PLANTING SHADE FOR THE NEXT GENERATION:
CURRENT AND POTENTIAL AGROFORESTRY IN A RURAL PARAGUAYAN VILLAGE

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Abstract

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Agroforestry, the integration of trees into farming systems, has been promoted in the developing world as a way to avoid deforestation, improve crop and livestock productivity, and provide greater economic benefit from agricultural land. Adding trees can improve soil fertility and physical properties, support biodiversity, and mitigate the effects of climate change while making farms more resilient. Successful agroforestry promotion will address site specific conditions, local concerns, and be compatible with existing agricultural practices. Paraguay has experienced one of the highest deforestation rates in the world in recent years and suffers from endemic rural poverty, land degradation, and a lack of economic opportunity for small farmers. As a Peace Corps volunteer in the rural village of Laguna Pytã, the author had the opportunity to live for two years in a small subsistence-farming community and observe residents' agricultural practices. Semi-structured interviews with 15 households, farm visits, and participatory group activities were used to determine agricultural attributes of the community, identify perceived agricultural issues, and characterize agroforestry systems currently used in the community. Farmers pinpointed increasing drought and declining soil fertility as the most pressing of seven main agricultural problems. Four traditional and four recently introduced agroforestry systems were observed in the village with varying rates of use. Based on these findings, recommendations are then made for improved agroforestry practices that can benefit the community ecologically and economically.

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To our family and community in Laguna Pytã, my wife and I owe our eternal gratitude and love. We would not have made it two years without their help, support, and friendship. *Aguijeite. Ndaikatui ajapo che trajabo pende apoyoyre ha pende amoryre. Peê ha'e ore familiaite ko'agã ha siempre peguara. ¡Peê rohechaga'u ha rohayhu! Hasta la próxima. – José el norte (ha Belén ombohasa saludos avei).*

To Oli and Baast. Thanks for keeping me sane and for the cuddles.

To my family, thank you for providing me with everything I ever wanted, needed, or even looked at. I understand slightly better now exactly how fortunate I have been, and I owe you guys everything. Thanks for the support and the freedom to explore, travel, and somethings do stupid things.

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I: Introduction

"One generation plants the tree, another gets the shade."

– Chinese proverb, author unknown

"No pienso en mí no más, lo hago para los jóvenes ahora."
(I don't think about myself anymore, I do it for the young people now.)

– Don Lidio León, Laguna Pytã elder and youth mentor

In December of 2017, my wife and I found ourselves in a completely new world. Although we had arrived in Paraguay three months earlier as Peace Corps volunteers, the small city outside the capital where we underwent training didn't feel that much different from any big town in the U.S. yes, the food was new, and recognizing September as springtime took some getting used to, but the host family we stayed with left the house each day for 9-to-5 jobs, ads for U.S. fast food chains were constantly on the television, and everyone spoke to us in Spanish, a common language back home. However, when our three-month introduction ended and we moved to Laguna Pytã, the rural village that we would call home for the next two years, the realization quickly dawned that we were very far from home. Although I had years of field experience with natural resource management, subsistence agriculture was as foreign to me as Guaraní, the indigenous language spoken by 90% of Paraguayans.

Admittedly, I knew little about Paraguay before we left the United States. As a Peace Corps Masters International graduate student in forestry, most of what I had heard regarded its very high rate of deforestation in recent decades (Hansen et al. 2010, Keenan et al. 2015). My attitude that people should simply preserve forest and stop cutting trees betrayed my suburban American childhood and ignorance of life in developing countries and rural life in general. Peace Corps service not only introduced me to a new culture and people whom I would soon regard like family, but to the complexities of conservation, economic development, and subsistence agriculture in a place where nature is not just for recreation and somewhat abstract services like carbon sequestration, but is directly responsible for providing daily, tangible necessities for millions of people. Sometimes, cutting down a tree in subtropical forest is not an act against nature; instead, it is an act of love to shelter and feed one's family.

Agroforestry, the intentional use and maintenance of trees in agriculture, is one of several tools that can bridge the gap between the sustainable use of landscapes for local and global benefits and enabling farmers around the world to support themselves, their families, and their communities (Vergara et al. 2016). This professional paper is an attempt to understand and explain what agroforestry is, what benefits it provides, what factors govern its use and further adoption, and what role it plays in increasing economic opportunity. Although many of the aspects in this paper regard developing countries and Paraguay in particular, agroforestry is applicable wherever food is grown. Its adoption and promotion are gaining in the United States and Europe to achieve ecological benefits, economic diversification, and climate change resilience (UMCA c2012, EURAF undated).

In the second section, I provide background information on Paraguay's environment, government, people, and land use. Section three defines agroforestry and characterizes the various forms that it takes. In it I also explain the ecological processes and economic theories (i.e. tradeoffs and distribution of resources) that form the foundations of agroforestry and discuss its benefits, disadvantages, and factors regarding its adoption. In section four, I discuss agroforestry in Paraguay specifically, from traditional systems in use for generations to recently introduced practices. Section five presents exploratory research that I undertook in my home village. Through informal interviews with farming households, field visits, and a participatory group activity, I investigated the agricultural problems of greatest concern to small farmers, the most important services provided by trees, and agroforestry practices that were already in use in the community. Based on these results, I recommend modified and improved agroforestry practices that could benefit Laguna Pytã economically and ecologically and make agriculture more resilient to climate change.

II: Background Information on Paraguay

Geography

Paraguay is a small, landlocked country in the middle of South America. With an area of 406,752 km^2, it is slightly smaller than the U.S. state of California (Roett and Sacks 1991). It shares borders with Argentina to the east and south, Brazil to the east and north, and Bolivia to the northwest.

Figure 1. Map of Paraguay with major cities, rivers, and highest point. Inset shows location within South America. (CIA 2020)

The Paraguay River essentially bisects the country into eastern and western halves. The eastern half is mainly flat with some rolling hills and four ranges of mountains. The highest point in the country is Cerro Trés Kandu, also known as Cerro Perõ (Bald Hill in Guaraní, the indigenous language), at 842 meters above sea level (CIA 2020). The climate is humid and precipitation ranges from about 1350 mm/year at the Paraguay River to over 1700 mm/year at the eastern border (Peace Corps Paraguay 2009).

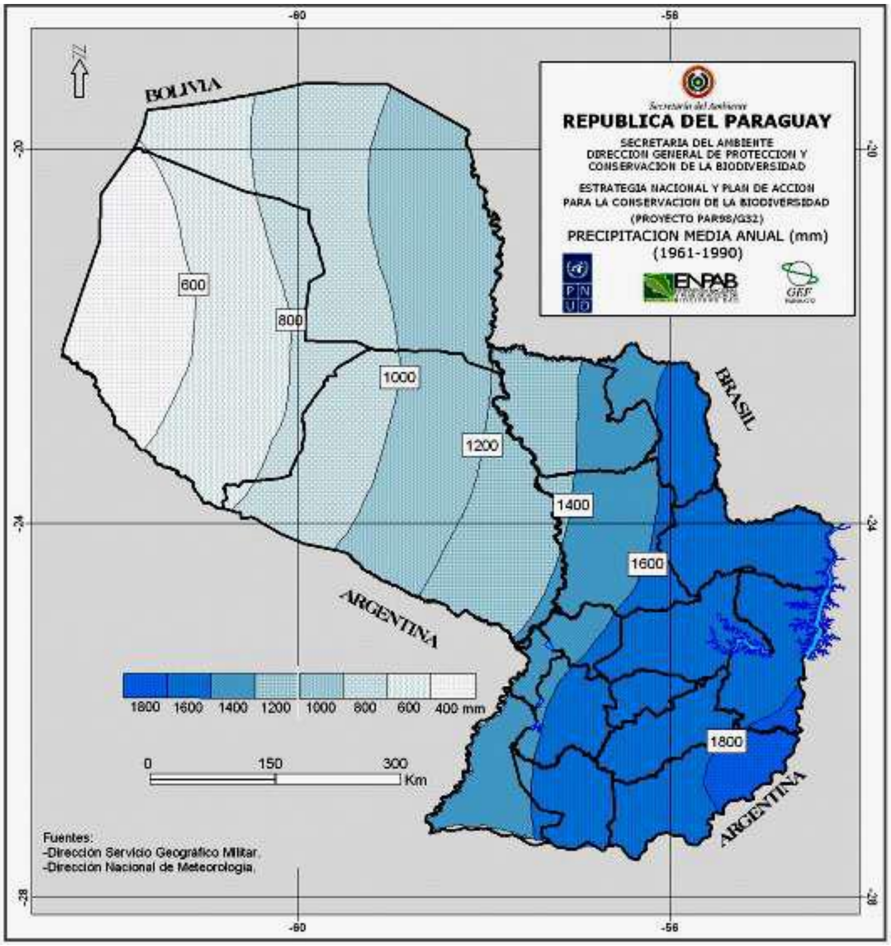

Figure 2. Map of precipitation gradient within Paraguay, based on mean annual precipitation 1961 - 1990. (Kernan et al. 2010)

Before the mid twentieth century, the eastern region was mostly a vast tropical to subtropical forested landscape, with some natural savannahs and wetlands towards the south where the Paraná River meets the Paraguay River (Peace Corps Paraguay 2009). The Upper Paraná Atlantic Forest, as the biome is known, is also located in eastern Brazil and northeastern Argentina and is known as a biodiversity hotspot for its large numbers of plant and animal species, including over 79 species of endemic bird (Kernan et al. 2010).

The western region, part of the larger Gran Chaco, has an area of 246,925 km², about 60% of the country's total (CIA 2020). This arid to semi-arid tropical plain, also covering parts of eastern Bolivia and northwestern Argentina, was known to Spanish conquistadors as "The

Green Hell" for its harsh, unforgiving climate and vegetation (Gimlette 2003). The Chaco is almost entirely flat and gently slopes down from west to east. Precipitation ranges from a low of 400 mm/year in the thorny scrubland of the westerly dry Chaco to 1300 mm/year in the palm savannah of the easterly humid Chaco along the Paraguay River (Peace Corps Paraguay 2009). The humid Chaco extends east past the river into a portion of eastern Paraguay (figure 3).

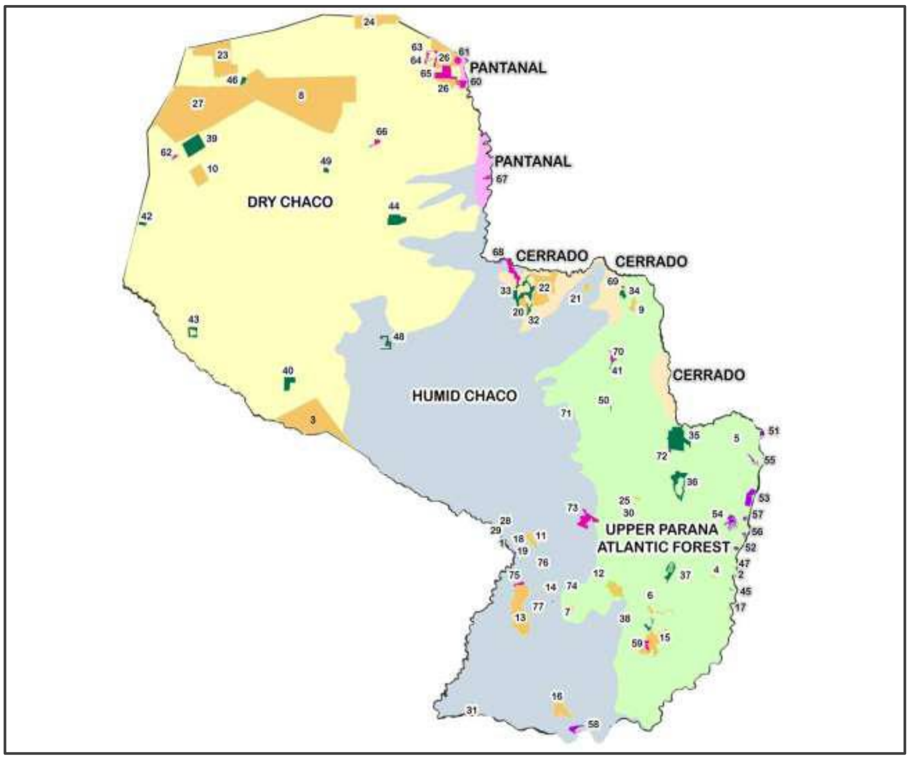

Figure 3. Map of ecoregions in Paraguay. (Kernan et al. 2010)

Two small ecoregions are located along the northern borders with Brazil. The Pantanal is the largest seasonally flooded wetland in the world. Although no species are specifically endemic to the Paraguayan Pantanal, the area plays a huge role for migratory waterfowl, mammals, and fish (TNC 2020). The cerrado ecoregion is a tropical savannah spreading over large part of Brazil south of the Amazon rainforest (Oliveira and Marquis 2002). It makes up a small portion of the land area of Paraguay but is important for biodiversity with endemic bird, amphibian, and reptile species (Kernan et al. 2010).

Government

Paraguay's system of government is set up as a presidential republic, with the latest constitution adopted in 1992 (CIA 2020). The president is democratically elected every five years for a single term (Kernan et al. 2010, CIA 2020). The legislative *Congreso Nacional* is made up two chambers similar to the US federal legislature. Senators are elected by the country as one bloc while the deputies of the lower chamber, akin to the House of Representatives in the United States, are chosen by 18 constituencies analogous to the departments and capital city (CIA 2020). Various ministries and secretariats make up the cabinet, which advise the president and administer the laws and policies.

Administratively, the country is divided into 17 departments, with only three spanning the entire Chaco region (Kernan et al. 2010). Each department is sub-divided into districts. Districts generally have one large town serving as the economic, political, and social hub where the municipal government is located. Surrounding the towns are rural hinterlands made up of *compañías* (villages) which don't have their own political representation, but which municipal and district federal agents are responsible for.

A discussion of government in Paraguay is not complete without mentioning the legacy of Alfredo Stroessner, the former military ruler with the distinction of being the longest serving dictator in Latin America (Zoomers and Kleinpenning 1990). Through bureaucracy, harassment, outright torture, and a subversive network of spies, Stroessner and his administration controlled the entire country from 1954 to his ouster in 1989 with a heavy-handed, top-down approach. Corruption was purposefully built into the system to enrich the dictator and his associates in government and business (Ardigó 2016, Patullo 2013). Nepotism was widespread, and merit-based hiring of government officials only began on a small scale in 2003 (Ardigó 2016). Power was exercised over citizens through an extreme partisan system. In order to receive government benefits or hold a civil service job, membership in the dictator's Colorado Party was required (Zoomers and Kleinpenning 1990). Additionally, a network of spies was set up throughout the countryside (Roett and Sacks 1991). Distrust of the government and even one's own neighbors was widespread during this time (anonymous community member 2019, personal communication). This legacy of corruption and nepotism has continued into the democratic era in Paraguay: the first president after Stroessner's removal from office was the dictator's second-in-command (Roett and Sacks 1991).

Partly due to this corruption, there is a pattern of fatalism and distrust among the rural population. Coupled with the poverty that most in the countryside have lived with their entire lives (detailed in the next section), rural Paraguayans tend to believe that little will change and that they have little control over their destinies (Peace Corps Paraguay 2009). Many feel that government officials do not have their best interests in mind and only seek to collect bribes and a government pension (Ardigó 2016, Personal observation 2018).

Demographics

The population of Paraguay is just over seven million, and 95% identify as mestizo, descended from a mixture of Spanish and indigenous people (CIA 2020). Despite the continued cultural presence of various figures from Guaraní mythology and legend, Roman Catholicism is the dominant religion. The church's influence is ubiquitous in Paraguayan life, especially in rural areas. Ninety percent of the population claims to practice Catholicism, although in recent years Protestantism and Mormonism have made significant inroads (CIA 2020).

Despite encompassing over 60% of the land area, the arid Chaco region west of the Paraguay River holds only 2% of the population (Peace Corps Paraguay 2009). The other 98% live in the smaller but more forgiving eastern region.

Both Spanish and Guaraní are official state languages. Due to the legacy and patterns of colonization, 90% of the population speaks Guaraní (Roett and Sacks 1991). Almost half speak Spanish in addition to Guaraní. Merely 15% speak only Spanish (CIA 2020). In rural areas, Guaraní is the dominant language and the primary language spoken in homes. Spanish is considered the language of official government and commercial business, while Guaraní is seen as the true language of Paraguayan hearts. From personal observation, much of the rural youth speak Spanish owing to the prevalence of television sets and foreign-produced media. Many older adults understand only limited Spanish and speak even less. This can lead to interesting, and in hindsight very humorous, experiences for newly arrived Peace Corps volunteers with just a few months of language training as they attempt to negotiate housing, rent, and utilities in their new communities.

The country has one of the most rural population distributions in Latin America, with just over 60% living in urban areas (Kernan et al. 2010). At 0.679, Paraguay's Human Development Index is the second lowest and its level of economic inequality is near the top for Latin American countries. Despite small enclaves of extreme wealth in the capital, the overall poverty rate in 2018 was about 24%, although this figure diminishes the severity of poverty in rural areas (DGEEC 2018). Over one third of the rural population is under the poverty line, defined by the Paraguayan government as 488,172 guaranies per month ($73.71 US). Ten percent of the rural population lives in extreme poverty, earning less than 239,969 guaranies per month ($36.24 US)(DGEEC 2018). Over 90% of the rural population is engaged in agriculture, with subsistence agriculture specifically being the primary socioeconomic activity in rural areas (Hamilton and Bliss 1998, Lopez and Thomas 2000).

One symptom and cause of the vast economic inequality is a skewed distribution of land ownership. This is partially due to the legacy of the disastrous Triple Alliance War (1864 – 1870) which pitted Paraguay against the combined forces of Brazil, Argentina, and Uruguay (Roett and Sacks 1991). A defeated Paraguay had to sell vast tracts of public land to cover its debt. At the turn of the 20th century, 11 property owners, each with more than 100,000 hectares, together possessed 35% of the land area in eastern Paraguay (Zoomers and Kleinpenning 1990). Another 1,119 elite landowners controlled an additional 62% in the east, although they had to make do with only 2,000 to 99,000 hectares each. Almost the entirety of the Chaco was owned by 79 individuals or corporations (Zoomers and Kleinpenning 1990). The situation has improved only slightly in the modern era; in 2013, one percent of the population owned 77% of the arable land nationwide (Ardigó 2016).

Blatant corruption has also contributed to the inequality of landownership. As noted above, favoritism is commonplace among those in power. In the 1990s, almost eight million hectares of public land designated to be redistributed to poor peasant families instead ended up the legal property of several elite businessmen, politicians, and military officials (Kernan et al. 2010). As mechanized soy production and extensive cattle ranching grew more lucrative, the same land was then resold to large foreign agricultural firms.

Land Cover and Land Use

Agriculture is the primary land use throughout Paraguay. In 2009, the area under crops alone was 30% of the land area in eastern Paraguay (Kernan et al. 2010). The same year, it was estimated that pasture was an additional 54%.

Kernan et al. estimated that in western Paraguay in 2009, almost one-quarter of the land was either natural or planted pasture (2010). Although this only illustrates the area of pasture, and not the area being grazed, other land conversion research based on satellite imagery strengthens the argument that large amounts of the Chaco are being razed to create large, industrial cattle ranching operations (Hansen et al. 2013).

Agriculture plays a large role in the country's economy, especially for exportation. Agriculture (including livestock and plantation forestry) amounted to just over 11% of GDP in 2017, down from 30% in 2014 (Ardigó 2016). However, it accounted for 90 - 98% of export income in recent years and employed almost half of the country's workers (BCP 2018, Schnobrich 2001, Kernan et al. 2010). Paraguay is the world's fourth largest exporter of soy and sixth largest in terms of area under cultivation (Gijsenbergh in Bechard 2017). It has also become a large exporter of beef as the Chaco is converted into large cattle ranches.

Mechanized agriculture covered 2.3 million hectares in 2008/2009, or 15% of eastern Paraguay's land area (Kernan et al. 2010). The use of expensive technology and chemical inputs is generally limited to large landholders of foreign extraction or corporations. Mechanized agriculture among smallholders is less prevalent, covering less than 400,000 hectares. Many Paraguayan mestizo smallholders still rely on animal and human labor to prepare their fields. Over 2 million hectares is cultivated this way (Kernan et al. 2009).

In 2009, intact primary forest was estimated to cover six percent of eastern Paraguay (Kernan et al. 2010). Degraded forest, considered any forest cover less than 1,000 contiguous hectares, covered an additional eight percent. In western Paraguay during the same year, an estimated 54% of the land area had forest or wooded land cover. This designation includes the Cerrado and Matorral biomes which have a variable range of ecotypes from xeric forest to savannah with scattered palms and trees (Kernan et al. 2010). This figure may be misleading and underestimate forest or woodland coverage as it does not include protected areas or land set aside for indigenous peoples, and these land types are likely to be covered in native vegetation.

Urban areas and bodies of water each cover approximately 1% of the surface area of the country (Kernan et al. 2010).

Deforestation

The most widespread and pressing environmental issue in Paraguay is deforestation. Other environmental issues facing the country, such as erosion, soil degradation, water quality,

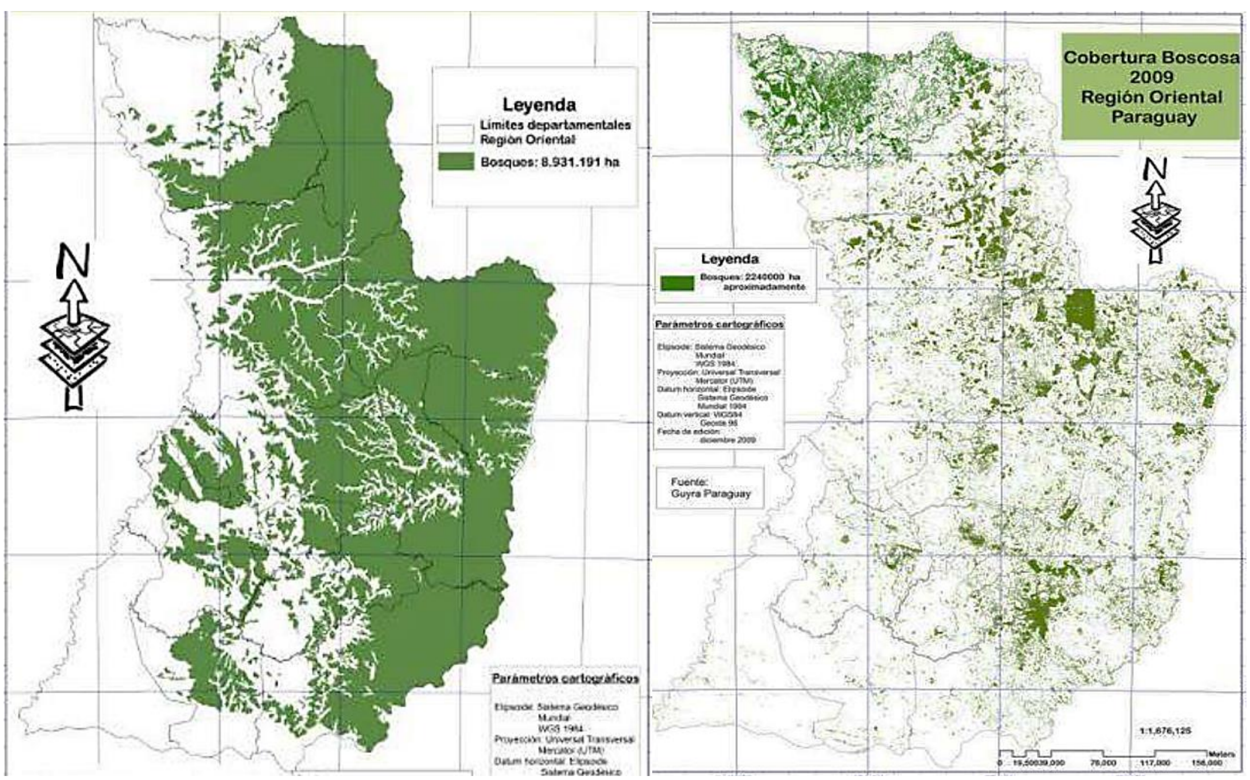

Figure 4. Maps of Atlantic Forest cover in eastern Paraguay. On left, original forest cover pre-1945. On right, scattered remnant fragments of forest left in 2009. (Kernan et al. 2010)

and powerful windstorms, can be linked to the decline in forest cover. Deforestation can be traced back to several cultural, political, and economic causes.

Between 2000 and 2012, Paraguay had one of the highest deforestation rates in the world (Hansen et al. 2010, Hansen et al. 2013). In Eastern Paraguay, most deforestation happened before this period. In 2004, Paraguay's legislature passed a law to prevent further forest conversion in the east and deforestation there dropped to 8,000 hectares per year from over 100,000 hectares per year (Guyra and WWF in Kernan et al. 2010). However, in the Chaco approximately 260,000 hectares of woodland per year continue to be lost from the conversion of xeric forest into extensive cattle pasture (Kernan et al. 2010). As of 2010, 14% of the original eastern forest cover is estimated to remain, and more than half of that is degraded and heavily fragmented (Kernan et al. 2010).

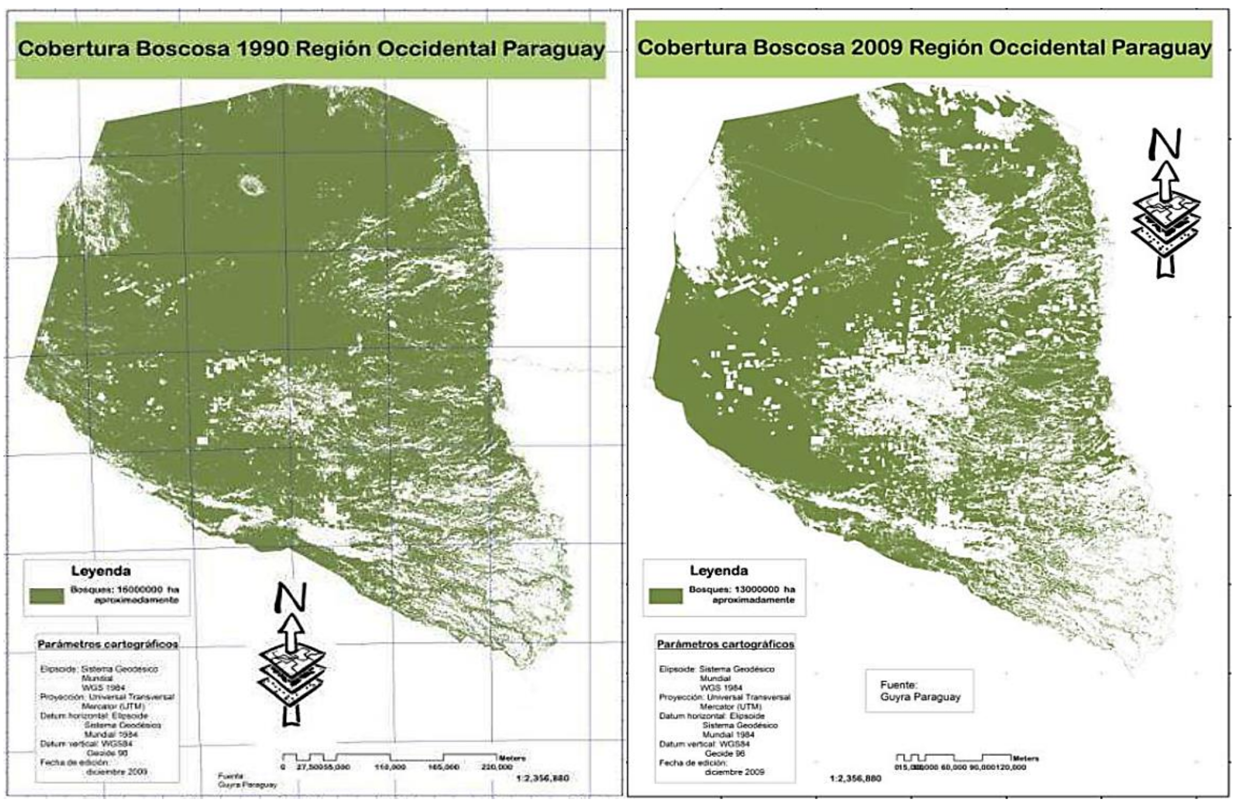

Figure 5. Map of woodland and forest cover in the Chaco region. On the left, forest cover in 1990. On the right, forest cover in 2009. (Kernan et al. 2010)

Historically, Paraguay was dominated by forests. In eastern Paraguay prior to 1945, forests covered nearly nine million hectares, or about 55% of the land area (Kernan et al. 2010, Da Ponte et al. 2017). In the Chaco, about 11.3 million hectares, or just under half of the total land area, was classified as forest or woodland (Kohler in Peace Corps Paraguay 2009). There were several industries that relied on wood extraction and tree felling, including the tannin production from quebracho (Schinopsis balansea) in the Chaco, *petitgrain* oil production from citrus in the east, and land clearing for subsistence agriculture but their scale was limited and the pace of forest exploitation was low (Klein 1947).

Land reformation in the era of the military dictatorship contributed greatly to the opening of unexploited or only lightly exploited primary forest. In 1963, Agrarian Statue 854 created the *Instituto de Bienestar Rural* (IBR, or Rural Welfare Institute), tasked with redistributing land among the landless. A series of highways was paved through the Atlantic Forest and peasants were encouraged to move east to make efficient use of "unproductive" land. Although theoretically aimed at providing land and therefore economic resources to migrating smallholders, the law did not significantly increase the material living conditions of those who took advantage. Peasants had neither the money nor technology to make a profit in their new settings. Instead of improving the quality of life for his countrymen, Stroessner's goal with agrarian reform seemed to be pacifying agricultural sociopolitical organizations and preventing uprisings among impoverished smallholders in the heavily populated areas around the capital (Zoomers and Kleinpenning 1990).

Starting in the 1960s, government policies began supporting the expansion of industrial agriculture for exportation (Zoomers and Kleinpenning 1990, Peace Corps Paraguay 2009). Monoculture plantations of soy and cotton appeared in the east as large landowners sold property to agribusiness concerns and immigrants from Brazil and Germany. Many of the immigrants purchased land with the express intent of speculation and profit. Intact blocs of forest were bought, logged and burned, and then quickly sold back to Paraguayan colonists moving east to the new settlements.

The inefficiency with which forested land was exploited contributed to deforestation. Several of the native species that constitute the primary forest of eastern Paraguay are held in high regard on the international timber market, including Spanish cedar (Cedrela fissilis), trébol (Amburana cearensis), peterevy (Cordia trichotoma) and lapacho (Handroanthus spp.) which is marketed as ipê on the international market (Klein 1947, ITTO 2020). Of the approximately 150-180 cubic meters of timber estimated in each hectare of primary forest, only 5-15 cubic meters of the most valuable wood were extracted (Peace Corps Paraguay 2009). The rest would be cut down and burned to hasten the conversion to farmland to increase its chance of being bought by a colonist.

Aspects of Paraguayan culture contributed to deforestation. Agriculture was the primary economic activity in the country for most of its existence, with slash-and-burn particularly common among the impoverished majority. Trees and forests were thus seen as impediments to farming (Evans 1988). As Bechard describes in an investigation of the cultural values around land in an eastern settlement, land was not valued for timber production but only agricultural potential (2017). Settlers arrived in their new communities "'armed with tools to fight' the forest" (Bechard 2017, p. 30).

Government policies reflected these cultural values. The Agrarian Statue 854/63 stated that private property in rural areas met their "socioeconomic function" only with rational use and efficient exploitation of the land (Kernan et al. 2010). If squatters entered private forested land and made it productive themselves (i.e. deforested and planted crops), they were entitled to colonize the land for themselves. While large estate owners were still able to profit from the law, it created a perverse incentive to deforest their own land or run the risk of squatters doing it for them and getting title (Zoomers and Kleinpenning 1990).

Severe deforestation has led to other environmental issues. Soil fertility has declined with the removal of forest cover. Without the resources to purchase chemical fertilizers, smallholder subsistence production demonstrates a yield gap between what the land theoretically can provide and what it actually provides (Carsan et al. 2014). Soils in eastern Paraguay should be producing up to 100 metric tons per hectare of *mandioca* (cassava, Manihot esculenta) instead of the 12-15 metric tons currently (Ultima Hora 2017; Agronomy Engineer Hernan Marecos, personal communication 4 March 2020). This is common in acidic tropical soils that lose forest cover via slash-and-burn agriculture (Montagnini et al. 2000).

Erosion has escalated with deforestation. Averages of 100 metric tons per hectare per year have been recorded in areas of Paraguay, with as much as 790 metric tons per hectare per year not unheard of (PNUD-FAO-SFN in Peace Corps Paraguay 2009). Most of this goes directly into streams and rivers and can severely diminish water quality. Deforestation has indirectly affected water quality in other ways. Conversion to industrial agriculture is quickly followed by application of chemical fertilizers which also end up in waterways following erosion and groundwater flow. During my service in Paraguay, citizens of Paraguay, Brazil, and Argentina were alarmed by a massive fish kill throughout the Paraguay River basin (Gutiérrez 2019). Subsequent testing by Brazilian officials found large amounts of agricultural pesticides present in the water.

Deforestation causes a loss of biodiversity, a quality of Paraguayan ecoregions that the country is celebrated for (TNC 2020). Kernan et al. identified deforestation, degradation, and fragmentation as the primary threats to biodiversity in the country (2010). Besides being a tragedy for the wildlife itself, loss of habitat directly affects the amount of game available for hunting, a traditional socioeconomic activity in Paraguay (Reed 1995). Biodiversity is recognized as an ecosystem service on several scales and produces benefits globally, not just locally (Jose 2009). Biodiversity increases the resilience of ecosystems and enables them to withstand disturbance without losing function (Pearce and Mourato 2004).

III: Literature Review – Agroforestry Theory, Benefits, and Drawbacks

Subsistence farmers in rural Paraguay face the self-reinforcing traps of environmental degradation and economic insecurity, as they do in much of the developing world. Deforestation and its associated consequences erosion and soil degradation have made soils devoid of nutrients, with a pronounced yield gap between potential agricultural productivity and that observed (Carsan et al. 2014, Ultima Hora 2017). Without being able to produce enough surplus beyond meeting basic subsistence needs, farmers are unable to increase household income or cover the costs of chemical inputs for increased yield, leading to a vicious cycle of poverty and environmental degradation. At the same time, the services produced, regulated, and supported by functioning ecosystems are declining with overexploitation and climate change, making the food, water, energy, and economic security situation even more drastic (Millennium Ecosystem Assessment 2005).

Correctly implemented, agroforestry holds the potential to improve soil fertility, diversify crop production, provide household goods, and restore or maintain ecosystem function (Mbow et al. 2014). The success of the system depends on the type and management of ecological interactions between agricultural components. To that end, in this section I define agroforestry and the different classifications of systems within the discipline. I then describe the biophysical and ecological economic theories upon which successful agroforestry implementation rests. Finally, I examine the potential benefits and disadvantages of integrating trees into agriculture and discuss how they affect adoption.

Definition and Classification of Agroforestry Systems

Agroforestry has been defined by various organizations and researchers in a multitude of ways (MacDicken and Vergara 1990a, Nair 1990). Essentially, it is the intentional integration of trees into agricultural systems to benefit from ecological interactions between trees and crops, trees and animals, or all three. Though research over the past four to five decades into complex systems and their scientific minutiae may paint agroforestry as a modern concept, it has been a traditional part of agriculture for generations in cultures around the world (Bhagwat et al. 2008).

Agroforestry can be classified according to several criteria, such as the components involved, the temporal scope, the function or desired output of the system, the ecosystem where implemented, or socioeconomic basis (Nair 1990). The most common ways to identify systems are by the nature of the components, arrangement of components, and protective function.

As stated above, agroforestry must involve the use of trees with crops and/or animals. When trees are combined with annual or perennial crops, the resulting system is an agrisilvicultural one. Trees and livestock together in space or time constitute a silvopastoral system. If all three elements are present, the system is known as agrosilvopasture. In a seminal work on the classification of agroforestry systems, Nair (1990) explains the rationale behind the different prefixes agri- and agro- and how the naming conventions of current classification schemes became cemented.

The arrangement of components is another way to differentiate between agroforestry practices. Elements may be densely concentrated in space, or diffuse. Homegardens, common throughout the developing world, are dense arrangements of fruit trees, annual crops, medicinal herbs, and/or vegetables; they work similar to the idea of guilds within permaculture wherein each item is analogous to a different canopy layer in a natural forest. Trees and crops or animals can have individual zones within a system, such as a block of trees in a corner of a pasture whose fodder is cut and carried to livestock. Boundary planting is a very traditional zonal arrangement in crop fields. Its use in Paraguay will be discussed later in the chapter. It may be hard to distinguish between boundary planting as an agroforestry system and a monocultural crop field surrounded by trees, but the difference is determined by the nature of interactions between trees and crop (Nair 1990). If trees serve to protect crops from the erosive force of wind or pruning residues from tree management is incorporated into crop soils to improve soil fertility, it is most certainly agroforestry.

Agroforestry systems may differ based on the pattern of elements in time. Alley cropping, involving agricultural crops nestled under rows of overstory trees, is an example of a simultaneous system as the elements coexist at the same time. Taungya, whose name originated in colonial Myanmar, is a sequential system popular for establishing timber plantations. It allows for short-term income or subsistence as crops are sown between recently established rows of tree seedlings (MacDicken 1990). As the trees mature and the canopy closes, crops are phased out and the stand is left for timber production. This system allows farmers who ordinarily could not afford the opportunity costs of giving up valuable food-producing land to reap benefits while establishing income-generating tree plantations.

Traditional fallow agriculture, wherein small plots of land within a larger property are cut and burned to create cropping space on a rotating basis, is also sequential.

The productive and protective function of a system may determine its classification. Riparian buffers around streams protect from pollution and runoff the ecosystems that serve as the resource base for our society, while windbreaks protect crops and can enhance productivity (Hillbrand et al. 2017). These are becoming more widespread throughout both the developing and developed world. Systems to produce specific products such as forage or firewood are common. High-priced boutique commodities like shade-grown coffee (Coffea ssp.) and cacao (Theobroma cacao) are other common protective agroforestry systems.

Systems may also be characterized by the ecosystem where they are to be implemented, for example a tropical highland agrisilvicultural scheme to combat erosion (Nair 1990). Alternatively, the socioeconomic factors of a system may dictate its characterization, such as the level of labor or inputs required or the desired scale of production (i.e. commercial or subsistence).

Ecological and eco-economic theoretical foundations of agroforestry

Ecological niche theory underlies agroforestry and explains why having mixed species together can potentially lead to increased productivity. Productivity and growth of plants depends on limited resources within a site, most importantly water, light, and nutrients, and how those resources are distributed throughout. Plants that exploit resources from the same ecological niche, such as those in monoculture agriculture, experience intense competition because the crown and root structure and resource needs are the same (Kelty 2000). After a certain density of plants is reached and growing space is fully occupied, productivity of each individual plant is limited. One cannot grow further except at the expense of another.

Species that exploit different niches can occupy the same area at higher mixed densities. Those that can exist next to others in close proximity without a drastic reduction in productivity exhibit ecological combining ability (Kelty 2000). Controlling for the effects of shading, a tree with a deep tap root may coexist easily with annual herbaceous plants with shallower root systems if the tree is able to utilize nutrients and water from subsurface soil layers while the herbaceous plants take advantage of those closer to the surface (Yadav and Khanna 1992, Akinnifesi et al. 1999, van Noordwijk et al. 2015). These species would be said to exhibit good ecological combining ability (Kelty 2000).

All components of agricultural and agroforestry systems interact with each other. Complementary interactions are those in which mixtures of species exploit resources more efficiently to the extent that yields of both are increased (figure 6) (Hoekstra 1990, Mercer et al. 2014). As an example, a nitrogen-fixing leguminous overstory tree increases soil fertility, decreases moisture loss, and drops its leaves during the rainy season thus limiting competition with grass growing beneath, while cattle grazing in its shade during the dry season contribute nutrient rich manure (Akinnifesi et al. 2008). However, due to the complexity of interactions between trees and crops in terms of resource availability and physiological structure, many of which are not fully understood, true complementarity is rarely observed or designed in agrisilvicultural systems.

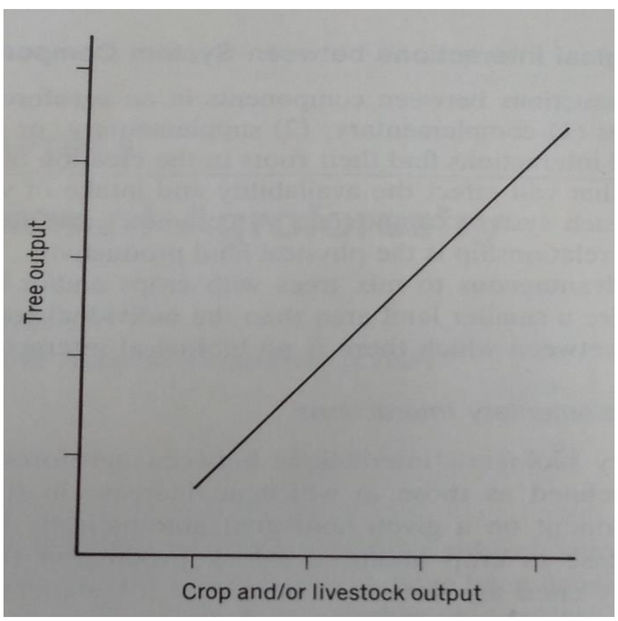

Figure 6. Complementary interaction. (Hoekstra 1990)

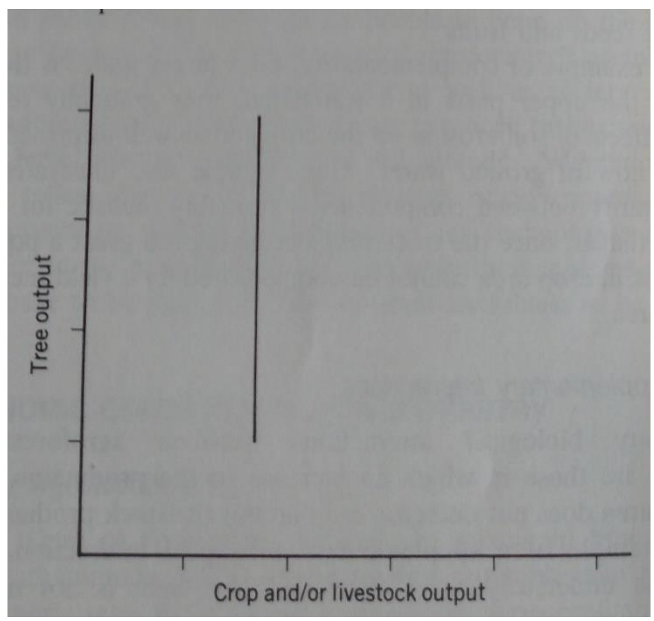

Figure 7. Supplementary interaction. (Hoekstra 1990)

Supplementary interactions occur when the presence or addition of one component has no effect on the productivity of another (figure 7). Dispersed mature coconuts often have little effect on understory crops in farmers' fields (Raintree 1983). As such, these and other tall palm species producing edible fruit or economically important oils have high potential for permanent simultaneous agrisilviculture designs (Ashton 2000).

Competitive interactions constitute the most common type observed in mixed species agriculture or agroforestry (Hoekstra 1990). A graphical representation of tree and crop yields in competitive interactions manifests as a Pareto frontier (the solid line in figure 8); one cannot increase without a resulting decrease in the other. However, synergies mentioned earlier in the discussion on complementarity can still play a role in competitive interactions (e.g. leguminous trees may improve soil fertility without need for expensive chemical inputs, benefiting annual crops). The upper dotted line in figure 8 shows a relationship where an increase in one component corresponds to a less than proportional decrease in the other (Hoekstra 1990). In other words, the net productivity of the whole system is greater than the sum of each component's weighted average in monoculture (Kelty 2000). This is also sometimes referred to as the Land Equivalent Ratio and a ratio greater than 1.0 means that mixed species plantings are more productive than monoculture (Ong et al. 2002). The lower dashed line shows a type of competitive interaction that is all around disadvantageous and should be avoided.

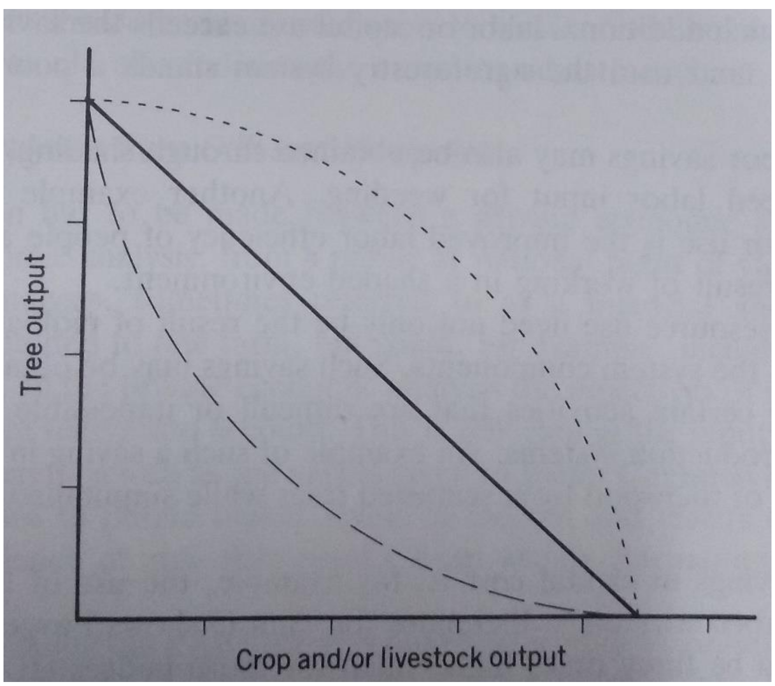

Figure 8. Competitive interaction. The upper dotted curve is still an advantageous relationship that can be useful in agroforestry. (Hoekstra 1990)

In simultaneous agrisilviculture, one of the most important yet obscure competitive interactions is that between roots of tree species and crops species (Nygren et al. 2012). The below-ground nature of the relationship makes it hard to examine directly or manipulate for controlled study. The effective rooting zone of annual crop roots such as maize (Zea mays) tend to be concentrated in the top 60 cm of the soil profile (Akinnifesi et al. 1999). Trees with shallow rooting systems are thus more prone to severe competition as their fine roots (i.e. those less than 2mm in diameter) are clustered with those of the crop, while trees with a deep primary tap root and low woody lateral root volume are more compatible with annual crops.

However, beneficial synergistic effects between tree and crop roots have possibly been overlooked. Tree roots serve as a source of available nutrients indirectly via root decay but also directly through root exudates and transfer between common mycorrhizal networks (Munroe and Isaac 2014, van Noordwijk et al. 2015). Tree roots also serve as a "safety net" for water and nutrients leaching below the effective rooting zone of crops and can remake them available for crop use (Ong and Leakey 1999). Early interpretations based solely on the presence of tree and crop roots together may therefore have overestimated competitive effects and minimized the beneficial value (Akinnifesi et al. 2004).

Advantages of agroforestry

When properly implemented and managed, agroforestry holds benefits for sustainable low-input agriculture, economic and food security, ecosystem services, and climate change mitigation and adaptation (Hillbrand et al. 2017). The scope of advantages ranges from the local, such as rural community poverty alleviation and production diversification, to the global, with a large need for landscape restoration and carbon sequestration worldwide (Vergara et al. 2016, Bastin et al. 2019).

Climate change mitigation and adaptation

Agroforestry is a viable strategy for the mitigation of climate change caused by greenhouse gas emission through the addition of more trees on agricultural land and avoided deforestation of existing primary forest. The Land-Use, Land-Use Change, and Forestry report of the Intergovernmental Panel on Climate Change identified agroforestry practices as the land use with the greatest potential for carbon sequestration above all others assessed (Watson et al. 2000). Estimates of the amount of carbon that can be sequestered in agroforestry system biomass range from 0.29 to 15.21 Mg per hectare, while soils under agroforestry hold potential to store more than 300 Mg per hectare (Jose and Bardhan 2012). In humid regions, average carbon storage by agroforestry systems is 50 Mg per hectare (Montagnini and Nair 2004). Silvopastoral systems were found to have higher aboveground, belowground, and soil organic carbon matter compared with monoculture forestry plantations and natural pasture (Montagnini and Nair 2004, Jose and Bardhan 2012).

Besides creating new carbon storage sinks, agroforestry can produce materials normally sourced from primary and secondary forests, thus preventing further deforestation. Dixon estimated that every hectare of well managed agroforestry had potential to prevent 5 – 20 hectares of deforestation in standing forest (1995). This is crucial for climate change mitigation in humid areas as although agroforestry is a better carbon sink than degraded cropland, tropical and subtropical humid forests still sequester more due to higher biomass (Montagnini and Nair 2004). Angelsen and Kaimowitz (2004) express skepticism over the extent to which agroforestry can prevent deforestation and believe that avoided deforestation area estimates, including Dixon's, all descend from one faulty study in the 1980s. However, they concede that in areas where land is scarce, agroforestry indeed has potential to lower deforestation.

Agroforestry can also play a role in climate change adaptation for small farmers, enabling agricultural systems to be more resilient and efficient. Mixed species diversity in agroforestry system means that disturbances, whether pest or drought or temperature extremes, do not affect all species or affect them to different extents (Angelsen and Kaimowitz 2004). Especially in water-stressed areas, deep-rooted trees redistribute moisture to shallower soil horizons making it available for uptake by crops (Bayala et al. 2008). Trees have an effect on microclimate in agriculture, and their shade can reduce solar radiation and buffer temperature extremes with benefits for both crops and livestock (PMRN 2007, Mbow et al. 2014). On larger scales, regional precipitation is highly dependent on forests, trees, and the evapotranspiration that supply atmospheric moisture (Ellison et al. 2012, FAO 2018). Higher numbers of trees lead to more precipitation locally and regionally.

Soil fertility, nutrient cycling, moisture content, and erosion

One of the most widely acknowledged roles of agroforestry is that which it can play in improving degraded soil conditions and the nutrient cycle. In Latin America and the Caribbean, at least 306 million hectares have been degraded to some extent, with over half of those witnessing a decrease in productivity of at least 25% (Bai et al. 2008, Vergara et al. 2016).

In tropical and subtropical areas that were originally forested, slash-and-burn agriculture commonly used by smallholders can lead to rapid decreases in fertility (Montagnini et al. 2000). The fertility of acid tropical soils is highly dependent on continuous replenishment of organic material from leaf fall, litter decay, and root decay. When forest cover is cleared, that cycle is interrupted. A study in southern Brazil and eastern Paraguay comparing soil organic matter content in six land cover types found that all agricultural sites had less than 2%, below the indicator of degradation and increased erosion risk (Riezebos and Loerts 1998). It is also postulated that the disruption of accumulation of organic matter reduces the availability of soil nutrients, especially labile phosphorous, by binding to iron and aluminum in mineral soil (Montagnini et al. 2000). A study in eastern Ethiopia regarding scattered trees on farms found that available P under tree canopies was up to 50% higher than away from trees (Gindaba et al. 2005).

Leguminous trees are specifically sought out in agroforestry design for their ability to fix atmospheric nitrogen for use by associated crops. Nitrogen is the macronutrient needed in largest quantities for plant growth and is a common limiting factor (Berlyn and Cho 2000). Akinnifesi et al. found that root growth of maize in an agrisilvicultural system was boosted by increased nitrogen made available by the intercropped leguminous trees (2004). An experiment in Malawi on degraded soil compared maize monoculture plots with maize intercropped with gliricidia (Gliricidia sepium), a nitrogen-fixing leguminous tree native to Central America (Akinnifesi et al. 2006). Yields of maize with gliricidia increased over maize monoculture by 100 – 500%. The study also concluded that while small amounts of nitrogen fertilizer can increase yields more than gliricidia prunings alone when the system is first established, maize response to additional fertilizer is low in later years indicating that nitrogen built up in the soil by leguminous tree contributions was more than sufficient for crop production. Nitrogen transfer between donor trees and receiver plants can happen in three ways: (a) decay and mineralization of leaves, litter, branches, and roots, (b) root exudates, and (c) transfer between mycorrhizal networks (Munroe and Isaac 2014).). Decomposition of leaves and roots was long seen as the dominant pathway, but the contributions of root exudates and mycorrhizal networks are increasingly acknowledged.

Non-nitrogen fixing trees contribute to soil fertility as well. Farmers in Honduras utilizing the Quezungual system attributed 80% yield increases in maize production to increased organic matter from timber and fruit tree prunings used as mulch (Hellin et al. 1999, Ayaraza and Wélchez 2004). Tree roots limit soil erosion and recycle nutrients that leach down below the effective rooting zone of crops through uptake and subsequent litterfall, acting as a safety net and increasing the efficiency of agroforestry systems (van Noordwijk et al. 2015). Trees can increase soil moisture content and the efficient use of rainfall. Ong et al. found that while the most efficient monocropping systems use only 40% of annual rainfall and lose the rest to runoff or deep drainage, agroforestry systems can utilize up to 80% due to deeper roots and utilization and redistribution of off-season rain (2002). The benefits are not just chemical. Agroforestry can improve soil physical properties like porosity, again boosting moisture retention and availability for crop production (Jose 2009).

As stated above, the risk of erosion is increased when native vegetation is cleared for crop fields, especially in degraded soils with low organic material and on bare soils when monocropped fields are recently planted. Erosion adds to the soil fertility dilemma by physically removing nutrients and lowering cation exchange capacity. Agroforestry systems in the Brazilian Amazon, even in the early stages of establishment, exhibited low erosion levels more like those of nearby forested environments than to local crop fields (Béliveau et al. 2017). Crop fields had significantly higher levels of total cation loss, regardless of slope, as cation loss was strongly correlated with soil loss. Agroforestry maintained soil integrity and limited nutrient mobility (i.e. leaching). This had implications for aquatic ecosystems as leaching of natural mercury in the soil effected water quality.

Biodiversity

Agroforestry has potential to contribute to greater biodiversity, especially in tropical and developing countries. Biodiversity has benefits ranging in scale from local to global as it increases the resiliency of local agriculture systems and regional ecosystems and is influential for local and global ecosystem services (Jose 2009, Santos et al. 2019). Crop and native species diversification reduce the chance that an entire area will be irrevocably damaged by extreme weather events like drought or hail and allow ecosystems and agroecosystems to bounce back quicker after disturbance as mentioned earlier in the section on climate change mitigation.

Much of the focus of biodiversity conservation centers on the preservation of seemingly untouched large tracts of wilderness. However, this view is misguided in several ways. These “pristine” areas are acknowledged more and more as the result of centuries of human use and disturbance, such as the fertile Terra Preta lands of the Amazon (Bhagwat et al. 2008). Regardless of their origin, preserving these areas often means preventing human use other than recreational which is not always beneficial. Protected areas tend to focus on a few high-profile ecosystems like primary old-growth rainforest, but do not cover the entire spectrum of habitats. Even more important to the long-term success of sustainable land use, the locking up of these landscapes breeds resentment by indigenous groups and local communities formerly reliant upon the resources therein, increasing the chances of trespass and political opposition (Bhagwat et al. 2008). Agroforestry is one of many land uses which can promote greater biodiversity and does so while still providing for socioeconomic needs.

As discussed previously, agroforests can lower rates of deforestation and forest degradation with the provision of products normally sourced from forested land. Bhagwat et al. (2008) describe several examples of rural communities in which families with homegardens or trees on agricultural land are less reliant on resources from nearby forest reserves. Buffer zones consisting of agroforestry strips between forest areas and agricultural lands provide for local economies while limiting further forest loss (Cullen Jr. et al. 2004). These buffer zones can also act as nurse sites for native vegetation, allowing for the possibility of additional forest area.

Buffer zones decrease the edge effect seen at abrupt boundaries between forested and non-forested land. This and other agroforestry practices increases habitat available for forest-reliant species as well as species tolerant of some disturbance (Laurance and Vasconcelos 2004, Jose 2009). Shade coffee agroforests, an agrisilvicultural system with perennial cash crops below a leguminous and timber tree canopy, exhibit similar structure to neighboring forests and are correspondingly more biodiverse than traditional agriculture (Bhagwat 2008, Jose 2009). Other lowland tropical agroforests have similar tree densities and basal areas to old growth reference forests (Saulo et al. 2016).

Agroforests in Brazil have higher levels of species richness compared to traditional agriculture, comparable to secondary forests although lower than primary forests (Saulo et al. 2016). In Costa Rica, Harvey and González Villalobos found that assemblages of bats and birds in agroforestry systems were as or more species rich, abundant, and diverse than forests, although for birds the species compositions were different (2007, in Jose 2009). This abundance and diversity may hold implications for pest control in agroforests as the attraction of predator species could limit populations and spread of detrimental insects.

An oft-cited advantage of agroforestry for biodiversity is its potential to increase connectivity between fragmented forest areas. Populations within fragmented landscapes are vulnerable to inbreeding, the loss of genetic heterogeneity, and extirpation (Laurance and Vasconcelos 2004). Corridors or unconnected stepping-stone zones consisting of agroforestry systems allow production of socioeconomic resources, making them more likely to be retained, while facilitating the movement of species and genetic variability (Laurance 2004).

Forage and livestock

Silvopastoral systems have the potential to produce large quantities of nutritious forage for the associated livestock. Leguminous, and a few non-leguminous, trees in particular can produce high-quality, high-protein feed. Canopy cover buffers livestock from extreme heat, cold, wind, and precipitation. Animals that are guarded against such stresses benefit in terms of health, milk production, weight gain, and breeding success (Cubbage et al. 2012). Shade from trees in hot environments increase warm-season grass production, reduce weeds in pasture, and can extend the grass growing season.

Place et al. (2009) evaluated the impact of mostly leguminous fodder shrubs on milk production in silvopastoral systems in East Africa. An additional 2 kilograms of dried shrub fodder increased milk yield by a liter per day. Over a year, cattle fed the 2 kg as a supplement to their normal diet produced 450 kilograms more, a 10% increase over base yields. Cattle gained between 0.02 and 0.26 kg per day when fed Leucaena spp. leaf meal at varying quantities, while cattle not fed the leucaena supplement lost an average of 0.3 kg per day. Their analysis of leguminous Calliandra calothyrsus leaves revealed the same digestible protein content per unit as expensive dairy meal. As well, they found that inclusion of these fodder shrubs in the diet increased the butterfat content of milk. While this doesn't always lead to a higher market price, it has big implications for home consumption and nutrition.

Woody biomass production

Agroforestry is recognized for its ability to augment, restore, or maintain the four categories of ecosystem services identified in the Millennium Ecosystem Assessment (MEA 2005, Jose 2009). With the addition of trees and/or woody shrubs on agricultural land, the increase in provisioning services is perceived as one of the most important benefits, especially for small farmers. While simple agroforests (those with low densities of trees and number of layers) have been shown to yield lower regulating and supporting ecosystem services than reference forests, both simple and biodiverse agroforestry systems had higher provisioning ecosystem services (Santos et al. 2019).

Firewood is still a common fuel for rural families in developing countries. Approximately one-third of the world's population uses wood for their primary energy source. At least 50% of harvested wood products globally are used as fuel, with that number increasing to 90% in Africa (FAO 2018). Despite the presence of two hydroelectric dams in Paraguay which annually generate more energy than the country uses in ten years, firewood still accounts for 22% of domestic and industrial energy use (Kernan et al. 2010). If speaking strictly of rural small farmers, 90% were reliant on firewood for subsistence purposes in one study (Da Ponte et al. 2017).

Timber is used for household use in home construction, as fence posts, and for various other needs. Timber from small farmers is recognized as a primary source of many countries' wood supply (Garrity 2004). If managed properly, timber can also provide an alternative and sustainable income source for small farmers. Many species of tropical timber trees are considered boutique and command high prices on the international market (ITTO 2020), although these prices do not reflect the actual amount received by the smallholder producer.

Certain agroforestry practices were developed specifically with timber in mind. The taungya system from colonial Myanmar was designed as a way to increase farmer participation in and benefits from the creation of teak plantations (Peace Corps Paraguay 2009). Another Peace Corps Paraguay volunteer in the 1980s was part of a strategic agroforestry promotion project based around Melia azedarach, or *paraiso gigante*, a fast-growing introduced timber species (Evans 1984). System establishment was similar to taungya, with annual crops planted between rows of *paraiso* and native nitrogen fixing trees. After the trees grew enough to shade out annual crops, perennial shade-tolerant crops like banana (Musa spp.) and pineapple (Ananas comosus) were planted beneath.

Firewood and local timber will likely not be replaced as primary resources for impoverished small farmers as it rarely requires a cash outlay, which is why forest degradation will continue if there is no alternative source. Several analyses of agroforestry systems have demonstrated an ability to provide this source. In Honduras, 47 out of 49 interviewed practitioners of the Quezungual Slash and Mulch Agroforestry System were able to meet their entire subsistence requirements of timber and fuelwood (Hellin et al. 1999). A farmer managed natural regeneration (FMRN) project in Ethiopia supplied enough firewood for the community's entire domestic need by the second year of implementation (Brown et al. 2011).

Sustainable development and socioeconomic benefits

In 2015, UN member nations adopted the 2030 Agenda for Sustainable Development which included 17 goals outlining objectives to reduce global poverty and inequality while combatting climate change, preserving functional ecosystems, and stimulating economic growth (UN 2015). While forests and agriculture arguably influence them all, the Food and Agriculture Organization identified the direct role that sustainable forest management plays for achieving ten of the Sustainable Development Goals (SDG)(FAO 2018). Within those, seven are explicitly linked to agroforestry.

Goals one and two are to end poverty and hunger. Agroforestry can play a large role in these. Income from the sale of timber, firewood, fruit, cash crops, milk, or meat produced from agrisilviculture and silvopasture can increase a family's economic security. An economic analysis in Place et al.'s (2009) assessment of the impact of shrub fodder on milk production estimated that farmers using fodder as a replacement for purchased meal could see a net savings of $122.23 US annually after the second year, while those using fodder as a supplement could increase household income by $114.86 US annually after year two. Tree impacts on soil fertility can boost crop productivity while increased biodiversity leads to better pollination, leading to surpluses that can be sold in local markets. Even in rural farming villages like where I served in Paraguay, the cost of school supplies, clothes, and occasional parties prohibit escaping entirely from the cash economy, even if food and other subsistence needs are met.

The increase in ecosystem resilience to climate change and other disturbances that results from diversification of species in ecosystems and agroecosystems has implications for goals one and two. Target 1.5 of SDG goal one aims to build the resilience of the poor and reduce vulnerability and exposure to disturbance. Reduced vulnerability of food systems lessens the chance that a farmer's entire crop will be wiped out by extreme weather events.

Gender equality and female empowerment are addressed by SDG five. Nontimber forest products (NTFP) such as honey, essential oils, medicinal herbs, fruit, or mushrooms are a common output of agroforests. In Brazil, South Africa, and Cameroon, about half of the people involved in the collection of nontimber forest products were female, and almost all the traders of NTFPs were female in Cameroon (Shackleton et al. 2007).

Sustainable development goal six aims for wider availability and the sustainable management of water resources. Trees in crop fields enable more efficient use of annual precipitation amounts, leading to more resilient crop systems and lessening the need for labor or cash intensive irrigation systems where in use (Jackson et al. 2000). Shade from tree canopies and higher soil organic matter content helps retain moisture in the soil (Hellin et al. 1999, Ayaraza and Wélchez 2004). Tree roots positively affect soil physical properties and allow greater infiltration of precipitation (Jose 2009). This recharges groundwater supplies and enables the soil to act as a sponge, absorbing excessive rainfall during extreme precipitation and releasing it slowly during drier times (FAO 2018). Greater infiltration also means less runoff and thus less erosion, protecting water quality for downstream users in a watershed (Béliveau et al. 2017).

The objective of SDG seven is access to reliable and sustainable energy sources. As discussed recently, agroforestry has great potential to provide fuelwood for small farmers. While burning firewood does emit carbon into the atmosphere, the increased biomass growth in agroforests can offset some of those emissions with carbon sequestration.

Sustainable goal 13 aims to mitigate the impacts of climate change. The benefits of agroforestry for climate change mitigation and adaptation, including avoided deforestation and increased resilience of agroecosystems, have been discussed earlier in the paper.

Goal 15 essentially encompasses most of the potential objectives of agroforestry. SDG 15 promotes the sustainable use and restoration of terrestrial ecosystems, an end to land degradation, and the protection of biodiversity. Most of the potential benefits of agroforestry discussed above target these objectives.

Agroforestry can have impacts on other socioeconomic aspects. At the subsistence farming level, labor rather than access to land is often the main production constraint (Hands et al. 1995). Once established, some tree-based agroecology systems have lower labor requirements than continuous annual cropping systems, or more evenly distribute the labor over the year, thus liberating farmers from cycles of extreme high and low labor demand common to annual cropping systems (Raintree 1990, Angelson and Kaimowitz 2004). This reduction in labor is thought to come from the control of competing weeds by the shade cast from overstory trees or the use of pruning residues as a smothering mulch (Hands et al. 1995, Ayaraza and Wélchez 2004).

Alternatively, agroforestry may increase opportunities for employment. Although labor can be lower or evenly distributed once established, agroforestry systems often require more labor in the first few years as farmers must weed around crops and tree seedlings to prevent competition mortality (Evans 1984, Hands 1998). This can be a short-term benefit in areas with high numbers of landless laborers who rely on seasonal employment in crop fields, although subsequent drops in labor requirements as mentioned above will have the reverse effect (Raintree 1990). Agrisilvicultural systems, especially in semi-arid regions with high water stress, often require management to limit competition between tree and crop roots (Yadav and Khanna 1992, Akinnifesi et al. 2004, van Noordwijk et al. 2015), providing yet another potential source for labor employment.

Some of the socioeconomic benefits of agroforestry have to do with cultural considerations. Saulo et al. included an ethnobotanical survey and assessment in a study of ecological outcomes and livelihood benefits of community managed agroforestry in Brazil (2016). Survey respondents mentioned over 440 naturally growing species of cultural importance from agroforests and secondary forests, as well as several native species deliberately cultivated in agroforests

In many rural areas, including Paraguay, farming is not just an economic activity but deeply embedded in the social fabric and cultural identity. Farmer committee meetings in my village were not just for business but were opportunities to socialize and relax. Many rural Paraguayans express great pride in their agricultural identity, and I was told on numerous occasions that I was only a true Paraguayan once I planted *mandioca* (cassava, Manihot esculenta) in my field. Beneficial impacts of agroforestry on soil fertility and economic security could allow rural families to continue farming sustainably and successfully without having to look for service-based employment. Most youth leave rural areas after high school, seeking jobs in the major urban centers (Kursky, unpublished data). If farming were more productive, perhaps fewer would leave.

Disadvantages of agroforestry

The benefits of agroforestry can make it appear to be a panacea able to cure all the ills of monoculture cropping and livestock raising. However, agroforestry has its drawbacks and the adoption and establishment of agroforestry systems require careful consideration of the economic and ecological tradeoffs involved. For this reason, agroforestry system design must by necessity be specific to the local environmental and economic setting (Jerneck and Olsson 2013).

Competition for water, light, and nutrients

One of the biggest and most common disadvantages of agroforestry, especially simultaneous agrisilvicultural systems combining trees and crops at the same time, is competition between tree and crop components. Recall in the discussion of ecological economic factors underlying agroforestry that competitive interactions are more frequent than supplementary and complementary (Hoekstra 1990). While the goal is to maximize the productivity of the system as a whole, crop yield is often more important culturally and economically in rural subsistence agricultural social settings. This may not be true in systems whose objective is timber production, such as taungya. In this case, crops that are less competitive than the tree component are more desirable as to not inhibit growth rates of the economically viable timber (Akinnifesi 2004).

In drought stressed or semi-arid regions, intense water competition can occur between tree and crop roots (Ong and Leakey 1999). If soils are highly degraded, common after long continuous cropping cycles where tropical or subtropical forest was converted to agricultural land, it is argued that the ability of agroforestry systems to increase nutrient availability for associated crops is low (Montagnini et al 2000) likely due to competition between trees and crops for those limited nutrients. Competition in simultaneous systems is increased when trees have shallow root systems with large woody lateral roots, or most of the fine root system is within the uppermost 60 cm of the soil where annual crop roots are concentrated (Akinnifesi et al. 2004). Competition is also increased as tree density increases. In the arid and semi-arid tropics, alley cropping rarely boosts crop yields due to the large competitive effect while sparsely scattered trees do positively influence crops (Ong and Leakey 1999, Akinnifesi et al. 2004, Sanchez 1995 in Ong et al. 2002).

Large lateral roots and abundant superficial fine roots are not as much of a problem in sequential agrisilvicultural systems such as improved fallow. In fact, it may be preferable as it enhances nutrient uptake and storage in biomass which is available for later crops as biomass is returned to the soil and decays (Rao et al. 2004), provided that not much biomass is removed from the system as firewood or timber.

Light competition can be another adverse interaction between shade-intolerant annual crops and overstory trees (common perennial agroforestry systems involve shade-tolerant species such as banana, pineapple, or coffee). Light energy intercepted by the tree component canopy can diminish or temporally interrupt that used by plants underneath for photosynthesis and thus biomass production (Berlyn and Cho 2000). Although this aspect is sometimes celebrated for its weed control applicability, it can negatively affect crop yields (Moreira et al. 2018).

Root or shoot pruning can minimize these competitive effects. Shoot pruning involves removal of side branches, pruning of leaves, pollarding above ground height, or coppicing at or near ground height (Rao et al. 2004, van Noordwijk et al. 2015). The main objective for shoot pruning is normally to limit light competition with crops, yet it also yields provisioning benefits such as fodder, green manure or mulch, firewood, and straighter timber production.

Belowground competition can also be manipulated by aboveground pruning. Crown pruning reduces transpiration loss and thus competition for water and causes root dieback and eventual decay, allowing easier direct transfer of nitrogen to crop roots from nodulated leguminous trees (van Noordwijk et al. 2015). Jackson et al. (2000) found that while minor pruning of the lowest meter of canopy of <u>Grevillea robusta</u> was sufficient to limit competition for light with maize, heavier pruning prior to the sowing of crop seeds reduced tree water demand, recharged the crop rooting zone, and enabled the crop root system to become hardy enough to better compete once the tree canopy recovered. This would likely affect the rotation time of G. robusta, increasing the time needed to reach harvest size.

Root pruning involves severing of large lateral roots that extend into the crop rooting zone or tillage to reduce fine tree roots in superficial soil layers (Rao et al. 2004). In an arid region of India, Yadav and Khanna compared two Prosopis cineraria trees, one with a poor mustard crop below and one with a robust crop below (1992). The tree over the poor crop had lateral roots in the top 35 cm of soil, while the tree with the healthy crop had all lateral roots removed to depth of 65 cm, with no apparent harm to the tree.

Root competition can be managed by design. An experiment in Benin, West Africa compared alley cropping to a block design that kept trees and crops in distinct areas of the same field (Lose 2003). Intense tree root growth in upper soil levels of the alley cropping system negatively influenced M. esculenta root development, but competition in the block design was limited to only the cassava row directly adjacent to trees. Competition in the whole field was reduced by limiting the length of the effective tree-crop interface.

Labor

Reductions in labor have been touted as a benefit of agroforestry systems. As discussed in the section on advantages, this is only partially true. The establishment of the system often requires more labor in the first few years. Management practices like pruning in alley cropping are not a temporary fix and must be repeated cyclically to reap the benefits of reduced competition. If labor is a constraining factor or if small farmers do not have the capital to pay workers, either agroforestry will not be adopted in the first place or established systems will fail (Raintree 1990, Barbier 2000).

Potential increase in deforestation

Perversely, successful agroforestry can sometimes lead to increased deforestation. In cases where the primary objective of agroforestry is to produce marketable commodities and land is not a scarce resource, deforestation rates can increase (Angelsen and Kaimowitz 2004).

Poor farmers face capital scarcity, and if they are not able to rely on family or neighbors for free labor may face labor scarcity as well. Impoverished farmers may therefore not be able to convert primary or secondary forest into expanded agroforests. However, if labor is not a constraint, a farmer has access to credit or capital, and agroforestry is perceived as more profitable than alternative uses (such as traditional agricultural practices or maintaining forest cover), farmers may convert more primary or secondary forest into agroforests (Angelsen and Kaimowitz 2004). Additionally, if reliable access to market economies exist and many farmers adopt successful agroforestry practices, an increase in production will lower prices of the commodity and corresponding profit margins. Farmers may then seek to increase the area under agroforestry at the expense of forest to maximize profit.

Delayed benefits and discount rates

Especially on already degraded soils, agroforestry takes time to manifest benefits. The accumulation of nitrogen and other nutrients for soil fertility improvement is a long-term process and not an immediate fix (Nygren et al. 2012). In some cases, chemical fertilizers are recommended during the establishment of tree-based systems to counter initial crop yield reductions, improve tree survival rates, and unlock synergistic benefits of agroforestry that otherwise would take years to develop (Akinnifesi et al. 2008, Hands et al. 1995, Hands 1998).

Estimates for the time necessary to see net economic benefits range from two years using fast growing shrubs for forage, three to six years in humid agrisilviculture systems, to 15 years in arid silvopasture with scattered slow-growing trees (Barbier 2000, Mercer 2004, Akinnifesi 2008, Place et al. 2009). Subsistence farmers who need to feed their family this year cannot wait that amount of time, nor can they risk the possibility of lower crop yields from untested agroforestry systems. This emphasis on short-term present value over future value is known in economics as the discount rate and is common in areas of high poverty (Pearce and Mourato 2004); looking ahead to future gains is a luxury out of reach to most impoverished smallholders.

Adoption

These and other socioeconomic factors affect adoption rates of agroforestry among small farmers. Agroforestry may sometimes make ecological sense, but social and economic variables rather than biological are more influential for adoption rates. Several environmental and socioeconomic conditions have been identified that play a role in adoption. Adoption is more likely in areas where landholdings are smaller or increasing population demand is limiting access to land (Hamilton and Bliss 1998, Mercer 2004, Akinnifesi 2008). An increase in wood demand, due to new markets or population growth, or a decrease in wood supply from forest scarcity or declining access to forest also leads to increased adoption.

Farmers constrained by food security or health security issues are less likely to adopt agroforestry (Jerneck and Olsson 2013). A paradoxical situation occurs in which the poorest farmers who stand to gain the most from agroforestry are least likely to adopt it as they cannot invest the time or labor to establish a new system and wouldn't risk their present food supply on untested alternatives (Barbier 2000).

Characteristics of agroforestry systems themselves influence the likelihood of their adoption. Traditional farmers are less apt to be concerned about conservation of resources than the production of outputs. Practices which emphasize local provisioning benefits rather than global ecosystem services such as carbon sequestration or biodiversity are more adoptable (Raintree 1990). Ong and Leakey suggest focusing attention on techniques providing immediate benefit to farmers while minimizing reductions in crop yields (1999). Subsistence farmers also rationally tend to resist more labor-intensive practices if the alternatives still provide enough to meet their basic needs (Evans 1988, Angelsen and Kaimowitz 2004).

Agroforestry practices that are compatible with or similar to existing practices have higher rates of adoption than unfamiliar new ones (Evans 1988, Ayaraza and Wélchez 2004). So are those which aim to meet an expressed need by farmers, rather than the goals of an outside NGO or government decree (Barbier 2000).

Due to the specificity of agroforestry design to local conditions and the increased complexity of interactions between components, agroforestry is more knowledge intensive than modern agricultural packages which boost yields with chemical inputs (Mercer 2004). Education of farmers and willingness to experiment are crucial for successful agroforestry, but this may have an inverse effect on adoption. If a farmer is aware of someone nearby experimenting with agroforestry, it is more logical for the farmer to continue traditional agricultural practices with a known outcome until they witness profitability from the agroforestry trial, even if traditional agriculture degrades the resource and is not sustainable or profitable in the long run.

IV: Literature Review – Traditional Agroforestry in Paraguay

Agroforestry has been practiced for millennia in many parts of the world (Miller and Nair 2006, Bhagwat et al. 2008). Paraguay is no exception and several agroforestry practices have been documented as part of traditional Paraguayan peasant agriculture. This section describes several traditional agroforestry practices from the literature and my personal observations from Paraguay. I will briefly touch on a few improved or modified systems developed to increase the productivity of traditional practices.

Slash-and-burn/Fallow agriculture

In slash-and-burn (also known as swidden, migratory, or shifting) cultivation, primary or secondary forest is cut down, burned to remove woody debris and release a quick pulse of nutrients, and planted in annual crops. After a few years, the land loses fertility and the farmer moves to a new patch to begin again. Soil loses its fertility through the leaching of mobile nutrients by precipitation to deeper soil layers, the loss of organic soil matter not replaced by overstory litterfall, and the immobilization of phosphorous by the increasingly mineral soil (Jose 2009, Montagnini et al. 2000).

Fallow refers to the period after cultivation stops and natural succession begins again as vegetation recolonizes the site (Peace Corps Paraguay 2009). Two woody shrubs that commonly recolonize fallowed fields are *tajy'i* (*lapachillo* in Spanish, Tecoma stans*)* and *chirca* (Baccharis spp.). Neither is nitrogen fixing nor produces usable timber or firewood, but *tajy'i* is melliferous and *chirca* is used for homemade brooms (Brack and Weik 1994, personal observation). When land is sufficiently available to allow enough time between periods of cultivation, soil regains fertility and structure and the cropping cycle can occur again productively. Reed (1995) suggests that within 10 – 20 years, a fallow site is indistinguishable from surrounding forest. However, as land scarcity increases, less time is available for the fallow period and land degradation quickly occurs.

Figure 9. Improved fallow of C. cajan in old field under scattered A. totai overstory.

A more recent practice, improved fallow, refers to the deliberate planting of leguminous woody shrubs or trees on fallow fields. The nitrogen-fixing capabilities hasten soil improvement, litter from trees contributes additional organic material, and the system can provide firewood or timber if allowed enough time. The speed with which it can rebuild soil fertility decreases the time need to leave a site fallow and reduces pressure to cultivate new land (MacDicken 1990). *Leucaena* (Leucaena leucocephala) and *kumanda yvyra'i* (Cajanus cajan) are two common exotic nitrogen-fixing species used for this purpose. *Kumanda yvyra'i* is widely known in Paraguay for its popular edible bean and can act as a nurse species to create a favorable microclimate for other shade tolerant crops or trees (Brack and Weik 1994). Due to the large amounts of nitrogen it can fix and its rapid growth for timber and firewood production, *Leucaena* has been hailed as a multipurpose tree of great potential throughout the humid tropics. However, its wood is not considered valuable and it is a prolific seeder that germinates easily, quickly turning weedy without careful management (Brewbaker 1987, personal observation).

Yerba mate harvest and cultivation

Yerba mate (<u>Ilex paraguariensis</u>) is a medium sized evergreen tree in the holly family native to eastern Paraguay and neighboring areas of Argentina and Brazil. It grows in greatest abundance in the Paraná River basin of the far eastern portion of the country, attaining heights up to 20 meters with a diameter at breast height between 20 to 45 centimeters (Lopez et al. 1987). It forms part of the woody understory or intermediate forest layer and is highly shade tolerant. Its leaves contain vitamins, anti-inflammatory properties, and stimulants that suppress feelings of hunger. Indigenous groups before European contact used the leaves for medicinal and ritual purposes for possibly thousands of years, but by the early 17th century the tea made from its leaves was one of the most popular drinks in Chile, Argentina, Paraguay, Bolivia, Peru, and even Spain (López 1974). The drink and ritual surrounding its consumption, referred to as *mate* when made with hot water and *tereré* with iced water, remain a hugely important part of Paraguayan culture. Much of my summers in Paraguay were spent passing around *tereré* with neighbors.

Exploitation of natural yerba mate stands (*yerbales*) throughout the forest quickly became one of the cornerstones of the colonial Paraguayan economy. Yerba was first collected by teams of indigenous laborers from small trees under the taller hardwood canopy. It is estimated that even in dense areas, it naturally comprised no more than 10% of the forest cover (Reed 1995). Although a natural forest ecosystem, I consider this a form of agrisilvicultural agroforestry with the yerba trees as a perennial crop under natural canopy. Management of the yerba trees (i.e. pruning leaves and small branches) was strictly controlled by cultural norms so as not to damage the resource beyond its regenerative capability. Laborers pruned each tree only once every few years. Reed (1995) studied a present-day indigenous group that maintained a subsistence economy of slash-and-burn agricultural plots, hunting and gathering from surrounding forests, and yerba mate harvesting supplemented by occasional labor for mestizo neighbors. He characterized their economy as spatially disconnected agroforestry with distinct areas for hunting, gardening, and yerba collection composing one agricultural system.

As mestizo culture dominated Paraguayan society and peasants began clearing forest for permanent settlements, another agrisilvicultural system became prominent. Farmers left yerba trees in fields to provide for home consumption and occasional cash income while planting annual crops in the spaces between (Peace Corps Paraguay 2009). This system eventually declined as the industry monopolized production and commercial yerba became widely available. After prices rose in the 1980s, some small farmers re-established home plantations with annual crops planted between rows. Current commercial and small-scale production is mainly concentrated in the southeast regions of the country near the borders with Argentina and Brazil (personal observation).

Scattered coco palms and native trees with crops

The Paraguayan coco palm (Acrocomia totai, commonly referred to by its Guaraní name *mbocaja*) is a native palm growing throughout eastern Paraguay but ubiquitous in the humid Chaco and wooded savannah east of the Paraguay River (Lopez et al. 1987). It grows 10 – 20 meters tall with a diameter at breast height of 15 – 30 centimeters. Although eaten as a snack and fed to animals, its fruit produces highly valued and commodified oils used for cooking, biodiesel, and soap production and is an important domestic and export industry in Paraguay (Lopez et al. 1987, Colombo 2018). Due to its abundant natural regeneration, lack of need for care, and unique role as a reliable cash crop in summer it is sometimes called "*Aguinaldo de los pobres*" or Christmas bonus of the poor (Carmelo Florentin, personal communication 18 November 2019).

In this traditional agrisilviculture system, farmers traditionally leave scattered randomly spaced *mbocaja* palms and a few desirable native trees in crop fields to fulfill multiple provisioning roles (figure 10). The A. totai component provides consistent cash income as well as food for humans and livestock. *Yvyra pytã* (Peltophorum dubium), valued for its durable red timber, and *yvyra ju* (Albizia hassleri), known for its quick drying firewood, are nitrogen-fixing species although they are not explicitly left for soil improvement (Lopez et al. 1987). *Cedro* (Cedrela fissilis), *tajy* (Handroanthus spp.), and *peterevy* (Cordia trichotoma) are valuable timber trees with international market value, although small peasant farmers rarely have access to those markets and value the timber for domestic construction (Lopez et al. 1987, ITTO 2020). The dispersed nature and low density of the palms and trees do not significantly shade or compete with the annual crops planted below. Many other useful hardwood species, such as *Kurupa'y kuru* (Anadenanthera colubrina) and *Kurupa'y ra* (Parapiptadenia rigida) are specifically removed from fields as farmers perceive them as "hot" species which burn crops, a possible reference to allelopathy (personal observation).

Figure 10. Dispersed A. totai palms in a recently plowed field. In the foreground is P. dubium.

In the early 1980s, the Paraguayan National Forest Service (SFN, now *Instituto Forestal Nacional* – INFONA) initiated the country's first agroforestry extension project with the cooperation of the Agriculture Ministry's extension service, Peace Corps Paraguay, and the Swiss Technical Development Mission (GTZ 1989). The project recommended establishing plantations of *Paraíso* (Melia azedarach var. gigante), a fast-growing exotic in the mahogany family valued for its timber, alongside *L. leucocephala*, yerba mate, and/or the native hardwoods mentioned above in a taungya-based system (Evans and Rombold 1984). Annual subsistence crops of maize, *mandioca*, beans (Phaseolus vulgaris), or peanuts (Arachis hypogea) would be planted between rows of trees for the first four years, followed by shade tolerant banana (Musa spp.) or forage grasses to convert the system to silvopasture.

While the system had high adoption rates in its pilot site and seemed ecologically successful, the project encountered issues and was eventually discontinued. Its biological downfall was a pathogen (Mycoplasma spp.) that attacked *Paraíso* eventually leading to tree mortality (GTZ 1989). Infrastructure problems were no less problematic. Institutional cooperation fell through and the Swiss mission abandoned the project after a few years (Evans 1988). The SFN lacked the financial means to maintain the program and inconsistency in the numbers of Peace Corps volunteers assigned to the project contributed to failures in the support of small farmers (GTZ 1989).

Scattered coco palms and/or native trees with livestock

Figure 11. Cattle grazing beneath A. totai canopy. In a few years this field will likely be rotated back into crop production.

This silvopastoral system is similar to the palm/tree agrisilviculture system above except farmers leave cows to graze beneath the overstory rather than plant crops (figure 11). Often, this is after a few years of a cropping cycle and the farmer has let the field go fallow to recuperate (Peace Corps Paraguay 2009). The shade of the canopy benefits cattle in the Paraguayan subtropical heat, while cattle manure adds organic material to the soil. Farmers commonly cut the *mbocaja* leaves to feed the cattle during the lean winter months when other fodder is lacking. If one considers this and the cropping cycle together in the long-term, it may be considered a temporally sequential agrosilvopasture system.

The *Proyecto Manejo Sostenible de Recursos Naturales* (PMRN - Natural Resources Sustainable Management Project) was a joint effort between the German federal development agency Society for Technical Cooperation (GTZ, now the *Deutsche Gesellschaft für Internationale Zusammenarbeit* – GIZ) and the Paraguayan Agriculture and Livestock Ministry (MAG) to support 17,000 small farmers in seven districts of Paraguay with technical assistance for conservation agriculture, forest management, and agroforestry (Borsy et al. 2013). Part of the agroforestry extension package were recommendations for improved silvopasture practices. These involved plantations of exotic timber like eucalyptus (Eucalyptus spp.) and *grevilea* (Grevillea robustus) with native hardwoods established with annual crops to ensure cultural management of seedlings. After the third year, trees would be tall enough to withstand livestock damage and introduced forage grasses like Brachiaria brizanta would replace annual crops. L. leucocephala could be planted in between timber trees as well to provide additional high-quality fodder for cows. Thinning, required for management, produces intermediary products of firewood and poles before final harvest at the end of the 10 – 15 year rotation.

Estimates of the theoretical gross and net income of this system demonstrate good potential to increase the economic security of adopting families (Borsy 2013, p. 117 – 119). However, anecdotal evidence suggests issues for long-term management of the timber system. A MAG specialist involved in a separate plantation project indicated that small peasant farmers do not fully grasp that thinning increases the plantation's value overall by boosting the growth of remaining trees and are reluctant to carry out thinning, believing instead that they are cutting down profitable wood (J Ogasawara, personal communication, 19 July 2019). My personal observation of plantations from that same project supports this.

Boundary planting

Throughout the country it is common to see trees left in the spaces between plowed fields, known as *linderos* (figure 12). The technique is typical throughout the humid tropics in areas with high population density and/or intensive land use where agricultural land is at a premium and the prevalent customs deem planting many trees on cropland as conflicting with farming (MacDicken 1990). The trees provide useful building material and firewood, delineate property boundaries, and can play a limited role as a windbreak. However, the numbers of trees in these spaces can diminish rapidly as farmers rarely replant purposefully, instead allowing natural regeneration to remain and mature.

Figure 62. Recently plowed field with sparse overstory of A. totai and native trees in background marking boundary between properties.

The PMRN project mentioned above included suggestions for protective agroforestry through improved windbreaks adjacent to houses or crop fields. In contrast to traditional boundary plantings with one row of trees in randomized locations, the project suggested planting a variety of multipurpose trees in three rows of increasing height (PMRN 2007). The first row consists of tall forage grasses or shrubs including C. cajan and elephant grass (*pasto Camerún,* Pennisetum purpureum). The second row contains short fruit and understory trees like *inga'i* (Inga marginata), citrus (Citrus spp.), or yerba mate. The highest strata of exotic or native timber trees is closest to the protected resource and directs wind over and above.

Mixed homegarden

The mixed homegarden is a common smallholder agroforestry system throughout the humid tropics and subtropics involving spatially intensive mixtures of multipurpose trees, shrubs, herbaceous plants, food crops, and/or animals. It may be one of the oldest agroforestry practices on record and Brownrigg (1985 in Soemarwoto 1987) documents artistic evidence for their existence from at least the 3rd millennium BCE. They may appear as "wild jungle-like" combinations with no apparent order or structure but represent important sources of food, firewood, traditional medicinal remedies, and timber (Willis 1914 in MacDicken 1990). Homegardens exhibit high plant diversity, are structurally and functionally the most like natural forest ecosystems and may represent refugia for species (Jose 2009). While it is possible for farmers to produce cash crops in homegardens, this system is more commonly used to produce food and materials for domestic use (Soemarwoto 1987).

Figure 13. Picture of the author's landlord's property. The landlord's house is approximately 10 meters behind the photographer. Species in the photo from left to right include mandarin orange (C. reticulata), banana (Musa sp.), cassava (Manihot esculenta), and lemon (C. limon). In the foreground is an unidentified medicinal shrub and in the background overstory is A. colubrina and P. dubium.

As in other warm humid regions where the inside of homes can get uncomfortably warm at times of the year, homegardens in Paraguay represent important social spaces (Soemarwoto 1987). Farming committee meetings, religious rituals following the deaths of family members, and neighborly conversations most often occur in the shade of naturalized mango (Mangifera indica) and hovenia (Hovenia dulcis) trees on the *patio* (maintained yard) around houses. Many citrus species have become naturalized in the country and many meals don't start until someone runs out to grab a lemon (Citrus limon) or *apepú* (bitter orange – Citrus aurantium) from the yard to squeeze over the food. The ubiquitous *tereré*, or cold yerba mate infusion, is often prepared with medicinal herbs including lemon verbena (Aloysia citrodora), mint (Menta spp.), and *burrito* (Aloysia triphylla) gathered from directly around the home that are said to refresh the body after work, settle indigestion, or simply taste good (personal observation). Guava (Psidium guajava), banana, papaya (Carica papaya), and mandarin oranges (Citrus reticulata) are common fruits often growing in homegardens.

V: Exploratory Case Study – Agricultural Issues, Current Agroforestry, and Recommendations in a Rural Paraguayan Village

This paper has so far explored broad issues such as the theories behind agroforestry and traditional agroforestry practices in Paraguay. However, the most important opportunity my Peace Corps service gave me was to become familiar with the residents, issues, and practices in Laguna Pytã, the village where I lived for two years. Morton (2007) and Jerneck and Olsson (2013) mention the specificity of smallholder agricultural systems and the need for directed, location-based research to address issues and devise solutions. Agroforestry practices are no different, and my position as a volunteer in the community offered a chance to analyze the needs and challenges confronting the farmers there.

To that end, this section presents exploratory research conducted during my service. It seeks to identify the agricultural issues of most concern for farmers in the village, the recognized services provided by trees, agroforestry practices currently in use there, and the opinions of experts on these issues. Based on that information, I will recommend some improved agroforestry practices which have potential to increase food and economic security while limiting environmental damage and promoting long-term, sustainable resource use.

Study site location and description

Acahay

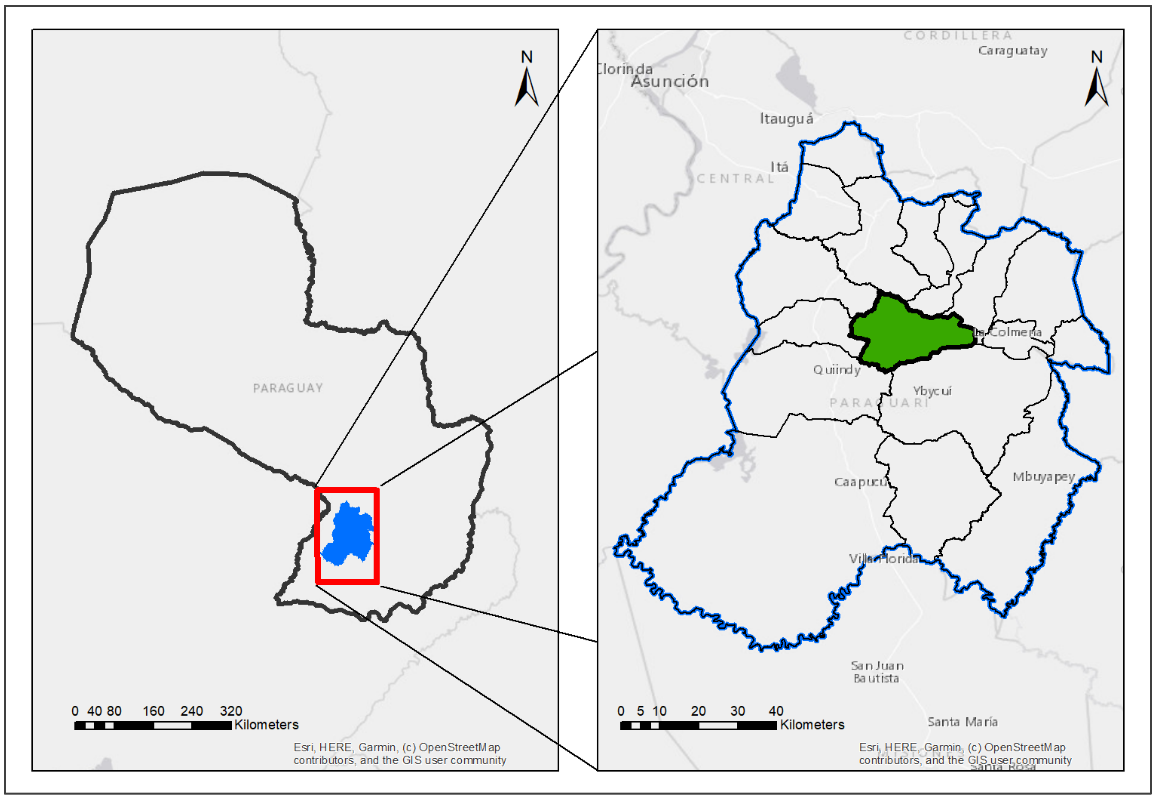

Figure 74. On left: Location of Paraguarí department within Paraguay. On right: Location of Acahay district within Paraguarí department.

Laguna Pytã is one of many outlying *compañías* (rural villages) surrounding an urban center in the district of Acahay, Paraguarí department. The entire department lies within the Paraguay River watershed. Acahay is a historic *pueblo* (town) approximately 64 miles (103 km) southeast of Asunción founded in 1783. As of 2015, it had a population of 16,074 (Municipalidad de Acahay 2015). Over 80% of the district population live in rural areas. Agriculture is the main economic activity in the district, employing 60% of the population, specifically in the production of *mandioca* (Manihot esculenta), maize (Zea mays), sugar cane (Saccharum spp.), cotton (Gossypium spp.), and medicinal herbs. Genetically modified cotton seeds are sometimes subsidized by the government, although sale prices are so low that many farmers do not think it worth the effort to cultivate. Sugar cane is a major industry in nearby districts such as La Colmena for industrial sugar and *caña* (rum) production, but most of the sugar cane for that comes from large industrial agribusiness. The sale of prepared medicinal herbs for *tereré* and *mate* consumption is a visible part of the informal economy sold at roadside stands.

As with most of rural Paraguay, the district has some low socioeconomic indicators. Although the Human Development Index value is 0.702, almost half of the population live in housing considered unsatisfactory for basic needs by the Paraguayan government, while over one-third have unsatisfactory household sanitary infrastructure by the same metric (Municipalidad de Acahay 2015). Life expectancy at birth is 66.3 years, almost 15% lower than the national average of 77.9 years (CIA 2020).

The municipality considers 80% of the population lacking legal property title to be a weakness (Municipalidad de Acahay 2015). Lack of secure land rights is generally considered a barrier to adoption of agroforestry as trees represent a long-term investment of money and/or care (MacDicken and Vergara 1990b). This is not a huge issue in Acahay, as most families have been on the same land for generations and have informal *derechos* (rights) of occupation (Hetherington 2009; E Leguizamón, personal communication, 27 September 2019). However, the lack of land title has implications for accessing formal lines of credit, which in Paraguay is often based on land titles (K Moriya, personal communication, 19 August 2019; Hernán Marecos and Dr. Milner González, personal communication, 17 September 2019).

Regional climate data is available from the nearest weather station in Paraguarí, the departmental capital located 28 miles (45 km) to the northwest. The climate is subtropical humid, with an average precipitation of 1,604.6 mm/year between 2008 and 2017 (DGEEC 2017). Precipitation is lowest in the cold winter months and highest in spring and fall. The average annual temperature in 2017 was 23.3°C, reaching an average monthly maximum of 33.5°C in January and an average monthly minimum of 14.1°C in June.

In one study, soils in the general area were classified as Plinthic Acrisols according to the World Reference Base system (Gardi et al. 2015). These are acidic soils with accumulations of clay and iron oxides in the subsoil which can form hardened layers upon repeated wetting and drying. They are generally nutrient poor and require fertilization for significant crop yields.

However, an earlier study specific to Paraguay classified the soils in the Acahay area as Typic Paleudalfs of the Alfisol order in the USDA soil taxonomy (López Gorostiaga et al. 1995). This soil type has good potential for agricultural production although cation exchange capacity is highly dependent on organic matter content, which is generally low. It has good water drainage with no horizon exhibiting permanent water saturation. They are common on flat to gently inclined areas of hilly landscapes over sandstone bedrock.

Laguna Pytã

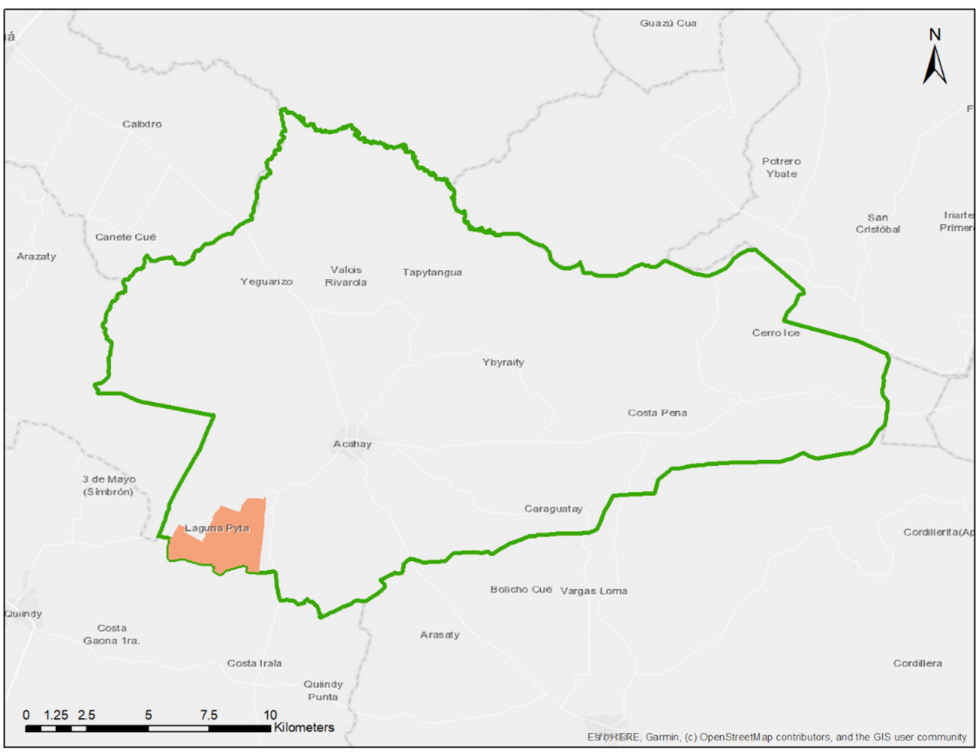

Figure 15. Location of Laguna Pytã within Acahay district.

Laguna Pytã is a small rural village on the southern border of Acahay district. Its name means “Red Lake” in Jopara, the mixture of Guaraní and Spanish spoken by most Paraguayan citizens. While there is no lake in or near Laguna Pytã, there is an unnamed stream bisecting the village. The topography is gently rolling, with views of the nearby Cerro Acahay, a national monument that is popular for hiking.

Based on local health post statistics, Laguna Pytã had a population of around 320 inhabitants in 2017 (Kursky unpublished data). Most families have been here for generations, if not centuries. All identify as *mestizos*. The majority of people are self-employed as farmers, however many in the younger generations leave the community after high school to find jobs in urban areas. Several people who live permanently in the community have manual labor jobs in construction and a few are employed by the municipality.

Most agriculture is for domestic consumption. Common subsistence crops include *mandioca*, maize, beans (Phaseolus vulgaris and Phaseolus lunatus), and peanuts (Arachis hypogaea). It is more common for community members to sell small quantities to neighbors upon request than to be involved in the larger regional market economy. Cash crops that are planted include cotton (Gossypium spp.) and, more rarely, sesame (Sesamum indicum), but prices for cotton are low enough to prohibit extensive cultivation. *Mbocaja* (A. totai) fruits harvested in early summer from palms left in crop fields represent one of the only consistent sources of cash income from agriculture. Soy (Glycine max), of which Paraguay is a major producer, is not present in Laguna Pytã. Many farmers plow with oxen and manually weed and harvest their fields, although the use of a tractor for initial field preparation is growing.

Laguna Pytã is a classic example of the *minifundista* zone of smallholder farmers within the zone of influence of Asunción (Roett and Sacks 1991, Lopez and Thomas 2000). This region is characterized by poverty, small properties after generations of division among heirs, and soils depleted by continuous use. Properties in Laguna Pytã are usually between 1 – 10 hectares, although there are a few outliers on either side. The few larger properties tend to be owned by outsiders from Asunción who married into a local family and purchased adjacent land (personal observation).

A soil report commissioned by the Ministry of Agriculture and Livestock for the entire eastern region of Paraguay includes data for multiple analyses conducted in Laguna Pytã, giving a general idea of the specific soil qualities in the village (Hahn Villalba 2017). On average, the soil has a high clay content between 30 – 40%, more than most in the department. Organic matter content is low, with more than half the plots containing less than one percent. Magnesium, calcium, sulfur, and potassium quantities trended low, while phosphorous was critically low across the board. As discussed in section 3, phosphorous is a common limiting nutrient in degraded tropical soils (Montagnini et al. 2000). Base saturation and cation exchange capacity tended to be low. The soil had low levels of aluminum and were generally not highly acidic, as almost all samples had a pH between 6.5 and 7.5.

The natural vegetation in the village is humid semi-deciduous forest (Lopez et al. 1987). Common emergent and dominant canopy trees are *tajy* (Handroanthus spp.), *peterevy* (Cordia trichotoma), *guajayvi* (Patagonula americana), *timbo* (Enterolobium contortisiliquum), *yvyra pytã* (Peltophorum dubium), *kurupa'y kuru* (Anadenanthera colubrina), and *kurupa'y rã* (Parapiptadenia rigida). Trees in the intermediate and lower strata include *laurel* (Nectandra spp. and Ocotea spp.), *inga'i* (Inga marginata), *kanelon* (Rapanea spp.), *kurupika'y* (Sapium spp.), and *sapirangy* (Tabernaemontana australis) among others. Along the banks of the stream can be found *ka'a oveti* (Luehea divaricata), *sangre de drago* (Croton urucurana), and *taruma* (Vitex megapotamica).

Methods

This case study is exploratory research based on informal interviews and observation. As the Peace Corps goals are based on capacity building, cultural exchange, and integrating into the community, I decided to focus on socioeconomic aspects of agroforestry.

My position as a Peace Corps volunteer and my work in the schools enabled me to gain the trust of the normally reserved Paraguayans. In general, they are open and welcoming but slow to share personal information due to the legacy of informants and repression during the Stroessner era (Roett and Sacks 1991). For this reason, I used opportunistic sampling to identify farmers with whom I had good relationships and who would be inclined to share information with me. Therefore, although they are fairly representative of average families in Laguna Pytã, the results of this study do not represent any larger population but instead show trends in agricultural life in the village.

As my project plan involved interviewing Paraguayans, I filed my project plan with Northern Arizona University's Institutional Review Board. I was granted an exemption as the board determined the project did not constitute human research and was not designed to contribute generalized knowledge.

I conducted 15 informal interviews with farmers in Laguna Pytã. The interviews were conducted in the farmers' houses or front yards in a mixture of Jopara and Spanish. Permission to take notes and record the conversation was asked and granted at the start of each interview. Either following interviews or at other opportune times, farmers accompanied me into their fields to describe their common practices. The interview outline, with questions in Spanish and Guaraní, is included in appendix 1 along with an English translation in appendix 2.

All interviews involved the male head of household. Traditional gender roles are still strongly followed in rural Paraguay and males are most likely to be involved in the sowing and care of field crops. It is not unheard of nor even taboo for women to farm, especially female heads of households, but it is less common. Eight interviews included the head of household's wife and three included adult children. The age of interviewees ranged from 34 to 76. All heads of households, like many of the adults in Laguna Pytã, had a basic primary school education which ended between 6^{th} and 12^{th} grades (US equivalent). None had college degrees. Although there are slight differences in material wealth, all households had a similar standard of living and can be classified as subsistence farmers.

I entered the responses into an Excel document for simple quantitative analysis. I analyzed most responses by summing frequency of mentions and calculating percentages of farmers who mentioned them (e.g. important uses of trees, reasons to not plant trees). To analyze the problems that farmers ranked in order of seriousness, I created a concern score by assigning a number from one to five to each issue mentioned by farmers, with one being least concern and five being great concern. No farmer mentioned more than five issues. I then multiplied an issue's mean rank by the number of times it was mentioned. For instance, if nine farmers considered pests an issue, and its mean rank among those who mentioned it was 2.9, pests was given a concern score of 26.1.

I organized one Participatory Analysis group exercise during a meeting with nine members of a farming committee in Laguna Pytã. With their assistance and input, I created a seasonal calendar to determine the timing of agricultural activities and seasonal needs. The group and I also did a pairwise ranking matrix to learn the priorities of the group in terms of ecosystem services that agroforestry can provide (Peace Corps 2005).

Results

Participatory Analysis

The seasonal calendar created with the farming committee reveals some insight into the timing of agricultural activities and needy periods of the year (figure 15). The main subsistence crops maize, *mandioca*, and beans are planted in winter, late winter, and early spring, respectively. Peanuts, if planted, are sown in late winter/early spring. Pigeon pea (C. cajan) is planted in summer, if used. *Mbocaja* (A. totai) fruits are collected from December to February, acting as a consistent source of cash income at this time. Vegetable gardens are started in March and April once the extreme heat of the summer is past and are tended until September when the heat returns.

Sugarcane and elephant grass are most commonly planted in Laguna Pytã for cattle fodder. They are primarily fed to cattle during the winter months.

The early spring is traditionally seen as the leanest time for both human and animal consumption. It marks the end of the availability of the previous season's corn and beans but is too early for the next harvest. Livestock are fed only sugarcane, elephant grass, or *mbocaja* fronds during the winter as grass and natural pasture go dormant, and by late September and early October these are lacking as well. This concerns farmers, who prefer pasture and believe livestock are malnourished during winter.

Plowing, still done primarily with oxen and plow, starts in June and July and can continue until December, based on the crops planted by that season. Weeding of crop fields is performed manually by hoe and occurs from August to January, depending on the crop. Pile burning of weeds, woody vegetation, and *mbocaja* spines occurs in June and July just before the first crops are planted. While broadcast burning is common in neighboring villages and districts, this practice is not prevalent in Laguna Pytã, perhaps due to previous extension work by Ministry of Agriculture officials.

The pairwise priority ranking matrix demonstrates the importance of ecosystem services provided by trees to the farmers (table 1). The group members ranked oxygen/clean air followed by forage as top priorities. Erosion control and soil fertility improvement were ranked at the bottom.

Table 1. Results of the pairwise ranking matrix. Farmers were asked what products and services trees provided, and then ranked each one against the others.

Product/Service prioritized	# of times preferred	Ranking
Oxygen/Pure air	8	1
Forage	7	2
Wood/Timber	5	3
Firewood	4	4
Mbocaja (Paraguayan Coconut)	4	4
Fruit	3	6
Fence posts	2	7
Erosion control	2	7
Soil fertility/improvement	1	9

Farmer Interviews

The 15 interviewed households owned an average of 6.5 hectares of land, ranging from 1.5 to 12 ha. On average, crop fields covered 2.9 ha and pasture covered 3.2 ha. Eight had patches of native forest on their property of at least 0.5 hectares.

Every farmer planted corn and *mandioca*. Ninety-three percent planted beans, 67% planted peanuts, and 27% had pigeon pea. One farmer planted peas (Pisum sativum) in his field. Twenty-seven percent planted cotton as a cash crop, while only seven percent (one farmer) planted sesame for the same reason.

All farmers harvested *coco* fruits from naturally regenerated palms for cash and consumption, although none deliberately planted the palm. Each farmer collected between 15 and 110 crates of *coco*, with an average of 58.3. In 2018 and 2019 farmers received about ₲14,000 ($2.15 US) per crate, each holding approximately 50 kg. Farmers harvested an average of 11 crates per hectare owned, although it is not known if *coco* was harvested from every hectare of land.

Fourteen of the households had cattle, ranging between 1 to 10 cows each. The average family owned 3.9 cows, mostly dairy cows or calves. Seven households owned two oxen each for plowing, while two owned one ox each. Thirteen houses had an average of 2.15 pigs. One family had two goats.

The most commonly planted forage crop was sugar cane, with 93% of farmers planting it. Eighty percent planted elephant grass. All farmers reported feeding their cattle *coco* leaves, while 33% fed *Leucaena* to their cattle. Only 13% (two farmers) used other trees for forage.

Farmers named seven agricultural problems they faced in their crop fields. The most concerning issue for farmers was drought, followed by closely by low soil fertility. Although many farmers in personal conversations mentioned their desire for more cash income, a lack of

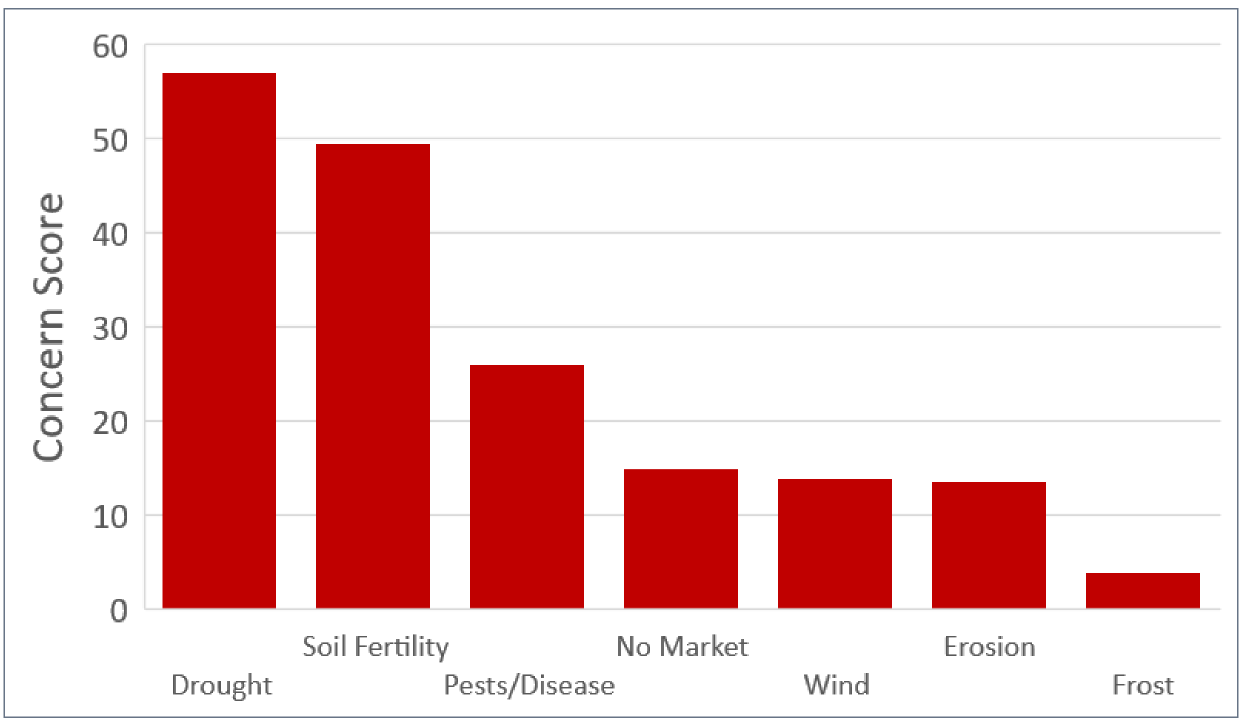

Figure 16. Chart of agricultural concerns among interviewed farmers in Laguna Pytã. Concern score was calculated by multiplying the average rank of an issue by the number of times it was mentioned.

access to markets did not rank highly as an issue. Figure 16 shows a chart of the farmers' stated agricultural issues and their associated concern scores.

All households used firewood as their main cooking fuel. In addition to firewood, 13 households used charcoal on occasion, five used propane, and three used electric stoves. However, families stressed that firewood was the principal and preferred fuel, as sitting around the fire was an enjoyable and traditional practice.

There is no clear pattern of gender roles in terms of gathering firewood. Men were primary gatherers of firewood in six households, women were primary gatherers in four households, while in five households they split the responsibility.

Eleven of the households claimed that there was enough firewood. Only three stated outright that it is difficult to find, while one household said it is sometimes easy and sometimes hard to find. There was a slight majority of households claiming there is less firewood now than before, although almost every household said there was less forest. Of the households that claimed there is more firewood now, all said it was because they had planted trees in the past and now used them for firewood.

The frequency with which important uses of trees were mentioned is shown in table 2. Firewood and fruit were the most commonly cited important uses, while windbreaks, oxygen production, and charcoal were each cited once.

Table 2. Frequency of mentions of important uses of trees.

Tree value	Frequency mentioned	Tree Value	Frequency mentioned
Firewood	14	Soil fertility (Green manure)	4
Fruit	14		
Fence posts	12	Erosion control	3
Timber	12	Windbreak	1
Shade	11	Pure air/Oxygen	1
Animal forage	5	Charcoal	1

Seven of the 15 households sold wood or whole trees from their property. Eight currently did not, but three said they planned to do so in the future.

Ninety-three percent of farmers had planted trees in the yards around their homes. Only one farmer, however, planted trees in his crop field, and that was with me during an agroforestry trial. Even though leaving scattered trees in fields is a traditional practice and farmers identified uses for trees left in fields, there is a cultural aversion to deliberately planting trees in crop fields as they are viewed as barriers to farming. The most commonly cited reason (by six farmers) against planting trees was competition with crops. Five farmers commented that trees got in the way of plowing, and four of those specifically mentioned tractors as being incompatible with trees. One farmer explicitly called out eucalyptus as drying out the soil, and one other farmer stated, "There are enough trees." When asked reasons to not plant trees or to remove them from fields, only one farmer countered by saying he did want trees in his field.

When asked if climate change was a concern for the future, 12 farmers said yes. Table 3 shows effects that those farmers state they have already witnessed as a result of climate change.

Table 3. Effects of climate change experienced by farmers for whom it is a concern.

Effect	Frequency mentioned	Effect	Frequency mentioned
Hotter temperature	12	Flooding	1
Drought	11	Increased southerly	1
Affects crop growth	11	wind (cold & drying)	
Stronger sun	5	Hail	1

All but one farmer stated that trees can help with changes in the climate, even those for whom climate change was not an issue. Table 4 displays the ways farmers said trees can help mitigate changes and the frequency they were mentioned.

Table 4. Ways in which farmers stated trees can counter climate change effects.

Mitigation effects	Frequency mentioned	Mitigation effects	Frequency mentioned
More rain/humidity	6	Buffers wind	3
Cools the air	5	Erosion control	1
Purifies air	5	No effect on climate	1

During field observations with the interviewed farmers, I observed eight agroforestry systems already in use. Of the traditional systems, 14 farmers utilized boundary plantings, 13 had mixed homegardens, seven used scattered trees and *coco* in crops, and four had cattle in silvopasture. Additionally, 12 households had native and/or exotic plantations on part of the farm, three farmers planted pigeon pea dispersed among crops, and one each had live fence posts or improved fallow with densely planted pigeon pea. Figure 17 shows the number of interviewed farmers using each system.

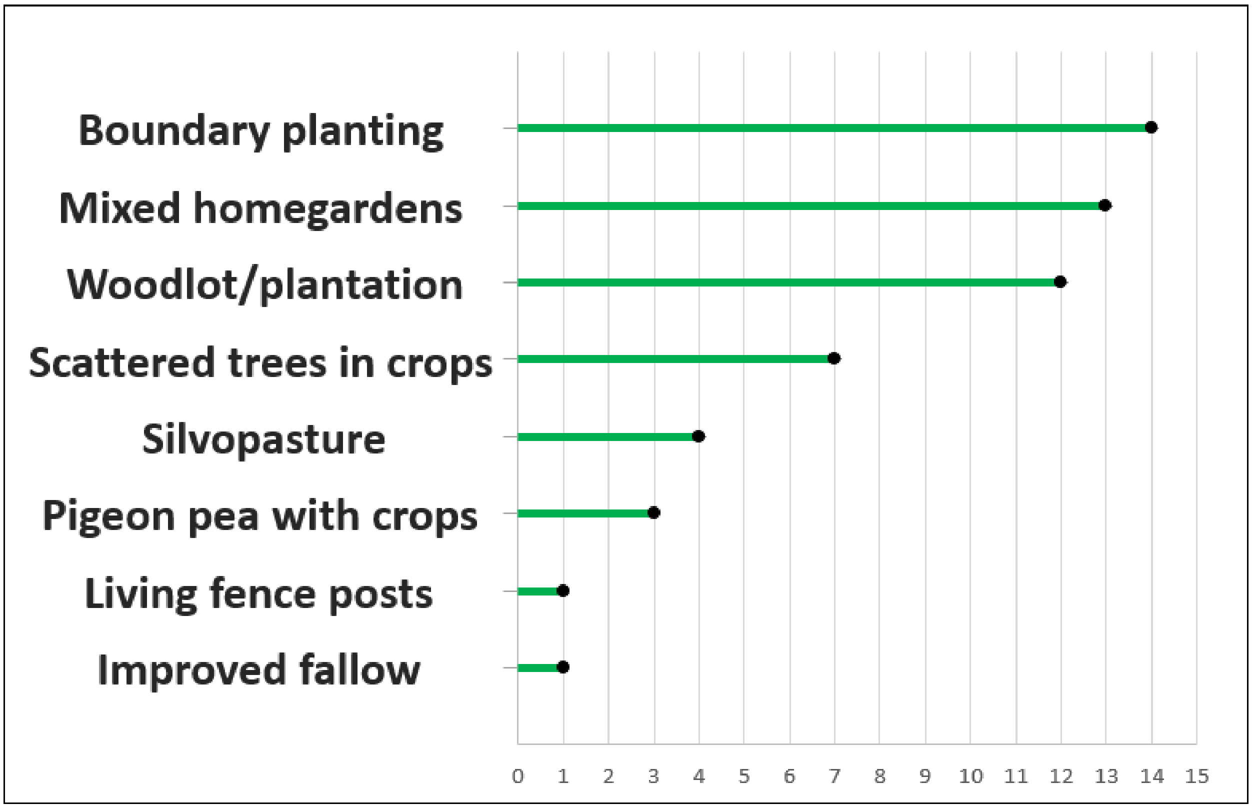

Figure 17. Agroforestry systems observed in Laguna Pytã and the number of interviewed farmers using them.

Most of these systems have been described previously. Live fence posts can be classified as a modified boundary planting system in which trees are established along the edges of fields or pasture and then utilized as fence posts as wire is attached to them (figure 18). Depending on the species used, the trees can provide multiple products and services like forage, fruit, organic material for soil improvement, and nitrogen fixation if leguminous. If the tree is a resprouting species, with pollarding it can provide firewood and timber without needing to be replaced as a post. At the same time, the tree is sturdier than traditional fence posts thanks to its living root system and lasts longer than decay-prone traditional posts.

Figure 18. Peltophorum dubium used as live fence posts. P. dubium is nitrogen fixing, resprouts well after pollarding, and provides valued timber.

Pigeon pea with crops is a more dispersed version of hedgerow intercropping (Nair 1990). Unlike in the systematic rows of densely planted leguminous shrubs or pruned trees in intercropping, the farmers in Laguna Pytã had sparsely planted rows of pigeon pea at random spacings throughout the field. Although primarily planted as an additional subsistence crop for the household, they still provided ecosystem services such as nitrogen fixation, organic material, and erosion control, and their woody stalks could be used as fuelwood after a few seasons.

Recommendations

Certain characteristics of new or improved agroforestry systems make them more likely to be adopted by small farmers. Most importantly, they must demonstrate a direct economic benefit to farm families, regardless of the contributions to larger scale environmental problems (Raintree 1990, Ong and Leakey 1999). Impoverished farmers are limited not just by land, labor, or capital, but by food security as well (Jerneck and Olsson 2013). Especially during the establishment phase, many agroforestry practices require higher labor inputs than traditional agriculture; no farmer is willing to create more work for themselves for abstract, globally oriented objectives.

Improved practices should directly address the self-identified needs and issues of the farmers, rather than those decided upon by government agencies outside the community or by NGOs (Barbier 2000). If not, there is little incentive to continue their use if outside support stops or is limited in the first place. Successful agroforestry extension also encourages new techniques that are compatible with existing practices. A small modification is easier to experiment with, less risky, and more likely to be adopted than a completely new one (Evans 1988, Barbier 2000). Farmers are more likely to have the knowledge base and tools required to implement such practices.

The interviews with farmers reveal that soil moisture retention and soil fertility are the primary agricultural concerns of the interviewed farmers in Laguna Pytã. The majority are concerned that climate change has already begun affecting their agricultural lifestyles and that it will continue to get worse in the future. Climate models support the validity of these concerns. The Food and Agriculture Organization estimates that under the worst-case Representative Concentration Pathway 8.5 scenario, by the year 2070 maximum temperatures will increase up to 3.3°C and minimum temperatures up to 4°C while precipitation decreases up to 15.9% (FAO 2020). Even under the more conservative RCP 4.5 scenario, maximum and minimum temperatures will go up while precipitation goes down.

Researchers expect these changes to negatively impact food security in Paraguay. Ervin and Gayoso de Ervin (2019) found evidence that household agricultural productivity will decrease with higher temperatures and lower precipitation, leading to fewer calories consumed by impoverished families. They estimate vulnerability to food insecurity go up by 8% by the middle of the 21st century and 28% by the end of it.

Agroforestry is recognized as a tool with high potential to address these issues. Farmers in the village are already using several agroforestry techniques in an extensive manner. It is my opinion that intensifying and making systematic a few of the practices already in use would improve soil characteristics, enhance the resilience of farms to climate change, and bring in more cash revenue for farmers while diversifying the resources that they currently rely on.

Systematized intensive coco palm and native trees with crops and/or animals

The system with the biggest potential economic potential for Laguna Pytã is planting a higher density of A. totai palms, native nitrogen fixing trees, and timber species within crop fields, arranging them in systematic rows, and implementing management like pruning or pollarding. This modifies and combines a system described in the *Proyecto Manejo Sostenible de Recursos Naturales* agroforestry manual with the cultural management techniques utilized in the traditional Quezungual Slash-and-Mulch Agroforestry System from Honduras (Hellin et al. 1999, PMRN 2007). I recommend a spacing of six meters between plants and ten meters between rows for A. totai (167 trees/ha), more than that recommended by PMRN, to account for the increasing use of tractors for field preparation in Laguna Pytã. Ten-meter rows should allow enough room for tractors to maneuver through the field. Native nitrogen fixing trees, fruit trees, and native and exotic timber species are to be planted at a 6 x 20 meter spacing, evenly within rows of A. totai but every other row (83 trees/ha). In total, this agrisilviculture system will have 270 trees/hectare.

Mbocaja, like most other palms, has a root system that does not compete with crops and lends itself to integration with permanent agrisilvicultural systems (Ashton 2000, Moreira et al. 2019). The more dispersed nature of the other tree species would limit the negative interactions between them and crops. A. hassleri, a native species that fixes nitrogen and is valued for firewood, also has a deep effective rooting zone and limited lateral spread, making it a good candidate for soil improvement and biomass provision (Akinnifesi et al. 1999). Other tree species applicable for this system are listed in table 5, but this list is not exclusive.

Pruning and pollarding the trees other than A. totai, as per the Quezungual system, and spreading the residues on the soil between tree rows has multiple benefits. It limits negative tree-crop interactions as described in section 3. The residue acts as a mulch on the soil, thus maintaining soil moisture, limiting erosion from wind and rain, and reducing weeding labor by smothering weeds (Hellin et al. 1999, Ayaraza and Wélchez 2004). The increased organic material, especially that from leguminous trees, improves soil fertility, increases soil pH, and functions as a source of essential nutrients.

Table 5. Useful tree species for improve agrisilviculture system (source: Lopez et al. 1987, PMRN 2007, Cuerpo de Paz 2009). An e next to a common name signifies exotic.

Common name	Scientific name	Use/Value
Cedro	Cedrela fissilis	High value timber
Ceibo	Erythrina spp.	Nitrogen fixer, deep roots, forage, resprouts
Grevilea (e)	Grevillea robusta	Fast growing, timber, firewood
Guatambú	Balfourodendron riedelianum	High value timber, forage, firewood
Hovenia (e)	Hovenia dulcis	Timber, firewood, edible fruit, forage, resprouts
Inga/inga'i	Inga spp.	Nitrogen fixer, edible fruit, forage, resprouts
Kamba akã guasu	Guazuma ulmifolia	Deep roots, forage, firewood, resprouts
Manduvirã	Samanea saman	Nitrogen fixer, timber, firewood, forage
Peterevy	Cordia trichotoma	High value timber, deep roots
Yvyra pytã	Peltophorum dubium	Nitrogen fixer, timber, forage, resprouts

The system theoretically improves crop production through soil improvement without the need for expensive inputs, although increased soil fertility may take a few years to manifest (Nygren 2012). It will provide more timber, firewood, and forage for domestic use. If fruit trees like Inga spp. or Citrus spp. are incorporated, more food is produced for the household and food production is diversified as a buffer against unforeseen events.

This recommendation will work as a silvopasture system in addition to or instead of the agrisilviculture one. As noted in the section four on the traditional systems of Paraguay, it is typical for farmers to let cattle graze under the scattered *coco* and tree overstory when farmers let crop fields go fallow. In the same way, this recommended agrisilviculture system can easily transition to silvopasture, in effect turning it into sequential agrosilvopasture. This will benefit cattle through additional sources of fodder. An evaluation of multiple Albizia species identified *yvyra ju* (A. hassleri, referred to by synonym A. niopoides) as one of the most palatable fodder species (Stewart and Dunsdon 2000). B. riedelianum, H. dulcis, Inga spp., G. ulmifolia, S. saman, and P. dubium are all recognized as fodder species as well, although they are not currently in common use as such in Laguna Pytã (PMRN 2007).

Additional shade from trees will make agriculture more resilient to increased temperatures expected with climate change. In the semi-arid tropics, crops and especially pasture grasses grown in the shade under trees have higher production, likely due to lower evapotranspiration rates (Vandenbeldt 1990). Tree cover protects livestock from heat stress, sun stroke, and dehydration, limiting their vulnerability and increasing their growth and milk production (Nair 1990, PMRN 2007).

The biggest direct economic impact will be from the increased sale of *mbocaja* fruit to local oil-producing industries. *Mbocaja* palms require five years to mature, after which they generally produce 25 kg of fruit per year. Every third year on average is a bumper crop of 35 kg per plant (PMRN 2007). Therefore, a field with 187 palms/ha can produce 83 – 131 crates of fruit per hectare every year. A household with the same average area in crops as the interviewees can expect to harvest 240 – 380 crates per year after year five, bringing in ₲3,360,000 – ₲5,320,000 ($517 – $819 US).

The demand for *mbocaja* is only expected to increase. A conversation with a local buyer who acts as a middleman between farmers and industrial buyers said the oil processing factory in the neighboring district received only 70% of the raw material supply it needed for the year (C Florentin, personal communication 19 November 2019). Recent research shows that *mbocaja* has the potential to become an important global oil crop (Colombo et al. 2018).

<u>Increased use of live fence posts and fodder trees</u>

I observed only one example of live fence posts in Laguna Pytã during my service. This system holds great potential for provisioning ecosystem services and for reducing the need to replace fence posts, which requires money and/or labor. Many native and naturalized species such as *yvyra pytã*, *yvyra ju, kamba akã guasu*, and *hovenia* resprout readily from pollarding, provide firewood or construction timber, and are sources of nutritious fodder for the same livestock that the fence is protecting.

The increased use of fodder trees in live fence posts, traditional boundary plantings, and other systems can benefit the households in Laguna Pytã for the reasons mentioned in the systematized *coco* system. Cattle raising is not commonly an income generating activity in

Laguna Pytã, instead providing fresh milk and homemade cheese for domestic consumption and neighborly trade. Animals also act as walking emergency funds, able to be sold quickly to either other community members or a butcher in town when unexpected financial stress presents itself. Nutritious forage from trees in agroforestry systems will socioeconomically benefit households by maintaining or increasing livestock live weight, increasing the quantity of milk produced or reducing the amount of forage needed to produce the same amount.

Gender

The United Nations specifically mentions women's empowerment and increased economic opportunities as one of its Sustainable Development Goals (UN 2015). In many countries around the world, the sale and harvest of nontimber forest products is already dominated by women. In Paraguay, selling and preparing medicinal herbs for *tereré* and *mate* consumption tends to be conducted by women in informal roadside stands near their homes. Cars and even cross-country buses will often pull onto the side of the highway upon spotting such a stand, quickly purchase some ice for their thermos and pounded herbs for their yerba mate and continue on their way. Selling fruit at roadside stands is also common, although harvesting fruit in fields is still dominated by men.

With traditional gender roles still in place in most of rural Paraguay, it is very common for women to remain in or near their houses for much of the day. Homegardens present an opportunity to increase the production of medicinal herbs around the home and provide the women of Laguna Pytã with marketable goods to sell. If larger quantities of fruit and herbs can be produced near women's traditional sphere of influence (the home), it may provide them with more economic opportunity. Unfortunately, Laguna Pytã is not located on a main thoroughfare, and is five miles from the nearest paved road in the *pueblo* of Acahay. As well, the *pueblo* is a small town and the roadside stand market seems to be nearly saturated. However, there may be an opportunity to sell herbs and fruit to the vendors already established in town.

The survey results indicated no clear gender division in terms of firewood collection among households in Laguna Pytã. Increased tree and shrub numbers in homegardens represent a potential source of available firewood close to the home. Although firewood scarcity was not a recognized issue, having a more abundant source closer to the home could only benefit the people and especially the women of Laguna Pytã.

A better analysis of agroforestry's role in gender relations and traditional roles in unfortunately beyond the scope of this professional paper. I did experience slight social discomfort when I attended women's committee meetings, even if my wife was present. It is my opinion that a female researcher would be better suited to understanding the values, desires, and perceived needs specific to the women in Laguna Pytã and other rural Paraguayan areas.

Barriers to success

Although improved agroforestry has the potential to increase socioeconomic and ecological benefits of agriculture in Laguna Pytã, multiple barriers to the adoption of new and improved systems exist. Overcoming them is the real challenge of implementing agroforestry. A farmer that experiments with a new agroforestry system can tweak aspects here and there to adapt it to its highest potential. But an agroforestry system that is not used will help no one.

A known barrier to success of agroforestry everywhere that also applies to Laguna Pytã is the change in labor requirements. To plant 270 trees per hectare, protect them from roaming livestock, and maintain them during drought until they are big enough to be resilient takes some effort. The future payoff may be great, but as discussed in section three regarding discount rates, impoverished subsistence farmers tend to place much more value on the present than they do on the future.

In addition to possible increases in required labor, there will likely be a time lag between the establishment of improved agroforestry systems and the perception of their benefits. Mercer (2004) estimated 3 – 6 years before seeing results. If a household is willing to risk experimenting and does not see a demonstrable benefit in one to two years, the risk to the family's food supply will not be the only problem. They will likely become the butt of many jokes within this risk-averse and at times fatalistic community (Peace Corps Paraguay 2009).

A lack of demonstration plots in Laguna Pytã prevents farmers from seeing the benefit of potential systems without taking the risk themselves. As Evans (1988) reported about an agroforestry extension program in Paraguay in the 1980s, farmers who were able to visit a demonstration farm and witness the innovation were quick to adopt it. However, without that resource it is hard to convince households whose food supply depends on minimizing risk to take an unknown gamble.

Government policies in Paraguay can sometimes make it harder to promote new agroforestry technologies. Planting hundreds of trees and securing the materials to care for and protect them require money and resources, something that most people in Laguna Pytã do not have in excess. One MAG official I spoke with bemoaned the lack of an easy system for low interest credit (K Moriya, personal communication, 19 August 2019). In order to get loans from a secure MAG credit bureau, one must have a physical property title. The other option is a loan from private parties who charge exorbitant interest rates.

Donations or grants from government agencies or non-governmental organizations are often the only known route to receive supplies and money for projects. As a Peace Corps volunteer, my role was often to connect farmers and community groups with such organizations in order to implement projects. However, without the presence of a volunteer, many rural Paraguayans would not know these organizations exist or would not know how to contact them. Even if a grant or donation did go through, organizations must ensure follow through, transparency, and commitment through the end of the project. Past critiques of government extension projects focused on perceived corruption within the agency and a lack of farmer support (Hamilton and Bliss 1998). Farmers complained that agents were in a hurry to set up projects and leave without further monitoring or support.

Finally, a lack of knowledge can be a big barrier to success. Agroforestry is more knowledge intensive that other agricultural improvement schemes, requiring in-depth understanding of location-specific interactions and the requirements of different elements. At this time, it is unknown how crop yields will respond to higher densities of trees in fields. Anecdotally, the one farmer in Laguna Pytã who had higher numbers of scattered trees in their field (and who, incidentally, had been a participant in a past conservation agriculture extension project) did have some of the healthiest and lushest looking maize in the community. His 0.5-hectare field had 128 trees/ha with a basal area of 2.5 m^2/ha. However, this provides no solid science-based evidence of causation, nor is it known if the farmer used chemical fertilizers or other soil amendments in the field.

Section VI: Conclusion

Paraguay is a land of contrasts. The capital city of Asunción has areas of extravagant wealth, luxury dining, and opulent colonial mansions. Yet other areas, particularly rural regions outside of the city, face extreme poverty, massive levels of inequality, and a lack of economic opportunity. People in rural villages are quick to laugh, smile, and won't take no for an answer as they share whatever they have with you. But often it is just enough to get by, and rural farmers have little options to feed their family or make some money for school supplies and family necessities while managing the natural resource base for future use and enjoyment. Agroforestry, incorporating the use of trees in agriculture, has potential to change that dynamic.

Agroforestry takes advantage of favorable ecological interactions between trees, crops, and animals while limiting negative ones. It can be classified according to the components used, their arrangement in space or time, the protective or productive function of the system, the ecosystem where it will be used, or socioeconomic level. Agroforestry takes advantage of the synergy of elements in the system for higher productivity from the system than if one element was present by itself. These synergistic interactions are usually between the canopy and understory and between tree roots and crop roots but can also involve nutrient cycling between animals and plants.

The potential benefits of agroforestry are relevant to local and global scales. Climate change mitigation via carbon sequestration in biomass and the avoided loss of further primary and secondary natural forest may limit the expected warming temperatures, changes in precipitation distribution, and acute climatic events for populations worldwide. Agroforests create more available habitat for forest-reliant species while still provisioning ecosystem services for human societies. They can act as corridors between larger natural preserves and refugia for threatened species, increasing gene flow and enabling smaller populations of species to remain genetically viable. Greater biodiversity makes ecosystems more resilient to shocks and may serve as sources for future pharmaceutical discoveries valuable to humankind.

Closer to home for farmers that adopt it, agroforestry can make agriculture more resilient to the changes that do occur. It can enhance the productivity of crops by improving soil fertility and physical properties, decrease moisture losses from evapotranspiration, increase the quantity of moisture-retaining organic material in soil, and prevent nutrient loss from leaching and erosion. Livestock stands to benefit from more nutritious and more available forage while windbreaks and shade protect them from the debilitating effects of higher temperatures, intense sun, and dehydration.

Human societies will profit from agroforestry. These systems directly address seven of the United Nations Sustainable Development Goals (UN 2015, FAO 2018). Products from agroforests scale up the availability of marketable non-timber forest products whose sale is already dominated by women in many locations. Lower erosion and less need for expensive irrigation helps poor farmers with sustainable water management. The provision of firewood and construction timber enhance reliable sources of cooking and heating fuel and lower reliance on outside supplies.

Of course, agroforestry needs to be properly designed and managed to decrease potential negative effects. Trees compete with crops for water, light, and nutrients. The establishment of agroforestry requires labor and supplies, and adopters may need to seek outside assistance for those. The benefits of agroforestry often take time to manifest, and impoverished farmers face constant pressure to feed their families in the present. They may not be willing to risk temporary drops in crop productivity or the effort needed to plant significant numbers of trees on their farmland.

In order to counter these issues, agroforestry promotion must consider the preferences of farming households and not focus on the desires of outside agencies. As agroforestry tends to be knowledge intensive, successful agroforestry outreach should be compatible with existing tools, crops, and cultural practices.

Traditional farming in Paraguay already includes agroforestry. With enough land available between rotations to allow recovery, slash-and-burn agriculture can be considered a sequential agroforestry system (Reed 1995). Yerba mate, the ubiquitous beverage of Paraguay that is exported worldwide, has for centuries been harvested below forest canopy, while most farmers leave a few trees in their fields for firewood and timber. The Paraguayan coco palm, A. totai, provides reliable cash income during the summer and supplies livestock fodder in lean times. Its position as an emerging oil crop will likely grow in importance in coming decades, presenting an opportunity for profit and market exploitation by small farmers (Colombo 2018). Homegardens provide fruit for families, herbs for *tereré*, and serve an important function as social and religious gathering spaces.

An investigation into perceived agricultural problems, the values and services that trees provide, and existing agroforestry in the village where I served as a Peace Corps volunteer reveals what's important to local farmers and what practices can be modified to increase the use of trees and their benefits. Drought and low soil fertility are the primary issues that concern local households. Trees are recognized for some abstract ecosystem services, such as air purification and oxygen production, but are generally valued more for provisions like firewood, timber, and fruit.

The present use of low intensity agroforestry practices such as dispersed trees in crops, grazing of animals under the same trees during fallow periods, and the rare use of live fences provide opportunities to promote more intensive and profitable techniques. A modification of a technique developed by a German-Paraguayan project, the planting of *coco* palms and trees in regular rows on farmland, can increase the expected cash income of small farmers and produce fruit, fuel, wood, and animal feed. More use of trees as live fence posts will provide much of the same products while reducing the need for costly fence posts and the labor required to fix and replace them every few years.

Family values are of the utmost importance in Paraguay, and the families in Laguna Pytã embraced my wife and I despite our challenges with their language and our lack of practice at most activities essential to rural life. We had to be taught the best way to wash laundry by hand, milk a cow, and hoe weeds without killing the crops (so sorry, Don Julian). With the support of our community, we were able to survive and thrive in a new place. But families around the world, especially in developing countries, face new challenges with regard to diminishing natural capital and increasing uncertainty with climate change. It is my hope that better natural resource management through the adoption of improved agroforestry practices can equip communities like Laguna Pytã around the globe with the ability to provide for present needs without disturbing the possibility of future generations to do the same.

A note on ethics

As a professional promoting agroforestry for natural resource management and restoration, it is imperative to abide by an ethical standard. The history of development work is rife with failed projects that may have accelerated ecosystem decline and reduced the opportunities available to their intended targets.

The Society of American Foresters Code of Ethics provides a framework applicable to decision-making in agroforestry design and promotion. Its first principle outlines the responsibility to land management for both current and future generations (SAF 2000). Agroforestry plays a large role in adhering to this principle, as its objective is more sustainable use of natural resources in the present while improving the resource for the future. Agroforestry has potential to improve ecosystem function on farmland while preserving and protecting existing forest resources (Dixon 1995).

The importance of sound science in natural resource management and public policy decision-making is paramount (SAF 2000). The potential of agroforestry to improve soil, boost crop yields, and enhance livestock health is very exciting. But designing systems for those purposes must rely upon scientifically founded studies specific to the conditions where they will be applied. Unknown and understudied interactions between agroforestry components have the potential to diminish productivity, create more work for farmers, and reduce the likelihood of success.

The Society for Ecological Restoration also abides by a Code of Ethics and Standards of Conduct pertinent to agroforestry promotion. Agroforestry, like other forms of ecological restoration, may sometimes involve causing harm by removing unwanted species or the unanticipated effects of competition (SER undated). Agroforestry implementation must acknowledge these limitations and they must be taken seriously during design and implementation.

The same Code of Ethics recognizes the validity of all forms of knowledge, especially the value of local and traditional ecological knowledge (SER undated). In rural agricultural areas like Laguna Pytã, families have been farming for centuries and have an intimate understanding of local conditions and patterns. It is arrogant to believe that outsiders can come in and fix all problems with western knowledge and technology, as it is often these same factors that have led to destructive land practices. Agroforestry promotion especially must acknowledge this through targeting the concerns of the farmers who will use it and adapting to existing customs and practices.

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Appendix 1: Interview guide in Spanish and Guaraní

<u>Guia de Entrevista para Laguna Pytã, distrito Acahay, Paraguay</u>

<u>Patrones Actuales de Uso de la Tierra</u>

1) *¿Cuántas hectáreas tiene? ¿Cuántas hectáreas son chacra? ¿Cuántas son piquete? ¿Cuántas son barbechas? ¿Usted tiene monte en su tierra? ¿Cuántas hectáreas de monte?*
   ¿Mboy hectarea rereko? ¿Mboy hectarea oreko nde kokue? ¿Mboy la pikete? ¿Mboy ndorekoi mba´eve? ¿Rereko piko ka'aguy? ¿Mboy hectarea la ka'aguy?

2) *¿Cuáles cultivos planta para autoconsumo? ¿Cuáles cultivos planta para vender?*
   ¿Mba´e cultivopa eñoty pe´u hagua? ¿Mba´e cultivokuerapa eñoty revende hagua?

3) *¿Qué tipos de animales tiene usted, y cuantos? ¿Cuáles tipos de forraje les da para comer? ¿Hay tiempos que faltan suficiente forraje?*
   ¿Mba´e mymbanguerapa rereko? ¿Mba´e forraje emongaru chupekuera? ¿A veces ndaipori la forraje oikoteveramo?

4) *¿Vende otros productos agrícolas de su tierra (Coco, frutas, verduras, queso/leche, miel)?*
   ¿Mba'e otro productopa revende pende yvygui?

5) *¿Qué usa su familia para cocinar (p. ej. leña, carbón, placa eléctrica, placa con garrafa)?*
   ¿Mba´epa oipuru nde familia ococina hagua?

6) *¿Quién de la casa junta leña? ¿Es abundante la leña, o escaso? ¿Este ha cambiado con los años (es decir, era más abundante o más escaso anteriormente)?*
   ¿Mavapa ombyaty la jepe´a? ¿Oipa heta tea ndaipori? ¿Mba'epa la cambio pehechava la jepe'are?

7) *¿De donde saca leña, y con que frecuencia? ¿Usted o alguien de la familia sacan del monte?*
   ¿Moõguipa pegueru la jepe´a, ha mboy veces cada mes? ¿Penohepa ka'aguygui?

8) *¿Cuáles son los problemas más graves en la chacra? Ponga en orden de gravedad.*
   ¿Mba´eapa la problema tuichaveva la kokuere? Emohenda petei escalape asegún la gravedad.

9) *¿Ha notado cambios en la cantidad de monte/bosque en la comunidad? ¿Cómo?*
   ¿Oi piko sa´ive la ka'aguy la comunidadme, tea oive la ka'aguy? ¿Ivai o iporã upeichapa?

10) *¿Plantó los árboles en su patio, o salieron nomás? ¿Si no, por qué los dejó?*
   ¿Reñotypa la yvyramatanguera la korapype, tea osente? ¿Osēnteramo hikuai, mba´erepiko reheja?

11) *¿Plantó los árboles en su chacra, o salieron nomás? ¿Si no plantó, por qué los dejó? ¿Para qué sirven los árboles en la chacra?*
¿Reñotypa la yvyramatanguera la kokuepe, tea osente? ¿Osēnteramo hikuai, mba´ẽrepiko reheja? ¿Mba´e ojapo piko la yvyramatanguera la kokue peguara, tea marapa oservi?

12) *¿Cuale de los usos de los árboles son más importantes (p. ej. fruta, sombra, abono verde)?*
¿Mba'e la uso iñimportanteveva la yvyramatagui?

13) *¿Vende madera o árboles de su tierra? ¿A quién, y con qué frecuencia? ¿Cuáles tipos quieren más?*
¿Revendepa yvyra o yvyramata nde yvygui? ¿Mavape, ha mboy veces cada año? ¿Mba´eichagua oipotave hikuai?

14) *¿Quema su chacra? ¿Con que frecuencia, y en que época?*
¿Rehapypa o rembokaipa la kokuepe? ¿Araka´e, mba´e época rejapo?

15) *¿Qué son razones para no plantar o dejar árboles en la chacra? ¿Por qué no los quiere en la chacra?*
¿Mba´erepa nareñotysei o ndarehejasei la yvyramata la kokuepe? ¿Mba´erepa la ndareipotai la kokuepe?

Cambio Climático

16) *¿Ha notado cambios en el clima recién? ¿Cómo? En caso afirmativo, ¿le han afectados los cambios a usted?*
¿Pehechapa cambio clima rehe? ¿Mba´eicha piko? ¿Pende afectapa la cambianguera?

17) *¿Le preocupan estos cambios para el futuro?*
¿Pendepy'apypa ko'ava cambianguera rehe la futuro peguara?

18) *¿Plantar árboles puede ayudar con algunos de estos problemas?*
¿Oñeñoty yvyramatanguerave ikatupa oipytyvo la problemanguerandive?

Appendix 2: Interview guide in English

Interview Guide for Laguna Pytã, Acahay district, Paraguay

Current Patterns of Land Use

1) How many hectares do you have? How many hectares are crop fields? How many are livestock pasture? How many are fallow? Do you have forest on your land? How many hecatres of forest?

2) Which crops do you plant for home consumption? Which do you plant for sale?

3) What types of animals do you have, and how many? Which types of forage do you feed them? Are there times when forage is scarce?

4) Do you sell other agricultural products from your land (*Coco*, fruit, vegetables, cheese/milk, honey)?

5) What does your family use to cook (e.g. firewood, charcoal, electric stove, gas stove)?

6) Who in the house collects firewood? Is firewood abundant or scarce? Has this situation changed over the years (that is, was firewood more or less scarce before)?

7) From where do you collect firewood, and how often? Do you or your family collect from the forest?

8) What are the most serious problems in the crop fields? Put them in order of seriousness.

9) Have you noticed changes in the amount of forest in the community? How?

10) Did you plant the trees in your yard, or did they just sprout naturally? If you didn't plant them, why did you leave them?

11) Did you plant the trees in your crop field, or did they just sprout naturally? If you didn't plant them, why did you leave them? What functions do the trees serve in the field?

12) Which uses or values of trees are most important (e.g. fruit, shade, green manure)?

13) Do you sell wood or trees from your land? To whom and how often? What types do they want the most?

14) Do you burn your fields? How often and in what season?

15) What are some reasons to not plant or leave trees in the field? Why wouldn't you want them in the field?

<u>Climate Change</u>

16) Have you noticed changes in the climate in recent years? How? If so, have they affected you?

17) Do these changes make you worried for the future?

18) Can planting trees help with some of these problems?