict how this indicator is related to forest distribution and climate that will be integrated with the generalized water conservation model to identify synergies or tradeoffs in landscape-scale forest conservation design and incorporated into the multi-scale systems model.

Aim 2.2 REGIONAL ECONOMICS OF COFFEE and CARBON

Coffee Economics: The market price of coffee is largely determined by exogenous market conditions and influenced by factors related to supply and demand. Demand, and therefore price, is based on quality (flavor) and is also a function of socially meritorious attributes and certifications such as organic or fair trade. We hypothesize that coffee buyers will be willing to pay more for coffee produced using sustainable practices and marketed for socially meritorious attributes. To test this, we will establish a base price of coffee from a statistical time-series modeling of the "other mild arabica" commodity price (the type of coffee grown in Honduras) available from the New York Commodity Market and International Coffee Organization. Price premia in excess of this base price will be estimated using a choice experiment (CE) designed to estimate wholesale coffee buyers' willingness to pay for attributes associated with sustainably grown coffee, including preservation of tropical forest habitat and biodiversity, quantity of sequestered carbon, water quality improvements, use of solar dryers, organic certification, women ownership/entrepreneurship and community stabilization. The online CE will present respondents with a series of hypothetical bulk coffee bean profiles described in terms of various levels of sustainable attributes and price. The CE and be pretested using a sample of 12-15 coffee buyers and modified as needed for exposition, clarity, accuracy and flow, then administered to a random stratified sample of 75-100 international wholesale coffee buyers via the Qualtrics platform. Results of this CE will provide information regarding how levels of on-farm sustainable attributes affect the probability of purchase and the expected price premium that coffee buyers are willing to pay. Expected outcomes include advice to farmers regarding costs and benefits of IOC practices and estimates of the economic and social returns to shifting towards more sustainable coffee production. A simulation of expected revenue changes associated with adoption of IOC and other production practices will be incorporated into the empirical systems model.

Carbon Economics: Forests and associated soils are a significant pool of terrestrial carbon and carbon flux[111,112] and sale of carbon offsets can be an effective mechanism to alleviate rural poverty[113]. We envision carbon offset revenue to farmers as a key incentive for the adoption of land-sparing IOC farming methods at a landscape scale. Similar to coffee, carbon prices may be affected by the "quality" of carbon which is enhanced when it is associated with renewable energy, biodiversity, forest conservation, and gender equality. However, the high cost of verification services, which must be imported from other countries, is a major barrier to sales of carbon offsets to global markets. We hypothesize that (1) carbon prices are influenced by environmentally friendly attributes and volume aggregation levels. We further hypothesize that (2) an economically feasible carbon verification mechanism can be developed and implemented locally by developing capacity and expertise. To test (1), we will assess the current state of the market for carbon offsets[114] and conduct an Expert Opinion study through a questionnaire to determine how aggregation levels as well as environmentally friendly and socially meritorious attributes influence the price paid by brokers and resellers in the US, Canada, South America, Europe and Asia. To test (2), we propose to develop a drone-based method for carbon verification. We will first use established methods to estimate carbon stocks and fluxes of 100 IOC farms, i.e., map and conduct vegetation surveys and sequestration using CO2FIX V3.1 software[115–117]. We will then deploy drones to collect high resolution aerial multispectral images of the same farms, process the images using *Arcadus* and *PictureThis* software and calibrate/validate the CO2FIX estimates. The documentation of the measurement process and IOC carbon protocols will be registered with the VERRA foundation (Verified Carbon Standard).The ability to reliably measure carbon in tropical landscapes using drones would reduce the labor intensive ground measurements, and efficient and accurate carbon measurement tools will advance the carbon certification process for low-income tropical countries. In Yoro, MDI will provide training in this carbon measuring and monitoring methodology to allow local entrepreneurs to form a company that will be accredited by the VERRA foundation to provide cost-effective carbon verification services in Yoro Biological Corridor and beyond, thereby mitigating a primary obstacle to carbon offset payments to IOC farmers.

Aim 2.3 GREEN TECHNOLOGIES FOR PROCESSING COFFEE

Coffee drying is highly energy-intensive. Conventional mechanized industrial dryers consume 0.07 m^3 of firewood and12.0 kWh of electricity to dry 100 lbs. of coffee[4]. The wet process of depulping coffee uses water resources and releases large volumes of pulp - a major source of water contamination[3]. At the same time, pulp is nutrient rich and has potential to be recycled for use as fertilizer. We are developing technologies for drying and depulping to address these issues. An industrial hybrid solar/biomass coffee dryer that eliminates the use of firewood and reduces electricity consumption by 80% over conventional dryers has been in operation at our pilot site in Honduras since 2012 (US Patent: 6922908). We have designed a new, improved carbon-neutral factory with five drying towers and a production line for milling and sorting. The facility will be powered by 100% renewable energy from solar, solid coffee husk biofuel, and liquid biofuel from locally sourced *Jatropha curcas* oil. Construction will begin in 2021 and the facility will be fully operational by the start of Phase two of the project. Our hypotheses are that it is technologically and economically feasible to (1) dry coffee entirely using renewable energy and eliminate the use of fuelwood and to (2) depulp coffee in a way that causes no pollution and recycles the waste material as fertilizer. To test (1), we will evaluate the energy and cost efficiency of the new drying facility (compared to conventional dryers). Energy flow analysis will be conducted for the drying process including energy flows (air and water) between subsystems: solar thermal collectors and solid fuel biomass boilers; energy transfer through the drying towers (mass transfer efficiency)[118] using data from built-in instruments. Mass flow transfer in the coffee drying elements will be measured and analyzed to ensure optimum drying rates and temperature to maintain quality. Efficiency of combined thermal and power generating units will be estimated as cost per kilowatt hour and cost per unit of coffee processed. We will use outcomes from this analysis to improve efficiencies in the operation of the facility and compare our costs and energy usage to those of conventional processing factories, which are well known and updated annually by national Coffee Institutes. The analysis will be used to promote carbon-neutral processing and attract additional investment in the technology. To test (2), we will develop a technology for de-pulping and washing coffee berries that will use biological and mechanical processes to convert waste pulp and wash water to organic fertilizer. The de-pulping stations will be designed to decontaminate wastewater through an artificial wetland before being released to local streams and rivers and mechanical equipment will be powered by electricity from renewable energy sources (solar and *Jatropha* biofuel). Preliminary work will consist of a literature review of aerobic and anaerobic composting, densification, drying, and transportation and a design review of an extant artificial wetland that removes solids and nutrients from wash water from a de-pulping station that was piloted earlier by MDI in Costa Rica. Initial conceptual designs will be produced, simulated, and tested in CAD software with iterations to produce improved design. A prototype mill will be constructed and tested, and once proven, the standardized design will be promoted by the Honduran Coffee Institute (IHCAFE) initially throughout the Yoro Biological Corridor, which will require between 40 and 60 such installations, and then nationwide. The Yoro Biological Corridor Initiative will promote and stimulate investment in clean processing technology through public/private partnerships.

Aim 2.4 SOCIAL INTERVENTIONS

Women in coffee producing regions are often excluded from management and decision-making positions within the coffee industry. Furthermore, lack of access to credit and bank accounts limits the productivity of their farming operations[7]. Due to our earlier efforts in the Yoro region, several local women completed university programs and now serve in management and mentorship positions, operating processing equipment, and managing quality control and coffee exports. Our hypothesis is that (1) further investing in women through training and loans will increase farm productivity and income and that, based on past experience, (2) hiring women will increase the efficiency and profitability of coffee processing. To test (1), we will, through the questionnaire and outreach conducted in phase one, enroll a larger percentage of women in ongoing training and outreach programs run by MDI that aim to promote adoption of IOC, and add to those programs before and after evaluation to determine if the participants found the training valuable. We will record the number of women who register their farms as IOC and amount of carbon payments to women. Additionally, MDI will employ a local consultant to develop and publicize (especially to women) microcredit programs for local producers in the region though local banks. The microcredit lender will provide anonymous data on numbers of bank accounts opened by women, loans to women, the use to which loans are put, repayment rate, and data obtained by a bank-administered questionnaire on the impact of the loan. To test (2), MDI will hire around 100 people to work at the new drying facility under a policy of hiring at least 60% women, including into key management and mentoring roles with the same pay structure for men and women. As well as the energy efficiency study described in aim 2.3, we will measure the work- efficiency (taking into account quantity and quality of coffee produced) of the plant and compare to known values for conventional drying facilities.

Aim 2.5 SYNTHESIS

To effectively design a sustainable coffee system and identify *a priori* how interventions will affect the sustainability and resilience of this complex system, we will create an empirical systems model based on the conceptual model (Fig. 2). Our general hypotheses are that: (1) the systems model can accurately and usefully represent the dynamics of the agroecosystem; (2) changes in specific drivers (climate, prices, practices, and policies) will result in significant system-wide changes to multiscale sustainability; and (3) collaborative construction of a systems model will be an effective convergence research tool. A large number of more specific hypotheses, regarding trade-offs and synergies and effects of climate change, will also be tested. Systems modeling is an effective approach to represent the structure and functions using state and flow variables, functions, and feedback processes that operate at discrete time steps involving multiple differential equations. Individual components of this socio-agroecosystem model will be synthesized into a larger multiscale ecosystem model using a dynamic systems software, STELLA (Systems Thinking for Education and Research; ISEE Systems Inc.). STELLA is an object-oriented graphical programming language designed for modeling dynamic systems[119]. Each scale and subsystem will be modeled by identifying the state variables, inflow/outflow processes, and converters. Each scale and subsystem will be modeled as modules and sectors in the STELLA environment and connected with feedback loops. The equations and datasets developed in previous aims will be used to graphically construct the differential equations for each of the state variables. Farm-level[120], regional[119], and global scenarios[121] will be modeled as sectors and dynamically linked as multiscale systems. The final model will be calibrated and validated for specific submodels and overall. Simulations of the synthetic systems model will be used to evaluate trajectories of multi-dimensional, multi-scale sustainability indicators under scenarios of climate change and land-cover[121]. As well as journal articles and conference presentations, we will produce (from STELLA) and widely disseminate visual illustrations and animations of system and subsystem dynamics to illustrate tradeoffs, synergies, obstacles, and critical processes in sustainability of agricultural systems. For overall project assessment and model calibration, a survey questionnaire will be used on strategic stages of the project. The questionnaire of coffee producers in year 1 will be re-administered at the beginning of year 5 to the same producers to measure potential changes due to the interventions that have been implemented. Specifically we will evaluate women participation in IOC farming, new income from carbon offsets, number of women with their own bank accounts and access to credit, number of women and men employed in professional managerial positions in the operation of carbon-neutral processing, supply chain management, accounting and finance, and mapping and measurement of carbon on IOC farms. A longer term assessment plan will be designed to determine the overall effectiveness of all interventions beyond the project timeline with annual updating incorporated into the monitoring programs of the Yoro Biological Corridor Initiative. Finally, we will record and disseminate accounts of the process of creating the conceptual and empirical models collaboratively, with the intention of furthering the growth of convergence research in sustainable agriculture and other systems.

BROADER IMPACTS

Central American Forest Conservation and Sustainable Agriculture. Our evidence-based information on sustainable coffee production systems will directly benefit conservation by informing the policies and practices of the Honduran Ministry of Natural Resources and the Environment (MiAmbiente) and the Honduran Park, Wildlife and Forest Service (ICF). MiAmbiente has expressed their intention to promote these practices throughout the Yoro Biological Corridor in Honduras. The coffee industry, the Central American Bank for Economic Integration, the International Finance Corporation, and the World Bank are interested in replicating them throughout Central America and worldwide. This project will benefit farmers, cooperatives, community water boards, municipalities, and the nation's electric utility. By sustaining ecosystems and enhancing rural economic potential and quality of life, these practices should help counter the necessity of many inhabitants to emigrate to cities within Latin America and the US.

Outreach. We will broadcast on the Honduran television network UTV, and disseminate findings through academic journals, conferences, technical reports, non-technical policy briefs, press releases in English and Spanish, and posts on the websites and social media accounts of MDI, Tulane, the U. of Massachusetts and the University of North Carolina Wilmington. Findings will be shared with procurement and sustainability departments of major coffee companies, carbon brokers and corporations interested in purchasing carbon offsets once they are validated (including Microsoft). The Central American Bank for Economic Integration, the International Finance Corporation, BANProvi, and Banco Atlantida are also interested in this work. As co-manager of two national parks, MDI regularly meets with the local communities, water boards, and municipalities in cooperation with SERNA (Secretariat of Natural Resources and the Environment). We will present to the board of the National Electric Utility (ENEE) who are stakeholders, as deforestation threatens power generation. The Yoro Biological Corridor Initiative is represented in the Partners in Flight Central American Conservation Plan, the Sustainable Coffee Challenge and the Smithsonian Institute's Bird Friendly Coalition.

Education. PI Taylor will incorporate STELLA programming and the design and modeling of socio-ecological systems into her graduate level "Mathematical Modeling in Ecology" course and modules on sustainable food systems into her Urban Ecology" course. PI Schuhmann will use the project as a case study in carbon credits and payments for ecosystem services, and will incorporate the choice experiment design, data collection and analysis into his undergraduate "Natural Resource Economics" course. Material will be made available for use in K12 and college-level teaching. Co-PI Raudales and Senior Personnel Trubey have developed curricula in an accounting course ("Case Study of Cafe Solar") and social psychology course ("Live as if your Life Depends on it"), which looks at consumer choice and purchasing decisions and includes interviews with Honduran women working in managerial positions.

Training. Our project will provide extensive opportunities for 2 MS students, 5 Ph.D. students, 3 postdoctoral researchers, 20-25 undergraduates, 5 field technicians and 4 survey enumerators and provide field experience for 2 medical students. All field technicians, the survey team, medical students, 2 undergraduates, 2 MS students, and 1 Ph.D. student will be Honduran. This provides a unique opportunity for students to work on their research in synergy with peers in a range of disciplines. Honduran Biology students have participated in work at our site since 2012, and 2018-2019 participation served as a placement requirement before obtaining undergraduate degrees at the Universidad Nacional Autónoma de Honduras. These activities will generate research capacity needed to meet future ecological challenges.

Results from Prior NSF Support.

Taylor was a co-PI on BCS-1313703 ("CNH: Diversity and Disease in a Post-Trauma Urban Landscape" 9/1/2013-2/28/2019, $1,410,363). ***Intellectual Merit***: This award investigated coupled feedbacks between socio-ecological diversity and infectious disease in post-Katrina New Orleans. ***Broader Impacts***: This award provided training for 3 postdocs, 6 graduate students, and 14 undergraduate students. It was covered by local and national media (e.g., NPR, NY Times), and 12 articles have been published (listed at the end of references). Data: Archived and publicly available through Genbank and Dryas