Spring 2017

Carbon Stocks in Shade Coffee: Strategies for Enhancing Carbon Storage in Smallholder Systems in Jinotega, Nicaragua

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CARBON STOCKS IN SHADE COFFEE:
STRATEGIES FOR ENHANCING CARBON STORAGE IN SMALLHOLDER SYSTEMS IN JINOTEGA, NICARAGUA

Master's Capstone Submitted to the Faculty of the Bard Center for Environmental Policy

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In partial fulfillment of the requirement for the degree of

Master of Science in Environmental Policy

Bard College

Bard Center for Environmental Policy

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May, 2017

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May 2017

Agradecimiento

Deseo agradecer a todos mis colegas del Departamento de Jinotega por tanto apoyo recibido en cada momento de este estudio.

A los productores cafetaleros de Jinotega, por darme su tiempo y su ayuda. Este trabajo de investigación no hubiera sido posible sin su cooperación.

A todo el personal del CIAT por haberme brindado la oportunidad de realizar este estudio. Al personal de las instituciones que trabajan en el sector del café nicaragüense, especialmente al personal de La Cuculmeca, Humidtropics, SOPPEXCCA, Aldea Global, CECOOSPROCAE, COOPSAEC, Funjides, y UCASUMAN.

A los técnicos y trabajadores que me ayudaron en la fase de levantamiento de datos: Evert López, Elbis Chavarría, Rosi Duarte Treminio, Allan Rizo Estrada, Toño Rostran, Walter Rivera Siles, William Vargas, y Elías Bucardo Hernández. Muchas gracias por darme la oportunidad de trabajar a su lado. Siempre estaré agradecida por su esfuerzo, su ayuda, y más que todo su amistad.

Acknowledgements

I would like to offer my sincerest thanks to my supervisor, Dr. Pablo Siles, for his dedication and support in the development and completion of this study. From teaching me field inventory methods to guiding my data analysis to providing invaluable commentary on a draft of this paper, your input made this research possible from start to finish.

To my advisor, Dr. Jennifer Phillips, for making this entire study possible. Your guidance shaped the direction of my research, and your thoughtful comments always challenged me to create my best work. I will never forget all of the work you did to help me realize this dream. Thank you for always making me feel like your top priority.

To Dr. Charles Staver for granting me the incredible opportunity to work on this project and for his comments on the organization of this paper. To his organization, Bioversity International, for providing the funding for this research.

To Dr. Gautum Sethi and Dr. Monique Segarra for their input on this research, which challenged me to strengthen the background and policy recommendations I present in this work.

To Dr. Caroline Ramaley, who will forever be the image I call upon as a model for my behavior when a situation requires me to be patient, gentle, and understanding. Thank you for helping me find effective ways to communicate my passion for this research.

To my parents, Marjorie and Evan Kichline, who instilled in me the sense of adventure, curiosity about the natural world, and independence to complete not only this thesis, but all aspects of my educational and personal development to date.

To Bill and Lori Testa, for their generous support, and for always treating me like family.

To the congregation of KCCUCC, for providing me with financial and emotional support that made this project possible.

To Rose Davies and Maryanne Tranter, the strong and inspiring women with whom I shared the experience of living in Jinotega, for always being on my team.

To my Bard CEP classmates, who have inspired and challenged me, and whose questions and suggestions improved both this paper and my spirits throughout the writing process.

I could not have done this without you.

Finally, I want to thank Jacob Testa, my source of stability and endless laughs through the entirety of my undergraduate and graduate studies. I couldn't ask for a better partner in life.

I could definitely have done this without you, but it wouldn't have been nearly as fun.

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Abstract

Climate change has recently shifted focus to adaptation and mitigation strategies in coffee production. Shade coffee systems, already widely recognized for their contribution to biodiversity and soil conservation, are now drawing attention for their role in carbon storage. Researchers have generally assumed that high carbon storage must come at the expense of reduced crop yields, implying that farmers must choose between sustainability and profit. This study uses field inventories of 70 farms in Jinotega, Nicaragua to estimate this tradeoff in smallholder shade coffee systems. Field inventories were used to develop three typologies representing different shade management strategies in use in the region. SExI-FS modeling of a subsample of nine farms then illustrates potential carbon storage improvements through scenarios for altered shade management. Interviews with farmers and cooperative officials revealed attitudes toward potential management strategies, priorities and constraints regarding shade management, and interest in a potential carbon payment program. Sample farms supported aboveground carbon stocks ranging from 2.16 to 180.39 Mg/ha, with average aboveground carbon storage of 26.16 Mg/ha. When soil organic carbon at a depth of 0-50 cm was included, estimated carbon stocks rose to an average of 160.10 Mg/ha. SExI-FS modeling demonstrated that carbon storage is not strongly linked to shade cover, suggesting that carbon stocks can be enhanced without sacrificing crop yields. Management scenarios added an average of 13.92 MgC/ha with no increase in estimated shade. Interview participants held a wide range of priorities regarding shade management, but all indicated that they would like to change their shade management if they had the financial and technical resources available. Thirteen of 14 participants stated that they would be interested in participating in a carbon payment program if one were to be developed. My results suggest that while carbon stocks in Jinotega’s smallholder shade coffee systems are significant, they can be enhanced through changes in shade management. The additional carbon stocks would also attract higher carbon payments, leading to improved coffee cooperative revenues. With access to greater financial resources, these cooperatives could provide long-term credit and hire technicians to facilitate changes in shade management to improve carbon storage in smallholder shade coffee systems.

Executive Summary

Coffee is Nicaragua's largest agriculture export, annually contributing $375 million to the national economy and creating jobs for 42% of the nation's rural labor force (Flores, Bratescu, Martinez, Oviedo, & Acosta, 2002; World Bank, 2015). In addition to its economic importance, coffee production is an emerging topic of environmental concern (Perfecto, Rice, Greenberg, & van der Voort, 1996; Jha et al., 2014). Coffee landscapes throughout Latin America fall within a range of tropical forest systems, which are recognized for their role in habitat preservation and carbon storage (Brown & Lugo, 1982; UN-REDD, 2010). Tropical forests are major biodiversity hotspots, and also support an estimated 50% of global carbon stocks (Brown & Lugo, 1982; UN-REDD, 2010). However, as production expands and intensifies, it threatens to cause large-scale deforestation and degradation of tropical forest systems (UN-REDD, 2010).

As the environmental threat grows, so does the market for more sustainably produced coffee (Bacon, 2010). This demand has led to the establishment of several major certification initiatives (Ponte, 2004). Farmers who meet certification criteria, which govern a range of environmental and social aspects of production, are paid a higher per-pound price for their crop to compensate them for their efforts (Gobbi, 2000; Ponte, 2004). These initiatives rely on international consumers' willingness to pay a price premium for specialty coffee (Philpott, Birchier, Rice & Greenberg, 2007; Ponte, 2004; Rijsbergen, Elbers, Ruben, & Njuguna, 2016). Although the specialty market is rapidly expanding, smallholders face significant barriers to participation (Bacon, 2015; Donovan, 2011; Philpott et al., 2007; Valkila & Nygren, 2010). When farmers have access to certified markets, studies show that these price premiums can produce improvements in smallholder livelihoods (Bacon, 2005; 2015; Donovan & Poole, 2014; Valkila & Nygren, 2010). Certification efforts have been much less successful, however, in

creating significant improvements in environmental quality (Blackman & Rivera, 2011; Hardt et al., 2005).

A second mechanism has developed to address environmental sustainability more directly: payment for ecosystem services (PES) programs provide cash incentives to land users who provide defined ecological services to the larger population (Cole, 2010). In practice, compensated services have included water purification, habitat for endangered species, and carbon storage (Gómez-Baggethun, de Groot, Lomes, & Montes, 2009). The United Nations Reducing Emissions through Deforestation and Degradation (REDD+) program provides a formal framework for international carbon payment initiatives (UN-REDD, 2010). Current REDD+ projects are focused on maintaining and enhancing forest carbon stocks rather than agroforestry systems (ASB, 2011). Shade coffee landscapes are not equivalent to undisturbed forest in either habitat value or carbon stocks, causing many in the conservation community to question direct compensation for coffee farmers (Bhagwat, Willis, Birks, & Whittaker, 2008; Hairiah, Sitompul, van Noordwijk & Palm, 2001). However, coffee systems with dense and diverse canopy cover are increasingly being recognized for their importance in global climate mitigation, leading to their increasing consideration for integration into future REDD+ or other PES programs (ASB, 2011; Hairiah et al., 2001; Jha et al., 2014; Perfecto et al., 1996). This study quantifies carbon storage in smallholder shade coffee systems in Jinotega, Nicaragua and explores the potential for enhancing carbon stocks without significantly affecting coffee yields and integrating these farms into a carbon payment scheme.

Methods and results

Research methods proceed in four stages. The first stage utilizes field inventories to estimate carbon storage in living biomass and soil organic matter in 70 farm plots. Within 1000 m^2 plots, we recorded the species, diameter at breast height (DBH), and approximate height of all shade trees. Diameter at 10 cm at height of coffee plants was measured in a 100 m^2 subplot. Soil samples collected at five points within the larger plot were analyzed for organic matter content. I then used allometric equations representing documented relationships between DBH or coffee stem diameter and total biomass to estimate the living plant biomass in each plot. Assuming that carbon accounts for 50% of biomass, I found that plots supported an average of 26.16 MgC/ha in aboveground living biomass. Including soil carbon, plots store 160.10 MgC/ha.

The second stage uses the k-means clustering algorithm to assign sample plots to three clusters representing similar shade communities. While the literature has identified five general typologies for shade coffee production, all farms in the present sample fall into the category of commercial polyculture (Moguel & Toledo, 1999). To explore differences within this category, I created clusters representing subtypes in which shade canopy is dominated by *Musa* (banana) plants (n=28), by nitrogen-fixing *Inga* trees (n=25), or by diverse shade (n=17). The *Musa*-dominated cluster was significantly lower in biodiversity than other clusters, but there were no significant differences in carbon storage due to large variation within each cluster.

In the third stage, I selected three farms from each cluster for detailed inventory, including geospatial mapping, and model generation. I then modeled scenarios for improving carbon storage in each cluster. For Clusters A (*Musa*-dominated) and B (*Inga*-dominated) I used the constraint that shade should not be increased above 50%, the level at which yields begin to decline (Soto-Pinto, Perfecto, Castillo-Hernandez, & Caballero-Nietoc, 2000). Farms in Cluster

C (diverse shade) already supported shade above 60%, so for these farms I maintained average shade at existing levels. For Scenario 1, I modeled replacing half of *Musa* with *Inga* trees in Cluster A. Scenario 2 modeled adding timber trees (*Juglans olanchana*) to Cluster B. Scenario 3 modeled altering diverse farms from Cluster C to meet the strict ecological standards of Smithsonian Bird-friendly certification. The resulting improvements in carbon storage were 6.17 Mg/ha in Cluster A, 26.45 Mg/ha in Cluster B, and 9.15 Mg/ha in Cluster C.

The fourth stage used stakeholder interviews to explore priorities and constraints in shade management. Coffee farmers (n=7) and cooperative officials (n=7) discussed a wide range of perceived benefits provided by shade trees; farmers tended to emphasize farm-level benefits such as improved growing conditions for coffee plants, while cooperative officials were more likely to mention broader ecosystem services provided by shade trees. All farmers interviewed stated that they were interested in altering their shade management, often to incorporate more diverse species, but felt that they lack the financial or technical resources necessary to make the change. Cooperative officials indicated that technical assistance to farmers is among the services they would like to provide to their members, but that they do not have the financial means to hire technicians. Thirteen of 14 interview participants stated that they were interested in participating in a carbon-focused PES program if one were to be developed.

Policy recommendations and conclusion

The results of this study suggest that farms store a significant amount of carbon, and that carbon storage could be meaningfully improved with minimal impact on coffee yields. Further, stakeholders are willing to make the necessary changes in shade management if they are provided with financing. This leads to the recommendation that a carbon payment program should be initiated to compensate shade coffee farmers in the Jinotega region for the climate mitigation service provided by the agroforestry systems they manage.

Lessons from previous PES schemes in Nicaragua and around the world suggest that the voluntary market is the most appropriate arena for sale of carbon credits developed from this program. Under this model, coffee cooperatives should take advantage of established relationships with international investors to sell carbon credits as offsets to private buyers, such as businesses looking to maintain a “green” image. Utilizing existing cooperative infrastructure will reduce investment risk by providing a framework with demonstrated success in uniting smallholders in working toward a common goal. Cooperatives may provide technical support and reduce the cost of assessing and monitoring carbon stocks.

Organizations are also an ideal recipient of group-level payments on the part of the farmers they represent, which would lower transaction costs and increase the value of carbon credit sales for participants. Cooperatives should put this additional income toward hiring technicians and providing long-term credit for smallholders who are interested in altering their shade management but do not have the financial means to do so. These two policies would significantly reduce farmers’ perceived barriers to improving carbon storage and increase the efficacy of a carbon payment program. The third barrier to improving carbon storage through shade management lies not in farmers’ perceptions, but in a general lack of awareness surrounding the issue of climate change. Although farmers recognized that climate change was negatively affecting their livelihoods, they had never received education about the connection between climate change and carbon as a greenhouse gas. Cooperatives should therefore dedicate a portion of proceeds to creating and operating workshops focused on helping farmers to understand the direct impact of their shade management choices on the future impacts of climate change in the region. This will increase stakeholder engagement in efforts to enhance carbon stocks in shade coffee systems.

I further recommend that a portion of carbon payments be directed to participating farmers as cash or in-kind payments at the discretion of each cooperative. In this way, carbon payments can serve as a tool for improving smallholder livelihoods in addition to increasing provision of ecosystem services. Cash payments for ecosystem services are controversial, but the literature suggests that this strategy can be successful in reducing poverty while preserving or improving ecosystem quality (Bulte, Lipper, Stringer, & Zilberman, 2008; Wunder, 2007; 2008). Food for work (FFW) programs represent a potential alternative strategy in which cooperatives use carbon payment funds to buy supplies of food, and households experiencing seasonal hunger receive this food as payment for labor in community infrastructure projects (Holden, Barret, & Hagos, 2006). These two potential policy choices would not only improve rural quality of life in the Jinotega region, but also reduce household reliance on low-carbon fruit trees, therefore creating increased opportunities to plant timber or other shade species that store comparatively high quantities of carbon.

For farmers interested in improving carbon storage in their coffee parcels, I recommend providing a variety of strategies for practical alterations in shade management. Scenarios modeled in this study demonstrated that there are at least three strategies to add biomass carbon without increasing shade. Farmers have a wide range of baseline shade communities and a similarly wide range of priorities for determining which shade species to plant. Shade trees are a major investment, and a prescriptive approach for carbon improvement that does not incorporate each farmer's individual situation is not likely to be successful in the long term. Future studies should address the impact of additional strategies for altering shade to allow program developers to provide farmers with as many options as possible.

1.0 Introduction

Tropical forests represent a significant yet vulnerable concentration of valuable ecosystem services (Costanza et al., 1997). These ecosystems have been estimated to contain nearly half of global carbon stocks, and are also recognized as biodiversity hotspots supporting unknown numbers of species (Brown & Lugo, 1982; UN-REDD, 2010). High altitude regions of tropical forests also provide ideal growing conditions for commercial production of coffee (DaMatta, Ronchi, Maestri, & Barros, 2007; Perfecto et al., 1996). As global coffee consumption increases, so too does consumer interest in protecting the rich ecosystems that produce the crop through promoting socially and environmentally responsible growing practices (Bacon, 2010; Flores, Bratescu, Martinez, Oviedo, & Acosta, 2002; Osorio, 2002). Agroforestry, covering a variety of methods through which trees are incorporated into agricultural landscapes, is a prevailing strategy for achieving the goal of sustainability in coffee production (ASB, 2011). Coffee farms with a dense and diverse shade canopy have the potential to provide high-quality wildlife habitat, sequester large quantities of carbon, and require lower rates of agrochemical application (Staver, Guharay, Monterroso & Muschler, 2001).

When humans use forests for agricultural production, degradation is all but inevitable: conversion of tropical forest land is responsible for 17% of annual anthropogenic greenhouse gas emissions[1] (IPCC, 2007). Agroforestry techniques could help to reduce this impact (ASB, 2011). Shade coffee can store up to 213.8 tons of carbon per hectare in plant biomass, leaf litter, and soil organic matter (Soto-Pinto, Anzueto, Mendoza, Ferrer, & Jong, 2010) This is significantly less than the carbon storage potential of intact tropical forests, which sequester carbon pools

[1] By comparison, the entire transportation sector accounts for only 13% of anthropogenic emissions (IPCC, 2007).

ranging from 242 to over 350 tons per hectare, but represents major improvement from clearcut agricultural land, which stores less than 50 tons per hectare (Chave et al., 2005; Dossa, Fernandes, Reid, & Ezui, 2008; van Noordwijk et al., 2002). Coffee agroforestry may therefore be a viable strategy for protecting carbon stocks while creating sustainable rural livelihoods (ASB, 2011).

Some 20 to 25 million families—about 125 million people across more than 50 developing nations—are dependent on coffee production for more than half of their household income (Lewin, Giovannucci, & Varangis, 2004; Osorio, 2002). The United States spends more than $40 billion on coffee imports every year, but a mere 6 to 8% of the consumer price goes to the smallholders who produce the majority of coffee crops (Ponte, 2004; Lewin et al., 2004; Rijsbergen et al., 2016). Coffee consumption has increased dramatically in recent years, especially in the United States and Japan, and there has been a corresponding increase in consumer awareness of the social and environmental issues associated with coffee markets (Bacon, 2010; Flores et al., 2002; Osorio, 2002). This global interest has shaken the conventional coffee supply chain. Market demand for a more sustainable product has outpaced the communities' ability to create instruments for defining and rewarding sustainability in coffee production (Ponte, 2004).

Throughout these market shifts, two mechanisms have developed to promote socially and environmentally sustainable practices: certification that provides a price premium to farmers who meet certain production standards and direct payments for ecosystem services provided by diverse shade systems (ASB, 2011; Ponte, 2004). Coffee certification programs are international efforts to pay farmers a higher per-pound price for crops to make up for the additional resource requirements and reduced productivity of shade-grown coffee (Gobbi, 2000; Perfecto et al., 1996; Philpott et al., 2007). Direct payments are a second, emerging strategy for incentivizing shade tree maintenance (ASB, 2011). The United Nations Program for Reduced Emissions from Deforestation and Degradation (REDD+) offers a potential mechanism for these payments through placing an economic value on carbon stored in forest systems and offering cash incentives to conserve these carbon stocks (UN-REDD, 2010). While both mechanisms offer farmers more money in exchange for an environmental service, they also have shortcomings. Coffee certification communicates production methods through product labeling, and therefore relies on consumers' awareness of and willingness to pay more for eco-friendly coffee; this can lead to uncertain results for farmers (Philpott et al., 2007; Ponte, 2004; Rijsbergen et al., 2016). Further, conservationists question the direct incorporation of heavily managed systems such as shade coffee farms into REDD+ because agroforestry systems are not equivalent to undisturbed forest in either habitat value or carbon stocks (Bhagwat et al., 2008; Hairiah et al., 2001). Yet, as trees located outside forest systems are increasingly recognized for their role in mitigating climate change, coffee systems with dense and diverse canopy cover are being considered for integration into future REDD+ programs (ASB, 2011; Hairiah et al., 2001; Perfecto et al., 1996).

This thesis examines the potential for carbon storage in smallholder shade coffee systems in northern Nicaragua. Because a large percentage of primary forest across Nicaragua was removed during the twentieth century, land-sparing approaches often advocated for tropical regions are less viable there (Philpott & Dietsch, 2003; Westphal, 2008). In this setting, agroforestry represents an especially promising strategy to reduce greenhouse gas emissions. The research presented here investigates the potential role that complex shade coffee systems in Jinotega, Nicaragua play in carbon sequestration through carbon storage in aboveground plant biomass (AGB) and soil organic carbon (SOC) on coffee farms. Interviews with farmers and cooperative officials are then used to explore attitudes and practices regarding certification and shade management in the region. The following chapter explores the unique history of Nicaragua's coffee landscape, as well as the different certification efforts in place and the organizing role of coffee cooperatives in smallholder practices. Next, I discuss the ecosystem services afforded by shade coffee farms and methods for quantifying these services, with a focus on carbon storage. These chapters provide context and justification for exploring a carbon payment scheme as an alternative to the current market-driven strategies for incentivizing canopy maintenance among shade coffee farmers in the Jinotega region of Nicaragua.

The methods chapter describes field measurements I utilized to estimate present levels of carbon storage and shade tree diversity. Then I describe the use of SExI-FS software to model potential changes in shade canopy management and the implications for the quantity of carbon stored. The methods chapter concludes with the approach used in interviews I conducted with coffee producers and cooperative officials to explore attitudes surrounding shade management, current certification programs, and future carbon payment initiatives. The results chapter summarizes shade canopy composition and carbon storage across sampled farms, and identifies differences across clusters and cooperatives. Finally, I present the results of the interviews regarding future shade management policies to increase carbon storage and openness to participation in a future carbon payment scheme. The work closes with a discussion of the policy implications of the results.

2.0 Smallholder Coffee and Incentives in Nicaragua

Coffee is Nicaragua's largest agricultural export, contributing an annual $375 million to the national economy (World Bank, 2015). Flores et al. (2002) estimate that coffee production provides permanent employment to 70,000 people and temporary employment to 350,000 seasonal workers each year. Approximately 42% of Nicaragua's rural labor is in coffee production, nearly double the average for all of Central America (Flores et al., 2002). This places the economic influence of coffee farming just below livestock production, which employs an estimated 46% of the rural labor force[2] (World Bank, 2015). However, Nicaragua's coffee sector has not always created stable livelihoods for rural households (Bacon et al., 2014). Ninety-eight percent of Nicaragua's approximately 48,000 coffee farms are managed by smallholders who farm fewer than 14 hectares (Flores et al., 2002). These smallholders are given little government support and have long been vulnerable to market volatility, despite their significant economic contribution (Bacon, 2005; 2010). Many national and international organizations have attempted to increase financial security and improve rural quality of life (Bacon, 2005; Westphal, 2008). Before exploring the current actors and structures influencing the Nicaraguan coffee sector, it is helpful to understand the history of the crop in the region.

2.1 History and politics of coffee in Nicaragua

Coffee was introduced to the Americas in the early eighteenth century (Perfecto et al., 1996; Samper, 1999). Early cultivation took place on a small scale in natural and artificial forest clearings (Samper, 1999). This method developed into the creation of large-scale dense, full-sun

[2] There is likely overlap where surveyed households produce both coffee and livestock. The two sectors are of roughly equal economic importance and far outweigh the contribution of other crops such as sugar cane and peanuts (World Bank, 2015).

plantations surrounded by living windbreaks (Samper, 1999). By the late nineteenth century, however, farmers began to experiment with planting shade trees to protect coffee plants from the elements and adapt cultivation to a larger range of climatic conditions (Samper, 1999). Farmers also adopted the practice of planting coffee into the understory of existing forest patches, leaving the canopy intact (Moguel & Toledo, 1999). These rustic polyculture systems utilized high shade, supported diverse biotic communities, and provided habitat and landscape connectivity for tropical ecosystems (Hardt et al., 2015; Perfecto et al., 1996; Perfecto, Vandermeer, Mas, & Pinto, 2005). Coffee proliferated across Latin America under wide range of production intensity and shade diversity. The Jinotega region of Northern Nicaragua, a premontane tropical moist to wet forest zone, produced especially high quality beans (Khatun, Imbach, & Zamora, 2013; Rocha, 2001).

Coffee management trends in Nicaragua have historically been closely linked to the nation's political circumstances. Through the mid-twentieth century, coffee production was centralized into large-scale haciendas created by violently disenfranchising indigenous communities and smallholders (Bacon, 2005). The Somoza dictatorship of 1936 to 1979 supported this consolidation of coffee lands into extensive tracts of private property owned by powerful political figures (O'Connor, 2005). This system gave landowners complete authority over crop management decisions, enabling major changes in intensity of cultivation. In the 1950s, the influence of the Green Revolution reached coffee producers across Central America, inspiring a dramatic increase in the use of agrochemicals (Perfecto et al., 1996). The concurrent removal of shade trees promised producers higher coffee yields per unit land area (Perfecto et al., 1996). This trend toward "modernization" gained momentum in the 1970s when producers observed increasing rates of a newly-introduced fungal disease known as coffee leaf rust

(Perfecto et al., 1996). Desire to control rust and other diseases, combined with the promise of increased crop yields, encouraged widespread conversion from agroforestry methods to high-input sun farming systems (Perfecto et al., 1996).

When the Nicaraguan people overthrew the Somoza dictatorship in 1979, the Socialist Sandinista regime seized the previous government's assets, and rural land tenure reform became a political priority (Bacon, 2010). In the decade that followed, Sandinista agrarian reform affected a third of the area of Nicaragua and granted property rights[3] to over 100,000 smallholders (Bacon, 2010; Westphal, 2008). Coffee had previously been grown on a small number of very large farms, but through Sandinista land reforms it became an important crop for smallholders (Colburn, 1986; Bacon, 2010). Bacon (2010) estimated that 42% of coffee producers in Jinotega and the neighboring city of Matagalpa received their land titles during this period. Coffee landscapes that were previously consolidated into large plantations were converted to communal properties, and farmers were organized into operating cooperatives (Bacon 2010; Westphal, 2008). These cooperatives technically held property rights, but were overseen by government extension agents who controlled management decisions (Bacon, 2010; Colburn, 1986).

In 1980, the Sandinista government launched the Comisión Nacional para la Renovación del Café (National Coffee Renovation Commission, CONARCA). The goal of CONARCA was to increase production and eradicate coffee leaf rust, but in practice it amounted to state-sponsored slash-and-burn deforestation of coffee lands (Junta de Gobierno de Reconstrucción

[3] Although clearly beneficial to many of the rural poor, land reform was often performed without properly transferring property rights to the state before redistributing the title, resulting in the majority of land transfer recipients never receiving formal titles (Liscow, 2013). Political corruption further undermined public trust in the program, and many land holdings were contested through the 1990s (Broegaard, 2005). The land reform efforts notably excluded indigenous communities, who were not granted formal titles to communal land holdings (O'Connor, 2005).

Nacional, 1980; Westphal, 2008). The government undertook the renovation of 12,000 manzanas[4] (mz) of productive land through clearcutting existing plantations and replanting using the large, high-input full sun plantations prevalent in Brazil as a model (Colburn, 1986; Westphal, 2008). At the same time, government programs made agricultural credit more accessible and agrochemical inputs less expensive for new landholders, promoting a rapid conversion of agroforestry systems to sun coffee (Colburn, 1986). The result of these policies was the almost complete deforestation of Nicaragua's agricultural land, a trend that continued until the Sandinista government lost power in the election of 1990[5] (Bacon, 2005; Liscow, 2013).

The liberal government of the 1990s favored the free market, which led them to implement a series of legal reforms that shifted property rights from cooperatives to individuals (Bacon, 2010; Westphal, 2008). These laws parceled cooperative-held properties into small farms of less than 5 mz and granted individual land titles to the members of the cooperative (Bacon, 2010). Farmers were given much more autonomy in land management, which had previously been the purview of government extension agents (Liscow, 2013). Reforms also privatized the state bank and liberalized interest rates, making agricultural credit much more difficult for smallholders to obtain: between 1991 and 1992, there was a 72% decrease in the number of agricultural loans granted to coffee producers (Bacon, 2005; Broegaard, 2005). Credit-constrained smallholders no longer had access to the expensive agrochemicals necessary for high-input coffee production, and many turned back to more traditional management strategies (Bacon, 2005). Producers replanted shade trees in their farms, creating new canopy

[4] The standard unit of measure for land holdings in Nicaragua, 1 manzana (mz) = 0.7 hectare (Westphal, 2008).
[5] The original Sandinista uprising did not result in a clean shift of power; civil war continued until 1990 (Liscow, 2013). Armed conflict affected the influence of government programs such as CONARCA and patterns of deforestation across Nicaragua (Stevens, Campbell, Urquhart, Kramer, & Qi, 2011). In the North, conflict prevented major land conversion until the 1990s (Stevens et al., 2011; Zeledon & Kelly, 2009)

communities designed by farmers, composed of preferred species such as fruit or timber trees (Bacon, 2005).

Despite this, rapid deforestation continued across Nicaragua throughout the 1990s, a phenomenon attributed to the eastward expansion of agricultural production from the Pacific region (Faris, 1999; Liscow, 2013; Zeledon & Kelly, 2009). In Jinotega, major conversion of forest to agricultural use occurred from 1987 to 1999 (Zeladon & Kelly, 2009). Nicaragua's coffee producers increased the area under production by 28% between 1995 and 2001 to keep pace with increasing global demand (Flores et al., 2002). Between 1990 and 2001, Nicaragua reported a 93.1% increase in coffee production and a 56.9% increase in export volume, indicating greater production intensification during this period than any other nation in Central America (Varangis, Seigel, Giovannucci, & Lewin, 2003). By 2000, less than 8% of Nicaragua's landscape was classified as intact forest (Potapov et al., 2017). In 2002, the coffee-producing area of Nicaragua covered approximately 108,300 hectares across the departments of Jinotega, Matagalpa, Las Segovias, Pacífico, and Boaco (Flores et al., 2002). The largest contributor, and the focal area of this thesis research, is Jinotega. One third of the department's area is currently devoted to coffee farming, and Jinotega produces more than half of Nicaragua's coffee harvest (Flores et al., 2002).

The single-crop focus means that the region is at risk. This problem was highlighted during the Coffee Crisis[6] at the turn of the twenty-first century, in which northern Nicaragua suffered enormously (Bacon, 2005). In Nicaragua, the coffee crisis was exacerbated by the destruction caused by Hurricane Mitch and three years of drought (Bacon, 2005). These

[6]The so-called "Coffee Crisis" was characterized by a significant decline in global coffee prices beginning in 1999 (Bacon, 2010). In 2001, coffee prices dropped lower than they had in 30 years (Flores et al., 2002). Coffee prices continued to fall from $1.20/lb in 2001 to between $0.45 and $0.75/lb in 2005, causing widespread food insecurity and loss of employment as coffee producers worldwide could no longer meet their basic needs (Bacon, 2005; 2010).

economic and climatic factors combined to seriously undermine the Nicaraguan coffee sector (Flores et al., 2002; Varangis et al., 2003). Between 1999 and 2001, coffee exports fell by 14% and revenues from coffee exports fell by 50% (Varangis et al., 2003). The impact on Nicaragua's coffee producers was significant: although the poverty rate in all rural households fell by 6% between 1998 and 2001, poverty increased by 2.4% for coffee farming families during that period (Flores et al., 2002).

Coffee producers employed several strategies to reduce household-level impact. Many farmers dealt with the loss by converting their landholdings from traditional methods of coffee production to pasture for cattle ranching, effectively turning a humanitarian tragedy into an environmental crisis (Bacon, 2010; Philpott & Dietsch, 2003). Other farmers increased labor, as much as doubling their family's labor time in an attempt to recoup sunk production costs and repay agricultural credits granted by cooperatives or local banks (Bacon, 2005). These farmers also avoided hiring seasonal laborers, leading to a 21% drop in seasonal employment across Central America (Bacon, 2005). Some farmers even abandoned non-coffee crops, sacrificing food crops for household consumption in order to dedicate all available resources to coffee production, leading to increased food insecurity and hunger (Bacon, 2005, 2010). The ramifications of the Coffee Crisis caused government agencies and NGOs to increase their focus on the alternative coffee market, which includes Fair Trade and eco-labeled products, as a potential solution to the low price of commodity coffee (Bacon, 2010).

Certification efforts sought to decrease the abandonment and conversion of coffee farms across Latin America (Bacon, 2005; Philpott et al., 2007). Programs range from producer-focused Fair Trade certification to efforts with more specific environmental standards including organic, Rainforest Alliance, and Smithsonian Bird-friendly. These certifications seek to provide a price premium for biodiversity-friendly management of coffee farms, including agroforestry practices (Philpott et al., 2007; Raynolds, Murray, & Heller, 2007). Despite the intention of these certification programs to provide a price premium to farmers who maintain environmentally responsible practices, evidence for a positive impact on household income is mixed (Ponte, 2004; Rijsbergen et al., 2016). The following sections outline the circumstances of smallholders and the grower cooperatives they operate in Nicaragua, as well as the outcomes of incentive programs designed to support the smallholder coffee sector.

2.2 Crop diversification in the wake of the Coffee Crisis

Income from coffee production is distributed unevenly throughout the year because both harvest and availability of temporary off-farm employment are seasonal (Bacon, 2004). This contributes to a lack of food security, which in turn influences coffee system management (Bacon, 2004). Approximately 93% of smallholders in northern Nicaragua report some degree of food insecurity, and over half of producers report that this insecurity is moderate or severe (Canto, Perez, Gonzalez, & Läderach, 2015). Nicaraguan coffee producers experience an average 3.15 months of seasonal hunger each year (Bacon et al., 2014). Where farmers are heavily reliant on coffee as the sole cash crop, they are also vulnerable to shifts in commodity prices (Canto et al., 2015; Flores et al., 2002; O'Connor, 2005). Shifts in coffee prices are difficult to predict or prepare for, but avoiding a monocrop focus may help farmers avoid hunger in the event of another Coffee Crisis (Flores et al., 2002; O'Connor, 2005; Osorio, 2002). Recognizing the household-level importance of diverse income streams for stability, the International Coffee Organization recommended crop diversification as a means of addressing the devastation of the Coffee Crisis (Osorio, 2002).

The majority of coffee producers in Jinotega also grow at least half of the food crops consumed by their household, including staple crops such as maize, beans, and bananas (Bacon, 2005). Shade trees such as avocado, citrus, guava, and mango supplement household consumption and, rarely, household income (Bacon, 2005; Donovan, 2011). Bananas are the most commonly marketed of non-coffee crops, grown by 76% of smallholders and providing farmers with an average of $180 in additional income each year[7] (Canto et al., 2015; Donovan, 2011). During periods of seasonal hunger, families can subsist on a diet of almost exclusively bananas (Bacon et al., 2014). The importance of productive trees in coffee agroforestry systems clearly extends beyond simply affording a more beneficial climate for coffee plants.

Coffee cooperatives and NGOs also recommend diversification as preparation for the shifting productivity of Nicaraguan farms as climate change affects the range of optimal coffee habitat (Bacon, 2014; O'Connor, 2005, Osorio, 2002). Philpott, Lin, Jha, and Brines (2008) suggest that more complex canopy cover can make coffee farms less vulnerable to the destructive impact of hurricanes. In a survey conducted by Tucker, Eakin, and Castellanos (2010), nearly a quarter of coffee producers identified extreme weather events as a serious concern. However, three times as many farmers perceived shifts in coffee markets as a threat (Tucker et al., 2010). This suggests that in the wake of the coffee crisis, coffee prices are the driving factor in influencing shade tree management. In light of this, coffee certifications that provide a price premium for responsibly-produced crops appear to be an appropriate starting point in efforts to incentivize shade in coffee systems.

[7] Revenues vary widely based on banana plant density and farm size. Donovan (2011) reported a standard deviation of $489.06 across a sample of 292 producers.

2.3 Incentive programs for environmentally-responsible coffee production

Market-based mechanisms to incentivize certain social or environmental standards have been developing since the mid-twentieth century, and the market is rapidly expanding: in 2012, specialty coffee accounted for 37% of coffee sales by volume and 50% of value in the United States (Bacon, 2005; Jha et al., 2014). However, the resulting programs still incorporate only a very small percentage of producers (Ponte, 2004). Bacon (2005) estimates that 80% of Nicaraguan coffee exports could hypothetically be sold in specialized markets including gourmet, Fair Trade, organic, shade, or other certification labels. Despite this massive potential, only 10-15% of Nicaraguan exports are presently sold as specialty coffee (Varangis et al., 2003). This gap represents potential for growth, but also highlights the limitations of certification programs in reaching the coffee producers they target.

Payments for ecosystem services (PES) programs represent an alternative to market-based incentives. These programs are designed to create financial incentives for landowners to provide defined ecological services to the larger population (Cole, 2010). Monetary valuation of ecosystem services began in the 1960s, and the research area expanded rapidly through the 1990s (Gómez-Baggethun et al., 2009). Commodification of ecosystem services has since led to the creation of both straightforward PES initiatives and markets in which ecosystem service credits can be bought and sold (Gómez-Baggethun et al., 2009). The markets developed through the PES lens have incorporated services ranging from watershed protection, endangered species habitat provision, pollination services, and atmospheric sink functions for sulfur and carbon gases (Gómez-Baggethun et al., 2009). In the twenty-first century, policymakers are increasingly recognizing the importance of coffee systems in providing these ecosystem services, and the benefits of incorporating shade coffee producers into future PES programs (Rosa, Kandel, & Dimas, 2004).

In PES initiatives, payments may be dispersed to individual households or to collective entities (Mahanty, Suich, & Tacconi, 2013). These collective recipients accept payments on the part of the community and put them toward creating local jobs or community infrastructure improvements (Mahanty et al., 2013). In practice, PES schemes have allowed for payments to be accepted by a collective entity and then distributed to individual participants (Mahanty et al., 2013). This strategy generally lowers the transaction cost for the buyers (Carlson & Curran, 2009).

Scherr, White, and Kaimowitz (2004, as cited in Milder, Scherr, & Bracer, 2010) identified four categories of buyers in PES schemes. The first is the public sector, government actors interested in maintaining ecosystem services for the public good. The second type consists of private sector actors who are legally required to pay ecosystem service providers as a means of mitigating their own polluting activities. The third group is voluntary private sector actors, which are businesses that buy ecosystem service credits to maintain an eco-friendly image, and NGOs and individual investors with an interest in supporting environmental quality. The fourth category is consumers of eco-certified products. In the case of coffee, these buyers agree to pay a price for the ecosystem services provided by shade coffee systems in addition to the price of the beans themselves (Ponte, 2004). At present, only this final category is active in the Jinotega region, but there has been interest on the part of public actors as well (Donovan & Poole, 2014).

The future of coffee crop management is a priority for government agencies, NGOs, and local coffee cooperatives aiming to mitigate poverty, habitat loss, and climate change (Donovan, 2011; Donovan & Poole, 2014). Since 1990, the Nicaraguan government has enacted 10 environmental laws and 13 decrees to promote conservation of natural resources (Suarez, 2002). The Nicaraguan government has demonstrated interest[8] in developing a PES project for promoting shade coffee, and went so far as to involve coffee cooperative officials in informational workshops, but no national PES initiative for coffee producers has yet been formally implemented[9] (Mendez, Bacon, Olson, Morris & Shattuck, 2010; Porras, Amrein, & Vorley, 2015). Further, land use designations and environmental laws are rarely and unevenly enforced in Nicaragua, implying that this area is not a high priority in the current policy agenda (Liscow, 2013). National Law 217, the General Environmental and Natural Resources Law, was approved in 1996, and a climate change commission was created under this directive, but the overall impact of the law has been minimal (Suarez, 2002). Liscow (2013) asserts that a top-down approach to forest maintenance is not likely to be effective in Nicaragua. No specific legislation has been enacted to create legal infrastructure for PES programs (Porras et al., 2015; Suarez, 2002). A payment system to reward shade tree maintenance implemented in conjunction with the price premium offered by specialty markets could incentivize shade management more effectively than the weak existing legal framework (Jha et al., 2014; Suarez, 2002). In Jinotega, coffee cooperatives currently play a leading role in organizing certifications to distribute price premiums, and they are well positioned to take on an administration role if government agencies do not have the resources to do so (Bacon, 2005; 2015; Donovan, 2011; Suarez, 2002).

The already well-developed coffee cooperative framework already in Nicaragua offers a potential network for facilitating carbon payments with minimal overhead. Many cooperatives

[8] Nicaraguan interest in PES program development was likely inspired by Costa Rica, which initiated direct subsidies for landowners through amendments to the national forestry law in 1996. The program incorporated nearly 315,000 ha of land, and subsidy payments of $0.60 per tree began in 2003 (Rosa et al., 2004).
[9] One NGO-led PES program has been initiated to promote reforestation of agricultural lands (Porras et al., 2015). I will discuss the example provided by this effort in section 2.6.

have experience receiving grants from international NGOs and investing those payments into technical or social development programs to benefit member farmers (Donovan, 2011; Bacon, 2005). Due to constraints in monetary and human capital, cooperatives may lack the technical capacity, however, to accurately quantify carbon storage across participating farms (Donovan & Poole, 2014). In the following sections I provide background of cooperatives and current certification initiatives as context for the potential development of carbon payment programs.

2.4 Grower cooperatives and certified coffee programs

Though coffee cooperatives as communal property holders in Nicaragua were disbanded in the early 1990s, the model persists with a marketing function, filling an important role in the supply chain (Bacon, 2005). Independent smallholders are frequently unable to produce coffee in the quantities required by processors and exporters, which can lead to these smallholders being forced to sell to intermediary buyers at a much lower price (Donovan, 2011). Joining into local cooperatives allows an alternative strategy, guaranteeing producers a higher price per pound and allowing smallholders to reach larger international markets that would otherwise be inaccessible (Bacon, 2005; Ruben & Zuniga, 2011). Cooperatives vary widely in membership, from fewer than 100 members to over 2,000 (Donovan, 2011). Local cooperatives composed of anywhere from 15 to 100 households often unite under the umbrella of larger organizations for access to greater social and financial capital (Donovan & Poole, 2014). In a two-tier structure, small cooperatives associate under the umbrella of a larger organizing body that handles national and international marketing, processing, and credit provision (Donovan, 2011). Under this model, cooperative membership often represents a relatively large geographic scale, and members share a set of common values and a history of working toward common goals.

Cooperative membership influences farmers' management decisions and provides resources necessary to put responsible practices into place (Bacon, 2010; Mendez, Shapiro, & Gilbert, 2009). Members often have greater access to technical assistance and to agricultural credit, allowing more intensive cultivation that leads to greater yields (Bacon, 2005; Donovan & Poole, 2014). Mendez et al. (2009) suggest that cooperative history and management style may influence the characteristics of member farms, potentially leading to different levels of ecosystem services across cooperative landscapes. Where cooperatives participate in certified coffee markets, farmers manage labor practices, plant selection, chemical application, and shade tree density differently from independent producers (Donovan & Poole, 2014; Ruben & Zuniga, 2011) Presently, to support smallholders who maintain high value shade systems, coffee cooperatives are playing increasingly important roles in facilitating certification schemes such as Fair Trade and eco-labeling programs.

2.4.1 Fair Trade

Fair trade certification, which requires farmers to cooperate with a Market Access Partner, provides a framework for the potential implementation of carbon payments (Bacon, 2005; Fair Trade USA, 2014; Ponte, 2004). Fair Trade is prominent in Nicaragua, where it is administrated by grower cooperatives (Bacon, 2005; Donovan, 2011). After organic certification, Fair Trade accounts for the second highest volume of specialty coffee (Ponte, 2004; Raynolds et al., 2007). Program goals are primarily social: grower empowerment, inclusive participation, supply chain transparency, freedom from forced labor, protection of youth, and occupational health and safety (Fair Trade USA, 2014; Ponte, 2004). Recently, however, Fair Trade compliance criteria have expanded to include measures of environmental stewardship (Fair Trade USA, 2014). These new measures include monitoring and promoting biodiversity, and are evaluated over a longer timeframe than other compliance criteria (Fair Trade USA, 2014).

Fair Trade has been in practice since the 1980s, and the adoption and promotion of Fair Trade coffee by major companies such as Starbucks and Folgers helped the program achieve broad consumer awareness (Bacon, 2005; Raynolds et al., 2007). Higher per-pound prices offered and greater market access offered to producers by Fair Trade cooperatives provided greater income security during the coffee crisis, but the model requires cooperative membership and therefore excludes unassociated smallholders (Bacon, 2005; Donovan, 2011; Valkila & Nygren, 2010). A number of studies have investigated the impact of participation in Fair Trade cooperatives on farmer livelihoods, finding an overall positive effect on household savings and educational attainment (Bacon, 2005; Bacon, 2015; Donovan & Poole, 2014; Valkila & Nygren, 2010).

While there is a large body of evidence supporting a positive impact of Fair Trade, this is not always the case. Cooperatives are not always capable of maintaining a high price premium over time or delivering promised benefits to certified farmers (Rijsbergen et al., 2016). Further, the price premium associated with certification fluctuates with commodity coffee prices, and tends to decrease when the price for uncertified coffee increases (Ponte, 2004). Theoretically, the additional income from certification promotes sustainability indirectly by providing smallholders with a living wage that enables them to continue shade farming rather than converting their land to higher-revenue uses such as sun coffee, corn, or cattle grazing (Raynolds, Murray, & Heller, 2007; Philpott & Dietsch, 2003). The greatest impediment Fair Trade faces in incentivizing agroforestry is that primary program standards govern labor standards, and environmental criteria have only recently been developed (Fair Trade USA, 2014; Raynolds, Murray, & Heller, 2007).

Fair Trade cooperatives often hold environmental sustainability as a goal, recognizing the importance of healthy ecosystems in supporting human communities (Bacon, 2005; Donovan, 2011). Cooperatives invest their additional revenue to advance social and environmental goals through development projects such as building latrines, improving roofing, and constructing less-polluting coffee processing facilities (Donovan, 2011). Additional investments made possible by carbon payments that are not tied to commodity prices would reinforce the desirability of agroforestry methods and could advance community development.

While their established roots in Nicaragua make them an attractive tool for potential distribution of carbon payments, Fair Trade cooperatives may not be the most appropriate vehicle. Fair Trade certification is not linked to any differences in quantity or diversity of shade trees, or in diversity of indicator animal species as compared with uncertified farms (Philpott et al., 2007). Since certified farms do not necessarily support more trees, it is not likely that they store significantly more carbon (Philpott et al., 2007). Other more recently initiated certification programs seek to directly address aspects of environmental integrity at the farm level. Though these goals also do not directly incorporate carbon storage, the high shade farms that these eco-certification initiatives reward are likely to be strong candidates for incorporation into future carbon payment schemes.

2.4.2 Eco-certification programs

Eco-labeling schemes encompass a group of certifications based on environmentally sustainable management practices such as reduced agrochemical use and maintenance of dense and diverse shade (Ponte, 2004). Organic certification, a market presence since 1967, is the most established eco-certification program (Ponte, 2004; Raynolds et al., 2007). Standards restrict the use of agrochemicals and require that producers undertake measures to conserve soil and water resources (Raynolds et al., 2007). However, organic standards do not include a baseline level for shade in participating farms; to this end, conservation NGOs have developed new certification efforts that implement additional requirements focused on structural diversity and habitat quality (Lewin et al., 2004; Ponte, 2004).

Two programs, Rainforest Alliance and Smithsonian Institute (Bird-friendly) certifications, both founded in the mid-1990s, are active in promoting shade canopy maintenance in Central American coffee production (Lewin et al., 2004; Raynolds et al., 2008). Bird-friendly certification was designed to promote habitat conservation through rewarding smallholders who maintain structurally diverse coffee systems (Raynolds et al., 2008; Smithsonian, 2017). This focus resulted in the most stringent environmental standards of all major certification efforts (Raynolds et al., 2008). Rainforest Alliance ecological requirements are more flexible and place greater emphasis on social goals in addition to environmental impacts (Ponte, 2004). Certified farms must meet the comprehensive standard of the Sustainable Agriculture Network (SAN), which uses a three-tier compliance system (Rainforest Alliance, 2017; see SAN, 2017). SAN standards recognize a similar definition of appropriate shade in coffee systems[10] as that promoted by Bird-friendly certification, but shade community is a third-tier criterion (SAN, 2017). Certified farms are required to create management plans and meet self-defined measures for

[10] SAN defines appropriate shade in coffee systems as 40% canopy cover with a minimum of 12 species present (SAN, 2017). Smithsonian Bird-friendly standards require 40% canopy cover with a minimum of 10 woody species, with a backbone layer 12-15 meters in height accounting for roughly 60% of foliage volume (Smithsonian, 2017).

improvement; six years after attaining certification, farms are must meet only 50% of SAN's 18 different third-tier criteria (SAN, 2017).

The impact of these certification efforts is the subject of debate (Blackman & Rivera, 2011). Proponents point out that farms with Rainforest Alliance certification do exhibit greater habitat value than uncertified farms, and both types of eco-certification are associated with greater bird and butterfly species richness (Hardt et al., 2005; Mas & Dietsch, 2004). However, the direct environmental impact of certification is unclear, as critics claim that sustainable practices and diverse systems would exist regardless of certification (Blackman & Rivera, 2011; Hardt et al., 2005). Eco-certification does not appear to be a strong incentive for farmers to reverse unsustainable practices (Blackman & Rivera, 2011). And attaining certification is a demanding process even when farmers do not need to change their management practices to comply: farms take two to four years to achieve Rainforest Alliance certification, and farmers, or the cooperatives to which they belong, must pay for yearly visits from certification teams (Gobbi, 2000; Hardt et al., 2015). When the price premium[11] for certified coffee is high, meeting the strict requirements of Smithsonian or Rainforest Alliance certification can lead to positive financial outcomes for farmers (Gobbi, 2000). However, the actual increase in farmers' income is not always high enough to recoup the costs of certification (Philpott et al., 2007).

Despite uncertain monetary impacts of the various certification schemes in which cooperatives participate, the proliferation of certified cooperatives across Central America demonstrates the flexibility of cooperative infrastructure in adapting to market demand for eco-friendly products (Philpott et al., 2007; Ponte, 2004). In addition to paying participating farmers

[11] Price premium varies widely, depending on certification type and conventional coffee prices (Ponte, 2004). Documented ranges for the per-pound price premium associated with the major eco-certifications are \$0.10 to \$0.80 for organic, \$0.04 to \$0.20 for Rainforest Alliance, and \$0.05 to \$0.28 for Bird-friendly (Giovannucci, Byers, & Liu, 2008).

slightly higher prices for coffee produced using environmentally-friendly practices, many cooperatives that participate in eco-certified coffee markets provide technical support to assist members in meeting cooperative goals (Donovan & Poole, 2014). Cooperative-employed technicians advise farmers on shade management as well as chemical application, weather adaptation, pruning, and other aspects of coffee production (Bacon, 2005; Donovan & Poole, 2014; Frank, Eakin, & Lopez-Carr, 2011). Technicians are often unavailable to farmers who are not affiliated with these cooperatives (Donovan, 2011). Throughout the growing season, technicians are active in providing cooperative management with harvest estimates, soil assessments, and basic shade tree inventories (Donovan, 2011; Frank et al., 2011). These activities are limited by the low budgets many cooperatives work with, and they represent a potential growth area if cooperative revenues increase (Frank et al., 2011).

Cooperatives are a strong social institution in northern Nicaragua (Bacon, 2005). These structures may form a basic framework useful for developing and distributing carbon-focused incentives, but they are not yet equipped with the legal or technical tools necessary to administrate such an initiative (Donovan, 2011). In the following section I explore the history and potential future of carbon-centered PES programs, with an emphasis on the integration of existing cooperative structures.

2.5 Carbon markets and the future of sustainability incentives

The United States government created the first large-scale market for atmospheric emissions through a 1990 amendment to the Clean Air Act (Bayon, 2004; Gómez-Baggethun et al., 2009). In an effort to address the problem of acid rain, this amendment created a sulfur dioxide emissions trading system in which polluters were issued tradable emissions permits (Bayon, 2004). The program's success drew attention from policymakers around the world, who saw a potential application of this model to the emerging issue of climate change caused by carbon emissions (Bayon, 2004; Gómez-Baggethun et al., 2009). Carbon markets have their roots in the 1997 Kyoto Protocol, in which 191 United Nations (UN) member states and the European Union agreed to address climate change through a global reduction in greenhouse gas emissions (Holloway & Giandomenico, 2009; Newell, Pizer, & Raimi, 2013). The Kyoto Protocol incorporated flexibility mechanisms designed to help industrialized nations meet their emissions reduction targets in a cost-efficient way; one of these was the Clean Development Mechanism (CDM), which allows developing nations to sell emission reduction credits generated through approved sustainable development projects (Kimura, Srinivasan, & Iyadomi, 2006).

Although policymakers initially envisioned a unified global carbon market under the Kyoto framework, a number of smaller regional and national carbon markets in practice have developed instead (Newell et al., 2013). Small-scale CDM projects represent a major market for carbon: in 2011, CDM projects generated 300,000 tons of emissions credits (Newell et al., 2013). However, demand for these credits has fallen in subsequent years (UN-FCCC, 2016). At the same time, national and regional governments have initiated cap-and-trade programs such as the European Union Emissions Trading System, the Regional Greenhouse Gas Initiative in the Eastern US, and the New Zealand Emissions Trading Scheme (Newell et al., 2013). The final arena for trading in carbon credits is the voluntary market, representing a variety of structures under which individuals or businesses buy emissions reduction credits marketed by projects around the world (Newell et al., 2013).

At the Bali Conference in 2007, the CDM concept of providing payments to developing nations for reducing carbon emissions through deforestation and degradation (REDD) was formalized into the REDD Program (Clements, 2010; Holloway & Giandomenico, 2009). REDD became REDD+ in 2010, incorporating a focus on conserving and enhancing forest carbon stores (USAID, 2014). Donor nations, beginning with Denmark in 2008, Finland in 2009, and Spain in 2010, contributed funding to initiate pilot programs in nine countries: Bolivia, the Democratic Republic of the Congo, Indonesia, Panama, Papua New Guinea, Paraguay, Tanzania, Vietnam, and Zambia (UN-REDD, 2010). The United Nations Framework Commission on Climate Change (UN-FCCC) established that a “forest” is an area greater than 0.5-1 hectare in area, with a minimum of 10-30% canopy cover and 2- to 5-meter tree height, although participating regions must individually define what constitutes a forest worthy of receiving payments (ASB, 2011). UN goals prioritize projects that create multiple benefits from REDD+ projects, including not only carbon storage but also indigenous rights, poverty reduction, and gender equity (USAID, 2012).

To examine the potential barriers to development of a carbon payment program in the Jinotega region, I turn to the lessons offered by an existing PES project in Nicaragua and by REDD+ pilot projects elsewhere in the world. The CommuniTree project managed by Canadian NGO Taking Root is the only reforestation project in Nicaragua financed exclusively through the sale of carbon offsets (Porras et al., 2015). Participating smallholders enter into a ten-year agreement in which they are granted financing to plant native forest species on portions of their farm properties and granted payments for the carbon stored by these plantings (Porras et al., 2015). The program does not require farmers to repay loans in cash; the loan is instead deducted from future PES payments (Porras et al., 2015). Carbon credits are sold on the voluntary market by Taking Root or by independent resellers to customers including the Inter-American Development Bank, the corporation Tuff Gong Worldwide, and several private investors (Porras et al., 2015). Between 2009 and 2014, the project gave out $152,498 in cash advances and $257,540 as PES (Porras et al., 2015). The CommuniTree project allows for trees to be planted in silvopasture[12] systems, as boundary fences, or in mixed-species forest plantations (Porras et al., 2015). The estimated net carbon benefits over a three-year project cycle are 191.9 MgC/ha, 214.80 MgC/km, and 299.7 MgC/ha, repectively (Baker, Baumann, Gervais, & van Mossel-Forrester, 2014). Payments over the ten-year period are delineated in each farmer's contract; the 2013 pricing structure guaranteed participants corresponding payments of $629.70 per hectare, $708.84 per km, or $983.44 per hectare (Porras et al., 2015). While these payments represent an increase in income for smallholders, the amount is relatively low when compared to the annual value of crops that could potentially be grown on this land[13] (Beuchelt & Zeller, 2011).

REDD+ pilot projects have not been any more successful in providing forest user groups with payments large enough to outweigh the cost of reduced forest use (Maraseni, Neupane, Lopez-Casero, & Cadman, 2014). This raises the question of how much money must be invested to make carbon payments profitable for Nicaraguan coffee farmers. Based on analysis of shade coffee production in Matagalpa, Nicaragua, Suarez (2002) suggested that annual payments of $16.10 per MgC would be required to make up for the opportunity cost of not pursuing the most profitable land use.[14] However, payments of just $1.50 per MgC would be sufficient to maintain existing coffee management rather than convert to higher-input production under the current

[12] Silvopasture refers to integrated systems of trees and forage crops for the production of timber, other tree products, and livestock (Klopfenstein et al, 1997).
[13] Beuchelt & Zeller (2011) documented that mean net income from coffee sales in Nicaragua in 2007 ranged from $489.90 per hectare for conventional to $716.10 per hectare for certified organic crops. While these numbers are subject to annual fluctuations, commodity prices have generally been even higher since 2007 (Jacks & Steurmer, 2016). This clearly exceeds the roughly $60 to $100 per hectare offered by the CommuniTree PES program (Porras et al., 2015).
[14] Analysis performed by Suarez (2002) determined that growing chayote squash was the most profitable land use, leading to net present value of $2,236 per ha with carbon storage of 33.6 tC per hectare. Shade coffee farmland in the study had net present value of $52.27 and carbon storage of 146.8 tC per hectare.

land-use change scenario (Suarez, 2002). Even low-diversity[15] coffee agroforestry systems sequester 53-57 more tons of carbon per hectare in aboveground biomass (AGB) than do sun coffee farms, implying that necessary payments would be roughly $80 per hectare (Jha et al., 2014; Palm et al. 2005; Soto-Pinto et al., 2010). These payments are far outside the bounds of current REDD+ program development: in 2012, pilot projects in Nepal paid forest user groups between $2.98 and $9.23 per hectare (Maraseni et al., 2014).

The low market price of carbon is not the only barrier to REDD+ development. High institutional, monitoring, and transaction costs impede project implementation (Carlson & Curran, 2009; Merger, Held, Tennigkeit, & Blomley, 2012; UN-REDD, 2011). Institutional development, stakeholder engagement, and legal preparation activities account for 89-95% of all project costs (Merger et al., 2012). Ongoing institutional costs comprise another 1% of project expenses, and transaction costs comprise the remaining 4-10% (Merger et al., 2012). The majority of transaction costs stem from monitoring and verification of carbon stocks (Rendón-Thompson et al., 2013). Cost and accuracy vary based on monitoring method (see Wertz-Kanounnikoff & Verchot, 2008). In an assessment of 12 REDD+ projects in the Peruvian Amazon, Rendón-Thompson et al. (2013) estimated average transaction costs of $0.73 per hectare per year. The average per-hectare transaction costs decrease as project scale increases, since costs are spread over a larger geographic area[16] (Merger et al., 2012). Monitoring inventories may also employ local community members rather than professional foresters, a

[15] Assessments are based on coffee farms with 1-3 shade species (Palm et al., 2005; Soto-Pinto et al., 2010). Higher biodiversity is associated with higher levels of carbon storage, suggesting that more diverse shade systems would warrant even higher carbon payments (Wardle, Bardgett, Callaway, & Van der Putten, 2011).

[16] However, with increasing scale comes increased complexity and investment risk as projects begin to incorporate more diverse land users (Carlson & Curran, 2009).

strategy which lowers cost and improves livelihoods without a significant decrease in accuracy (Danielsen et al., 2011; Larrazábal, McCall, Mwampamba, & Skutsch, 2012).

In the previous section I have discussed the Nicaraguan context for shade coffee and outlined existing efforts to influence coffee management toward improving farmer livelihoods and advancing environmental goals. The following section explores these environmental goals in greater detail, beginning with the more established reasons that conservationists and humanitarian organizations have promoted shade coffee since the mid-1990s. I then focus on carbon storage in shade coffee landscapes and methods for carbon estimation to demonstrate both the value and the challenge of developing large-scale inventories of carbon storage in Nicaraguan smallholder coffee systems.

3.0 Services Provided by Shade Trees in Coffee Landscapes

Coffee production today represents a range of management techniques that lead to a wide variety of shade cover and species richness (Perfecto et al., 1996). Rustic agroforestry systems, which most closely resemble intact forest, utilize high shade and support diverse biotic communities (Perfecto et al., 2005). Commercial full-sun coffee, on the other hand, is produced in a monoculture system that relies on high levels of agrochemical inputs (Perfecto et al., 2005). Smallholders across Central America tend to utilize traditional polyculture methods, producing structurally complex agroforestry systems that contribute a wide range of ecosystem services (Moguel & Toledo, 1999; Perfecto et al., 2005). Nicaragua's coffee farms incorporate deliberately-planted functional shade such as fruit trees, timber species, or nitrogen-fixing *Inga* species (Suarez, 2002; Westphal, 2008). These farms represent a commercially-focused shade system, functionally inferior to intact forest but richer than open sun plantations. Canopy cover in this type of shade system ranges from as low as 10% to over 60% depending on the density of trees and execution of management techniques such as pruning (Moguel & Toledo, 1999; Perfecto et al., 2005).

Shade trees are maintained in coffee farms because they are beneficial both for coffee management and for the broader environment. Shade coffee landscapes provide a wide range of ecosystem services, including reducing erosion, protecting water quality, providing wildlife habitat, and sequestering carbon (Albrecht & Kandji, 2003; Mendez et al., 2009; Montagnini & Nair 2004; Perfecto et al., 1996). In this chapter, I discuss the services provided by shade in coffee systems using the Common International Classification of Ecosystem Services (CICES) outlined in the Millennium Ecosystem Assessment (MEA, 2005). This framework divides ecosystem services into provisioning, cultural, and regulating and maintenance services. I expand on these services, and then focus specifically on the ecosystem service of climate regulation through carbon sequestration. The chapter concludes with a summary of the questions and objectives developed from this background information that motivate the current research.

3.1 Provisioning Services

Provisioning services are the nutritional, material, and energetic outputs of the system (Haines-Young & Potschin, 2011; MEA, 2005). These benefits are generally directly visible to coffee producers. Shade trees in coffee systems afford smallholders important benefits in all three categories of provisioning services.

Nutritional benefits include production of food for household consumption and maintaining drinking water quality (Bacon et al., 2014; Cerdan, Rebolledo, Soto, Rapidel, & Sinclair, 2012; Jha et al., 2014). Fruit produced in diverse shade systems contributes to smallholders' food security (Bacon et al., 2014). Shade coffee also protects water sources, as coffee is often cultivated on steep slopes high in the watershed, in areas prone to high rates of erosion (Perfecto et al., 1996; Varangis et al., 2003). Downstream water sources are often heavily impacted by sediment influx and agrochemical runoff (Rappole, King & Rivera, 2003; Perfecto et al., 1996). Shade trees can reduce the effects of erosion by retaining topsoil through root networks and production of leaf litter that forms a protective barrier over the soil, as well as through canopy interception of heavy rainfall (Cerdan et al., 2012; Perfecto et al., 1996).

Shade trees also provide material benefits, including the production of timber and alternative crops for market (Bacon et al., 2014; Cerdan et al., 2012; Jha et el., 2014; Peeters, Soto-Pinto, Perales, Montoya, & Ishiki, 2003). These products provide an important source of additional revenue for smallholders when coffee prices are low (Beer, Muschler, Kass, &

Somarriba, 1998). In Southern Mexico, Peeters et al. (2003) estimated the total value of timber in traditional polyculture coffee systems to be over $18,000 per hectare. Farmers receive income from timber harvest once per cutting cycle. Sustainable harvest from forests is defined by cutting cycles of 25 to 60 years, but in coffee systems, timber from some species may be harvested after as little as eight years (Ramírez, Somarriba, Ludewigs & Ferreira, 2001; Sasaki et al., 2016). Bananas, the most commonly marketed secondary crop from coffee systems, are valued at approximately $100 per hectare per year in diverse shade systems (Suarez, 2002).

Energetic outputs from shade coffee systems come primarily through production of fuelwood. In rural areas, fuelwood is important for cooking, boiling water for drinking, bathing, and heating the home (Rice, 2008). The common shade genus *Inga* is preferred for firewood, but many shade species are suitable for use as fuel (Peeters et al., 2003; Rice, 2008). Peeters et al. (2003) found that diverse shade systems in Mexico produce just as much fuelwood biomass as *Inga*-dominated systems, demonstrating that dense shade canopies provide this service regardless of composition.

3.2 Cultural services

Cultural services, defined as the overall recreational, spiritual, and symbolic value of the system, are more difficult to measure than provisioning services (Haines-Young & Potschin, 2011; MEA, 2005). Shade coffee systems support species used in traditional medicines and handicrafts (Soto-Pinto et al., 2000). In Peru, plants from shade coffee farms are used in some indigenous religious rituals (Jha et al., 2011).

In a more abstract sense, shade coffee systems also support other cultural activities by providing livelihoods and promoting social identity formation. Cultural history is connected to current coffee management practices (Moguel & Toledo, 1999, cited in Jha et al., 2011). Coffee farmers form strong connections among groups of smallholders using similar practices, and these social identities are strengthened through cooperative membership (Frank et al., 2011). When smallholders cannot support themselves through coffee farming, they may be forced to abandon traditional lands and livelihoods in order to migrate in search of work (Bacon, 2005; Jha et al., 2011). Shade coffee farming therefore supports cultural connections between communities and their ancestral lands.

3.3 Regulating and Maintenance Services

Regulating and maintenance services comprise benefits that regulate ecosystems and maintain biological processes (Haines-Young & Potschin, 2011; MEA, 2005). Shade canopies in coffee systems regulate the on-farm ecosystem by improving the growing conditions for coffee plants, increasing pollinator diversity, and suppressing pest populations (Cerdan et al., 2012; Jha et al., 2015; Siles, Armand & Vaast, 2010; Westphal, 2008). Diverse shade landscapes also regulate water and nutrient cycling and maintain habitat and genetic diversity (Perfecto et al., 2005; Jha et al., 2015).

Both farmers and scientists recognize that shade trees improve the growing conditions for coffee (Cerdan et al., 2012; Siles et al., 2010; Westphal, 2008). Maintaining shade in coffee systems may create a more favorable microclimate for coffee flower and fruit production by reducing stress from high temperature and solar radiation, as well as by increasing relative humidity (DaMatta et al., 2007; Siles et al., 2010). In Brazil, average ambient temperatures in sun plantations are 5.4°C higher than in agroforestry systems (de Souza et al., 2012). Authors suggest that this makes shade maintenance a key strategy in adapting coffee production to climate change. The higher relative humidity under shade also increases stomatal conductance of CO_2, leading to higher rates of photosynthesis and growth in coffee plants (see DaMatta, 2004). There is evidence that shade reduces annual branch dieback in coffee plants, sustaining the increased growth over time (DaMatta et al., 2007). Overall, the literature suggests that the favorable climate provided by shade in coffee systems increases crop yields and reduces annual fluctuations in yield (Alemu, 2015; DaMatta et al. 2007; Jha et al., 2014; Siles et al., 2010).

In addition to improving aboveground growing conditions, trees may also improve soil quality through production of leaf litter and nitrogen fixation (Jha et al., 2014). Leaf litter produced by shade species adds organic matter to, protects, and improves soil (Haggar et al., 2011; Siles et al., 2010). This leaf litter also increases rates of nutrient cycling in coffee systems (Cuenca, Aranguran, & Herrera, 1983; Dossa et al., 2008; Haggar et al., 2011). Leguminous shade species, such as the commonly-cultivated *Inga* genus, increase soil nitrogen pools (Cerdan et al., 2012). Babbar and Zak (1994) documented annual nitrogen mineralization rates of 14.8 g per m^2 under *Erythrina* shade, compared with 11.1 g per m^2 in full sun plantations.[17]

Increased availability of soil nitrogen means that agroforestry systems may require lower rates of fertilizer application, and where diverse shade reduces the impact of pests and disease on coffee crops, it also reduces the need for agrochemical application and the corresponding level of chemical runoff in downstream water sources (Alemu, 2015; Jose, 2009; Staver et al., 2001). Low-input shade systems offer reduced rates of pollution and ecosystem degradation (Fernandez & Muschler, 1999, cited in Haggar et al., 2011). Trees in agroforestry systems also reduce erosion by wind and precipitation, leading to lower concentrations of particulate matter in the air and in downstream water sources (Ataroff & Monasterio, 1997; Jose, 2009).

[17] However, nitrogen mineralization is significantly higher in intact forest than in either agroforestry systems or full sun coffee farms (de Souza et al., 2012).

The improved growth and production of coffee plants finds complement in high populations of beneficial birds, bats, and insects supported by shade trees. Larger and more diverse communities of pollinating insects in shade systems improve coffee yields, a service valued at $1.7 billion annually (Jha & Vandermeer, 2010; Ricketts, Daily, Ehrlich, & Michener, 2004). Shade systems also provide natural pest and disease control, which improves yields up to 14% (Kellerman, Johnson, Stercho, & Hackett, 2008; Karp et al., 2013; Staver et al., 2001; Williams-Guillén, Perfecto, & Vandermeer, 2008). Pest and disease control is not a universally accepted benefit of shade in coffee systems; isolated studies have suggested that shade trees may increase the impact of pests and fungal disease (Beer, 1987; López-Bravo, Virginio-Filho, & Avelino, 2012). However, Soto-Pinto et al. (2002) found no evidence for higher levels of insect pests or plant disease in shade coffee farms. Further, multiple studies indicate that the microclimate produced by shade trees supports populations of beneficial insects such as parasitoid wasps, and the structural diversity in habitat provided by multistrata shade supports populations of birds and bats that prey on harmful insects (Borkhataria, Collazo & Groom, 2006; Jha et al., 2014; Kellerman et al., 2008; Karp et al., 2013; Staver et al., 2001; Williams-Guillén et al., 2008).

The most widely recognized maintenance service provided by shade coffee systems is habitat provision and the corresponding protection of genetic diversity. Coffee-growing areas of Central America overlap a major biodiversity hotspot, and coffee farming often takes place in especially vulnerable high altitude regions (Varangis et al., 2003). Shade coffee farms initially drew attention from the conservation community because the diverse canopy in some agroforestry systems can provide valuable habitat for bird species (Perfecto et al., 1996; Mas & Dietsch, 2004). Perfecto et al. (1996) reported that shade coffee farms support a wide range of forest birds including both generalists and specialists, but suggested that more significantly altered habitats are more suitable for neotropical migrants because these species have more flexible habitat requirements. Shade trees also provide fruit and nectar, supporting bird populations when insect populations drop during the dry season (Vannini, 1994). Levels of canopy cover present in Nicaragua's reforested coffee farms are not likely to provide quality habitat for highly sensitive species, but response to canopy removal varies widely among taxa (Perfecto et al., 2005; Westphal, 2008). Greenberg, Bichier, and Sterling (1997) found that *Inga*-monoculture and rustic shade systems support similarly high bird populations. This implies that even coffee farms with less dense and varied shade support species diversity. In general, shade coffee farms clearly support more wildlife than deforested monocrop farms (Greenberg et al., 1997; Perfecto et al., 2005).

Diverse canopy structure also makes shade coffee landscapes a high-quality habitat for bats, small mammals, and other vertebrates (Estrada, Coates-Estrada, & Merritt, 1993; Gallina, Mandujano, & Gonzales-Romero, 1992; Perfecto et al., 1996). Gallina et al. (1992) reported the presence of small cats and otters, species which are highly vulnerable to habitat disturbance. Shade coffee is not ideal habitat for all taxa, but can support up to half of snake species found in intact forest (Sieb, 1986, as cited in Perfecto et al., 1996). Inventories comparing agroforestry systems to full-sun plantations further demonstrated higher populations and diversity of reptiles, amphibians, and insects in shade coffee (Gordon, McGill, Ibarra-Nuñez, Greenberg, & Perfecto, 2009; Lenart, Powell, Parmerlee, Lathrop, & Smith., 1997; Jha & Vandermeer, 2010; Mas & Dietsch, 2004; Perfecto et al., 2005). Agroforestry systems also increase landscape connectivity, which is especially important for tropical species (Hardt et al., 2015; Lovejoy et al., 1986).

The regulating and maintenance services provided by shade in coffee systems are increasingly important in the context of climate change. Shifting climatic patterns are predicted to negatively impact coffee production by increasing average temperatures in coffee production regions and increase the frequency of extreme weather events (Gay, Estrada, Conde, Eakin, & Villers, 2006; Philpott et al., 2008). Diverse shade can address this growing threat by creating coffee systems that are less vulnerable to extreme weather impacts from hurricanes and landslides (Philpott et al., 2008; Schroth et al., 2009). Shade also regulates the microclimate for coffee plants, protecting them from excessive heat (DaMatta, 2004; Schroth et al., 2009). This service will become more necessary as global temperatures continue to rise (Gay et al., 2006; Jha et al., 2014; Schroth et al., 2009). Maintaining shade reduces also overall rates of deforestation, which may help regulate rainfall patterns and mitigate the effects of climate change through carbon storage in shade tree biomass (DaMatta, 2004; Faris, 1999; IPCC, 2014; Jha et al., 2014; Noponen et al., 2013a; Soto-Pinto et al., 2010).

3.4 Climate mitigation services: Carbon sequestration in shade coffee landscapes

Coffee can grow to over two meters in height depending on cultivar, climate, and management, and dense coffee plantations may store significant carbon even when shade canopy is sparse (ASB, 2011). As a perennial plant, coffee serves as a relatively stable carbon sink throughout the productive lifespan, which can last up to 50 years (ASB, 2011; DaMatta et al., 2007). However, shade in coffee systems dramatically improves carbon stocks.

In general, higher biodiversity is associated with greater levels of carbon storage (Ruiz-Benito et al., 2014; Strassburg et al., 2010). However, the dynamics of carbon storage in coffee plantations may be more complex. Soto-Pinto et al. (2010) found no significant difference in carbon storage between polyculture plantations and *Inga* monoculture shade farms in Chiapas, Mexico. Still, both traditional and commercial polyculture shade systems maintain significantly higher biomass carbon stocks than sun coffee farms (Soto-Pinto et al., 2010). In an inventory of heavily managed coffee systems, Noponen et al. (2013a) found that carbon stocks ranged from 22.6 tons of carbon (MgC) per hectare for coffee systems with pruned leguminous shade trees to 115.8 MgC per hectare under timber species. Sun coffee plots in the same study were found to store only 9.1 MgC per hectare (Noponen et al., 2013a). Full-sun farming methods are associated with higher greenhouse gas emissions; adding trees to sun farms can decrease net emissions by 10 to 60 tons CO_2 equivalents per year (Hergoualc'h, Blanchart, Skiba, Hénault, & Harmand, 2012; Noponen et al., 2013a).

Carbon storage varies widely across farms even when management is similar. An overview of carbon storage in coffee systems is available in Table 1. Suarez (2002) reported that aboveground carbon in coffee plantations in Matagalpa, Nicaragua ranged from 6.4 to 41.2 MgC per hectare depending on management. This variability can be partially attributed to canopy tree age: older shade trees provide greater total carbon storage, but younger trees accumulate carbon at a much higher rate (Oelbermann, Voroney, & Gordon, 2004). Farmers also vary in their use of management practices that affect carbon stocks, such as regular pruning or harvesting shade trees for household uses including timber and fuelwood (Roshetko, Lasco, & Delos Angeles, 2005). However, even when aboveground carbon stocks are frequently rotated through pruning or culling or shade trees and coffee plants, consistently high levels of below-ground carbon in agroforestry systems help to ensure permanence of carbon storage (Soto-Pinto

Table 1: Literature values of carbon stocks (Mg/ha) in coffee systems. Aboveground carbon (AGC), soil organic carbon (SOC), and total carbon sequestration under different shade regimes.

Location	Shade typology	AGC	SOC	Total	Reference	Notes
Costa Rica	Full sun	3.03			Noponen et al. 2013	
Costa Rica	Full sun	8.25			Siles et al., 2010	
Brazil	Full sun			11	Palm et al., 2005	
Costa Rica	Full sun	11.4			Magaña, Harmand, & Hergoualc'h, 2004	
Southwestern Togo	Full sun	13.8			Dossa et al., 2008	
Jinotega, Nicaragua	5 shade species, age 3-4 years	5.5			Medina-Benavides et al., 2009	Living biomass only
Brazil	Complex shade			60	Palm et al., 2005	
Matagalpa, Nicaragua	Commercial polyculture, <5 m	6.4	138.3	144.7	Suarez, 2002	
Costa Rica	*Musa* sp.	11			Polzot, 2004	
Jinotega, Nicaragua	*Inga* sp. and timber	11.1			Medina-Benavides et al., 2009	Living biomass only
Costa Rica	*Erythrina poeppigiana*	14.25			Noponen et al. 2013	
Costa Rica	*Inga* sp.	14.6			Polzot, 2004	
Nicaragua	Commercial polyculture	16.98	142.78	163.88	Connolly & Corea-Siu, 2007	
Jinotega, Nicaragua	*Inga* sp., age 8-9 years	19.9			Medina-Benavides et al., 2009	Living biomass only
Costa Rica	*Inga* sp.	24.1			Siles et al., 2010	Includes leaf litter and root biomass
Costa Rica	*Eucalyptus* sp.	28.4			Magaña, Harmand, & Hergoualc'h, 2004	
Costa Rica	Diversified	31.6			Polzot, 2004	
Jinotega, Nicaragua	Diversified	18.72	142.78	163.88	Connoly-Wilson & Corea-Siu, 2007	Includes leaf litter, herbs, and roots.
Matagalpa, Nicaragua	Commercial Polyculture, >10m	41.2	125.5	166.7	Suarez, 2002	
Costa Rica	*Chloroleucon eurycyclum*	47.24			Noponen et al. 2013	
Chiapas, Mexico	Polyculture shade, non-organic	55.9	135	190.9	Soto-Pinto et al., 2010	
Chiapas, Mexico	*Inga* sp. shade, organic	62.8	151	213.8	Soto-Pinto et al., 2010	
Southwestern Togo	*Albizia adianthifolia.*	67			Dossa et al., 2008	

et al., 2010; Suarez, 2002; Thangata & Hildebrand, 2012).

Soil organic carbon (SOC) accounts for 75-97% of total carbon storage in coffee systems (Suarez, 2002). There is not clear evidence that shade coffee systems store significantly more SOC than do sun farms, but the importance of soil as a carbon sink should not be overlooked (Jha et al., 2014; Noponen et al., 2013b; Tumwebaze & Byakagaba, 2016). Agroforestry methods are also likely to maximize SOC by increasing organic matter input and slowing decomposition of soil organic matter (Oelberman et al., 2004). Further, management practices that reduce erosion, including maintaining canopy cover in coffee plantations, help to conserve carbon stocks in soil (Soto-Pinto et al., 2010).

Agroforestry methods provide clear benefits over sun coffee production, including global climate mitigation through carbon storage. Current climate change scenarios highlight the mounting importance of this ecosystem service (IPCC, 2014). The current study adds to the body of research on the ecosystem service of carbon storage in shade coffee systems. I address carbon storage in smallholder shade coffee systems in Jinotega, Nicaragua.

3.5 Research questions

This research assesses carbon storage in 70 smallholder shade coffee farms in Jinotega, Nicaragua in order to evaluate carbon stocks in smallholder agroforestry systems under different shade regimes. I then use detailed study of nine representative farms to model potential changes in shade regime to increase carbon storage. Through interviews with coffee farmers and cooperative officials, I explore attitudes toward shade management and potential incentive programs that could be applied to smallholder shade coffee in Jinotega.

This research addresses the following questions: (1) What is the carbon density of Jinotega's smallholder shade coffee landscape; (2) Do coffee systems with denser and more diverse shade communities support the highest carbon stocks; (3) Can carbon storage be improved without excessive increases in shade; and (4) What attitudes among coffee farmers and cooperative officials might influence efforts to improve carbon storage?

4.0 Research Methods

This chapter discusses research methods used to investigate present carbon storage in shade coffee systems, potential improvements through changes in canopy management, and stakeholder attitudes toward shade. First, I discuss field surveys conducted on 70 coffee farms surrounding the city of Jinotega and how this data was used to estimate existing carbon stocks. Next I present my approach to investigating the impact of alternative canopy management schemes on carbon storage using the Spatially Explicit Individual-based Forest Simulator (SExI-FS) modeling software. The chapter concludes with a description of methodology for conducting interviews with coffee farmers and coffee cooperative officials. Research was conducted through a project funded by the Consortium Research Program Humidtropics through Bioversity International with in-country sponsorship in Nicaragua through the International Center for Tropical Agriculture (CIAT) Nicaragua. Local NGO La Cuculmeca provided field assistence.

4.1 Field inventory and carbon estimation

Inventories were conducted in the department of Jinotega (N 13º 8" 19" W 86º 52' 19") located in north-central Nicaragua. The region is classified as a premontane moist to wet tropical forest zone (Khatun et al., 2013). Average rainfall is 1,800 mm per year, primarily between May and November, with a dry season from December to April, and mean annual temperature is 20-21°C (Fenzl, 1988, as cited in Medina-Benavides, Calero-Gonzáles, Hurtado, & Vivas-Soto, 2009). Soil types are primarily alifisols and molisols (Suarez, 2002). Ten farms from each of seven local cooperatives (a total of 70 farms) were selected from participants in an ongoing study on soil fertility management as part of the Humidtropics CGIAR Research Project lead by CIAT in Central America. Local technicians identified these farms as representative of the zone and the cooperatives active in the region. Sample farms contained at least one hectare of coffee and had coffee as their primary agricultural activity. Plot elevation ranged from 900 to 1,500 m above sea level.

4.1.1 Field inventories

Carbon storage inventories were conducted between August and September of 2016, during the rainy season. Coffee crops require less intensive labor on the part of the farmer during this period, so presence of researchers is less intrusive. When possible, farmers accompanied researchers during inventories to provide directions and identify any unknown tree species. Sample plots were established in the same areas where samples were collected for the previous soil study.

Shade tree inventory

On each farm, shade trees were inventoried in a 0.1 ha representative plot, 50 m by 20 m (after Kalacska et al., 2004; Sánchez-Merlo et al., 2014; Somarriba et al., 2013). Within this plot, all trees with a diameter at breast height (DBH; 137 cm) > 2.5 cm were identified. DBH was recorded and height was visually estimated. Where an individual tree had multiple trunks at 137 cm, DBH was recorded for each trunk with an apex height greater than 1.5 m. For *Musa* sp. (banana plants), pseudostem diameter was recorded as DBH (after van Noordwijk et al., 2002) and for *Theobroma cacao* (cacao trees), diameter was recorded at a height of 30 cm (after Somarriba et al., 2013). Where trees had more than one trunk at 137 cm, these observations were treated as a single individual for density and diversity calculations, but as separate plants for basal area and biomass calculations.

Coffee plant inventory

Coffee plants were inventoried in a 0.01 ha subplot (10 m by 10 m) established in a representative corner of the larger plot. Height was recorded for all coffee plants >1 m. Stem diameter was measured at a height of 15 cm (after Segura et al., 2006 & van Noordwijk et al., 2002). Where plants had more than one stem at 15 cm, diameter and height were recorded for each stem.

Soil sampling

We collected soil samples at the same time as tree and coffee inventories. Five subsamples of depth 0-20 cm were taken at points five meters diagonally inward from each corner and at approximately the center of the plot. The samples were combined into a composite sample of approximately 500 g. At the center point we also sampled at a depth of 20-50 cm. Samples were sent to the soil laboratory at LAQUISA (Laboratorio Químico, S.A.) in Leon for soil organic matter (SOM) analysis using the Walkley-Black method (after De Vos, Lettens, Muys, & Deckers, 2007).

4.1.2 Carbon estimation

Forest carbon pools include AGB, belowground biomass, litter, and soil carbon (Hamburg, 2000). The most accurate method of determining AGB is destructive sampling, but tree removal is costly and generally not feasible on smallholder agricultural lands (Ketterings et al., 2001; Picard, Saint-André & Henry, 2012). Allometric equations, based on the principle that species-specific relationships between dendrometric characteristics can be used to generate relatively accurate estimates of plant biomass allow us to predict biomass based on other tree characteristics such as height or diameter, are the accepted method for nondestructive biomass estimation (Chave et al., 2005; Picard et al., 2012).

Aboveground carbon pools

For the most common species in coffee agroforestry, I estimated biomass using allometric equations from the literature (Table 2). When no species- or genus-specific allometric equation was available, I used a general equation for tropical dry forest (Brown, 1997 as cited in Návar-Cháidez, Rodríguez-Flores, & Domínguez-Calleros, 2013). Due to uncertainty in root biomass calculations (see Cairns, Brown, Helmer & Baumgardner, 1997), the current research omits belowground plant biomass. I assumed that carbon accounts for 50% of shade tree biomass (after Elias & May-Tobin, 2011).

Soil organic carbon

Soil organic carbon (SOC) was estimated using Equation 1, which relates SOC stock in Mg/ha to soil volume (1 ha * soil depth in m), bulk density, and the fraction of soil organic matter that is composed of carbon, assuming 58% carbon (after Nelson & Sommers, 1982). I assumed a bulk density of 1 kg/m^3 (after Rousseau, Fonte, Téllez, van der Hoek, & Lavelle, 2013; Tonucci, Nair, Nair, Garcia, & Bernardino, 2011).

$$SOC\ stock\ \left(\frac{kg}{ha}\right) = \frac{Soil\ organic\ matter\ (\%)}{1.72} * bulk\ density\ \left(\frac{kg}{m^3}\right) * soil\ volume\ \left(\frac{m^3}{ha}\right) \qquad (1)$$

4.2 Canopy modeling and shade management scenarios

I selected representative farms from the initial sample to revisit for detailed shade inventory and

Table 2: Allometric equations used for estimating aboveground biomass (AGB) in Mg of shade trees and coffee plants. Based on stem diameter at breast height (DBH), at 30 cm (D_{30}), or at 15 cm (D_{15}) in m.

Allometric model	Family	Genus	Species	Reference
$\ln(AGB) = -2.772 + 2.562\ln(DBH)$	Annonaceae	*Annona*	*muricata* *reticulata* *purpurea*	van Breugel et al., 2011
$\log_{10} AGB = -0.755 + 2.072 \log_{10} DBH$	Boraginaceae	*Cordia*	*alliodora*	Segura et al., 2006
$\log_{10} AGB = -1.417 + 2.755 \log_{10} DBH$	Juglandaceae	*Juglans*	*olanchana*	Segura et al., 2006
$\log_{10} AGB = -1.684 + 2.158 \log_{10} D_{30} + 0.892 \log_{10} H$	Malvaceae	*Theobroma*	*cacao*	Somarriba et al., 2013
$\ln(AGB) = -2.054 + 2.389\ln(DBH)$	Melastomataceae	*Miconia*	*argentea* *albicans*	van Breugel et al., 2011
$\log_{10} AGB = -0.889 + 2.317 \log_{10} DBH$	Mimosaceae	*Inga*	*ruiziana* *oerstediana* *vera*	Segura et al., 2006
$\log_{10} AGB = -0.559 + 2.067 \log_{10} DBH$	Mimosaceae	*Inga*	*punctacta*	Segura et al., 2006
$AGB = 0.0303DBH^{2.1345}$	Musaceae	*Musa*	AAA AAB	Hairiah et al., 2001 & van Noordwijk et al., 2002
$\ln(AGB) = -2.305 + 2.351\ln(DBH)$	Ulmaceae	*Trema*	*micrantha*	van Breugel et al., 2011
$AGB = 0.0890DBH^{2.5226}$	Ulmaceae	*Quercus*	*insignis* spp.	Návar, 2009
$\log_{10} AGB = -0.755 + 2.072 \log_{10} D_{15}$	Rubiaceae	*Coffea*	*arabica* *robusta*	Segura et al., 2006
$\ln(AGB) = -1.996 + 2.321\ln(DBH)$	Mixed – dry tropical forest			Brown 1997 as cited in Návar, 2009

spatial mapping of shade trees. For this subsample, I generated models of farm plots and simulated scenarios for changing shade management. This section describes the methods for generating SExI-FS farm plot scenarios and for estimating the impact of shade management on carbon storage and canopy light interception.

4.2.1 Spatial mapping and SExI-FS scenario generation

I selected five farms at random from each cluster (see Data Analysis) and chose three of these farms to revisit. We picked the most level of the available plots, because SExI- FS models of light interception assume terrain to be flat when not specified (Harja & Vincént, 2008). At each of the nine farms, we reestablished the 50 m by 20 m plots used in shade inventories. I collected canopy openness measurements on each plot at five points: five paces in from each corner and in roughly the center of the plot. Using a spherical densiometer, I measured canopy cover in the four cardinal directions at each point, and averaged the four measurements to estimate mean percent shade in each plot.

We then completed a detailed inventory of all shade trees taller than 1.5 m and with DBH greater than 2.5 cm. To record position, we measured the compass angle and distance to a set reference point within the plot, either a corner of the plot or another tree. These measurements were converted to x-y coordinates using trigonometric relationships. For each tree, we measured the canopy radius in four directions by measuring the distance from the trunk to the terminus of the farthest branch. In the first plot, we measured height of the first foliated branches and apex height using a clinometer. I created generalized linear regression equations based on these measurements for the relationship between DBH and crown depth and between DBH and total height for *Musa* (R^2 = 0.86) and for other trees (R^2 = 0.66). For all subsequent plots, I used these equations to estimate tree height and crown depth.

SExI-FS software generated plot models based on X position, Y position, species, DBH, height, crown depth (distance from the first foliated branch to the top of the tree), crown curve (which I assumed to be equal to half of the crown depth), and crown radius (Harja & Vincént, 2008). In the light interception module, SExI-FS produced estimates of canopy openness at points across the plot in a grid of 5 m by 5 m at a height of 1 m. I averaged these estimates and subtracted the number from 1 to determine the mean percent shade in each plot, then compared this estimate with the observed level of canopy cover measured by a densiometer.

4.2.2 Management scenarios and possible implications for carbon storage and crop production

Using SExI-FS, I simulated scenarios for changes in shade management designed to represent incremental improvements in carbon storage and other ecosystem services. For all scenarios, shade was used as a constraint, maintaining shade below 50% or roughly equal to existing shade in plots where existing shade was higher than 60%. For all scenarios, trees were removed from plot regions where estimated shade was relatively high and added to regions where shade was low. This was based on subjective determination, and outcomes could change slightly with repeated scenario generation.

I used allometric equations (Table 2) to estimate changes in carbon storage for each scenario. The SExI-FS light interception module modeled changes in shade. For each scenario, I use available data to discuss potential impacts on household income streams. The three scenarios are outlined below.

Scenario 1: Replacing *Musa* with *Inga*

In plots dominated by *Musa*, I modeled replacing banana plants with *Inga* sp., a beneficial shade genus which also sequesters significantly more carbon than *Musa* (Hairiah et al., 2001; Soto-Pinto et al., 2010). I retained roughly half of the banana plants in each plot. *Inga* trees placed in this study were modeled as a hypothetical tree with dimensions equal to the average of all *Inga* trees sampled. *Inga* trees were placed in the x-y position of existing *Musa* plants. Where additional trees could be placed without exceeding 50% light interception, I placed simulated *Inga* in large gaps in the canopy.

Inga trees are generally larger than *Musa* and produce higher levels of shade. However, these trees are often pruned to regulate shade levels and to produce leaf litter (Cerdan et al., 2012; Moguel & Toledo, 1999; Perfecto et al., 2005). I simulated this by reducing the canopy radius of existing *Inga* trees so that average light interception fell below 50%. During this modeled pruning, canopy size did not fall below observed measurements of *Inga* trees with similar DBH.

Scenario 2: Adding timber trees

For Cluster B, the plots dominated by *Inga*, I modeled replacing some *Inga* trees with timber species. These trees are larger and store greater quantities of carbon (Hergoualc'h et al., 2012; Noponen et al., 2013a; Peeters et al., 2003). Their greater height increases the structural diversity of the farm and improves habitat value. These trees also importantly provide a future source of income for the farmers, who can harvest and market trees after 20 to 30 years. Timber species identified during initial inventories were cedar (*Acrocarpus fraxinifolius*) and walnut (*Juglans olanchana*). Of these, *J. olanchana* was found on a greater number of the 70 inventoried farms (n=13) than was *A. fraxinifolius* (n=2). Further, *A. fraxinifolius* was not present on any of the 9 plots in which height and canopy dimension parameters were observed. For this reason, I selected *J. olanchana* as the timber species in this scenario[18] and created an average tree of this species using the average measurements for DBH, height, and crown depth. Three to five individuals were added to each plot and *Inga* trees were removed to keep the average shade level at 50%.

<u>Scenario 3: Improving shade to meet Smithsonian Bird-friendly certification standards</u>

Cluster C plots are presently characterized by diverse shade tree communities. To capitalize on this, I modeled altering the plot to meet Smithsonian Bird-friendly certification standards as outlined by Smithsonian's National Zoo & Conservation Biology Institute (2017). Although Bird-friendly standards apply to the entire farm, I applied all standards at the level of the 1000 m^2 plot. I increased species diversity to meet the SAN standard for appropriate shade in coffee systems of 12 total species per plot, exceeding the Bird-friendly minimum of 10 woody species (SAN, 2017; Smithsonian, 2017). When species were added, these species were drawn from individuals present on other farms. I used average DBH from initial canopy inventories and estimated the height and crown depth using the same regression equations used to create initial farm models. Standards also call for a minimum of three visible height strata, with a backbone layer of 12-15-m in height composing approximately 60% of foliage volume. The remaining 40% is split between an understory of smaller fruit trees and an emergent layer of greater than 15 m. Certification teams appraise these strata by visually estimating tree height and foliage density,

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[18] It is worth noting that *A. fraxinifolius* tends to be favored by farmers due to its rapid growth and low maintenance requirements, and may therefore represent a viable alternative or complement to *J. olanchana* (Franzel, Hitimana, & Akyeampong, 1995).

so I used visual appearance of plot models to determine the appropriate level of foliage at each height (Philpott et al., 2007). Standards also require a minimum of 40% average canopy cover as measured by a densiometer (Smithsonian, 2017). Though not included in scenario modeling, additional standards must also be met in order to achieve Bird-friendly certification, including standards for secondary vegetation, leaf litter, organic certification, living fences, and buffers along waterways (Smithsonian, 2017).

4.3 Interviews on attitudes and practices regarding shade management

The interview component of this study was used to investigate the practical applications of the field research and modeled management scenarios. Farmers and cooperative officials are the key actors in implementing any significant changes in shade management that may influence carbon storage. I designed simple questionnaires for both farmers and coffee cooperative officials to explore current strategies and areas for improvement of carbon storage. In order to assess openness to participation in a carbon payment scheme, I asked about participation in and attitudes toward certification efforts. The Internal Review Board for Research on Human Subjects at Bard College approved the interview procedures and questionnaires.

4.3.1 Farmer interviews

I recruited farmer participants when visiting farms for geospatial mapping. Seven farmers participated, three representing Cluster A and two representing each of Clusters B and C. I conducted interviews, in Spanish, wotj a a native Spanish speaker, who recorded participant responses in writing.

Farmers were asked about their personal attitudes and experiences in shade tree selection and management as well as certification programs. I then asked whom they consult for information on shade trees and what they perceive to be their cooperative's standing on agroforestry. The interview concluded with questions on their awareness of and interest in participating in a future carbon payment scheme. An English translation of interview questions in available in Appendix A.

4.3.2 Cooperative official interviews

I contacted officials of the seven cooperatives represented in this study by inquiring in person at the cooperative offices accompanied by a native Spanish speaker. We set up appointments with officials chosen based on the recommendation of my local research partners and the receptionists at cooperative offices. Seven officials representing six cooperatives participated. I conducted interviews, in Spanish, with a native Spanish speaker; interviews were recorded on a cell phone and transcribed within a week of the appointment.

I began the interview by asking about the history and goals of the cooperative. I then asked about the cooperative's role in shade management, certification programs, and addressing climate change. The interview concluded with questions on willingness to participate in a future carbon payment scheme and perceived barriers to implementation of this scheme. An English translation of interview questions is available in Appendix B.

4.4 Data analysis

Inventories were used to assess canopy composition across sample farms. In addition to characterizing overall species composition and diversity, a method of clustering farms by composition was used to characterize variations in shade management across farm plots. The following sections present the approach used for this characterization, as well as for analyzing interview data.

4.4.1 Shade canopy characteristics

To assess canopy composition, I separated shade species into three functional types representing the most common shade trees on sample farms: *Musa*, *Inga*, and other shade trees (including fruit and timber trees). I calculated the density (number of trees per hectare), basal area (the total area covered by tree trunks based on DBH), plant biomass per hectare, and carbon stored in plant biomass per hectare for each of the three shade categories. I then calculated the richness (number of unique species within the plot) and the Simpson's Diversity Index (D), a measure of biodiversity that incorporates both richness and evenness of species (Peet, 1974).

4.4.2 Clustering based on canopy characteristics

The literature has identified five general types of coffee systems ranging from rustic polyculture to full sun production (Moguel & Toledo, 1999). Sample farms in this study would all be roughly categorized as commercial polyculture under this set of typologies. To more accurately capture the diversity of shade communities in the region, I clustered sample farms to create subcategories under the larger category of commercial polyculture.

I identified three clusters of farms with similar shade communities using the k-means clustering algorithm in R version 3.3.1. The algorithm divides datasets into *k* number of clusters based on input vectors describing data characteristics (Ray & Turi, 1999). I used *Inga* density, *Musa* basal area, and other shade tree density as input vectors. *Inga* density was selected to represent the prevalence of *Inga* in shade communities. *Musa* basal area was selected to represent the amount of the plot covered by banana plants. Basal area was selected rather than *Musa* density because connections via subaerial stems made it difficult to accurately establish which plants were unique individuals. Tree density represented the number of other trees in the plot, and was significantly correlated with species diversity. Input vectors were scaled prior to cluster calculation.

I used one-way ANOVAs to compare cluster means for *Inga* density, *Musa* basal area, tree density, coffee plant density and biodiversity. I further compared carbon storage in shade biomass, coffee biomass, and soil carbon. Where the main effect of the ANOVA was significant, I used Tukey's HSD to determine differences between unique clusters.

4.4.3 Analysis of shade management attitudes and practices

Interview responses resulted in qualitative data, and were not statistically analyzed due to small sample size. Several questions asked participants for multiple responses; these answers are reported as a count representing the number of participants listing the item.

I used one-way ANOVAs to compare mean shade tree densities and carbon storage in farms representing each cooperative. Where the main effect of the ANOVA was significant, I used Tukey's HSD to identify differences between individual cooperatives. The objective of this analysis was to compare differences in stated attitudes of cooperative officials with actual shade management strategies on member farms.

5.0 Results and Discussion

Sample plots (n=70) supported a total of 4,462 shade trees representing 98 species, an average of 7.46 species and 136.29 trees per hectare. Across all farms, 57.96% of shade trees were below 3.5 m in height, 42.58% were between 3.5 and 15 m, and 5.56% were taller than 15 m. Almost all shade trees were useful species: 71.40% were fruit trees (most prominently banana, citrus, mango, avocado, and guava), 19.52% were nitrogen-fixing species, and 3.05% were timber species. The most prominent genera were *Musa*, representing 59.05% of individuals, and *Inga*, representing 17.30% of individuals. Average Simpson's Diversity was 0.54 for all plots (where 0 represents monoculture and 1 represents the highest possible biodiversity). Farms stored an average of 160.10 Mg/ha of carbon, 83.60% of which was in the form of soil organic carbon (SOC).

K-means clustering created three clusters representing shade communities dominated by *Musa* (Cluster A), *Inga* (Cluster B), or diverse tree species (Cluster C). Shade typology cluster characteristics are presented in Table 3.

Table 3: Characteristics of farm clusters. Mean per hectare ± standard error. Superscripts denote differences significant at the 0.05 level identified using Tukey's HSD.

	Cluster A	**Cluster B**	**Cluster C**
Description	Dominated by *Musa*	Dominated by *Inga*	Dense, diverse shade
Number of farms	28	25	17
Inga density (ha^{-1})	44.64 ± 7.94^{a}	137.20 ± 15.71^{b}	102.35 ± 14.39^{b}
Musa basal area (m^2)	10.90 ± 1.34^{a}	6.19 ± 1.24^{b}	11.46 ± 1.71^{a}
Tree density (ha^{-1})	86.07 ± 10.38^{a}	63.2 ± 11.59^{a}	326.47 ± 29.38^{b}
Coffee density (ha^{-1})	4471.43 ± 414.45	5048 ± 358.57	5758.82 ± 542.06
Simpson Index	0.42 ± 0.04^{a}	0.57 ± 0.03^{b}	0.67 ± 0.04^{b}

5.1 Cluster characteristics

Overall biodiversity, as measured by Simpson's Index, was the lowest in Cluster A. Tree biomass varied widely in Cluster A, resulting in large variation in carbon stocks (Table 4). The relatively high total shade biomass was generally driven by one or two large trees (>15 m in height) per plot rather than a thick layer of middle strata trees (Fig 1).

Farms grouped into Cluster B supported high numbers of *Inga* species representing a high *Inga* biomass (Table 4, Fig. 1). Basal area of *Musa* sp. and density of other trees was significantly lower in Cluster B than in either of the other shade typologies. Tree density was also low in comparison with published inventories of *Inga*-dominated farms (Noponen et al., 2013b). Despite the low number of trees, plots in Cluster B had an average Simpson's Index higher than farms in Cluster A. The high coffee plant biomass supports the suggestion that pruned *Inga*-shaded plantations result in improved coffee growth in regions where overall growing conditions for coffee are optimal (Siles et al., 2010). Peeters et al. (2003) also found that *Inga*-shaded plantations had higher coffee plant density when compared with traditional shade,

Table 4: Aboveground carbon stocks in coffee farms under three shade typology clusters. Clusters represent Musa*-dominated (A),* Inga*-dominated (B), or diverse shade (C). Mean Mg/ha ± standard error. Superscripts denote differences significant at the 0.05 level identified using Tukey's HSD.*

Biomass Carbon Pool	**Cluster A**	**Cluster B**	**Cluster C**
Musa	3.11 ± 0.39[a]	1.76 ± 0.36[b]	3.23 ± 0.48[a]
Inga	2.30 ± 0.36[a]	12.70 ± 1.02[b]	5.24 ± 0.61[c]
Trees	15.22 ± 6.20	6.17 ± 1.60	21.24 ± 8.19
Coffee	2.65 ± 0.32[a]	4.53 ± 0.60[b]	2.63 ± 0.36[a]
Total	23.28 ± 6.12	25.16 ± 1.91	32.33 ± 7.90

which translated to higher coffee yields under *Inga*. Romero-Alvarado, Soto-Pinto, García-Barrios, and Barrera-Gaytán (2002) found no significant difference between crop yield under *Inga*-dominated or diverse shade in Chiapas, Mexico. The current study did not assess coffee yield per tree, so it is not clear if coffee production is significantly higher in Cluster B.

Cluster C was characterized by a high density of trees and high species diversity (Table 4). *Musa* basal area was similar to that observed in Cluster A, but in Cluster C *Musa* served as understory rather than the dominant shade species. Although differences in total carbon storage were not significant due to large variation within clusters, there was a slight trend toward

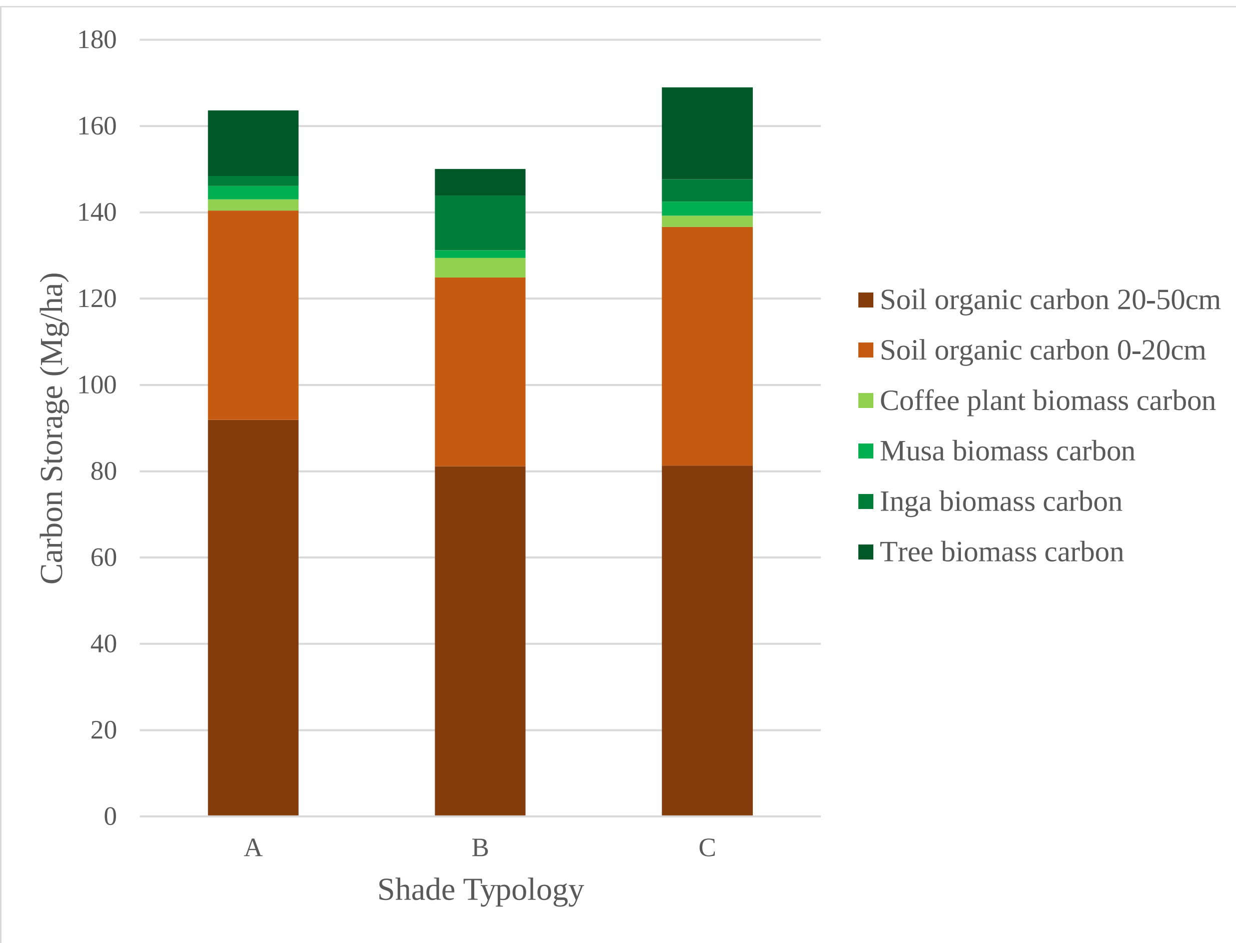

Figure 1: Estimated carbon stocks in sample plots (n=70). Shade typology clusters represent Musa-*dominated shade (A),* Inga-*dominated shade (B), and diverse shade (C).*

higher carbon storage in Cluster C, farms characterized by diverse shade (Fig. 1, Table 4). This result is congruent with published correlations between carbon storage and biodiversity (Poorter et al., 2015; Strassburg et al., 2010). The lowest average carbon stocks were observed in Cluster B, *Inga*-dominated shade, primarily due to lower estimated soil carbon. This finding contrasts with Soto-Pinto et al. (2010), who observed greater SOC stocks in coffee farms under *Inga* shade than in traditional polyculture systems.

This study overall supports the inference that there is little correlation between above- and below-ground carbon stocks in coffee systems (Noponen et al., 2013b). However, methods used to estimate soil carbon could be improved in future studies by calibrating both the local bulk density and the soil organic matter to SOC conversion factor. The conventional conversion factor of 1.7 used in this study has been questioned in the literature; Pribyl (2010) claimed that a conversion factor of 1.9 is more appropriate for most soils. This adjustment would lower average SOC estimates from 133.99 Mg/ha to 129.29 Mg/ha. A difference of almost 5 Mg/ha is significant in the context of the shade alteration scenarios, and of determining appropriate carbon payments for farm owners.

5.2 Light interception and carbon storage

Observed canopy cover was lower on average than modeled shade in SExI-FS simulations, $t(8) = 2.43$, $p = 0.04$, with an average discrepancy of 11%. Some of the difference is due to the small sample size of densiometer measurements, which covered a limited area of the plot. The model could also be improved by incorporating a species-specific factor for crown porosity, a measure of transparency based on foliage density. Individual measurements of crown form and rotation would further improve model accuracy.

There was no significant relationship between biomass carbon storage and observed canopy cover, R^2 = .16, F(1, 7) = 1.33, p = 0.29 (Fig. 2). This result contradicts the intuitive conclusion that higher biomass will result in higher light interception and would necessarily have a detrimental impact on coffee yields. Based on this, I suggest that carbon storage in these coffee plots can be improved without a significant increase in shade.

5.3 Improved management scenarios

Modeled shade alterations increased estimated carbon storage by an average of 14.82 Mg/ha. This represents an average increase in aboveground biomass carbon (AGC) of 156.28% over the initial canopy structure across the nine sample plots (Fig. 3). These increases in carbon storage came with very little increase in shade, and even slight decreases in shade in clusters B and C

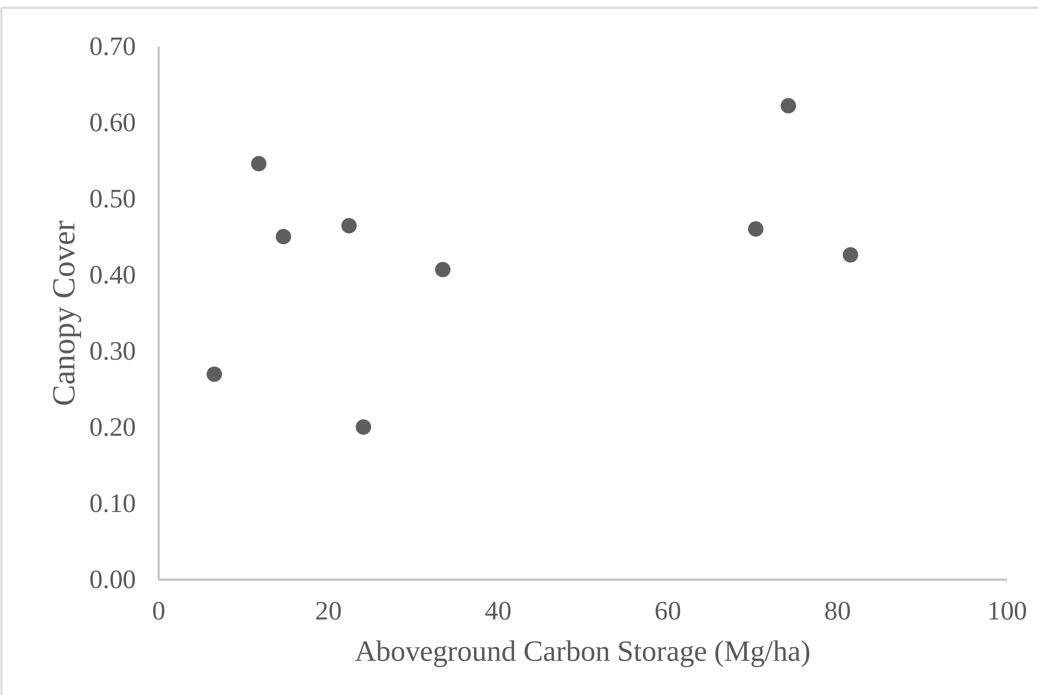

Figure 2: Relationship between estimated aboveground carbon storage in sample coffee farms and observed canopy cover was not significant.

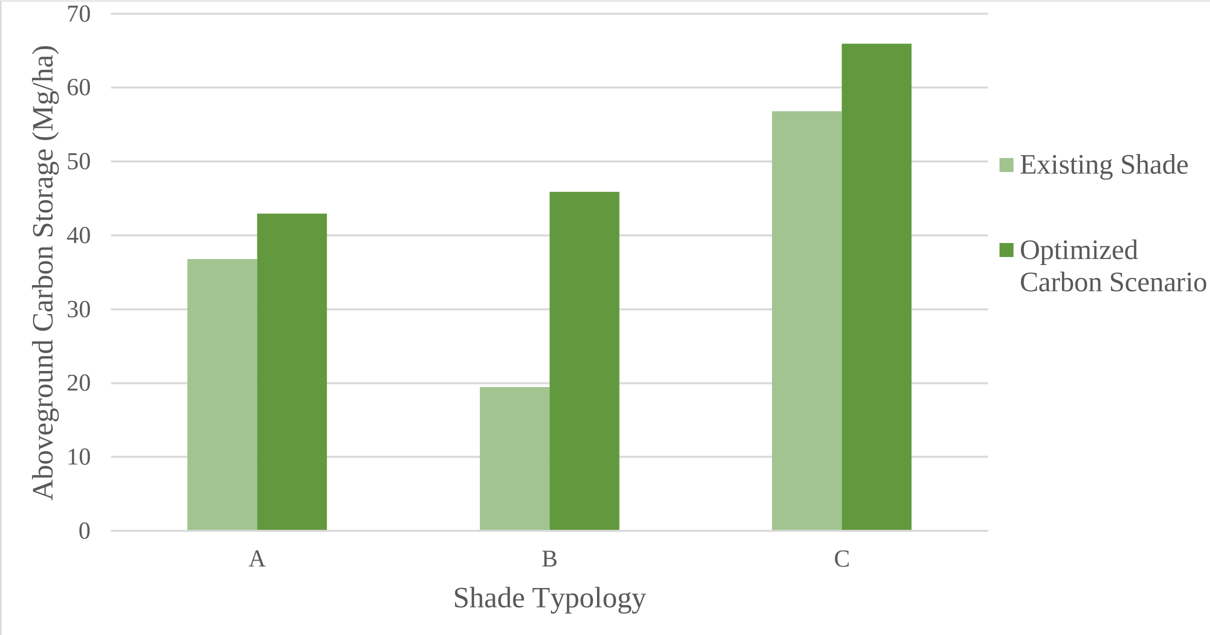

Figure 3: Change estimated aboveground carbon storage across sample plots for modeled management scenarios. In Cluster A, Inga *sp. was added to* Musa*-dominated shade. In Cluster B, timber trees were added to* Inga*-dominated shade. In Cluster C, diverse shade was improved to meet Smithsonian Bird-friendly standards*

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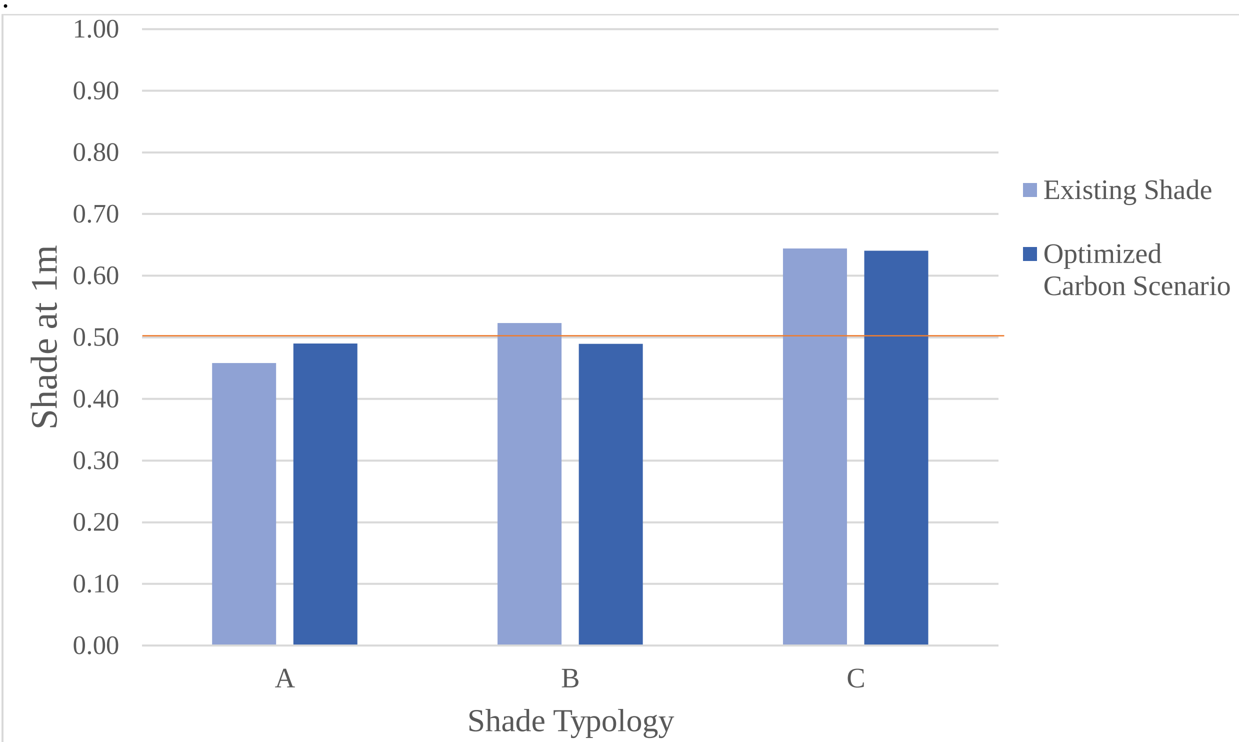

Figure 4: Changes in shade level across coffee plots as a result of modeled scenarios for optimizing carbon storage: adding Inga *(A) or timber trees (B) or increasing canopy complexity to meet Smithsonian Bird-friendly certification standards (C). Red line represents 50% shade, the level above which coffee yields suffer (Soto-Pinto et al., 2000).*

(Fig. 4). Since SExI-FS simulations overestimate light interception by an average of 11%, carbon storage could likely be increased further with a higher shade threshold.

5.3.1 Scenario 1: Replacing Musa *with* Inga *in banana-dominated farms*

In three farms from Cluster A, I modeled removing half of *Musa* plants and adding *Inga* trees. Results from one representative plot are presented in Fig. 5. SExI-FS simulation images of all three plots are available in Appendix C1. The change led to an average carbon storage increase of 6.17 Mg/ha, from 36.79 to 42.96 Mg/ha, representing an average increase of 41.63% from initial estimated carbon storage (Table 4). In addition to increased carbon storage, this scenario

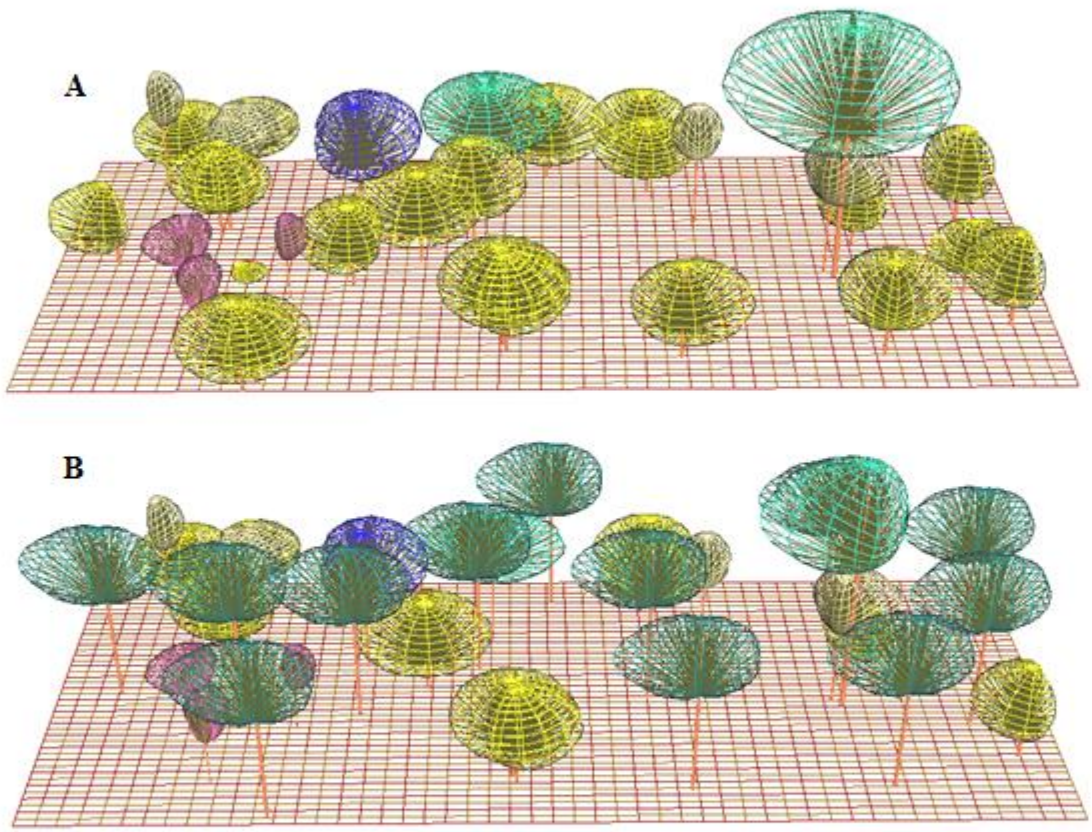

Figure 5. Change in farm plot appearance from existing shade community (A) to optimized carbon scenario (B) for Plot 2 in Cluster A, when half of Musa *plants (represented in yellow) are replaced with simulated* Inga *trees (represented in light blue).*

Table 4: Simulated carbon enhancement for Cluster A. Changes in plot-level density of Inga *and* Musa, *estimated change in per-hectare carbon storage, and increase in modeled shade at 1 m when half of* Musa *were replaced with a simulated* Inga *tree.*

Plot	Δ*Inga*	Δ*Musa*	Carbon storage increase (Mg/ha)	Percent change in carbon storage	Percent change in light interception
1	+11	-22	5.98	+17.87%	-6.70%
2	+12	-12	7.33	+112.12%	+0.65%
3	+8	-6	5.19	+7.38%	+15.57%
Average	+10.33	-13.33	6.17	+41.63%	+3.17%

would provide farmers with some additional ecosystem services. Coffee farmers grow *Inga* trees because these species improve soil through nitrogen fixation and protect plants and soils from heavy rain through provision of organic litter (Cerdan et al., 2012). Improved soil quality could mean that farmers are required to spend less money on nitrogen fertilizers.

Although the improved shade scenario led to clear improvements in carbon storage, this change would come at a cost to farmers. The trees cost money to plant: Gobbi (2000) estimated a cost of $1 per seedling, though the cost could potentially be higher. After trees are planted, pruning and other management activities are more difficult for *Inga* sp. than for *Musa*, meaning that the improved shade scenario would require greater labor input (Cerdan et al., 2012). Bananas are also important contributors to household food security, and it maytherefore be unrealistic to remove such a high number of *Musa* (Bacon et al., 2014; Canto et al., 2015; Donovan, 2011).

5.3.2 Scenario 2: Adding timber trees to Inga-*dominated farms*

I modeled adding timber trees (*Juglans olanchana*) to plots from Cluster B. Results from one representative plot are presented in Fig. 6. SExI-FS simulations of initial shade and timber trees at 20-30 years for each plot are available in Appendix C2. The change led to an average carbon storage increase of 24.18 Mg/ha, from 19.45 to 45.90 Mg/ha representing an average increase of 128.94% from initial estimated carbon storage (Table 5). This scenario would also provide farmers with an additional revenue stream: after 20-30 years, trees can be harvested and sold for approximately $100 per tree (Farmer #6). This implies a potential value of $3,000-5,000 per hectare after 20-30 years. Assuming a discount rate of 10% (after Gobbi, 2000) and harvest at 25 years, the present value of added timber trees is approximately $280 to $460 per hectare.

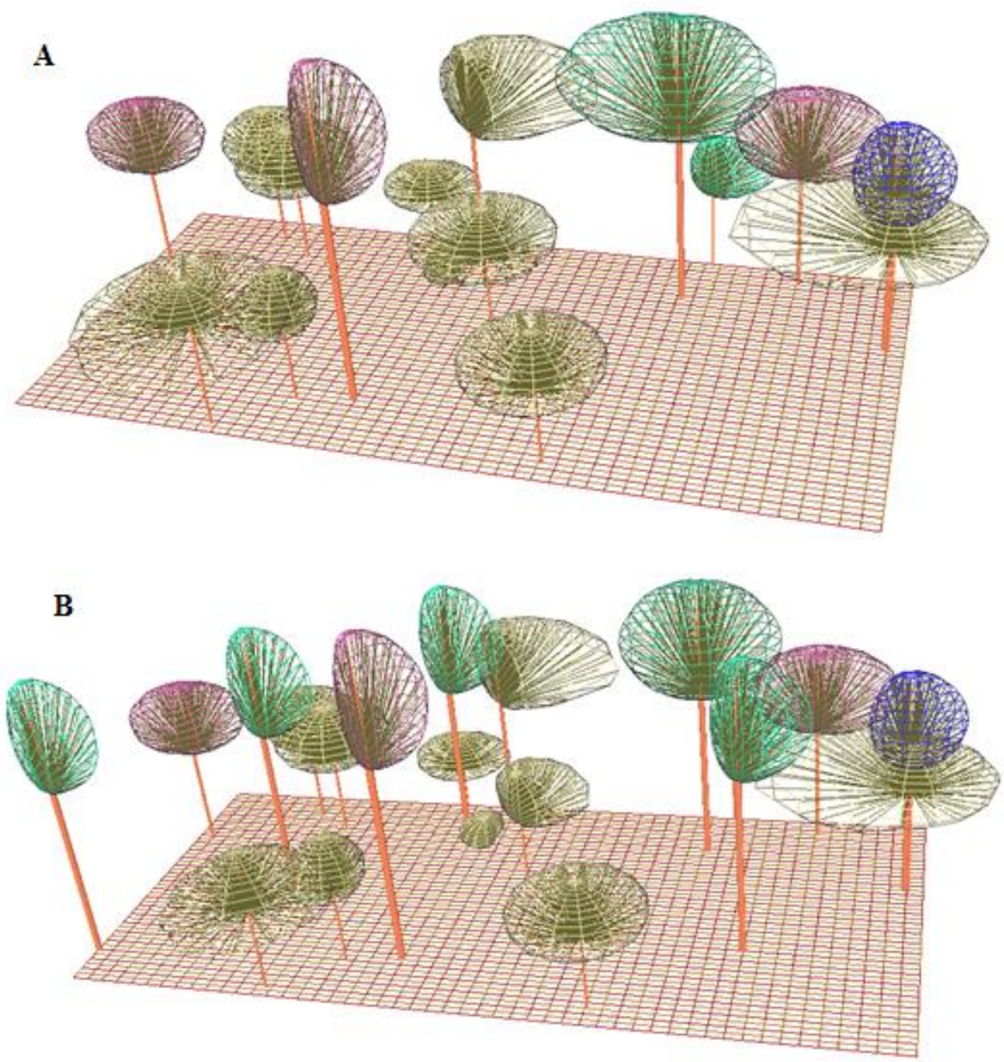

*Figure 6. Change in farm plot appearance from existing shade community (A) to optimized carbon scenario (B) for Plot 3 in Cluster B, when simulated timber trees (*Juglans olanchana*, represented in aqua) are added to plots dominated by* Inga *(represented in beige).*

Table 5: Simulated carbon enhancement for Cluster B. Changes in plot-level tree density, estimated change in per-hectare carbon storage, and increase in modeled shade at 1 m when timber trees were added to Inga*-dominated plots.*

Plot	Trees added	Carbon storage increase (Mg/ha)	Percent change in carbon storage	Percent change in light interception
1	+4	28.87	+119.66%	-0.86%
2	+5	26.30	+223.03%	-12.50%
3	+4	24.18	+107.78%	+3.30%
Average	+4.33	26.45	+150.16%	-3.35%

Estimated light interception decreased by 3.35% in this scenario due to modeled pruning of existing *Inga* trees. However, the additional trees would not significantly impact yield for several years due to slow growth cycles, so this pruning would not be immediately necessary. The additional income provided by timber sales would also help lower the marginal costs associated with additional labor required for maintaining *J. olanchana* in shade communities (Stavins & Richards, 2005).

A greater concern in this scenario is the permanence of carbon storage, since timber trees are intended to be harvested as an additional income stream. Timber extraction is generally not permitted in forest patches incorporated into REDD+ projects (Myers, 2007). However, selectively logged forest patches retain a large percentage of initial carbon storage and biodiversity, indicating that responsible timber extraction may be reasonable within REDD+ initiatives (Putz et al., 2012). Moreover, Sedjo and Marland (2003) suggested that all carbon stored in forestry projects is best viewed as temporary. In this frame, carbon credits could be seen as rented rather than purchased, with a set expiration date based on the lifespan of the tree and the half-life of carbon stored in timber products (Sedjo, Wisniewski, Sample, & Kinsman, 1995; Olschewski & Benítez, 2010).

Carbon storage and biodiversity in selectively logged forest patches can be maximized through less-frequent harvesting (Schwenk, Donovan, Keeton & Nunery, 2012). In this scenario, if trees are harvested at 30 years rather than after 25, present value falls to approximately $170 to $290 per hectare. Temporary carbon payments could make up for this reduction in potential income, and provide farmers with additional revenue during the long investment period between initial planting and final harvest.

5.3.3 Scenario 3: Altering shade structure to meet Bird-friendly certification standards

I modeled adding additional species and increasing the height of select understory trees to improve plots from Cluster C to meet Smithsonian Bird-friendly certification standards (Smithsonian, 2017). Results from one representative plot are presented in Fig. 7. SExI-FS simulations of initial and improved shade communities in each plot are available in Appendix C3. The modeled management change led to an average carbon storage increase of 9.15 Mg/ha, from 56.82 to 65.97 Mg/ha, representing an average increase 34.33% from initial estimated carbon storage (Table 6).

While estimated shade was explicitly designed to stay within a specified range in scenario modeling, the high shade level in this cluster is likely to have a detrimental effect on potential coffee yields. The changes made in this scenario would require a longer timeframe for tree growth and greater effort in planning, planting, and managing new species, this investment may be offset by the 10-30% price premium commanded by Bird-friendly certified coffee (Gobbi, 2000; Ponte, 2004). These farms represent the highest overall carbon storage both before and after the modeled change in management, and therefore should be rewarded event though the incremental change is small when compared with potential improvements in Clusters A and B (Fig. 3). Certification in addition to carbon payments could help provide such an incentive.

In considering this scenario, it is important to remember that receiving Bird-friendly certification requires more than just a complex shade regime. Coffee farms must also support epiphytes, allow 5-10 m buffers of native vegetation along waterways, and also hold organic certification (Smithsonian, 2017). These requirements represent additional barriers for smallholders in Jinotega, Nicaragua. Many producers in the Jinotega region do use organic

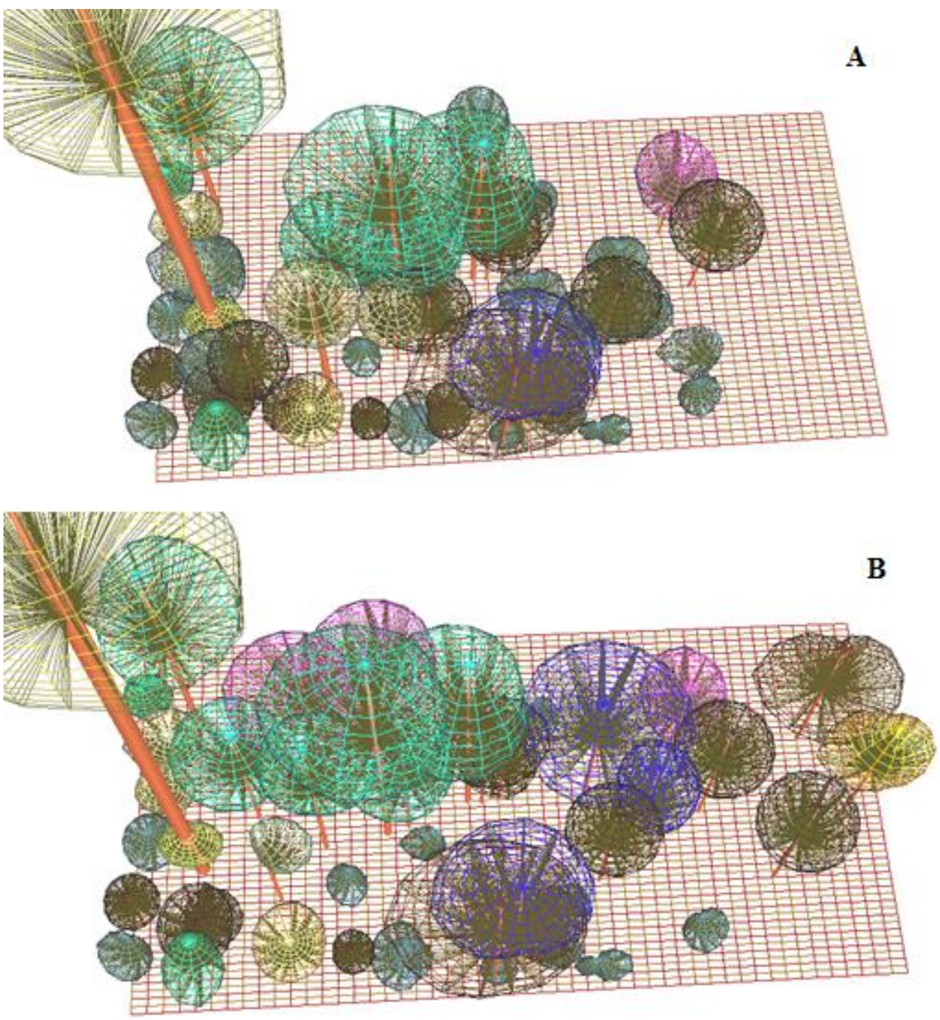

Figure 7. Change in farm plot appearance from existing shade community (A) to optimized carbon scenario (B) for Plot 2 in Cluster C, when shade was modified to meet Smithsonian Bird-friendly certification standards. Each color represents a different canopy species.

Table 6: Simulated carbon enhancement for Cluster C. Changes in plot-level species richness, estimated change in per-hectare carbon storage, and increase in modeled shade at 1 m when forested plots were altered to meet Smithsonian Bird-friendly certification standards.

Plot	ΔSpecies Richness	Carbon storage increase (Mg/ha)	Percent change in carbon storage	Percent change in light interception
1	+5	12.14	+82.65%	-0.47%
2	+2	2.32	+2.84%	-1.42%
3	+2	12.98	+17.48%	+0.04%
Average	+3	9.15	+34.33%	-0.61%

methods, but do not hold certification from a USDA-approved agency. For others, the conversion to Bird-friendly farming would require a change in agrochemical usage in addition to increased shade complexity. This could mean further reduction in coffee crop, since organic yields tend to be lower than conventional yields (Seufert, Ramankutty, & Foley, 2012). However, yields from smallholder production in Nicaragua are generally low whether conventional or organic methods are utilized (Valkila, 2009). The decline in yields would likely not be so significant as to outweigh the advantage provided through a combination of certification price premium and carbon payments.

5.4 Interviews

All interview participants felt that shade trees provide farmers with concrete benefits. Although both producers and officials believed that shade provides benefits, the perceived benefits differed between the groups (Table 7). Farmers listed more benefits relating to on-farm conditions and revenue, while cooperative officials noted a greater number of ecosystem services provided by shade trees, such as habitat value and improved air and water quality. All interview participants also expressed interest in achieving certification for themselves or for a greater percentage of cooperative members, indicating a general willingness to participate in initiatives that provide

Table 7: Number coffee farmers (n=7) and coffee cooperative officials (n=7) listing benefit of shade trees. Percent represents number of times the benefit was mentioned as a percent of all interviewees (n=14).

Shade Benefit	Coffee Farmers	Cooperative Officials	Percent
Organic material	5	1	43%
Improved coffee growth	4	2	43%
Nitrogen fixation	3	2	36%
Firewood	2	3	36%
Timber	2	2	29%
Coffee plant protection	2	1	21%
Soil protection	2	1	21%
Fruit for consumption	1	2	21%
Habitat value	0	3	21%
Protection of water sources	0	3	21%
Ecotourism potential	1	1	14%
Protection from plant disease	1	1	14%
Fruit for sale	0	2	14%
Climate change adaptation	0	2	14%
Improved air quality	0	1	7%
Payments for ecosystem services	0	1	7%

farmers with compensation for responsible production. Moreover, all farmers and all but one cooperative official stated that they would be interested in participating in a carbon payment scheme if one were developed. The following section discusses interview responses from coffee farmers and coffee cooperative officials in greater detail. I discuss the attitudes revealed during interviews in relationship to shade management scenarios and potential development of a carbon payment scheme to benefit smallholders in the Jinotega region.

5.4.1 Interviews with coffee producers

Coffee farmers all believed that their shade regime provided them with benefits, but all also noted that maintaining shade trees comes at a cost. Producers were primarily concerned with labor required for adequate pruning of shade trees (n=7). One interview participant explained that "to maintain just a quarter-manzana of coffee, it takes two people per day to regulate the shade trees. That takes money." Another participant mentioned that labor is not limited only to pruning; they must also regulate which seedlings are growing so that they can be sure to keep the most beneficial species.

All farmers indicated that they would like to change their shade community in some way. Desired changes included increasing *Inga* to improve soil quality (n=4), adding new species to improve ecosystem services (n=3), replacing nonbeneficial species to improve coffee growth (n=2) or to increase timber production (n=1), and reducing shade to improve coffee growth (n=1). These priorities are congruent with modeled management scenarios, suggesting that farmers would be willing to participate in an initiative to improve shade regimes. Despite their interest in changing their shade management, farmers felt that they face serious obstacles to maintaining diverse shade. The majority of farmers felt that they needed greater financial resources (n=5) and technical support (n=4) to improve shade. Secondary concerns—including plant diseases (n=2), climate change (n=2), and the importance of maintaining the appropriate shade level (n=1)—could likely be overcome if farmers had access to greater financial and technical resources.

No farmer participants had previous knowledge of potential carbon payment programs, but all stated that they would be interested in participating if such a program were developed. Farmers were divided on whether carbon payments should be given as a lump sum to the cooperative (n=3) or as smaller payments directly to producers (n=3). Those who felt that cooperative-level payments were more appropriate noted that this would be convenient, would allow the cooperative to provide them with better technical support, and would be fairer because all producers would benefit equally regardless of the size of their farm. Farmers who favored direct payments noted that producers who maintain more trees would deserve bigger payments. Additionally, these participants felt that farmers have better knowledge of how additional revenue should be invested than their cooperative does.

5.4.2 Interviews with coffee cooperative officials

The six participating cooperatives were established between 1990 and 2001 and represent a wide range of sizes, from 26 members to over 6,000 members. Stated cooperative goals included economic (n=7), environmental (n=3), and social (n=3) priorities. Officials representing four of the six cooperatives expressed that their organizations recommend that members maintain a minimum number of trees or level of shade. Others left shade management to the farmers' discretion, but all cooperatives stressed the importance of planting native trees adapted to the climatic conditions of the regions.

Cooperative officials universally recognized the impact of climate change on coffee producers in the Jinotega region. Interview participants noted that rainy periods have shifted or shortened (n=5), rates of coffee plant diseases are increasing (n=4), and coffee quality has decreased (n=2). To combat these negative effects, officials stated that their cooperatives use a variety of strategies including education programs, coffee certification, research on climate-resilient coffee varieties, reforestation efforts, and crop diversification. Trees were seen as important to climate adaptation, but no cooperatives provided credit to farmers specifically for maintaining shade. Instead, shade management fell into the range of costs covered by general coffee production loans provided by cooperatives.

The majority of officials (n=6) stated that their cooperative would be interested in facilitating carbon payments for their members. Perceived limitations included the need for a clear legal framework (n=5), the complexity of quantifying carbon stocks (n=2), lack of interest from yield-focused farmers (n=1), and cooperative expenses associated with providing necessary technical support to producers wishing to improve carbon stocks (n=1). Cooperative officials stated that if their organization received additional revenue through participating in a carbon payment program, these funds would be directed toward capacity development for cooperative members (n=4), providing technical and financial support for sustainable farming (n=3), crop diversification efforts (n=3), eco-friendly post-harvest coffee processing (n=2), watershed conservation projects (n=2), and specialty coffee marketing (n=1). These results suggest that a carbon payment scheme in which cooperatives serve as the primary beneficiary would lead to positive outcomes for associated farmers.

5.4.3 Differences in shade composition and carbon storage across cooperatives

There was no significant difference between participating cooperatives in total carbon storage or AGB. This suggests that cooperative goals do have a significant impact on farm-level management practices. However, the lowest mean AGC (18.84 ± 2.39 Mg/ha, compared with the overall plot average of 26.16 ± 3.17 Mg/ha) were observed in the cooperative that offers only credit and no technical support to members. During our interview, the official from this cooperative stated that the organization gives no specific shade recommendations and has no specific environmental goals. This official was also the only interview participant who was not interested in a carbon payment program. It is possible that differences in on-farm shade characteristics would be more pronounced if cooperatives had greater resources to implement their environmental objects and provide technical support and education to farmers.

6.0 Policy Recommendations

This study has presented data quantifying carbon storage in the smallholder shade coffee landscape of Jinotega, Nicaragua, and has discussed the priorities and opinions of farmers and coffee cooperative officials relating to shade management, future goals, and interest in and perceived barriers to participating in a carbon payment program. These results indicate that smallholder shade coffee stores significant amounts of carbon and that virtually all stakeholders are interested in participating in a carbon payment program if one were to be developed. The implications of this study lead to the following key policy recommendations: (1) develop a carbon payment program in the voluntary market, building on existing cooperative infrastructure; (2) improve availability of financial, technical support, and educational resources; and (3) distribute carbon payments between shared cooperative-level payments to provide support services and direct compensation to farmers. The following sections develop these recommendations and their potential outcomes in greater detail.

6.1 Develop a carbon payment program

The first policy recommendation resulting from this study is straightforward: develop a carbon payment program. Potential participants have secure land tenure and are willing to be part of a carbon payment scheme, which are factors identified as important to project success (Bulte et al., 2008). Moreover, management scenarios demonstrated a strong potential for additionality: carbon storage could be increased in all plots without a meaningful increase in shade level. Simulated changes in shade composition are not likely to reduce coffee yields in the long term, but improved shade would require a large up-front investment and increased labor in management. Carbon payments could help offset the cost of planting and maintaining new trees.

Where possible, carbon incentives should be paired with eco-certification to increase benefits to farmers.

6.1.1 Focus on voluntary carbon markets

Although the Nicaraguan government initially demonstrated interest in developing a PES program to incorporate coffee farmers, there has been little progress in the past ten years (Mendez et al., 2010). Interviews revealed that this delay has caused cooperative officials to doubt government interest in carbon payments. Government participation is necessary to develop appropriate legal frameworks, but an efficient carbon payment program should not rely on the Nicaraguan government as an intermediary in distribution of payments, as federal development priorities clearly lie elsewhere. Voluntary carbon markets also have the benefit of reduced bureaucracy and potentially higher cost efficiency than government-created markets (Newell et al., 2013). Rather than rely on the Nicaraguan government to invest in and oversee a fledgling carbon payment program, a cooperative interested in participating in such an initiative should look to a private buyer for funding. Larger cooperatives in the Jinotega region have existing ties to international corporations and NGOs (Donovan, 2011). These relationships should be used to market carbon offsets to international buyers.

6.1.2 Work within existing institutional frameworks

In Nicaragua, existing cooperatives are an ideal community for accepting carbon payments on behalf of the smallholders they represent. All cooperative officials interviewed for this study expressed some interest in participating, and most were enthusiastically in favor. Farmers generally trust cooperative leadership to oversee such a program: half of interviewed farmers stated that carbon payments should be distributed to cooperatives in lump sums rather than as smaller payments directed to farmers. This is important because transaction costs are the primary barrier to incorporating smallholders into a large-scale carbon payment program (Carlson & Curran, 2009; UN-REDD, 2011). Buyers can reduce costs may by distributing payments to communities rather than individuals (Carlson & Curran, 2009).

Large cooperatives already have relationships with international investors and experience marketing the eco-friendly nature of their product on the international market (Donovan, 2011; Donovan & Poole, 2014). Several larger cooperatives are also already engaged in collecting some of the data necessary for appropriate distribution of carbon payments, including farm size, shade tree density, and soil carbon. Cooperatives will help minimize the cost of participation, and their bottom-up structure will ensure high levels of stakeholder engagement. A successful carbon payment program should take advantage of existing cooperatives as monitoring entities and payment recipients.

6.1.3 Offer options for improving carbon storage rather than prescribing a standard approach

Farmers bring a range a different priorities, practices, and knowledge bases to shade management. The results of this study suggest that several very different management scenarios can increase farm-level carbon stocks. Farmers should be presented with different options for altering their shade regime, rather than receiving a standardized plan for maximum carbon storage. For example, not all farmers are willing to invest in timber because of the long timeframe of the investment. The management scenarios explored in this study provide a starting point for offering farmers options based on their personal constraints.

6.1.4 Combine carbon payments with eco-certification where possible

Changes in shade management on farms with an already diverse shade canopy should use Bird-friendly certification standards as a model. Previous studies have recommended that farmers achieve multiple certifications to ensure that they maximize the benefits of higher prices, institutional support, and wider distribution channels offered through participation (Philpott et al., 2007; Ponte et al., 2004; Rijsbergen et al., 2016). Carbon payments would complement the potential 10-30% price premium provided by certification to create a meaningful improvement in farm revenue (Gobbi, 2000). Further, certification programs have an established infrastructure for assessing compliance, which could contribute to the monitoring and administration needs of an emerging carbon incentive scheme (Ponte, 2004).

6.1.5 Prioritize improving shade in Inga-*dominated systems*

Simulations demonstrated the greatest potential for improvement in AGC in Cluster B, the farms in which shade canopy is dominated by *Inga* species. Although *Inga* trees store more carbon than *Musa*, the *Musa*-dominated systems tended to support a small number of very large trees that contributed to higher overall carbon storage. In modeled scenarios, carbon stocks were more than doubled by adding timber trees. The promise of additionality makes these farms especially suitable for incorporation into a carbon payment scheme. Planting timber species is a management strategy to increase carbon stocks while diversifying revenue streams, but further research should investigate the impact of other changes in shade management.

6.2 Improve distribution of monetary and technical resources

Any change in shade management will require both financial investment and technical knowledge on the part of farmers. Certification programs can serve as a model for potential impacts of a carbon payment program. These efforts often require a significant upfront investment from farmers to meet program standards, as well as yearly visits from oversight teams (Gobbi, 2000; Hardt et al., 2015; Ponte, 2004). Oversight is a necessary feature of a carbon payment program as well, though administration through cooperative structures may help reduce the cost to individual farmers. The following recommendations are aimed at minimizing the initial cost of participation and strengthening stakeholder engagement in an ongoing initiative to improve carbon storage.

6.2.1 Make credit available for shade alteration

First, cooperatives should make long-term credit available to farmers who want to improve their shade management. While all cooperative officials interviewed stated that their organization does offer coffee production credits that can be applied to shade tree maintenance and alteration, farmers still perceived the necessary investment as a major barrier to altering the shade community on their property. Cooperatives grant short-term credits for coffee farming, but with these loans comes pressure to invest in activities that will turn a profit within a single growing season. Shade trees take years to mature and offer little concrete return under current systems. Long-term shade management credits that are separate from credits granted for other coffee production activities would ensure that farmers have the financial resources necessary to make significant changes in shade communities.

6.2.2 Increase availability of technicians

For carbon payments initiatives to be successful in developing countries, participants need technical support (Scherr et al., 2004). In interviews, farmers stated that they perceive a lack of technical knowledge and support to be a major barrier to making changes in shade management. To allay these concerns and reduce perceived risk of investing in shade trees, cooperatives should use a percentage of carbon payment revenues to hire field technicians to advise farmers on a regular basis. Technicians are a trusted source of information, and can have a strong influence on farmers' management decisions (Donovan, 2011; Frank et al., 2011). Interviews revealed that cooperatives would like to provide greater technical resources to their members, but currently lack the financial resources to do so. A greater base of field technicians would also improve a cooperative's capacity to monitor carbon stocks and quantify increases in carbon.

6.2.3 Educate farmers on carbon and its importance

Stakeholders can only be truly engaged in a carbon payment program if they understand the impact of participation. During interviews, farmers indicated that they were concerned about climate change, but that they were not aware of the role of carbon as a greenhouse gas. Participating cooperatives should provide their members with educational materials and workshops to help farmers connect shade management practices with the climate change issues that affect them. Several officials stated that their cooperative already offers educational outreach programs on topics ranging from environmental issues to business skills. These programs should be adapted to a carbon focus to help farmers understand the benefits of improving carbon storage by altering shade management. These education programs should involve youth as well as landowners: it is important that cooperatives invest in future leaders and professionals who will manage carbon markets in subsequent generations (Scherr et al., 2004).

6.3 Carbon payments should be split between cooperatives and farmers

Additional income from carbon payments could enable cooperatives to advance their economic, environmental, and social goals. Cooperative officials stated that their organizations would invest new revenues in marketing, coffee processing, education, reforestation, and crop diversification projects. All of these ideas address perceived needs of smallholders in the region and represent concrete improvements that a carbon payment program could achieve. The benefits would be even greater if participating farmers were also granted cash payments representing a percentage of cooperative-wide proceeds from carbon payments. This would help cooperatives sell the program to their members, because it would bring an additional revenue stream independent of yield. Direct payments would also ensure farmer satisfaction with the program, since half of interview participants indicated that they preferred direct payments rather than larger cooperative-level payments.

A direct payment strategy could increase environmental benefits by enabling farmers to replace a larger proportion of low-carbon *Musa* with other shade species that have greater benefits in terms of both carbon storage and habitat value. Modeled scenarios in this study retained half of *Musa* and most other fruit trees present because this produce is important for household food security. Bananas are most critical as a food source during the “lean months” in the middle of the growing season, after money from the previous year’s crop sales has run out (Bacon et al., 2014). Although cooperatives participating in Fair Trade markets have attempted to improve food security, these efforts have been only marginally successful in Nicaragua

(Bacon, 2015; Donovan, 2011). Unlike the price premium associated with specialty coffee markets, carbon payments would not be tied to crop sales. Payments could therefore be disbursed during the June through August period, when smallholder food access is at its lowest due to a lull in income-generating on-farm activities (Bacon et al., 2014). This timing strategy has the potential to improve smallholder quality of life by smoothing the monthly variability in household income. Beyond this, it could reduce the importance of fruit trees to households. Carbon payments distributed directly to farmers when they are most in need of income can help cooperatives achieve long-term social goals while making concrete environmental improvements.

6.3.1 Consider developing a Food-for-work program as an alternative to cash payments

Cash payments for improving or maintaining ecosystem quality can aid in poverty alleviation by smoothing fluctuations in income for smallholders (Bulte et al., 2008). However, direct compensation can also lead to negative outcomes, such an inequitable distribution of payments and erosion of perceived inherent value associated with shade trees (Wunder, 2007). Corbera (2012) suggested that PES leads to the "commodification of nature." However, virtually all trees in inventories were identified as useful species, and farmers stated material reasons for their tree selections; trees in these coffee systems are already commodified.

The question of how to disperse payments to farmers to achieve multiple goals of environmental and social improvement still remains. Cash payments are generally viewed as the most appropriate compensation when participants sacrifice potential cash income to participate (Wunder, 2008). It is not clear how much income participants in this project would be required to give up, since proposed shade alterations are not likely to reduce yields in the long term and previous policy recommendations include financing for shade alteration. In this case, in-kind payment such as a Food-for-work (FFW) program may provide more appropriate compensation (Wunder, 2008).

FFW programs, in which cooperatives use carbon payment funds to buy and distribute supplies of food, offer the dual advantages of guaranteeing a basic income to food-insecure households and providing labor for community infrastructure projects (Holden et al., 2006). This compensation method is generally viewed an effective means of addressing the goal of poverty alleviation because it targets only the truly needy, although this is the subject of debate (Barrett & Clay, 2003). With proper targeting, FFW initiatives would remove the problem of determining how to properly distribute carbon payments to farmers and the need for cooperative officials to determine which participants are worthy of what monetary compensation. This provides an alternative policy option for addressing the ongoing problem of seasonal hunger among smallholders in the Jinotega region (Bacon et al., 2014; Holden et al., 2006).

6.4 Conclusion

Smallholder shade coffee in Jinotega, Nicaragua sequesters significant amounts of carbon, but the landscape has greater carbon storage potential. As demonstrated by the scenarios explored in this research, carbon stocks could be improved through changes in shade management. Stakeholder priorities and constraints vary, so providing a variety of management strategy options is necessary to allow flexibility in meeting carbon storage goals. Strong institutions are already in place; cooperatives are ideally positioned to administrate a carbon payment program if one were to be developed. Further, both cooperatives and farmers are actively interested in participating in such a program. By providing a revenue stream independent of crop yield, carbon payments have the potential to improve livelihoods and support both social and environmental goals. Future research should address the cost-benefit analysis of management changes using more concrete figures, the impacts of additional management scenarios, and actual changes in shade biomass over time as high-carbon management practices are adopted.

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APPENDIX A
Questionnaire for interviews with coffee farmers

1.) What do you see as the benefits of the shade trees in your coffee farm?

2.) Are there costs to maintaining your current shade regime? If so, what are they?

3.) Would you like to change the types of shade trees in your farm? Would you like to increase or decrease the number of trees in your coffee parcel?

4.) If you would not like to change your shade regime, why not? If you would like to change, what additional resources would you need to make the change?

5.) What limitations do you face in maintaining a diverse shade canopy?

6.) What sources do you consult for information about shade management?

7.) What is the attitude of your cooperative about maintaining shade trees?

8.) Does your cooperative participate in any certification programs? Does your farm have any certifications? If so, what are they?

9.) Would you like to receive additional certifications? If yes, what do you need to do in order to receive them?

10.) Have you heard of payments for carbon sequestration or for maintaining a large number of shade trees?

> [If their response was no: There is a possibility that a program could compensate coffee producers for maintaining a large quantity of trees because they serve to purify the air of excess carbon, which is a greenhouse gas that contributes to climate change.]

11.) If these payments were available, would you be interested in participating? Would your organization want to participate?

12.) Would you prefer to receive a direct payment, although it would be very small, or for your cooperative to receive a somewhat larger payment that it could invest in its projects? Why?

APPENDIX B
Questionnaire for interviews with cooperative officials

1.) Please tell me a little about your cooperative. When was it founded? How many producers are members?

2.) What are the mission and vision of your cooperative?

3.) What do you see as the role of the cooperative in shade management in members' coffee farms?

4.) What do you see as the benefits for producers of maintaining shade trees?

5.) Does your cooperative recommend that members maintain a certain number or certain species of shade trees? What are the reasons for these recommendations?

6.) According to you, what is your role in the decision-making process regarding shade management in your members' farms?

7.) In addition to your cooperative, are there other organizations that work with technical assistance in coffee agroforestry systems? What influence do they have?

8.) Is climate change affecting the members of your cooperative? In what way?

9.) What do you see as the role of your cooperative in addressing the problem of climate change, especially in coffee systems?

10.) Does your organization assist members in achieving certification? What certification programs do your members work with? Would you like to work with more certification efforts?

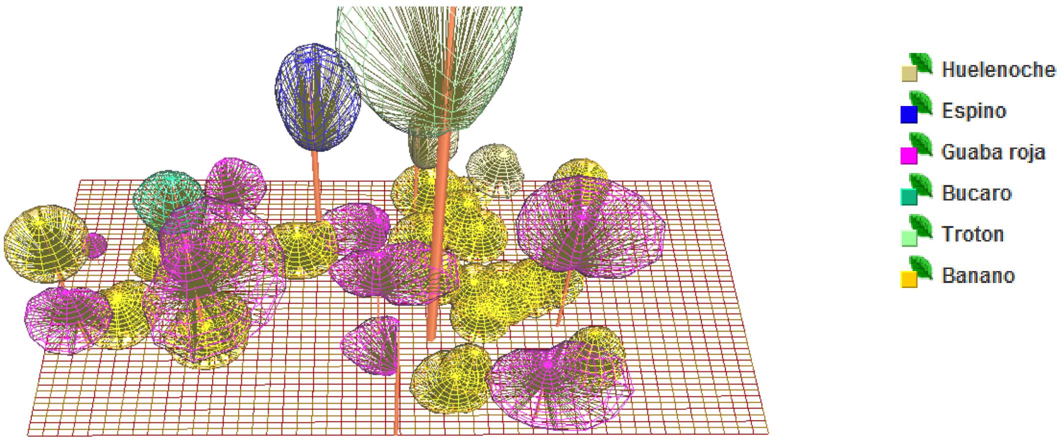
11.) If a carbon payment initiative existed to compensate farmers who maintain a large number of trees in their farms, would your cooperative be interested in participating? Would the members of your cooperative want to participate?

12.) What do you see as the potential limitations of developing and participating in this type of initiative?

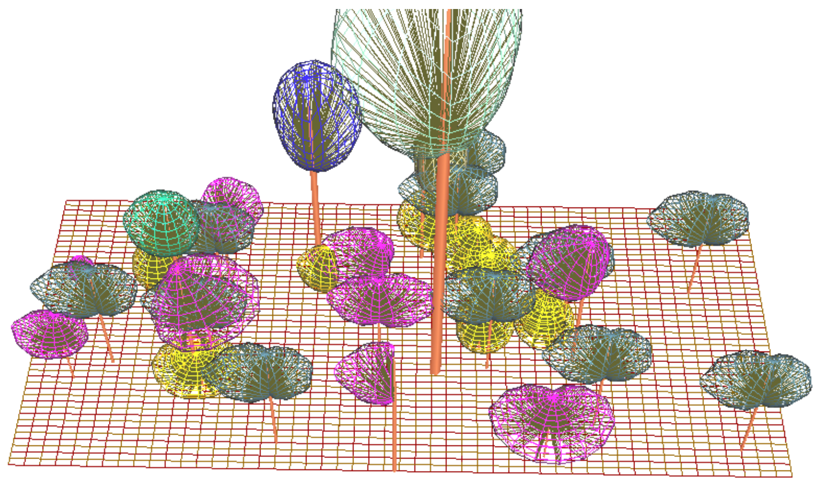
13.) In credits granted to producers, does your cooperative offer loans to cover activities to improve or alter shade canopy in coffee farms?

14.) If your cooperative had access to greater financial resources, what additional services would you like to offer to your members?

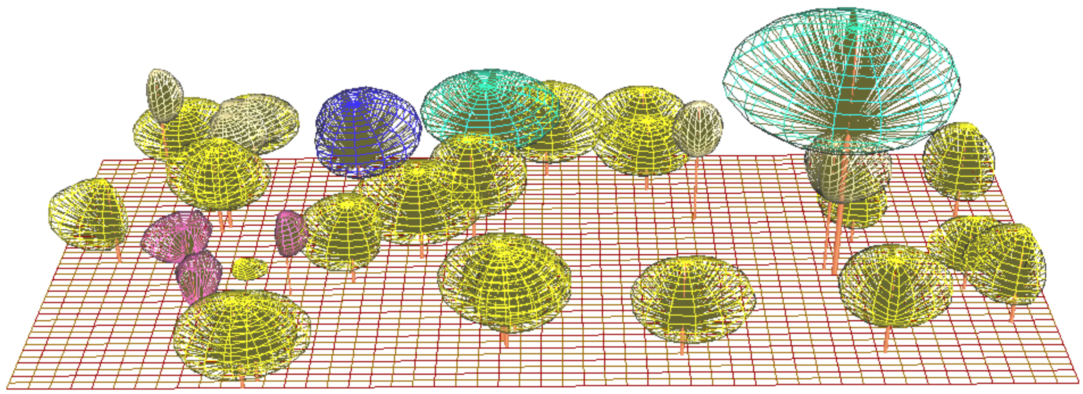
APPENDIX C1
SExI-FS Simulations of Shade Management Scenario 1:
Musa Replaced with *Inga* trees



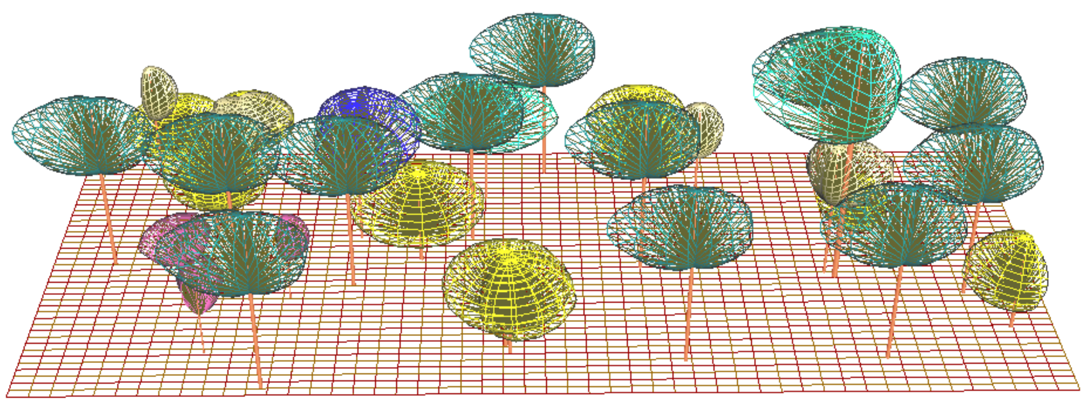
Cluster A plot 1, existing shade community.



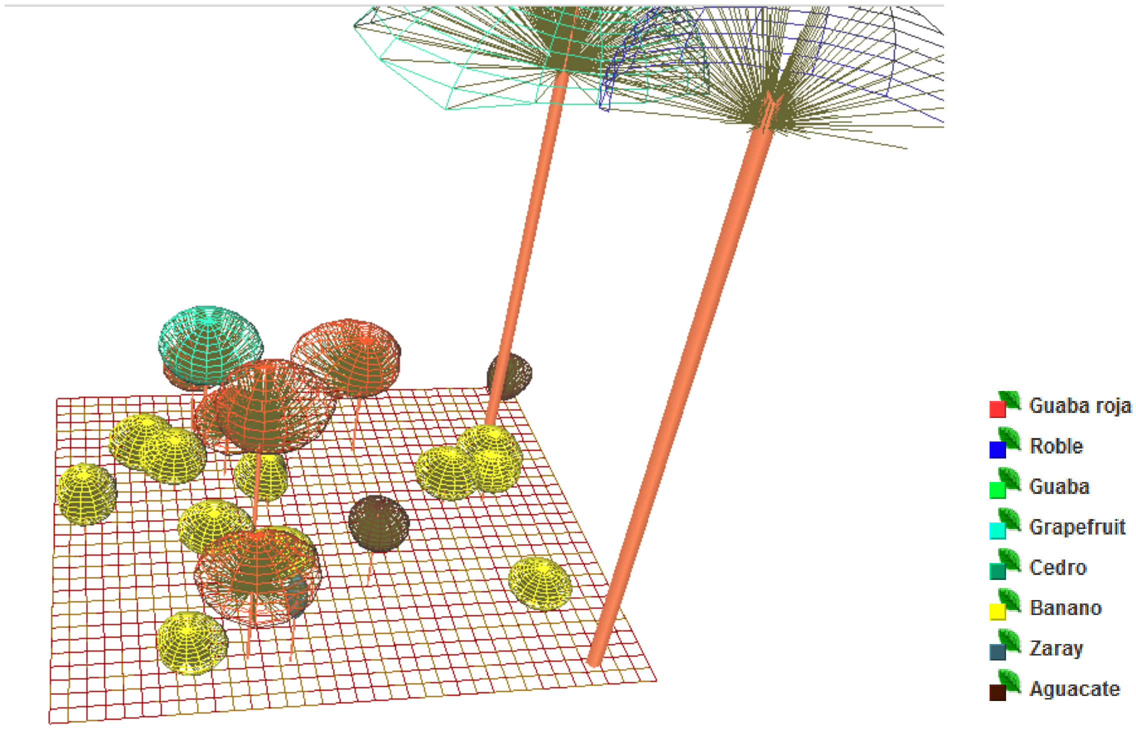
Cluster A plot 1, improved shade scenario: half Musa *replaced with simulated* Inga *sp.*



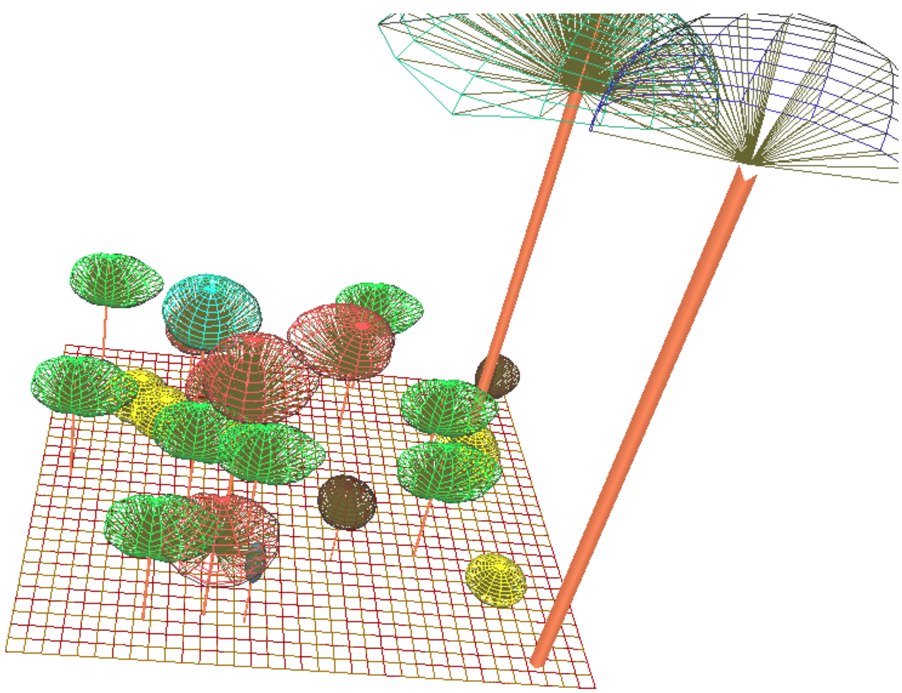
Cluster A plot 2, existing shade community.



Cluster A plot 2, improved shade scenario: half Musa *replaced with simulated* Inga *sp.*

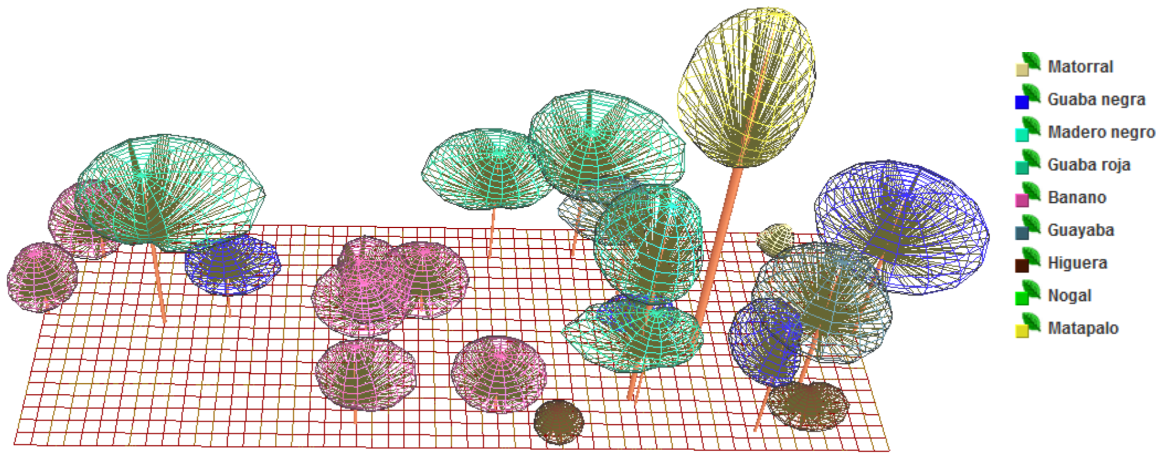


Cluster A plot 3, existing shade community.

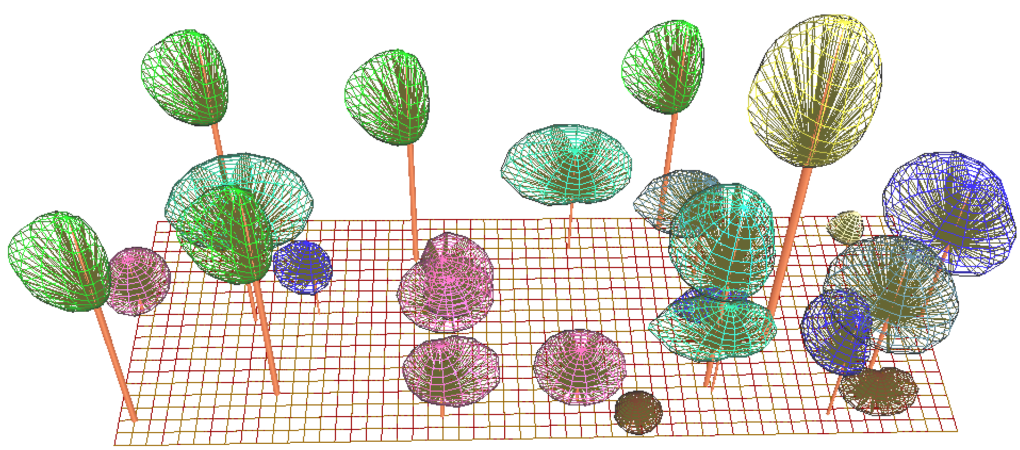


Cluster A plot 3, improved shade scenario: half Musa *replaced with simulated* Inga *sp.*

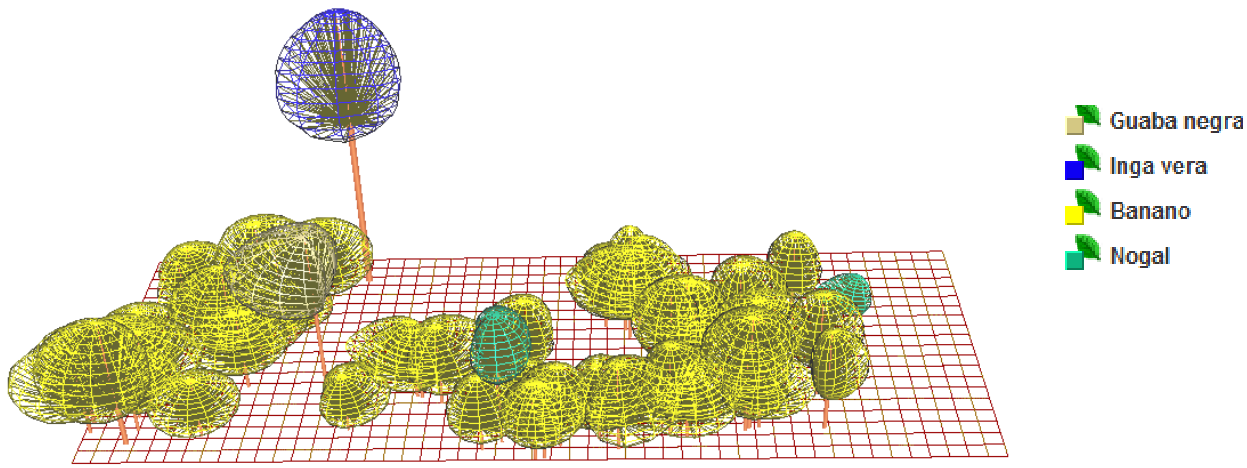
APPENDIX C2
SExI-FS Simulations of Shade Management Scenario 2: Timber Trees (*Juglans olanchana*) Added



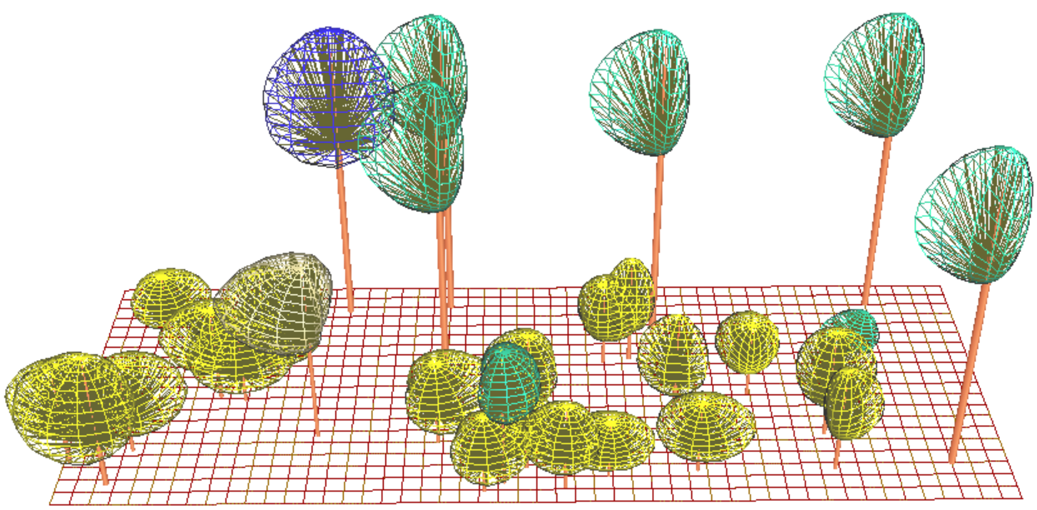
Cluster B plot 1, existing shade community.



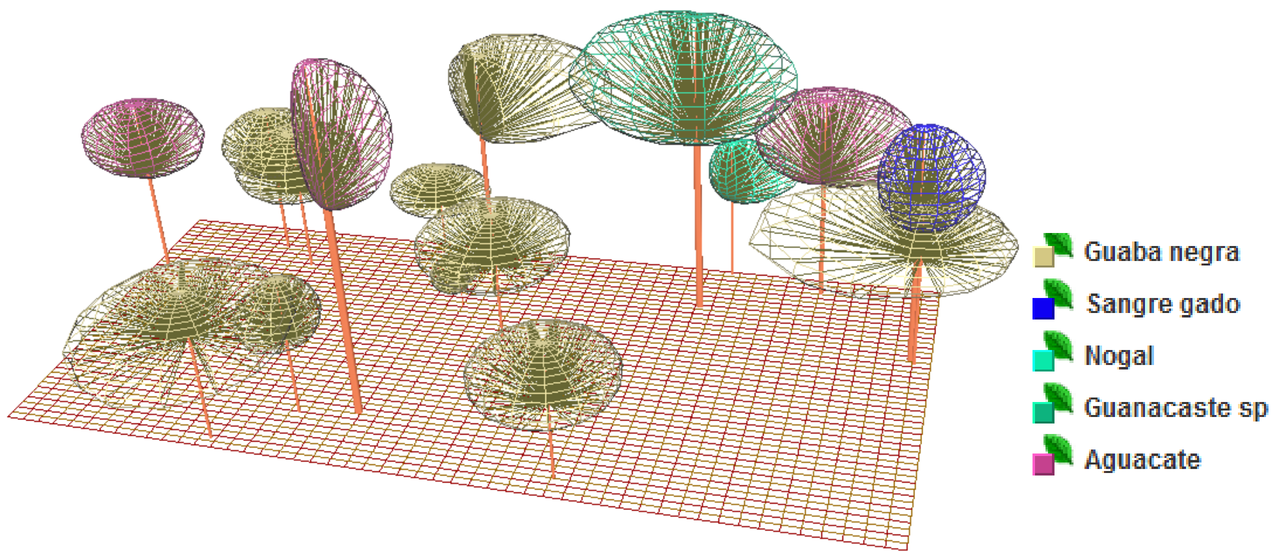
*Cluster B plot 1, improved shade scenario: timber trees (*J. olanchana*) added.*



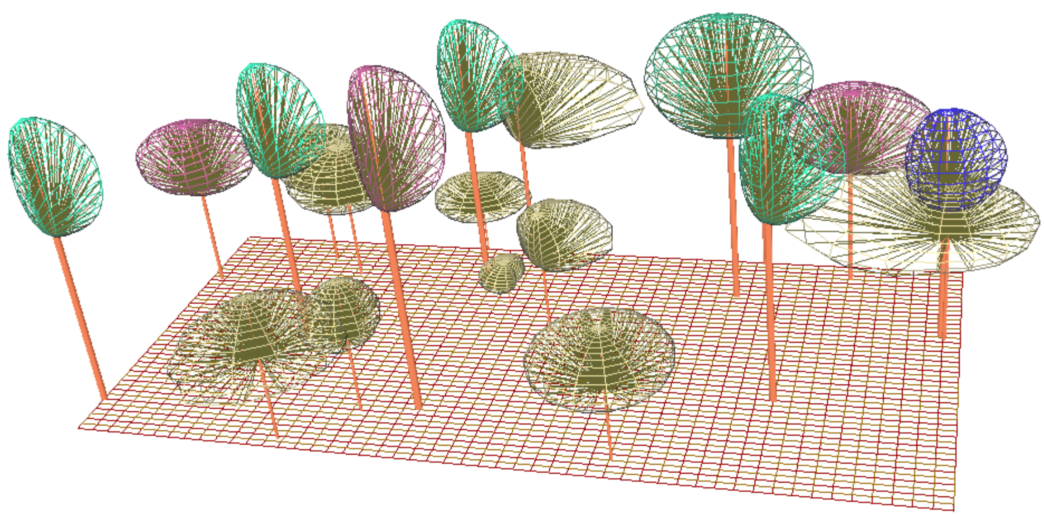
Cluster B plot 2, existing shade community.



*Cluster B plot 2, improved shade scenario: timber trees (*J. olanchana*) added.*

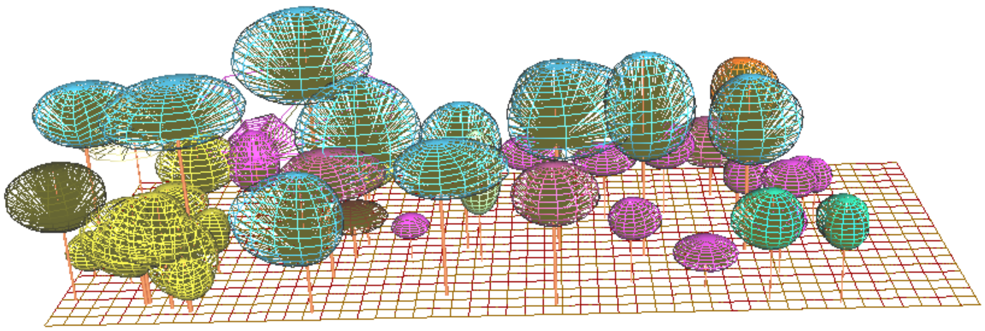


Cluster B plot 3, existing shade community.

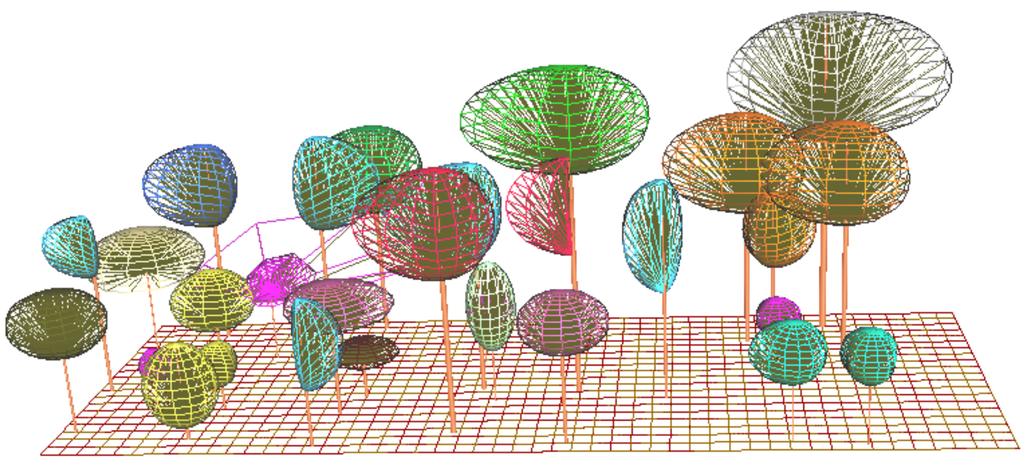


*Cluster B plot 3, improved shade scenario: timber trees (*J. olanchana*) added.*

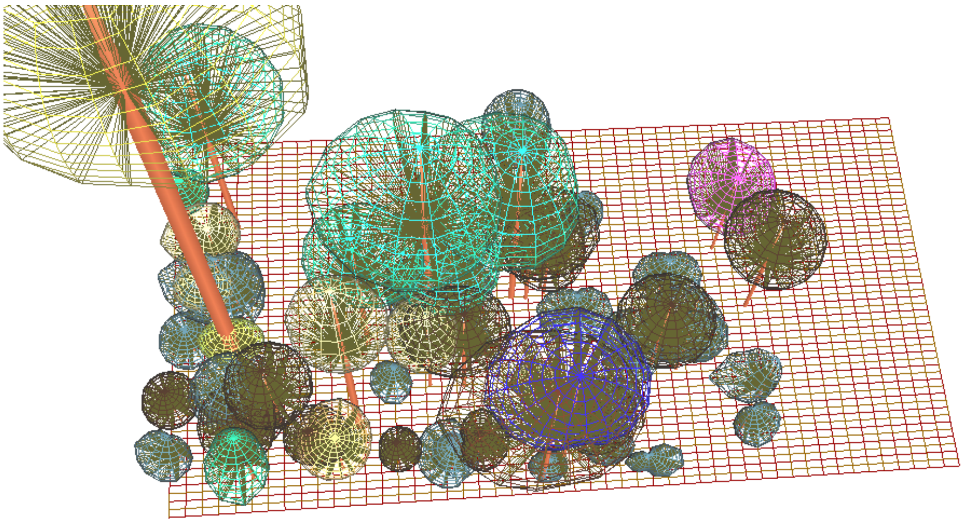
APPENDIX C3
SExI-FS Simulations of Shade Management Scenario 3:
Shade Community Altered to Meet Bird-Friendly Certification Standards

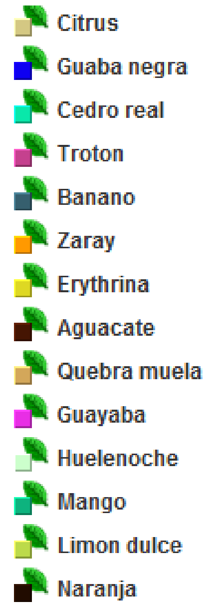


Cluster C plot 1, existing shade community.

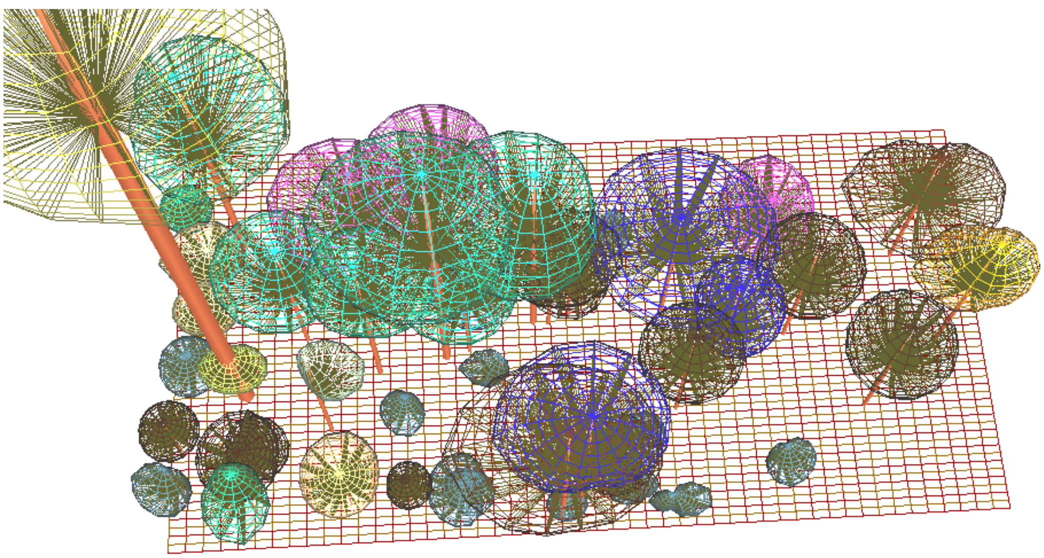


Cluster C plot 1, improved shade scenario: Bird friendly.

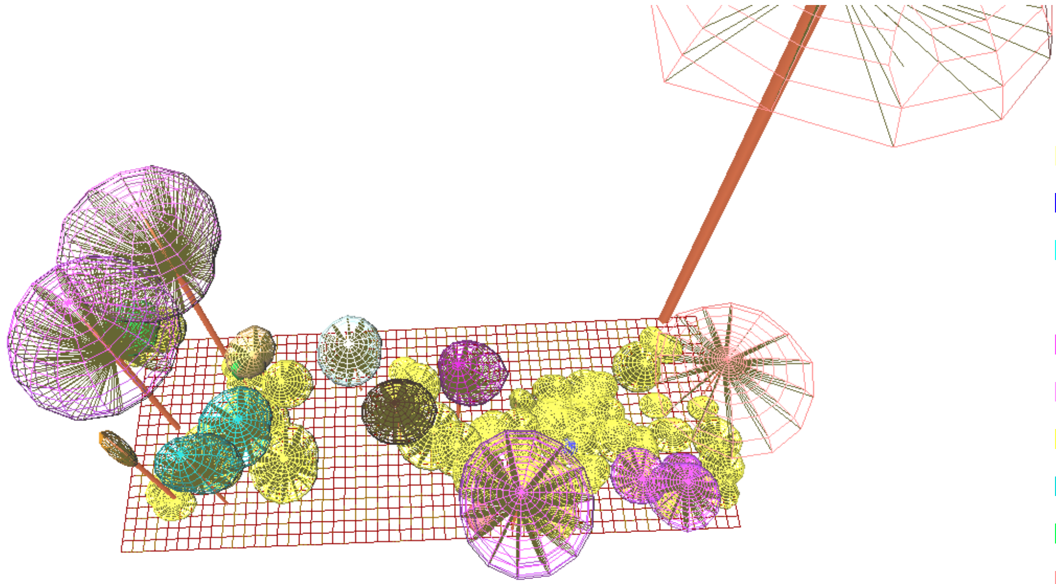




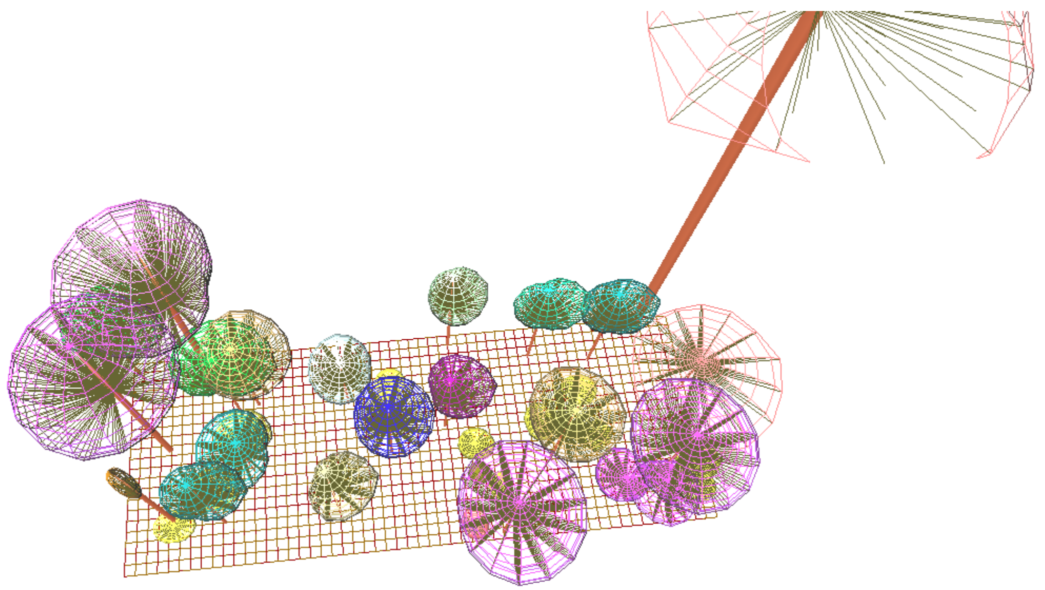
Cluster C plot 2, existing shade community.



Cluster C plot 2, improved shade scenario: Bird friendly.



Cluster C plot 3, existing shade community.



Cluster C plot 3, improved shade scenario: Bird friendly.