Carbon Storage in Coffee Agroecosystems of Southern Costa Rica: Potential Applications for the Clean Development Mechanism

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ABSTRACT

Climate change is one of the greatest environmental and economic threats facing the world today. Human activities, particularly the burning of fossil fuels and clearing of forests, have increased the level of greenhouse gases – the primary contributors to global warming – in the atmosphere. This accumulation is changing the Earth's weather patterns, resulting in higher global temperatures, rising sea levels and a potential shift in the distribution of the world's ecosystems.

There is a growing need to develop strategies that will reduce current levels of greenhouse gases in the atmosphere and curtail future emissions. The Kyoto Protocol represents an international strategy: it establishes emission reduction targets for industrialized countries and incorporates a Clean Development Mechanism for trading carbon credits generated by projects implemented in developing countries.

Tree-based land-use systems, such as the shade-grown coffee agroecosystems of southern Costa Rica, sequester carbon dioxide from the atmosphere and store it in their biomass. Simultaneously, these agroecosystems provide additional products and services to local residents and reduce pressure on existing forests. Therefore, increasing tree cover in coffee production is a viable option for mitigating climate change that also provides social, economic and ecological benefits.

The objective of this study is to generate aboveground carbon-stock inventory data for five coffee production systems in southern Costa Rica, which employ various degrees of structural complexity in their shade layer. The sites include coffee grown with poró (*Erythrina poeppigiana*), guaba (*Inga* sp.), banana (*Musa* spp.), eucalyptus (*Eucalyptus deglupta*) and diversified shade (primarily *Terminalia amazonia* and *Cedrela odorata*). An advanced secondary-forest site at the Los Cusingos Neotropical Bird Sanctuary is used as a control. The carbon-stock of shade trees, coffee bushes and leaf litter is calculated for each site, and the income that could be generated from a one-time payment for the environmental service provided by shade trees (carbon storage) is estimated.

Results indicate the coffee production system that stores the most amount of carbon per hectare in its aboveground biomass is Diversified Shade (31.6 t C ha^{-1}), employing a variety of shade-tree species in three distinct layers. Conversely, the *Inga* sp. system – a shaded monoculture with low structural complexity in its shade layer – stores the least carbon (11.0 t C ha^{-1}). The carbon-stock of the other systems examined falls within this range and varies according to structural complexity, species composition and management practices.

This study recommends that the shade layer in coffee agroecosystems be made more complex for increased carbon storage and maintenance of biodiversity, as previous papers suggest. In the case of southern Costa Rica, a carbon sequestration project implemented under the Clean Development Mechanism could provide farmers with an incentive to select management practices that favour higher carbon-stocks and biodiversity. Such an endeavour would have social, economic and environmental benefits and would provide an example that could be replicated in other small watersheds of Central America.

RESUMEN

El cambio climático es uno de los desafíos más importantes para la comunidad internacional de hoy. Las actividades industriales y la deforestación y quema de los bosques han aumentado la concentración de los gases de invernadero en la atmósfera resultando en un calentamiento de la Tierra, un aumento en los niveles de las aguas océanicas, y un cambio en la distribución de los ecosistemas.

Es importante formular estrategías que reducen las emisiones de los gases de invernadero y que también disminuyen sus concentraciónes en la atmósfera. Un ejemplo es el Mecanismo de Desarollo en Limpio del Kyoto Protocol, la cuál presenta oportunidades por los países en desarollo de participar en el comercio internacional de carbono.

Los sistemas agroforestales de café de Costa Rica sequestran dióxido de carbono desde la atmósfera y lo almacenan en su biomasa. Estos sistemas también proveen madera, frutas, y otros servicios ambientales a sus proprietarios, mientras que disminuyen la deforestatición de los bosques. Esta investigación cuantifíca y valora el servicio ambiental "almacenamiento de carbono" en sistemas agroforestales de café con poró (*Erythrina poeppigiana*), guaba (*Inga* sp.), *Musa* spp., eucalypto (*Eucalyptus deglupta*) y Sombra Diversificada (más de dos especies de árboles de sobra) en el Corredór Biológico Las Nubes/Los Cusingos de Costa Rica. Un sitio de bosque secundario es incluido para comparacíon.

Los resultados indican que el sistema que almacena más carbono es lo de Sombra Diversificada (31.6 t C ha^{-1}) y lo que almacena lo menos es café con guaba (*Inga* sp.) (11.0 t C ha^{-1}). Se recomienda un aumento en la producción de café con sombra, y en el número y divesidad de árboles de sombra utilizados en los cafetales de la zona. A través del Mecanismo de Desarollo en Limpio, el pago por los servicios ambientales que los sistemas agroforestales proveen podría servir como incentivo para render la producción de café en dicho corredór más sostenible.

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FOREWORD

I began my studies at the Faculty of Environmental Studies (FES) of York University with a background in ecology and conservation and some experience working in Latin America. I chose the Masters Program at FES (MES) because I wanted to combine my expertise in the natural sciences with other disciplines that would allow for the opportunity to examine the social, cultural and economic parameters that influence conservation efforts in Latin America today. More specifically, I no longer wanted to explore conservation in isolation from human society, as I had previously done. Instead, I wanted to take a trans-disciplinary approach that would let me explore how the biological values of a region can be conserved while the livelihoods of local people and those of future generations are enhanced.

This led to the formulation of my MES area of concentration, *Conservation and Sustainability in Latin America*, which examines the ecological, economic and socio-cultural foundations for sustainable development in this region of the world. Through its three components – 1. *Concepts of sustainability*, 2. *Principles and concepts for ecologically-based sustainability* and 3. *Theory and practice of conservation in Latin America* – it emphasizes the integration of ecology in formulating ecologically sensible, economically productive and socially just development strategies.

My major paper explores the carbon storage potential of coffee agroecosystems in southern Costa Rica. More specifically, it is a comparative study of the carbon-stock of five coffee production systems observed in the communities of Santa Elena and Quizarrá that employ different types and combinations of shade trees. It uses the Los Cusingos Neotropical Bird Sanctuary as a control treatment, representing the carbon storage potential of an advanced secondary forest site. This research contributes to an overall understanding of forest-based climate change mitigation strategies, and the role that national and international funding mechanisms can play in promoting conservation and sustainable livelihoods in southern Costa Rica. Its results complement those of other studies conducted in the region exploring the environmental services provided by shade-grown coffee systems.

This study integrates the three components of my area of concentration. The first, *concepts of sustainability*, is explored through investigating a potential development strategy for this region of Costa Rica (carbon-sequestration projects) that considers all ecology, economics and long-term cultural sustainability. The second, *principles and concepts for ecologically-based sustainability* is explored through examining the concept of carbon storage in forest-based systems, its measurement and exploration of the relationship between the structural complexity of the shade layer and climate change mitigation potential. The third component, t*heory and practice of conservation in Latin America*, is addressed through examining a tree-based land-use system in southern Costa Rica that fosters the conservation of biodiverisity and protection of the Rio Peñas Blancas watershed. The ecological and management practices of shade-grown coffee production are examined within the socio-cultural and economic parameters of Costa Rica, and increased shade cover for increased carbon storage is recommended.

This research also contributes to fulfilling the objectives of the Las Nubes Conservation and Research Project, namely promoting biodiversity conservation and rural sustainability within a community development framework. More specifically, through the promotion of biodiversity-friendly and sustainable land-use practices in the communities surrounding Las Nubes, the project aims to create a biological corridor between Los Cusingos and Las Nubes. The corridor would connect Los Cusingos to a neighboring network of protected areas including Chirripó National Park and La Amistad Biosphere Reserve (shared by Costa Rica and Panama).

The project also aims to enhance the livelihoods of local residents by expanding conservation practices in the Las Nubes/Los Cusingos Biological Corridor,[1] particularly promoting greater shade-grown coffee production by facilitating access to specialty coffee markets in North America. In this way, farmers can receive a just price for their harvest and can continue to produce coffee, as has been done in this region for many generations. Therefore, understanding the capacity of different coffee production systems to store carbon, and how compensation for the environmental services provided by trees (particularly carbon storage) may offer incentives for increased shade cover, contributes to fulfilling the project's objectives of greater habitat connectivity and rural sustainability in this region.

[1] Since the time of this research, and in honour of the late Dr. Alexander Skutch, a proposal has been submitted to change the name of the Las Nubes/Los Cusingos Biological Corridor to the Dr. Alexander Skutch Biological Corridor.

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I am very grateful for having had the opportunity to conduct my major paper research in a country as wonderful as Costa Rica. The time I spent there was not only valuable in academic terms, but more importantly it was an unforgettable life-experience that resulted in many friendships and cherished memories. None of it would have been possible without the assistance and support of the following.

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CHAPTER 1: INTRODUCTION

1.1 Research Issues, Questions and Objectives

Climate change is one of the greatest challenges now facing humanity and will likely remain so for generations to come. An increasingly large body of evidence suggests that the Earth is getting warmer and that continued warming will have negative effects on human affairs, the natural environment and biodiversity. An increase in the concentration of greenhouse gases (GHGs) in the atmosphere – released primarily through the burning of fossil fuels, deforestation and agricultural and industrial processes – is generally accepted to be the primary contributor to global warming (Pfaff *et al*., 2000). Among these gases, carbon dioxide (CO_2) is of outermost importance. Its abundance in the atmosphere has been steadfastly increasing due to the burning of fossil fuels for energy production, and the clearing and burning of forests.

Given human society's strong reliance on activities that emit carbon dioxide, there is an increasing need to design strategies that will both curtail emissions and remove excess CO_2 from the atmosphere. One way to ease CO_2 accumulation in the atmosphere is by removing it from the air and storing it on land in the form of biomass and soil-carbon reservoirs. While forests play a key role in removing carbon from the atmosphere through photosynthesis, the contribution that agroforestry systems, such as shade-grown coffee production systems, make to this end cannot be ignored. As a result, there is an increasing need to quantify the amount of carbon stored in agroecosystems in order to determine their contribution to climate change mitigation and, more generally, to establish the economic value of the environmental services they provide.

To this end, the research presented in this paper quantifies and compares the amount of carbon stored in the different shade-grown coffee production systems found in the Las Nubes/Los Cusingos Biological Corridor of southern Costa Rica. Its results contribute to an overall understanding of climate change mitigation strategies, and complement those of other studies conducted in this region exploring the environmental benefits provided by coffee agroecosystems, including the provision of habitat for biodiversity (Znajda, 2000 and Hall, 2001). More generally, this research explores the role that carbon sequestration projects and international agreements, such as the Kyoto Protocol, play in addressing global warming and promoting conservation and sustainable livelihoods in Costa Rica.

Figure 1.1 - Map of Costa Rica indicating location of study region (source: http://www.centralamerica.com/maps, 2004)

The central questions addressed by this research are:

- *Do the different coffee production systems found in the Las Nubes/Los Cusingos Biological Corridor of Costa Rica display different aboveground carbon-stocks?*
- *How much carbon is stored in each of the aboveground components of these systems (trees, leaf litter and coffee bushes) and how do these vary between agroecosystems?*
- *How do the aboveground carbon-stocks of the various agroecosystems examined compare to that of an advanced secondary forest site in the region (Los Cusingos)?*

There are a number of objectives associated with these central research questions, including:

- To quantify the aboveground carbon-stock of five coffee production systems found in the Las Nubes/Los Cusingos Biological Corridor of Costa Rica.

- To determine the aboveground carbon-stock of the interior secondary tropical forest of Los Cusingos (this serves as a control treatment for comparison with selected coffee farms).

- To draw general conclusions about the role carbon sequestration projects and the Clean Development Mechanism (CDM) of the Kyoto Protocol can play in mitigating global climate change, promoting conservation, livelihoods and sustainability in Costa Rica.

1.2 Research Context

An international scientific consensus has emerged suggesting that the Earth is getting warmer. Data shows that although global temperatures have fluctuated between warm and cool periods over the decades, the overall trend in the last 150 years is one of net global warming. In conjunction with this warming, there are increasing concerns about alpine glaciers retreating, sea levels rising and ecological and climate zones shifting. The consequences of these changes could be highly disruptive to present and future human societies.

The two primary contributors to global climate change are increased emission in anthropogenic greenhouse gases, particularly carbon dioxide, methane (CH_4) and nitrous oxide (N_20), and increased rates of deforestation and land-use change, particularly in tropical regions. More specifically, Hughton *et al*. (1993) report that if global rates of deforestation and fossil-fuel use continue to rise as they have in past decades, they will result in an increase in the Earth's average temperature of between 0.2^0 and 0.5^0 C per decade over the next century.

Greenhouse gas emissions, particularly CO_2, are likely to continue to rise as the world's population grows and the demand for fossil fuels and forest products increases. Stabilization of this trend will require dramatic and immediate reductions (over 60%) in emissions, particularly of CO_2 as it alone is expected to account for approximately 60% of the Earth's warming over the next century. To illustrate, the effectiveness of $C0_2$ in trapping the Earth's outgoing radiation is four times higher than that of the next most important heat-trapping gas, CH_4 (Houghton, 1993).

The world's oceans have the ability to significantly mediate climate change by absorbing some of the eight billion metric tons of carbon that humanity dumps into the atmosphere each year. This process, however, is slow in comparison to current rates of emission (Houghton, 1993). Alternatively, forests display the potential to accumulate carbon rapidly through the process of photosynthesis, or by removing carbon from the atmosphere and storing it in their biomass and soil reservoirs on land. The role of forests in climate change mitigation is significant; it has been suggested that initiatives that slow deforestation and promote forest regeneration and increased tree cover could offset as much as 12 to 15% of global fossil-fuel carbon emissions between 1995 to 2050 (Watson, 1996).

Given that the Earth's terrestrial vegetation can successfully sequester carbon from the atmosphere and store it on land, it follows that any land-use practice that increases vegetative cover, or slows-down its removal, could have an influence on the global carbon budget by increasing the terrestrial carbon sink and thus mitigating the enhanced greenhouse effect. In this context, agroforestry systems – production systems that employ the inter-planting of trees and crops sequentially or simultaneously – are of interest for at least two reasons. First, their woody component fixes carbon from the atmosphere via photosynthesis and stores it on land. Secondly, agroforestry production systems reduce the pressure to clear additional forested lands for agriculture, as they allow for both the production of cash crops and the maintenance of tree cover (Schroeder, 1994).

Agroforestry has been demonstrated to be a promising mechanism of carbon sequestration in India (Singh *et al*., 2000), Mexico (De Jong *et al*, 1997), sub-Saharan Africa (Unruh *et al*., 1993) and elsewhere. This practice also has strong implications for sustainable development since it provides a viable combination of carbon storage, food production and environmental conservation. More specifically, some of the social and environmental benefits associated with agroforestry practices include helping to secure land tenure, food security and increased farm income, restoring and maintaining aboveground and below-ground biodiversity, expanding corridors between remaining forest patches, prevention of soil erosion and maintenance of watersheds. Moreover, through the incorporation of a woody component, agroforestry systems mitigate the demand for fuelwood and fodder, thus reducing pressure on natural forests to satisfy these needs. Therefore, agroecosystems have the potential to act as carbon sinks and carbon storage pools while contributing to increased farm production, environmental conservation and poverty alleviation (Pandey, 2002).

The international community has recognized the role played by terrestrial vegetation in climate change mitigation and, as a result, forest-based carbon sequestration projects have been incorporated into international agreements such as the Kyoto Protocol. More specifically, the Clean Development Mechanism (CDM), as defined by Article 12 of the 1997 Kyoto Protocol, allows for industrialized countries with greenhouse gas emission reduction commitments to receive credit towards their obligations by investing in projects in developing countries. These projects must produce "certified emission reductions" (CERs) that are "additional to any that would occur in the absence of the activity". Additionally, the projects must contribute to the host country's sustainable development (Hardner *et al*., 2000).

Activities that can be implemented under the CDM include afforestation and reforestation, or projects that directly remove carbon from the atmosphere and store it on land – including those that promote and implement the expansion of agroforestry land-use systems. Therefore, through the creation of a market for carbon, developing countries might be able to increase tree cover and improve their natural environments by rendering those environments economically productive.

As mentioned, climate change mitigation projects that reduce deforestation or forest degradation and promote increased tree cover also contribute to the conservation of biodiversity and the promotion of sustainable livelihoods in the host countries. For this reason, the conservation community has become an important CDM stakeholder and non-governmental organizations in the environmental sector play a key role in implementing pilot projects in forest-based carbon sequestration. The small Central American republic of Costa Rica has been a pioneer in attempting to achieve environmental protection goals by creating markets for the environmental services provided by trees and forests, including the service of carbon sequestration. In this way, Costa Rica provides an attractive option for carbon investment and research – one that is facilitated by the existence of a strong green policy that engages government, civil society and the private sector.

For many years Costa Rica based its economic growth on the waste of its natural resources. In 1950, forests covered more than half of the country; by 1986, forested areas had declined to 29% to make way for the expansion of pasturelands and agriculture (Segura, O., 1997). Beginning in the 1970s, the protection and efficient use of natural resources, including forests, became a priority on the national political agenda. The country's protected area network was expanded and strengthened and deforested areas were partially re-grown either by spontaneous regeneration on abandoned pastures or the establishment of plantations. Although these measures have been important in arresting the loss of Costa Rican forests, outside protected areas forest degradation and deforestation continue to proceed, resulting in an increasingly fragmented forest landscape (Segura, O., 1997).

As a result, in the 1990s a remarkable set of institutional innovations took place in the Costa Rican forestry sector that attempted to address deforestation outside protected areas. In 1996, Costa Rica adopted new forestry legislation (Law Number 7575) that explicitly recognizes the environmental services offered by forests and permits private landowners to be compensated for providing such services to society. These include hydrological services, biodiversity protection, provision of scenic beauty and, most importantly, carbon sequestration. During this time Costa Rica also moved aggressively to participate in the emerging sphere of carbon trading and became a pioneer among developing countries for designing a system that allows landowners to grow a "commodity" (carbon) that can be sold to foreign investors.

In 1994, Costa Rica became the first developing country to establish a Joint Implementation agreement with Norway for the financing of in-country activities that reduce greenhouse gas levels. Following this, similar agreements were signed with the United States and the Netherlands, among others (Miranda *et al*., 2002). These experiences, and in a broader context the existence of a stable democracy, environmental research institutions and NGOs with international recognition and secure land tenure for small and middle-size landowners, have contributed to a favourable climate for further carbon investment in Costa Rica under the auspices of Kyoto's CDM.

Lastly, as agricultural practices occupy approximately one third of the world's total land area, it is imperative to explore the carbon-storage potential of agricultural systems. In this context, the coffee agroecosystem is ideal for investigation, as it is one of the leading production systems and sources of foreign exchange in Latin America, occupying approximately 44% of permanent cropland area and covering 2.7 million hectares (Perfecto *et al*., 1996).

Coffee is traditionally grown in the tropics at middle elevations below a natural forest canopy. However, this traditional method of production has been largely replaced with more intensified systems employing monocultures of genetically improved coffee varieties that are grown in the absence of trees. In Costa Rica, approximately 75% of land currently used for coffee production employs some form of shade, with extremes ranging from very little to excessive (ICAFE, 1998). This "continuum of shade" creates an ideal opportunity to investigate and compare the carbon storage ability of the various coffee production systems found in the Las Nubes/Los Cusingos region and to assess the potential contribution of these systems to climate change mitigation.

Various authors, including Brown (1997), Dixon (1995), Marquez (1997), Budowski (1999) and Segura, M. (1997) have alluded to the importance and need for further research to be conducted that attempts to quantify the amount of carbon sequestered and stored in forest-based systems, including agroforestry systems, as a means of establishing the economic value of the environmental services they provide. In this context, the research presented in this paper seeks to contribute to this new and developing knowledge base and, more generally, to a greater understanding of mechanisms that seeks to improve both the environment and the livelihoods of local people within that environment.

1.3 Organization of Research

The introductory chapter (Chapter 1) presents the reader with the inquiry focus of this research paper, or the questions and objectives that are explored hereinafter. It also places the research topic in a broader context, that of climate change and climate-change mitigation strategies that support the promotion of sustainable livelihoods. Chapter 2 discusses, in further detail, the climate change phenomena and the enhanced greenhouse effect. It then proceeds to explain the role of forests, silvicultural plantations and agroforestry systems in sequestering carbon from the atmosphere and storing it on land. Chapter 3 explores international efforts and agreements in confronting climate change, including the United Nations Framework Convention on Climate Change and the most important protocol to the Convention, the Kyoto Protocol. It also introduces the Clean Development Mechanism and the role of the forestry sector within it. It concludes with a discussion of Costa Rican responses to the Convention and the development of the national Environmental Services Payment programme (ESP). Chapter 4 introduces the reader to the various coffee agroecosystems of southern Costa Rica and discusses benefits associated with shade-grown coffee production. Chapter 5 distinguishes between the processes of carbon sequestration and carbon storage and presents research methods that are currently available for measuring the biomass and carbon-stock of forestry systems. Chapter 6 introduces the study region, research methods and the sampling sites used in this investigation. Chapter 7 presents the carbon-stocks of the various systems examined, and a breakdown of these according to each system's components. It also includes a valuation of the environmental service (carbon storage) provided by shade trees in coffee farms. Lastly, Chapter 8 concludes the research and makes recommendations for future study and investigation in the region.

CHAPTER 2: CLIMATE CHANGE

2.1 The Enhanced Greenhouse Effect

Climate change is one of the most pressing challenges facing the international community today. The reasons are obvious: we all share a common planet, the concentration of greenhouse gases in the atmosphere has markedly increased over the last century and an increasing body of scientific evidence suggests that if the greenhouse effect continues unchecked, the distribution of the Earth's ecological zones as we know them will change. Species will become extinct, sea levels will rise and extreme weather events will become more frequent.

The Earth's atmosphere is naturally composed of layers of gases that allow the sun's energy to penetrate and warm the planet, thus making it habitable. Of the incoming solar radiation, approximately 30% is reflected back to space by clouds and the Earth's surface, 25% is absorbed by the atmosphere and radiated back to space and 45% is absorbed by land and water (Houghton, 1997). The energy that reaches the surface is essential to drive vital processes on Earth such as photosynthesis and water evaporation. Given the size of the planet, its surface temperature should be lower than it actually is, however, due to the presence of greenhouse gases in the atmosphere, including CO_2, nitrous oxide (N_2O), methane (CH_4) and water vapour, the radiation that rebounds back to the atmosphere is intercepted and absorbed, resulting in a natural warming of the Earth's surface and lower atmosphere (Houghton, 1997).

Therefore, the amount of GHGs present in the atmosphere is directly related to the amount of heat retained, and in turn to the character of the climate on Earth. Without the presence of GHGs in the atmosphere the planetary surface would be approximately -15^{o} C, or 30^{o} C cooler than its average temperature of 15^{o} C (Houghton, 1997). It is evident that this natural greenhouse effect is essential for the maintenance of a habitable planet and the Earth as we know it. However, since the Industrial Revolution human activities have released an excess of GHGs into the atmosphere, resulting in an enhanced greenhouse effect. More specifically, the concentration of CO_2 alone in the atmosphere has increased by 30% since pre-industrial times while the global temperature has increased by as much as 0.6^{o} C (Tattenbach *et al*., 1999). Moreover, in the last 100 years alone, sea levels rose by as much as 0.2 meters (Aldy *et al*., 2001).

The main contributors to an increase in the concentration of GHGs in the atmosphere are the burning of fossil fuels (primarily coal, oil and gas), deforestation, agricultural and industrial processes and the discharge of manufactured chlorofluorocarbons (CFCs) into the air. Carbon dioxide is the most important of the greenhouse gases, due to both its abundant concentration and superior ability to trap heat (Houghton, 1997). Each year, humans discharge roughly eight billion metric tonnes of carbon into the atmosphere, 6.5 billion tonnes come from the burning of the coal, oil and natural gas that drive the industrial world's economy and 1.5 billion tonnes come from deforestation and burning of forests to clear land for agriculture and settlement (http://www.worldwatch.org. Accessed February 2, 2004).

2.1.1 The Carbon Cycle

One of the most crucial mechanisms in nature is the circulation of carbon between air, land and water, a process known as the carbon cycle. Humans participate in it constantly by breathing in oxygen, burning carbon ingested through food and exhaling it to the atmosphere in the form of carbon dioxide. In this way, humans receive the energy they need for survival, as do other animals. Fires, rotting wood and the decomposition of organic matter on Earth and in the soil also contribute CO_2 to the atmosphere in the same way. To counterbalance respiration, plants and trees work in the opposite way through the process of photosynthesis – the absorption of carbon dioxide from the atmosphere in the presence of light. The carbon removed from the air is used for growth and stored in the plants' biomass. Oxygen is expelled as a by-product.

Therefore, from the Boreal forest of the north, to tropical rainforests, to phytoplankton blooms in the oceans, plants remove a considerable amount of CO_2 from the atmosphere each year and store it on land in their biomass. The presence and expansion of this terrestrial carbon sink is vital to moderating the anthropogenic buildup of carbon in the atmosphere. Conversely, the loss of forest cover, particularly in the tropics, significantly contributes to CO_2 accumulation by both reducing the vegetative cover available to sequester carbon and by promoting the liberation of CO_2 to the atmosphere though the burning and decomposition of biomass, including organic materials found in soil.
Thus, it is evident that in order to mitigate the enhanced greenhouse effect and its potential deleterious consequences, a combination of curtailing emissions, designing and

implementing the use of cleaner sources of energy, reducing deforestation and forest burning, and increasing tree cover are necessary.

2.2 The Role of Forest-Based Systems in Carbon Sequestration and Storage

Forestry activities contribute to climate change mitigation either by preventing emissions or by sequestering carbon. Conservation and protection of primary and secondary forests, improved forest management, and the production of bioenergy all contribute to preventing emissions. Conversely, forestry activities that contribute to carbon sequestration include the expansion of land-use systems that employ trees, such as the establishment of plantations on degraded lands, natural re-growth of secondary forests and the application of agroforestry practices on agricultural lands (Smith *et al*., 2000). The premise of reforestation for carbon sequestration and increased carbon storage is that human use of the land base has generally reduced woody biomass and that such lands have a potential for re-accumulating carbon if appropriately managed.

2.2.1 Forests

Forests store between 20 and 100 times more carbon per hectare than agricultural lands (Cairns *et al*., 1994). Carbon is sequestered and stored in aboveground biomass, roots, litter and soil. Most of this carbon is lost when forests are removed and replaced by other land-uses. Brown *et al.* (1984) report that tropical moist forests average between 155 and

187 t C ha^{-1} (aboveground), whereas tropical dry forests average between 27 and 63 t C ha^{-1}, depending on location. Table 2.1 presents the carbon storage potential of various ecosystems and illustrates the significant impact that tropical forests have on the global carbon cycle.

The amount of biomass accumulated through forest tree-growth gradually decreases as forest age increases; it follows that the carbon sequestration potential of forests also decreases over time. Nonetheless, Kyrlund (1990) reports that undisturbed tropical moist forests show net growth, and thus net carbon sequestration, for 100 years after establishment. Therefore, although other forest-based systems, such as young plantations, can sequester carbon at a higher rate than mature forests, primary forests conserve much more carbon per hectare, thereby conserving the terrestrial carbon pool and preventing carbon release into the atmosphere (Kyrlund, 1990). Moreover, although fire and oxidation contribute to CO_2 emission, forest gaps created by these events allow for additional carbon to be sequestered, if natural regeneration takes place.

Ecosystem	**Carbon Storage (t C ha^{-1})**
Tropical forest	220
Temperate forest	150
Boreal forest	90
Grassland/savanna	15
Agriculture	5

Table 2.1 - Mean carbon storage of various ecosystems (Source: Cairns *et al*., 1994)

In Costa Rica, various studies have examined the carbon sequestration potential of different forest types. Tosi (1996) reports that humid tropical forests can sequester up to 16.7 t C ha^{-1} yr^{-1} and premontane humid forests 5.1 t C ha^{-1} yr^{-1}. Segura, M. (1997) reports that high-elevation forests in Costa Rica sequester 1.87 t C ha^{-1} yr^{-1} and forests of the Cordillera Volcanica Central remove between 1.9 and 2.6 t C ha^{-1} yr^{-1} from the atmosphere.

The conservation of primary forests for carbon sequestration and storage provides benefits beyond those of climate change mitigation. Forests provide habitat for biodiversity and are essential for the maintenance of indigenous cultures. More specifically, forests provide tangible goods such as food, fiber, fuels and medicine. They are also providers of essential ecological services including water and air purification, soil maintenance, watershed protection and pollination. These ecological goods and services form the basis for sustainable economic development; therefore strategies that conserve forests and help stem global warming are also likely to enable humans to sustainably meet essential needs. Additionally, it may be less expensive to curtail deforestation than to reforest large expanses of land. It follows that slowing deforestation may be a more effective and affordable option to combat climate change than reforestation.

Secondary forests also contribute to the removal of carbon from the atmosphere. Carbon sequestration rates of secondary forests vary depending on the rate of biomass production or growth potential of the vegetation, and prior land-uses (Finengan *et al.*, 1997). Generally, secondary forests that develop on abandoned pasturelands grow slower, due to soil compaction, than those growing on lands previously used for short-term agriculture, thus having an impact on their capacity to accumulate biomass and sequester carbon (Finengan *et al*., 1997). Therefore, slowing the deforestation of primary and secondary forests is imperative for achieving both reductions in carbon emissions and increased carbon sequestration. However, in order for deforestation to be reduced, the causes driving it must be understood. Since human knowledge of deforestation processes is still imperfect, it follows that climate change mitigation strategies must include efforts that contribute to a better understanding of deforestation, its causes and primary actors.

2.2.2 Silvicultural Plantations

Plantations have received much attention as a forest-sector option to combat global warming and it has been suggested that tropical countries, such as Costa Rica, possess adequate climate, soil and conditions for their establishment (Cairns *et al*., 1994). While preserving old-growth forests helps conserve the existing terrestrial carbon pool, establishing plantations on degraded lands or non-forested lands serves to expand it. Furthermore, although primary forests conserve much more carbon per hectare, young plantations sequester carbon at higher rates; especially if fast-growing species with short rotation cycles are planted (Cairns *et al*., 1994).

The value of plantation forestry in carbon sequestration rests in its temporary utility; since plantations conserve carbon as biomass only for a limited period before newly planted trees are cut. The effectiveness of plantations in removing accumulated carbon from the atmosphere depends primarily on the species employed, the rotation cycle and, most importantly, on the end use of the wood produced. Employing fast-growing species that produce good quality timber is ideal, as they provide the best scenario for long-term storage of fixed carbon.

In a study of aboveground biomass accumulation in mixed and pure plantations in the Atlantic humid lowlands of Costa Rica, Montagnini *et al*. (1998) report that the average annual biomass increment in mixed plantations is 10 - 13 t ha^{-1} and that they constitute a longer-term sink for fixed carbon than pure plantations, due to the presence of slower-growing species in mixed plantations. Conversely, Asumadu (1999) repots that one hectare of forest plantation can sequesters up to 10 t C yr^{-1}, depending on local conditions and the species employed.

Live trees usually comprise the greatest fraction of the aboveground biomass found in plantations. For instance, in one of the plantations examined by Montagnini *et al*. (1998), the overstory comprised 92 % of the total aboveground biomass, while the understory and litter components comprised 3.7 % and 4.3 %, respectively. Moreover, the undergrowth component is expected to make an even smaller contribution to biomass accumulation in highly managed plantations, although this may vary with weeding intensity and planting distance. The absence of a significant understory and litter layer in plantations also has an effect on their ability to sustain biodiversity.

Because fast-growing tropical tree plantations accumulate considerable amounts of nutrients in their biomass over a relatively short time period, site fertility declines and limits the sustainability of a plantation over time. Soil fertility in plantations can decrease through excessive removal of living biomass, especially if the nutrients in tree crowns are lost through harvest or site preparation. This factor can be particularly serious when plantations are established on soils that are originally nutrient deficient. In their study, Montagnini *et al*. (1998) report that four years after planting, decreases in soil nutrients were apparent in pure plantations employing fast-growing species; while mixed plots showed intermediate values for the nutrients examined and sometimes, even improved soil conditions. Thus, when examining the role of tropical plantations as carbon sinks an integrated approach must be taken that not only considers their carbon sequestration rates, but also their potential deleterious effects on nutrient pools, biodiversity and people.

Concerns regarding large-scale expansion of plantations in tropical countries as a global warming response are not only environmental and technical in nature, but also social. More specifically, the installment of plantations sometimes requires the relocation of people to surrounding regions, thus disrupting local societies and, at times, even interrupting the provision of goods and services to relocated communities (Fearnside, 1999). Moreover, the spatial pattern of commercial plantations – characterized by the usurpation of large, continuous expanses of land in order to minimize transportation and management costs – does not always provide local populations with sufficient space for food production.

Well-designed and managed tropical plantations can provide a viable alternative to help reduce levels of atmospheric CO_2. However, caution must be applied to ensure that all economic, social and environmental dimensions are considered and addressed. Plantation forestry may be appropriate on degraded lands, where there is a need for watershed rehabilitation or an acute fuelwood shortage. However, given that carbon loss from deforestation occurs more rapidly than reforestation can sequester carbon, it may be less effective to focus on plantations, except as an alternative to removing more primary forest. Thus, in terms of mitigating climate change, reducing deforestation rates and protecting primary and secondary tropical forests are more attractive options than promoting silvicultural plantations.

2.2.3 Agroforestry Systems

Agroforestry refers to a land-use system where woody perennials are deliberately used in the same land-management unit as annual agricultural crops and/or animals with the aim of obtaining greater outputs on a sustained basis (Nair, 1987). Agroforestry relies on the complex interaction between trees and other elements of the system, provides habitat for biological diversity, and produces goods and services. Types of agroforestry practices are as diverse as the number of locations where they are practiced. More specifically, agroforestry systems include trees on farm boundaries, shifting cultivation, home gardens, crops grown under shade, alley cropping, live fences and silvipastoral systems, among others. Despite the large variety of systems, most types of agroforestry employ one of three combinations. Agrosilviculture combines trees and annual crops, silvopastoralism combines trees and grazing animals on wooded pasture or rangeland, and agrosilvopastoralism combines trees, crops and livestock (Nair, 1987).

Although various forms of agroforestry are practiced globally, their most widespread application is in the tropics. Approximately 1.2 billion people, or 20 % of the world's population, depend directly on agroforestry products and services in developing countries, and most agroforestry practitioners are found in rural areas (Pandey, 2002). Given its significance and widespread use, an important question to be addressed is whether agroforestry, implemented locally to satisfy local needs, can also provide carbon sequestration and storage benefits to help mitigate the accumulation of CO_2 in the atmosphere.

In the context of the global carbon cycle, agroforestry is important for two primary reasons (Pandey, 2002): (1) the tree component in agroforestry systems fixes carbon from the atmosphere via photosynthesis and stores it on land. More specifically, trees employed in agroforestry systems act as carbon sinks until they are cut or die. (2) Agroforestry contributes to reduced deforestation by alleviating the need to clear additional forests for agriculture or shifting cultivation. Pandey (2002) reports that agroforestry systems can sequester carbon at a rate of 0.2 to 3.1 t C ha^{-1} yr^{-1}, and estimates indicate that agroforestry has the potential to sequester 7 Gt of carbon between 1995 and 2050 globally; however, better country-specific assessments are needed to refine this estimate.[2]

Dixon (1995) reports that the carbon storage potential of agroforestry systems ranges from 12 to 228 t C ha^{-1}, with agroforestry in the humid tropics displaying the greatest carbon storage ability. Moreover, Kursten *et al*. (1993) report that the amount of carbon sequestered directly by the aboveground tree component of agroforestry systems ranges between 3 and 25 t C ha^{-1}. Carbon storage in agroforestry systems is highly dependent on the tree species employed, the density of planting, the age of the various components and on local conditions including climate, soil type and management practices applied, for example pruning or harvesting of timber.

Furthermore, the net effects on carbon storage of promoting agroforestry depend on the carbon content of the land-use practice it replaces. According to Schroeder (1994), there are at least three land-type categories that would be ideal candidates for conversion to agroforestry: currently degraded and non-productive land, agricultural or pastureland that could be supplemented with tree planting, and land under short fallow agriculture. The first two categories generally display depleted aboveground carbon pools; thus the net carbon increase provided by conversion to agroforestry would be most significant under these conditions.

Not only do agroforestry practices have the potential to store carbon and remove CO_2 from the atmosphere through the growth of trees and shrubs, but they also have strong implications for sustainable development due to the secondary social and environmental benefits they provide. More specifically, agroforestry systems help to attain food security and secure land tenure in developing countries, increase farm income, restore and maintain above and below-ground biodiversity, maintain watershed hydrology and decrease soil erosion. For example, in an agroforestry system employing shade trees over

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[2] Gt (gigatonne) = one million metric tonnes

crops, the tree component provides increased soil nutrients for the crop, fuelwood for home use, fodder for livestock, and shelterbelts that increase soil moisture, decrease erosion and moderate micro-climate. Although a single agroforestry practice will not provide all these benefits at once, successful systems are documented throughout the temperate and tropical biomes, and the potential for application of agroforestry systems remains significantly untapped (Nair, 1987).

2.2.3.1 Shade-Grown Coffee and Carbon Storage

Traditionally, coffee is grown under the shade of natural unaltered forest canopy, where the composition and structure of the forest remains intact. However, due to agricultural intensification and expansion, much of the coffee grown today is produced in the form of monocultures that, despite physical and social drawbacks, result in greater production and yields. In Costa Rica, approximately 75 % of the area currently used for coffee production employs some form of shade, ranging in intensity from very little to excessive (ICAFE, 1998). Like other agroforestry systems that employ a woody component, shade-grown coffee agroecosystems contribute to the removal of carbon from the atmosphere and its storage on land.

A study conducted by Fournier (1996) in Ciudad Colón, Costa Rica, found that a shade-grown coffee farm employing *Erythrina poeppigiana* shade trees contains 198 t C ha^{-1} – including all aboveground, root, soil and leaf-litter components. Conversely, in a study of the shade-coffee production systems of the Valle Central, Costa Rica, Avila Vargas

(2000) reports a total carbon-stock (including soil) of 195 t C ha^{-1} when coffee is grown under the shade of *Erythrina poeppigiana*, and 168.74 t C ha^{-1} when grown under *Eucalyptus deglupta*.

Marquez (1997) reports that coffee grown under the shade of *Inga* and *Musa* species in Guatemala contains a total carbon-stock of 115.5 t C ha^{-1}, including all above and below-ground components. Also in Guatemala, Alvarado *et al*. (1999) report that coffee agroecosystems contain, on average, 91.64 t C ha^{-1}, including all system components (species of shade trees employed are not specified). Lastly, in a study conducted on coffee farms employing different types of shade trees in the Metagalpa region of Nicargua, Suárez Pascua (2002) reports a range in carbon storage from 144.7 t C ha^{-1} to 166.7 t C ha^{-1}. Furthermore, this study found that 75-97 % of the carbon stored in the farms examined resides in the soil, 5.6-14 % in the shade trees, 2.3-3.9 % in the leaf litter, and 0.1-1.5 % in the coffee bushes.

CHAPTER 3: INTERNATIONAL AGREEMENTS AND PAYMENT FOR ENVIRONMENTAL SERVICES

Although some scientific questions about global warming remain unanswered, it is certain that it is a global threat, affecting all countries and societies. Addressing it requires co-operation between nations and demands policy action by the international community. Global co-operation entails not only further study of the science of climate change, but also of its economic and social impacts and its potential resolutions.

The first international meeting that focused on environmental issues and the need for international co-operation in addressing them was held in Stockholm in 1972. Better known as the United Nations Conference on the Human Environment, it led to the establishment of the United Nations Environment Programme (UNEP), which encourages international collaboration among nations and acts as a central monitoring network for global environmental issues. Although the conference was significant because it was the first such global meeting on the environment, it was not meant to solve specific problems, but rather to be an initial step toward addressing them (Houghton, 1990).

In 1988, the UNEP created the Intergovernmental Panel on Climate Change (IPCC), an advisory group of officials and scientists from a number of countries, to examine the causes and impacts of, as well as potential responses to, climate change (Houghton, 1990). That same year, representatives from forty-six nations met in Toronto at the

World Conference on the Changing Atmosphere. At the conclusion of that meeting, the delegates recommended an international policy of reducing GHG emissions by 20% from their 1988 levels by 2005. Moreover, given the primary role that unsustainable energy consumption patterns play in global climate change, the delegates urged the rapid adoption of greater efficiency in energy use and greater reliance on greener sources of energy (Houghton, 1990).

In 1990, the IPCC published a report titled *Scientific Assessment of Climate Change*, stating that to stabilize GHG concentrations in the atmosphere at 1990 levels would require an immediate reduction in greenhouse gas emissions of 60% (Houghton, 1990). Due to this urgency, at the World Climate Conference that year governments from around the world recognized that a convention must be negotiated to protect global climate patterns from human disruption. The outcome was the signing of the 1992 United Nations Framework Convention on Climate Change (UNFCCC).

3.1 The UN Framework Convention on Climate Change

Representatives from 166 countries signed the UNFCCC at the 1992 Earth Summit in Rio de Janeiro. It stipulated that industrialized countries develop national emission standards and limits and report periodically on progress to the Conference of the Parties (COP) (http://UNFCC.int Accessed March 2, 2004). Specific targets or dates were not consolidated at the time; instead, countries accepted a more ambiguous goal of reducing their GHG emissions to "earlier levels" that would prevent dangerous interference to the climate system. Moreover, the convention states that this goal "should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (http://UNFCC.int Accessed March 2, 2004).

The Convention proposed to achieve this through a series of commitments from signatory nations, including (http://UNFCC.int. Accessed March 2, 2004):

- annual reporting of national GHG inventories;
- regular disclosure and review of progress on regional GHG abatement programs;
- technological assistance to developing countries especially vulnerable to climate change;

and

- participation in the meetings of the Conference of Parties (COP) to the Convention.

In 1994, 186 countries ratified the Convention, including Costa Rica (http://UNFCC.int. Accessed March 2, 2004). Following this, the Berlin Mandate was signed at COP-1, which stipulated a pilot phase for "activities implemented jointly" (AIJ). This pilot program (1996-2000) was established to promote investment in projects that reduce, sequester or avoid GHG emissions and that are implemented jointly among Annex I Parties to the Convention (industrialized countries) or between Annex I and non-Annex I countries (developing countries) (http://UNFCC.int. Accessed March 2, 2004). AIJ was the first program to be developed with the intention of creating an international carbon market for climate change mitigation.

The UNFCCC also included provisions for updates (called protocols) that would set mandatory emission limits for Annex I countries and stronger stipulations on AIJ. The principal update to the Conference is the Kyoto Protocol, which has become more widely known than the UNFCCC itself.

3.2 The Kyoto Protocol

The Kyoto Protocol to the UNFCCC was adopted in 1997 at COP-3 in Kyoto, Japan. The Protocol represents a potentially legally binding international treaty that stipulates specific actions to be taken to combat climate change. More specifically, although required emission-reductions differ for each country, industrialized countries are committed to collectively reduce GHG emissions by 5 % below 1990 levels by the years 2008-2012. The emission reduction targets (with respect to 1990 levels) taken on by developed countries in Kyoto include 8 % by the European Union, 7 % by the United States and 6 % by Canada and Japan. Russia's commitment is to stabilize emissions at 1990 levels, and developing nations are not subject to emissions reduction caps (http://UNFCC.int. Accessed March 2, 2004).

The Kyoto Protocol was signed by 84 countries in 1999, however, it will only enter into force when a minimum of 55 nations that account for at least 55 % of the Annex I carbon dioxide emissions in 1990 have ratified it. Thus far, 120 countries have ratified the Protocol, including Canada and Costa Rica. However, since these countries collectively represent only 44% of the total 1990 carbon dioxide emissions, the Protocol has yet to enter into force (http://UNFCC.int. Accessed March 2, 2004). Moreover, several events have jeopardized the fate of the Protocol, including a decision by the United States (the largest emitter of CO_2 in the world) not to ratify and uncertainty on ratification by Russia.[3]

The Kyoto Protocol offers three mechanisms for industrialized countries to try to meet their target reductions. These include International Emissions Trading (IET), Joint Implementation (JI) and the Clean Development Mechanism (CDM). IET and JI apply only to nations with quantified emission caps (industrialized countries), whereas the CDM allows for developing nations to participate in the Protocol.

3.2.1 The Clean Development Mechanism

The Clean Development Mechanism (CDM), as defined by Article 12 of the Kyoto Protocol, was developed as a successor to AIJ. It allows for countries with legally binding GHG emission reduction commitments to receive credit towards their obligations by investing in projects that enhance carbon sequestration or reduce emissions in the forestry or energy sectors of developing countries. More specifically, the stated purposes of the CDM (Article 12.2) are to (Greenpeace International, 1998):

[3] At the time of this writing.

> “ assist Parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention”

and

> “assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments under Article 3 (industrialized country commitments)”.

Therefore, the CDM is original in its objectives and differs from other emission trading mechanism such as JI and IET in that its stated purpose is not only to lower the costs of reducing emissions for Annex I countries, but also to promote sustainable development in host countries.

The CDM allows industrialized countries that have ratified Kyoto to use emission credits gained from projects undertaken in participating developing countries to meet “a part” of their emission reduction obligations under the Protocol. Industrialized countries are permitted to receive credit toward their Kyoto commitments for AIJ carried out before the first budget period of 2008-2012, starting in 2000, provided that the Kyoto Protocol enters into force. Certifiable projects under the CDM need to meet three general criteria (Article 12.5) (Greenpeace International, 1998):

- voluntary participation of each Party;

- produce Certified Emission Reductions (CERs), or "real, measurable, and long-term benefits related to the mitigation of climate change." CERs are specifically authorized to apply to Annex I emission reduction targets, they must be certified by a third party and must be renewed every five years to ensure continuity in emission reduction or carbon sequestration;

and

- produce reductions in emissions or enhanced sequestration "that are additional to any that would occur in the absence of the certified project activity".

Prospective investors in the CDM and host countries might place different values on its stated objectives, with industrialized countries favouring projects that provide the most cost-effective emission reductions and host countries favouring those that contribute most to national and local development priorities. The wide range of domestic and international emission reduction strategies made available by the Protocol, together with the availability of host countries to participate, implies that only those CDM projects that satisfy both investor and host-country interests will be implemented (Hardner *et al.*, 2000).

Although participation by non-Annex I countries in CDM projects is voluntary, Steward *et al*. (2000) outline three benefits they may bring to host countries, including:

- increased financial and technological transfer to support the revitalization of industry, equipment and economic development;

- increased social and environmental health (projects that promote a transition to cleaner sources of energy and a reduction in GHG emissions will contribute to increased health of local populations; likewise, those that support the revitalization of forests will contribute to the maintenance of soil productivity, water quality and biodiversity);

and

- since emission credits under the CDM can be generated starting in 2000, an incentive is created for Annex I countries to begin emission abatement activities before the initial budget period of 2008-2012, thus effectively producing economic and environmental benefits in developing countries that are additional to those accrued during that period.

3.2.2 International Funds

Since the signing of the Kyoto Protocol a number of international funds have been created to support climate change mitigation projects worldwide. In 1999, the Word Bank created the Prototype Carbon Fund (PCF), with the objective of combating climate change, promoting sustainable development and demonstrating possibilities for public-private partnerships. GHG emission reduction projects supported by the PCF can be implemented either in industrialized countries, through JI, or in developing countries through the CDM. The PCF – with a total investment of nearly US $200 million – currently supports over 30 projects, including a hydro and wind project in Costa Rica that was approved in 2002 (http://www.prototypecarbonfund.org. Accessed March 17, 2004).

However, much controversy surrounds the operation and efficiency of the PCF. A number of environmental, human rights and indigenous groups have referred to the fund as "destructive green-wash," and have criticized it for supporting projects that exacerbate existing human rights violations and environmental destruction in developing countries (Barry, 2004). Nevertheless, the PCF is scheduled to continue operating until 2012.

In 2003, at the World Summit on Sustainable Development, the World Bank announced the launch of its Community Development Carbon Fund (CDCF), with a budget of US $100 million. The fund is specifically designed to support small-scale projects implemented in developing countries, including mini-hydro and agroforestry activities, which might be at a disadvantage when competing for carbon finance due to their small-scale and high risk. Requirements that must be met in order to qualify for CDCF funding include: (1) the project must be community-based, (2) the project must promote sustainable development in the host country, and (3) the project must not sequester more than 10,000 t CO_2 yr^{-1} (in the case of a forestry projects) (http://www.carbonfinance.org. Accessed March 17, 2004).

Also in 2003, the Special Climate Change Fund (SCCF) and Least Developed Countries Fund (LDCF) were made operational. The Global Environment Facility (GEF) administers both funds; the SCCF supports a number of project activities including adaptation, mitigation and technology transfer, while the LDCF provides financial resources to developing countries for implementing projects under the CDM (http://UNFCC.int. Accessed March 17, 2004).

3.2.3 The Forestry Sector within the Clean Development Mechanism

Projects eligible for credit under the CDM must be implemented in either the energy or forestry sectors of developing countries. COP-7, held in 2001, resulted in the Marrakech Accords, agreements outlining the options available to Annex I countries trying to meet emission-reduction targets through land-use, land-use change and forestry (LULUCF) activities. More specifically, the Accords affirm that the implementation of LULUCF activities must "contribute to the conservation of biodiversity and sustainable use of natural resources," and restrict eligible project activities to those of afforestation[4] and reforestation[5] (Niesten *et al*., 2002). These could range in scope from small-scale agroforestry and native forest restoration to large-scale industrial plantations. In the case

[4] Defined within the CDM as "the direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources".

[5] Defined within the CDM as "the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested but that has been converted to non-forested land".

of agroforestry projects, credits can be generated only by the tree component of the system; the carbon sequestered by the crops is inadmissible for credit.

Projects implemented under the CDM resemble those of AIJ, where an industrialized country and a developing country agree to collaborate on a project that is later certified by an independent auditor. Prior to the initiation of the project, the "baseline" or previous amount of carbon emitted or sequestered from the area in question must be established. This figure is then used to show that declared GHG emission reductions or increased carbon sequestration are "additional" to what would have occurred in the absence of the project. Technical questions remain regarding how to measure and monitor the progress and outcome of LULUCF projects. Nonetheless, it is imperative that some independent entity monitor project-progress in order to ensure the proposed benefits accrue over time (CERs must be renewed every five years) (Niesten *et al.*, 2002).

Rules governing LULUCF activities were further discussed in December 2003 at COP-9 in Milan, where the Parties adopted decisions setting forth the modalities and procedures for sink projects in the first commitment period (2008-2012). The primary consensus reached was the differentiation between temporary CERs (tCERs), valid for only one commitment period, and long-term CERs (lCERs), valid for the project's full crediting period (either 20 years, with the possibility of two renewals for a total of 60 years, or 30 years with no renewals) (http://UNFCC.int. Accessed April 5, 2004). However, despite the adoption of amendments to the functioning of LULUCF activities within the CDM, the Milan conference produced only modest progress, as uncertainty over the fate of the Kyoto Protocol emerged once again as Russia announced that it might not ratify.

Moreover, although during COP-9 most delegates reaffirmed their strong support for the Protocol, a growing interest and acknowledgment of efforts being undertaken outside the UNFCCC process emerged, along with recognition that future efforts in climate change mitigation must be pursued both within and outside the UNFCCC. COP-10 is scheduled to take place in Buenos Aires in late 2004, despite suggestions by some delegates to postpone the meeting until 2005 to allow additional time for Russian ratification (http://UNFCC.int. Accessed April 5, 2004).

3.2.4 Criticism of LULUCF Activities within the CDM

The idea of creating a carbon market and incorporating LULUCF activities to generate carbon credit within it has been controversial since its inception (Smith *et al*., 2000). Supporters of it argue that forest owners and managers in developing countries need to be compensated for the environmental services they provide, thus "making conservation pay" and creating incentives for afforestation and reforestation. Others believe that carbon farming ignores the full range of goods and services provided by forests, and that climate change mitigation would be more effective if it focused on reducing the use of fossil-fuels – the primary source of GHGs (Smith *et al*., 2000). Therefore, some perceive the CDM as a way for industrialized countries to "export" their pollution without really addressing the root of the problem, namely unsustainable consumption patters.

Criticisms for incorporating LULUCF activities in the CDM include:

(1) Additionality - In order for a project to qualify under the CDM of the Kyoto Protocol, it must result in GHG emission reductions that would not occur in the absence of the project. This means that forest conservation projects would only qualify if the conserved forest is under threat of deforestation; projects aiming to protect forests against future encroachment do not qualify for funding. Also, reforestation projects only qualify if they are not financially viable without CDM funding or support for implementation. Therefore, it is argued that initial estimates of available land for LULUCF activities need to be reduced, since many projects will not qualify due to additionality restrictions (Smith *et al*., 2000).

(2) Leakage - This occurs when the GHG emission reductions achieved by a project cause increased emissions in another area. For instance, leakage would occur if a community decided to reforest and protect an area and later deforested nearby lands to compensate for reduced access to forest products. Another example of leakage is provided by projects that restrict logging with the aim of protecting forests and later result in increased timber prices, thus translating into increased logging elsewhere. This situation would offset the original sequestration benefits of the project by reducing carbon uptake and potentially increasing carbon emissions elsewhere (Gelbspan, 2000).

(3) Non-permanence and duration of forestry projects – Smith *et al*. (2000) argue that LULUCF projects are not competitive because they only sequester carbon while the

forest exists. By comparison, when a new clean technology is invented and adopted it exists in perpetuity, thus preventing or reducing GHG emissions ad infinitum. Moreover, a host-country's conservation and development objectives may change with time, particularity if social, market and political conditions change, thus rendering long-term forest conservation obligations and/or project renewal potentially unappealing. Therefore, it is argued that non-permanent forestry projects should be viewed more as a way of "buying time" until more permanent ways of reducing emissions become available.

(4) Political factors - Because LULUCF activities within the CDM of the Kyoto Protocol are influenced by a large number of stakeholders (government, local communities, private sector, NGOs, etc.), their implementation may be more complex and time consuming than energy-sector alternatives. Moreover, forest conservation and reforestation may be unattractive to some developing countries, particularly those with strong pressures to convert forests to other uses. As a result, these countries may be unwilling to participate in carbon markets, thus limiting the scope of LULUCF activities to countries that have displayed the political will to conserve or increase forest cover (Richards *et al*., 2001).

3.3 Costa Rican Responses to UNFCCC

3.3.1 Valuation and Payment for Environmental Services

Costa Rica ratified the UNFCCC in 1994 and the Kyoto Protocol in 2002 (OCIC, 2000). In response to obligations assumed in the UNFCCC, this Central American republic has developed a strong institutional framework to achieve the design and implementation of AIJ under the Convention. In 1995, a co-operative agreement was signed between the Costa Rican government and the non-governmental and private sectors to create the Costa Rican Office on Joint Implementation (OCIC). This agreement was supported by the Ministry of Environment and Energy (MINAE), the Foundation for the Development of the Central Volcanic Mountain Range (FUNDECOR, an NGO with extensive experience in forestry), and the Costa Rican Association of Energy Producers (ACOPE, representing private generators of electricity from renewable sources). The OCIC facilitates investment, provides guidelines, evaluates and follows-up on AIJ under UNFCCC and reports to the UNFCCC Secretary (OCIC, 1999).

Further to the creation of the OCIC, Costa Rica adopted a new Forestry Law (Law Number 7575), which explicitly recognizes the environmental services provided by forests and permits landholders to be compensated for them through the national Environmental Services Payment programme (ESP). Its three primary goals are (Chomitz *et al.*, 1998):

- to produce the socially optimal level of carbon sequestration and hydrological services;

- to conserve biodiversity;

and

- to boost smallholder incomes.

Adopted in 1996, Law No. 7575 explicitly recognizes four environmental services provided by forests, including carbon fixation, hydrological services, biodiversity protection and the provision of scenic beauty. Moreover, the Law defines sources of financing and rules for the disbursement of funds for environmental service(s) provided. More specifically, funds are to be channeled through the National Forestry Fund (FONAFIFO), a subsidiary organization of MINAE; its primary objective is to "get funds for the national ESP programme and other necessary activities to develop the natural resources sector." (Chomitz *et al*., 1998).

FONAFIFO receives its funding from three sources (see Table 3.1). The main source is the fossil fuel tax raised by the Costa Rican government. In 2003, the fund received approximately 3.5% of the annual national fossil fuel tax revenue, or about US $13 million.[6] Secondly, FONAFIFO receives funding from the sale of carbon bonds on the international market, such as those sold thus far under AIJ agreements. These funds are collected on the international carbon market by OCIC and transferred to FONAFIFO. Lastly, FONAFIFO receives funding from private hydropower plants interested in protecting the watersheds within which they operate. This money is transferred through the ESP programme to landowners in the watershed that conserve existing forests or reforest their lands under legally binding contracts (Subak, 1999).

Forest Services	Origin of Payment for Services
Carbon fixation	Sale of carbon bonds (CTOs)
Hydrological services	Hydropower companies
Biodiversity protection	Gasoline tax
Provision of scenic beauty	

Table 3.1 - Forest services recognized in Forestry Law No. 7575

Some of the environmental services recognized by the Forestry Law are provided directly by the government, either from national parks or public lands. However, the most innovative part of the ESP programme is the incorporation of services provided by private landowners under contract. Currently, the programme reimburses three types of action by landowners: reforestation, sustainable forest management and forest preservation (Chomitz *et al*., 1998). The details of eligible activities are provided in Table 3.2. In each case, the payments are made over a five-year period, during which the landowners cede their environmental service rights to FONAFIFO. Upon completion of the five years, they are free to renegotiate prices, however, they must commit to manage

[6] Ing. José Cubero Maya of FONAFIFO. August 1, 2003, San José, Costa Rica. Personal Communication.

or protect the forest for a period of twenty years (fifteen in the case of reforestation). This obligation is noted in the contract and applies to future purchasers of the land.

The landowner, in conjunction with a supervising forester (usually from FUNDECOR), must establish a detailed management plan for the property, which becomes part of the contract. The forester is then required to inspect the property at least twice annually and payments are made upon receipt of a positive report. Payments to private landowners under the ESP programme were formally started in 1997. During that year, US $14 million was allocated to 79,000 ha of forest protection, 10,000 ha of forest management and 6,500 ha of reforestation (Chomitz *et al*., 1998).

Local intermediaries and NGOs, such as FUNDECOR, play a vital role in the implementation and functioning of the ESP programme. More specifically, FUNDECOR arbitrates between government and landowners. It provides landowners with many services including the design of management plans, monitoring of performance and handling of paperwork related to the application for ESP payments. It also provides technical assistance to reforestation and sustainable management projects and contributes funding for the purchase of seedlings.[7] Participation in the ESP programme by the non-governmental sector is thus imperative for its efficient functioning.

Activity	Current name of instrument	Minimum area (ha)	Maximum area (ha)	Total payment (US $ ha^{-1} over 5 years)	Annual payment schedule (per year)
Reforestation	Certificado de abono forestal (CAF)	1	--	400	50%, 20%, 15%, 10%, 5%
Reforestation (by group of small producers)	Certificado de abono forestal adelantado (CAFA)	1	10	400	50%, 20%, 15%, 10%, 5%
Forest management	Certificado de abono forestal para manejo del bosque natural (CAFMA)	2	300	300	50%, 20%, 10%, 10%, 10%
Forest regeneration	--	2	300	200	20% annually
Forest protection	Certificado de proteccion del bosque	2	300	200	20% annually
Agroforestry (introduced in 2003)	--	--	Total of 3500 trees	0.80 per tree	Limited to 3 yrs, 65%, 20%, 15%

Table 3.2 - Payment levels and eligible areas for private ESP contracts (Source: Chomitz *et al*., 1998 and personal communication with engineers from FONAFIFO)

3.3.2 Certified Tradable Offsets

Another national response to the ratification of the UNFCCC was the creation of a "carbon commodity" that could be sold internationally by Costa Rica under AIJ. Certifiable Tradable Offsets (CTOs) are externally certified reductions in GHG emissions

[7] Ing. José Cubero Maya of FONAFIFO. August 1, 2003, San José, Costa Rica. Personal Communtication.

(expressed in tonnes of carbon) that have been reduced or compensated through AIJ projects implemented in Costa Rica, and which have been reported to the Secretary of the UNFCCC. The offset amount is the difference between the actual carbon emissions and the baseline emissions, or those that would have been emitted in the absence of the project (Miranda *et al*., 2002).

CTOs are very similar in nature to the CERs created by the CDM of Kyoto Protocol, inasmuch as interested buyers in industrialized countries can purchase CTOs in order to offset their domestic GHG emissions. CTOs purchased after the year 2000 will be creditable under the 2008-2012 commitment period of the CDM, as long as the Protocol comes into force.

Costa Rica has created and marketed CTOs under three umbrella projects: the Protected Areas Project, which creates CTOs through the expansion of the national protected area network; the Private Forestry Project, which creates offsets based on ESP contracts as described above; and projects that sponsor energy-related activities. Funds received from the sale of CTOs are deposited into the National Specific Fund for the Conservation and Development of Sinks and Deposits of GHGs, managed by OCIC. All funds are eventually transferred to FONAFIFO for financing further activities (Miranda *et al*., 2002).

Costa Rica has been implementing AIJ since the mid-1990s. Transactions have been made with a number of countries, most notably Norway and the United States (OCIC, 1999). All projects have been directed to improve both environmental quality and the quality of life of small and middle-size landowners who have received social and economic benefits from them. In this way, Costa Rica has become the leading developing country on the carbon market, with extensive experience on the design, functioning and implementation of carbon transactions and payment for environmental services.

3.3.3 Costa Rican AIJ Project Summary

Some of the most important AIJ projects implemented to date in Costa Rica include (details presented in Table 3.3) (OCIC, 1999):

ECOLAND - Piedras Blancas National Park (Costa Rica/USA)

This project aims to preserve tropical forest through the purchase of approximately 2,340 ha in the Piedras Blancas National Park of Costa Rica at a cost of US $1 million. The land was transferred to the Costa Rican national protected areas system managed by MINAE. Tenaska Inc., an independent energy producer in the USA, received GHG emission reduction benefits of 366,200 t C, as a result of avoided deforestation and stimulation of natural regeneration.

KLINKI Forestry Project (Costa Rica/USA)

This project involves hundreds of private landowners in the Turrialba region of Costa Rica and a number of U.S. organizations interested in compensating their GHG emissions. The primary goal of the project is to convert pastures and unproductive lands to commercial tree plantations by promoting the planting of 6,000 ha of private farms with a mixture of fast-growing species, including Klinki trees (*Araucaria hunsteinii*) as a major component. GHG mitigation is estimated at 1,999,495 t C and project collaborators include Reforest the Tropics, a non-profit organization that will distribute the GHG offsets to companies and organizations in the USA, the Forestry School of Yale University and CATIE of Costa Rica.

Private Forestry Project (PFP Project) (Costa Rica/Norway)

The Private Forestry Project (PFP) began with the sale of 200,000 tonnes of carbon (sold at US $10/tonne) to the government of Norway and a group of private Norwegian companies. The objective of the project is the conservation, sustainable management and reforestation of 4,000 ha in the Virilla River watershed of Costa Rica undertaken in order to increase the efficiency of a hydropower plant found in the region though increased availability of water and water quality. The Norwegians invested a total of US $2 million in CTOs, which are executed and administered by FONAFIFO.

Moreover, the project incorporates an agreement between the government and the private forestry sectors of Costa Rica to annually promote, through the ESP programme, the planting of 15,000 ha of land and the sustainable use and protection of 7,000 and 50,000 ha of existing forest, respectively. The government, based on technical criteria provided by MINAE and FONAFIFO, fixes the annual incentive payment per hectare for each type of activity. Other participants in this project include OCIC, FUNDECOR and the National Power and Light Company of Costa Rica.

Consolidation of Protected Areas Project (PAP) (Costa Rica/USA)

This project aims to consolidate, both territorially and financially, twenty Costa Rican national parks and seven biological reserves through the purchase of intermediary lands not currently protected and the establishment of a trust fund for protection in perpetuity. The project is expected to consolidate over 550,000 ha and fix approximately 18 million tones of carbon throughout its duration. CTOs are generated through the avoided deforestation of 420,000 ha and the natural regeneration of 130,000 ha of land purchased. Project participants include MINAE, the World Bank (who provids financial assistance) and the Societé Generale de Surveillance (an independent certifier). PAP is expected to generate US $180 million in revenues.

Name	Type	Area (ha)	Lifespan (yr)	Total Cost (US $ million)	Emission Reductions (t C)
ECOLAND	Conservation	2,340	15	1	366,200
KLINKI	Reforestation	6,000	40	3.8	1,966,495
PFP	Conservation Reforestation Regeneration	2,000 1,000 1,000	25	3.3	313,646
PAP	Conservation	422,800	25	180	18,000,000
Total		**542,838**		**188.1**	**20,646,341**

Table 3.3 -Summary of four AIJ projects implemented in Costa Rica (Source: OCIC, 1999)

The growing uncertainty regarding the fate of the Kyoto Protocol, and therefore the introduction of an official international carbon market, has resulted in a drop in carbon prices. Prior to COP-7 in 2001, researchers and businessmen were predicting that prices per tonne of carbon could drop to US $0.50. However, the COP-7 delegates agreed that the market price per tonne of carbon should remain at approximately US $10, although they realize that this will vary according to demand and which industrialized countries choose to participate in market transactions (Miranda *et al*., 2002).

The average price that Costa Rica has received for the sale of CTOs in the past is higher than that negotiated in other AIJs worldwide (see Table 3.4). This discrepancy cannot be explained only by variations in the carbon sequestration potential of the land, as influenced by local characteristics, but also by the high trust investors have in Costa Rica. More specifically, due to its well-developed institutional capacity, stable democracy, strong green policy and secure land tenure, Costa Rica presents an attractive and safe option for carbon investment. For these reasons, additional energy and forestry sector projects are currently being designed and implemented in this country, and if the Kyoto Protocol comes into force this number will surely continue to rise.

Selling Country	Buyer	Project Name and Type	Price (US $ / t C)
Costa Rica	Norway	Reforestation and Forest Conservation (PFP Project), forest protection	10
Bolivia	American Electric Power, USA	Noel Kempff National Park, forest protection	0.5
Ecuador	Global ReLeaf Fund, USA	Forestry protection, afforestation	3-4
Guatemala	AES Thames, USA	Reforestation	1
Paraguay	AES Barber Point, USA	Agroforestry and preservation	1.5
Malaysia	New England Electric System, USA	Sustainable forestry	2
Russia	Tenaska, USA	Afforestation	1-2

Table 3.4 - Carbon prices received in several AIJ projects (Source: Otarola, 2000)

Given that the most significant increases in carbon storage on land can be achieved by moving from low-biomass land-use systems to tree-based systems, the practice of agroforestry presents a viable option for forest-based climate change mitigation. Individual agroforestry systems – such as the shade-grown coffee production systems of Costa Rica – are of limited size; however, on a per area basis, they can accumulate significant amounts of carbon while contributing to household production and income generation needs. Therefore, an opportunity exists to promote farm management that leads to higher carbon-stock in the production of cash crops such as coffee. To this end, incentives should be put in place to ensure farmers will benefit from selecting management practices that favour higher carbon-stocks.

The concept of using forest sinks for mitigating climate is supported by those who believe that the conservation of tropical forests and a transition to agroforestry modes of production will be difficult unless landowners are compensated for the environmental services their lands provide. Others think that by focusing on just the "carbon-farming" aspect of forestry, other social concerns and the full range of products provided by forests are ignored (Smith *et al*., 2000). Therefore, it is imperative to recognize that although forest-based systems are efficient at sequestering carbon from the atmosphere, and thus have a role to play in climate change mitigation, the promotion of forest-based projects for these purposes should not detract attention from the need to reduce fossil fuel emissions, change unsustainable patterns of energy consumption – particularly in the industrialized world – and develop and use cleaner sources of energy.

CHAPTER 4: AGROECOSYSTEMS: COFFEE PRODUCTION IN COSTA RICA

Agriculture is a predominant land-use system within the global mosaic of landscapes that covers approximately one third of the Earth's surface (http:// FAO.org. Accessed March 2, 2004). Agriculture not only occupies a large land area, but also plays an important role in the global economy and affects both the ecosystems within which it is practiced and the societies who practice it. Since agroecosystems are an important and wide-ranging form of agriculture in many regions of the world, safeguarding their health and ensuring their continued application is essential for the maintenance of agricultural economies, human societies and the diversity of the global landscape mosaic.

This chapter serves to introduce the coffee production system of southern Costa Rica and the physiology of the shade-grown coffee agroecosystem. It also highlights the implications of agricultural expansion and intensification on coffee production. The main objective of this chapter is to convey that there are many benefits – environmental, social and economic – associated with shade-grown coffee production. Further, it argues that since these systems show high potential for carbon storage, their preservation and expansion should be promoted.

4.1 Coffee Production in Costa Rica

In many parts of Latin America, coffee is second only to oil in value as a legal export commodity, and in some countries it is the most important source of foreign exchange. Coffee produced in Latin America generates US $10 billion annually in revenues, and occupies 2.7 million hectares of land, or approximately 44% of permanent cropland in the region (Perfecto *et al*., 1996). Coffee production has historically been, and continues to be, an important land-use system and economic activity in Costa Rica. Moreover, in the southern communities of Santa Elena and Quizarrá, coffee production, along with pastureland and sugarcane, is one of the most prominent forms of land-use. Therefore, ensuring that coffee production is ecologically sound is imperative for the maintenance of environmental and social health in the region.

In order to understand the coffee agroecosystem, one must acquire a basic understanding of the ecology of the coffee plant itself. It is a fruit-bearing tropical plant that grows between the latitudes of 25^{o} north and 25^{o} south, but requires very specific environmental conditions for commercial cultivation, depending on the variety grown (Clifford, 1985). More specifically, two coffee varieties dominate international markets – *Coffea arabica* L. and *Coffea canephora* L., more commonly known as *robusta*. Ideal average temperatures range between 15-24° C for *arabica* coffee and 24-30° C for *robusta*, which can tolerate hotter, drier conditions but not temperatures much below 15°, as *arabica* can for short time periods (Clifford, 1985).

Coffee needs an annual rainfall of 1,500 to 3,000 mm. The availability of rainfall and pattern of rainy and dry periods is important for plant growth, budding and flowering. Whereas *robusta* coffee can be grown at low elevations (up to 800 meters a.s.l.), *arabica* does best at higher altitudes (greater than 1000 meters a.s.l.) and is often grown in hilly areas (Clifford, 1985).

Arabica is cultivated in Central America, Brazil, Colombia, Kenya and Tanzania and is characterized by lower caffeine content than *robusta*; thus, this species is most often used for brewed coffee. *Robusta*, on the other hand, is a lower quality variety primarily grown in Uganda, Tanzania, Vietnam and Indonesia. It displays a stronger taste and higher caffeine content; thus it is generally used for instant coffees (Sick, 1999).

Coffee was introduced to Costa Rica in the latter half of the 18th century and was initially cultivated in the Meseta Central, an area with ideal climate and soil conditions for coffee production. By the mid-1800s coffee growing had surpassed cocoa, tobacco and sugarcane as a major source of foreign revenue and shortly thereafter became the nation's major export product (Sick, 1999). The coffee variety that was first introduced in Costa Rica and the one that is grown almost exclusively today due to its higher market quality and superior taste is a*rabica*, native of Ethiopia. There are several cultivars of the a*rabica* species grown in this country, including borbon, catimor, catuai, caturra and tipica. These are able to grow in complete sunlight, but also produce good yields under shade cover (Sick, 1999).

Variations in the coffee production cycle are dictated by local conditions. In Costa Rica, activities related to coffee-production include: [8]

(1) Pruning: takes place between January and August, when farmers weed and clean fields, remove dead trees and prune coffee bushes. These are usually completely pruned every four years to increase productivity and replaced every ten to fifteen years. Between March and May, farmers prune shade trees, particularly leguminous species such as *Inga sp.* and *Erythrina poeppigiana*.

(2) Application of chemicals: takes place between March and May, when fertilizers and insecticides are applied to fields.

(3) Coffee planting: takes place from May to July.

(4) Coffee harvesting: usually takes place between September and December, depending on local conditions and annual climate.

Once red and ripe, the coffee berries are harvested by hand by local farmers and their families. Coffee production in Costa Rica has also come to depend on cheap, seasonal labour, most of which has come from Nicaraguan immigrants that are attracted by Costa Rica's lower unemployment and higher standard of living. Once collected, the handpicked berries are dropped off at receiving stations (*recibidores*), where they are

[8] Santa Elena coffee farmers. July 2003. Personal Communication.

weighed and quantified into *fanegas*.[9] At this point farmers are issued a receipt for their product that is redeemable at the processing plant's (*beneficio*) office. The berries are then trucked to the *beneficio*, where they are scrubbed and washed to remove the fruity outer layer of each bean. The moist beans are dried, their leathery skin is removed and they are sorted according to size and shape before being shipped to international markets (Peters *et al*., 2001).

4.2 Classification of Coffee Production Systems

Several coffee cultivation systems exist in Latin America. Traditional methods of cultivation involve planting young plants in the understory of forests where native tree cover remains. These kinds or plantations are still found throughout tropical regions of the world, but because of their lower productivity, fewer plants per unit area and susceptibility to damage from insects and disease, they have been increasingly substituted by coffee production in direct sunlight.

Moguel *et al.* (1999) developed a coffee production classification system in Mexico, which was later applied to other locations including El Salvador. The model includes five classes of production differentiated by structural diversity and complexity. These include rustic, traditional polyculture, commercial polyculture, shaded monocuture (or technified shade), and unshaded monoculture (Figure 4.1).

[9] Unit of measurement equivalent to 256 kilograms

These five systems can be further classified in two ways. A distinction can be made between monocultures, or systems employing only one commercially valuable species and polycultures, which employ more than one economically valuable component. Moreover, the systems can be differentiated as shaded or unshaded. Of the five categories included in Moguel *et al*.'s (1999) classification system, four are considered shade coffee production systems, however the structural diversity and complexity of these varies greatly between categories.

In the *rustic* production system depicted at the top of Figure 4.1, coffee is cultivated under the shade of a natural forest canopy, where composition and structure are unaltered. In *traditional polycultures*, or *coffee gardens*, the level of structural complexity remains high, as coffee is still grown under the shade of forest canopy that has been altered to include tree species with economic importance. *Commercial polycultures* are shaded predominantly by introduced tree species, planted mostly for their commercial value. In *shaded monocultures,* the natural tree canopy is completely removed and replaced with commercially valuable species or, as is often the case in southern Costa Rica, leguminous trees. These represent an engineered landscape, with minimal structural complexity and variability. Lastly, *unshaded monocultures* are characterized by complete absence of shade trees; thus, coffee bushes are grown in complete exposure to sun.

As Figure 4.1 illustrates, the *rustic* and *traditional polyculture* systems represent traditional coffee production systems, *shaded* and *unshaded monocultures* are considered modern production systems, and *commerical polycultures* are a hybrid between these two categories.

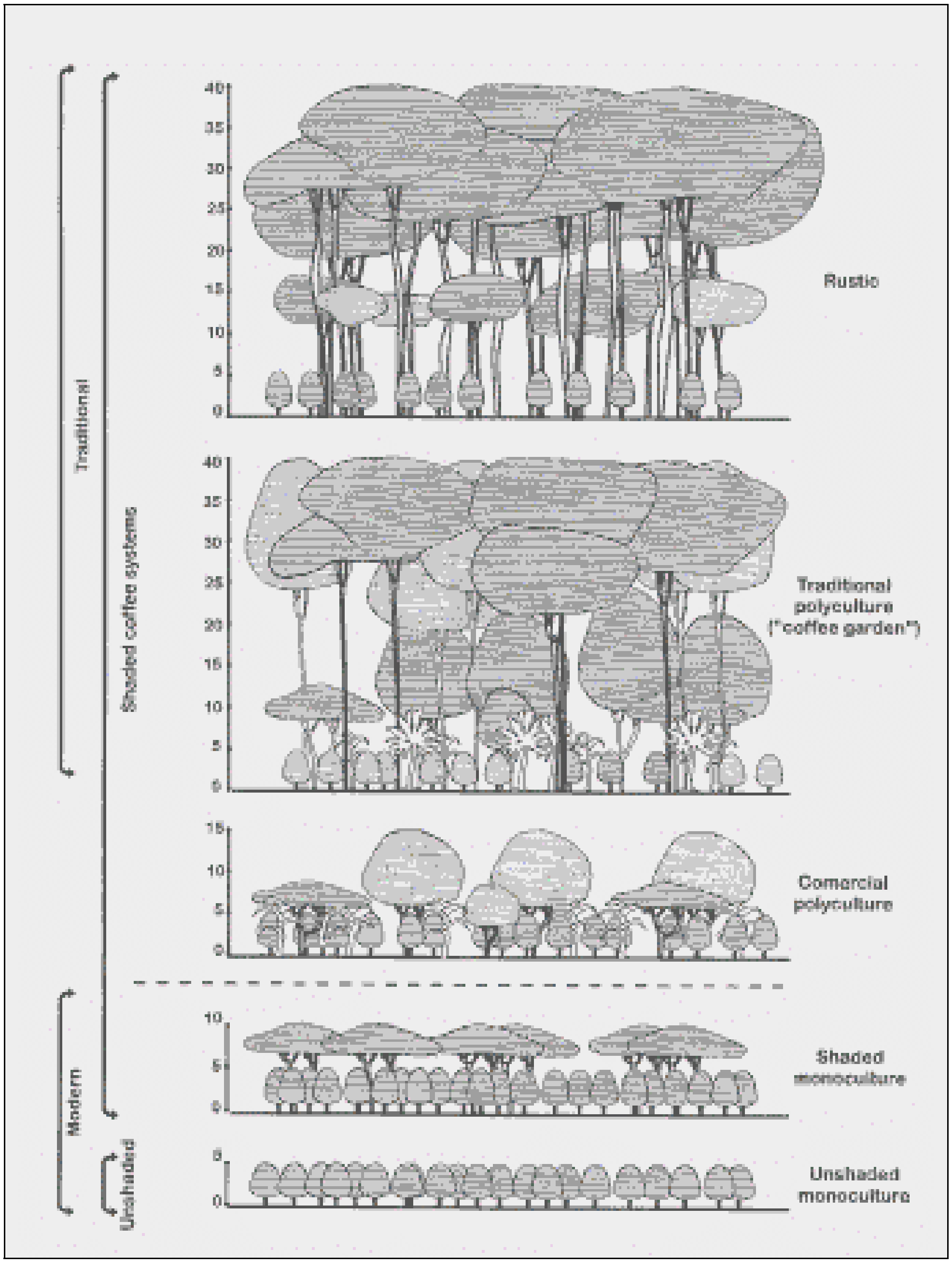

Figure 4.1 - Classification scheme by Moguel *et al*. (1999) for different coffee production systems in Mexico

4.3 The Intensification of Coffee Production

The 1970s saw the beginning of a simplification trend in coffee production, where traditional, shaded modes of production became increasingly replaced by less diverse, unshaded systems. Several coffee-producing countries worldwide adopted this trend, including Costa Rica, in order to increase yields. It was estimated that by 1990, more than half of the coffee-producing area in Latin America was changed to an intensive monoculture system shaded by either one species of shade tree, or exposed to direct sunlight. More specifically, recent estimates suggest that 41% of the 2.7 million ha of coffee production lands in Latin America have been converted to unshaded or reduced shade plantations (Gobbi, 2000).

Increased pressure to maximize yields and thus revenues from coffee sales led to the development of new coffee varieties that are tolerant to direct sunlight. These can be grown in the absence of a forest canopy thus allowing for greater mechanization of the production system, greater resistance to disease and higher yields. These intensive systems also respond well to external inputs and have exclusive market aims. For these reasons, sun coffee production became increasingly popular with international aid organizations, national agricultural agencies and large-scale producers in tropical areas (Rappole *et al.*, 2003). As a result, to accelerate the total removal of shade in Central American coffee production, the use of modern techniques – including improved varieties, high fertilizer, herbicide and pesticide input – was officially encouraged by providing generous credit from state banks and coffee extension programs developed for these ends. An increase in production per hectare was achieved; this particularly benefited large estate owners who were often protected by credit and above all the favorable coffee prices prevalent during most of the 1980s (Budowski, 1993). However, many small producers had financial difficulty acquiring herbicides, pesticides and fertilizers. They also had problems applying them and incidents of human poisoning from herbicides were reported (Budowski, 1993).

Intensive methods of coffee production do not take into consideration the environmental and social consequences of such an agricultural model. Because sun coffee displays a reduction in structural complexity and diversity, it is associated with a number of negative by-products ranging from reduced forest cover, increased soil erosion, chemical runoff and water contamination to consolidation of plantations under large landowners. Moreover, the complexity that characterizes more traditional modes of production, which encompasses higher species richness, greater shade-tree density and greater number of strata represents a natural source of human food, medicine, construction material and firewood that is forgone in the modern production systems.

4.4 The Need for Incentives to Promote Shade-Grown Coffee

From this perspective, the need to revert to more sustainable production systems, or to assume a more integrated approach to coffee production – one that considers contributions to producers' livelihoods and conservation objectives – is evident. However, in order for producers to revert to more traditional methods of production, the profitability-gap between sun and shade-grown coffee must be closed. In this way, growers who are considering converting existing plantations to unshaded production would leave them in shade coffee, and ones that have already made the transition would consider increasing and diversifying shade cover on their farms once again.

In order for the profitability-gap to be closed, a system of incentives must be put in place in order to render shade-grown coffee an attractive option for growers to revert to. These incentives include access to specialty coffee markets, such as organic and biodiversity-friendly coffee, where conscientious consumers in industrialized countries are willing to pay a premium for specialty coffee that translates into economic gains and incentives for producers. A second incentive mechanism is to compensate farmers for the ecological services provided by shade trees on coffee farms. One of these services is carbon sequestration. Therefore, studying the carbon profile of shade-grown coffee agroecosystems and promoting their application are important steps in the search for, and application of, global climate change mitigation strategies.

4.4.1 Benefits Associated with Shade-Grown Coffee Production

The effects of maintaining shade cover over perennial crops have been investigated and documented since the late nineteenth century. For instance, Lock (1888) provided an assessment of the positive and negative effects of shade trees in coffee fields based on studies conducted in present-day Sri Lanka (Table 4.1). Other authors, including Saenz (1895) and Cook (1901), published early accounts of the potential role of shade trees over coffee.

- Climatic range: Shade is not universally beneficial. The need for shade is a function of climate (it is especially important in hot and dry climates).
- Benefits of shade: Diminished crop exhaustion, and increased longevity of coffee plants, reduced costs, maintenance/improvement of soil fertility, increased litter, value of timber.
- Drawbacks of shade: Coffee yield is reduced, but compensated by increased longevity.
- Beneficial shade-tree attributes: Small foliage, provision of timber, fodder, fuelwood, food, nutrients recycled by fallen leaves.

Table 4.1 - Key aspects of shade cover and shade trees of coffee production in present-day Sri Lanka (Source: Lock, 1888)

Some of the benefits of employing shade trees in coffee production include:

(1) *Soil organic matter and soil fauna:* Soil organic matter increases with time under coffee agroecosystems. Beer *et al*. (1998) report that over a ten-year period following conversion of sugar cane fields to shaded coffee plantations employing *Erythrina poeppigiana* and *Cordia alliadora*, soil organic matter increased by 21% and 9%, respectively. Moreover, shaded plantations host higher numbers of fungi and bacteria

in the soil – primarily due to increased litter inputs – thus contributing to an expansion of the organic-matter reservoir the soil (Beer *et al*., 1998).

(2) Nitrogen fixation: The use of leguminous species for shade, such as *Erythrina poeppigiana*, *Inga* sp., and *Gliricidia sepium*, has an effect on nitrogen fixation rates. More specifically, Fassbender (1987) reports that as much as 60 kg N yr^{-1} may be fixed by *Erythrina poeppigiana* in shade-coffee association.

(3) Nutrient cycling: The cycling of nutrients in shade plantations is enhanced by the presence of shade trees. Specifically, natural leaf fall and shade management practices, such as pruning of tree branches, have a critical influence on nutrient transfer from tree to soil, provided that the pruned branches are left on the farm. Thus nutrient turnover and the transfer of N, P, K, Ca, and Mg to the soil are greater in shaded plantations (Beer *et al*., 1998).

(4) Soil erosion: Natural litter fall and the application of pruning residues to coffee fields all contribute to reduced soil erosion and soil loss in shaded plantations. A low canopy crown with small leaves will also serve to protect soil from the effects of heavy rainfall and reduce drip damage from leaves.

(5) *Temperature and wind speed:* A shade canopy can buffer daytime and nighttime temperature extremes, thus contributing to coffee production. More specifically, tree cover reduces heat-load on the coffee bushes during the day and reduces heat losses at night. The inclusion of shade trees on coffee farms also reduces wind speed in the crop strata, resulting in less desiccation, crop damage and soil loss (Beer *et al*., 1998).

(6) *Weeds:* If properly managed and selected, shade trees can reduce labour inputs and weeding costs in coffee fields since shade shifts weed species composition to less aggressive, more broadleaf weeds (Beer *et al*., 1998). This further reduces synthetic herbicide use.

(7) *Pests and disease:* Although increased humidity, due to increased shade, can favour the incidence of some fungal diseases, such as *Mycena citricolor* in coffee, shade has also been shown to control the incidence of other fungal diseases, such as *Cercospora coffeicola*, which is more common in sun plantations. Moreover, shade trees in coffee agroecosystems may provide habitat for biological control agents, thus reducing the incidence of disease and dependence on pesticides (Beer *et al*., 1998).

(8) *Timber and fuelwood production:* Timber-producing shade trees have low management costs and can be considered "revenue storage" for farmers that can be cashed during periods of low coffee prices or crop failure. These can also be used as construction materials and as sources of fuelwood for household consumption.

(9) *Food production:* The inclusion of fruit-bearing trees as shade in coffee plantations presents farmers with access to additional food sources such as mangos, oranges, bananas and avocados, among others. These can supplement household diet, contribute to household income, or be used as supplemental animal feed, as is often the case in Costa Rica.

(10) *Conservation of biodiversity:* Given their structure and ecology, many traditional shade coffee plantations resemble natural forests more than any other agricultural system in use (Perfecto *et al*., 1996). A number of studies have examined the potential of shade-grown coffee production systems to conserve biodiversity. Studies in Mexican shaded coffee plantations reveal that these compare favourably to natural forests as refuges for migratory birds. Moreover, studies in Costa Rica report that shade coffee is better able to support avian and arthropod diversity than sun-grown coffee (Znajda, 2000 and Hall, 2001). Lastly, these agroforestry systems can act as buffer zones to protected areas and serve as biological corridors, thus providing pathways for the migration of animal species between natural reserves.

(11) *Water quality:* The application of synthetic fertilizers in sun-grown coffee fields presents increased risks for groundwater contamination. To illustrate, in the Central Valley of Costa Rica, where 50% of the groundwater recharge area is under intensive coffee production with little or no shade, groundwater contamination by nitrate and

nitrite constitutes a human health hazard (Beer *et al*., 1998). However, the use of shade reduces both synthetic fertilizer inputs in coffee fields, and N leaching into groundwater.

(12) *Carbon sequestration:* Compared to unshaded plantations, shade-grown coffee stores significant amounts of carbon in both the aboveground woody biomass of shade trees and the litter layer and soil organic matter. These pools contribute to GHG emission reductions and the alleviation of GHG accumulation in the atmosphere. Moreover, with respect to climate change, a viable contribution of shaded plantations lies in the protection of remaining forest by offering farmers a sustainable cash-crop production alternative to slash-and-burn cultivation. According to Beer *et al*. (1998) this could prevent the release of up to 1000 t C ha^{-1}. Thus, it is imperative that the contributions shaded coffee plantations make to climate change mitigation be further investigated.

4.5 Summary

Driven by technological innovations and increased pressure to meet human needs, agricultural practices worldwide have been subjected to a process of expansion and intensification. This trend has had a variety of effects on both human societies and the environment. Coffee production in Latin America followed suit and underwent a transition from rustic polycultures, displaying structural diversity and complexity, to simplified and specialized monocultures that are highly dependant on external inputs. Recently, a paradigm shift has begun to take hold, where traditional production systems that were once considered unprofitable are being revisited. Moreover, due to a continuous low in the world coffee price, incentives for the transition to more sustainable modes of production that will provide farmers with a better price for their product must be developed and put into place. These include compensation for the ecological services that coffee plantations provide to society.

To this end, recent research indicates that agroforestry systems have the potential to sequester significant amounts of CO_2 from the atmosphere and reduce pressure on natural forests for agricultural expansion. Nonetheless, this field of research is still in its initial stages; therefore, additional work must be conducted in order to quantify the ability of agroecosystems, including shade-grown coffee, to capture CO_2 from the atmosphere and contribute to climate change mitigation. More research is also needed to establish how farmers could be compensated for the ecological services provided by shade-coffee and whether this could provide an attractive incentive for reverting to more structurally diverse and sustainable modes of production.

CHAPTER 5: CARBON-STOCK AND CARBON SEQUESTRATION DEFINED

Worldwide, a number of pilot forest-based projects have been designed and implemented. This has allowed for some experience to be gained in measuring, monitoring and accounting of the carbon benefits derived from forestry systems. However, despite these endeavors, a consensus on a single method to quantify carbon fluxes between the atmosphere and biosphere that is applicable at the local and global levels is still lacking (Tosi, 1997). This lack of agreement is attributable to geographic complexity, problems of measurement, and uncertainty about future climatic, energy and land-use events that may affect the atmospheric carbon balance (Dixon *et al.*, 1994).

Being able to quantify with some certainty the biomass density, carbon-stock and carbon sequestration potential of forest-based systems is essential in determining their role in the global carbon cycle – both as climate change mitigators, through the conservation and management of tree cover, and as contributors to CO_2 emissions through forest loss and burning. Therefore, the objective of this chapter is to define and differentiate between the various carbon-offset processes provided by trees, and to outline methods that are presently available to quantify the biomass and carbon-stock of forestry systems, particularity as they apply to the research presented here.

5.1 Biomass Defined

Generally, the biomass of a forest can be thought of as the difference between production through photosynthesis and consumption by respiration and harvesting. More specifically, biomass is defined as the total amount of aboveground living organic matter in trees (including leaves, twigs, branches, main bole and bark) expressed as oven-dry tonnes per unit area (Brown, 1997). Quantifying and tracking the biomass of these components is a useful measure of assessing changes in forest structure, as brought about by natural succession and human activities.

Measuring the biomass of a forest is very useful when considering the question of carbon offsets, as biomass measurements provide an estimate of the carbon pool contained in the vegetation because 50% of it is carbon (Brown, 1997). Therefore, biomass represents the amount of carbon that is stored by forest vegetation and that potentially could be added to the atmosphere as CO_2 when trees are cleared and/or burned. Biomass estimates also allow for establishing the amount of carbon dioxide that can be removed from the atmosphere by reforestation, as they yield rates for biomass production and the upper bounds for the sequestration of carbon. Thus, the initial and essential step in calculating carbon storage and carbon sequestration rates of forests and forest-based systems is to measure biomass.

5.2 Carbon-Stock Defined

Various carbon pools can be identified within forest-based systems. These include the soil pool, the live wood pool in trees, the underground wood in roots, and the dead litter pool on the forest floor. The quantity of carbon contained in each pool is referred to as the carbon-stock, and the total carbon-stock in an ecosystem is simply the sum of the carbon-stocks of the different pools. Carbon-stock is usually expressed in tonnes of carbon per hectare ($t\ C\ ha^{-1}$).

Primary forests (old-growth) display the largest possible permanently stored biomass (and thus organic carbon), however little or no net annual on-site carbon accumulation takes place in these systems, since death and decay are essentially in balance with new growth (steady-state) (Tosi, 1997). Tropical forests, accounting for about half of the world's forest area, store 46% of the world's living terrestrial carbon pool. No other biome stores as much carbon in the biota. However, tropical forests store only 11% of the world's soil carbon pool, whereas boreal forests, tundra, grasslands and peatlands store substantially larger amounts (Brown *et al*., 1982).

The carbon-stock of a forest or forest-based system will not be liberated to the atmosphere for as long as forest cover is maintained. In this case, the payment for environmental service provided (avoided emissions) would be a one-time payment for forest conservation, or avoidance of land-use change.

5.3 Carbon Sequestration Defined

Carbon sequestration refers to the process of removing gaseous carbon from the atmosphere and fixing it in soil or woody material on land. This measure is a *rate* of the net flow of carbon, and thus includes measures of quantity, area and time. Therefore, carbon sequestration is most often expressed in t C ha^{-1} yr^{-1} (Avila Vargas, 2000). Carbon sequestration measures do not express the total amount of carbon stored in a given pool, but only provide information about the rate at which that pool is increased. Since the process and rate of carbon flow can occur in either direction, a system that sequesters carbon from the atmosphere is referred to as a *sink* and a system that emits carbon is known as a *source*.

Net annual carbon sequestration in forests is positive for growing forests, but sequestration rates will diminish through time as the forest matures, and can become negative during periods of forest decline and/or loss when carbon emissions from dead trees or fire exceed carbon uptake by live trees (Nowak *et al*., 2002). In this case, payments for the environmental service provided (carbon sequestration) would be administered periodically as compensation for the carbon sequestered during a given time period.

5.4 Methods for Measuring Biomass and Carbon-Stock

Three approaches currently exist for measuring or estimating the biomass of woody formations. The first is based on the use of volume estimates, the second directly estimates biomass using existing biomass regression equations and the third, and most complex method, involves the collection of primary data and field measurements in order to develop site-specific regression equations.

5.4.1 Biomass Calculations Based on Volume Data

This method is best used for estimating the biomass of secondary to mature closed forests growing in moist to dry climates, since the original data base used for developing this approach came from forests under these conditions. The data necessary for calculating biomass is the volume of the bole (from buttress to crown point) of all trees with a minimum diameter at breast height (dbh, 1.3 m above the ground) of 10 cm. Bole volume is then converted to biomass by multiplying it by the average wood density of the given tree species and a biomass expansion factor (defined as the ratio of aboveground oven-dry biomass of trees to oven-dry inventoried volume). These ratios have already been calculated from inventories of broadleaf forest types (Brown, 1997).

This method of calculating aboveground biomass is generally not applicable to open forests or woodlots, as trees in these systems have different branching patters (and thus expansion factors) than those of closed forests. Moreover, suitable inventoried volume data for open systems is generally lacking, and using that of closed systems will result in an underestimate of biomass since trees with a dbh less than 10 cm that are not considered in closed systems need to be considered in open systems (Brown, 1997).

5.4.2 Biomass Calculations Based on Existing Regression Equations

Brown *et al*. (1982) and Brown *et al*. (1992) have developed general regression equations based on physical data of broadleaf forest species from various tropical regions of the world. The application of these equations will yield estimates of biomass per tree, based on the diameter of each tree. Existing equations are classified into three main climatic zones, including dry (<1500 mm rain/yr), moist (1500-4000 mm/yr) and wet (>4000 mm/yr).

Although these equations can, and are used to estimate biomass of trees grown in open systems, a more accurate measure is yielded if equations are locally derived. More specifically, the application of general regression equations does not take into consideration tree species, height and the different branching patters of trees grown in open conditions. The advantage of this second method, however, is that it produces biomass estimates without having to make volume estimates or having to destructively sample trees to develop site-specific equations, which is not always feasible.

5.4.3 Biomass Calculations Based on Field Measurements

The most accurate way to calculate the biomass of an open forest system, such as a coffee agroecosystem, is to measure the oven-dry-weight of trees by directly felling them, oven-drying their components and weighting them. The selected trees must come from the population of interest, represent the major species in the system and represent all size classes (Brown, 1997). In open systems, trees of smaller stature (with a minimum dbh of 5 cm) should be included in field sampling as they represent an important component of the overall biomass. Moreover, in the case of multi-stemmed trees – common in open forests and woodlands – the diameter at 0.3 m above the ground should be used instead of dbh (Brown, 1997). Finally, the sum of the dry-weight of all components is correlated to the height and dbh of trees and regression coefficients and equations are developed.

In terms of this research, it was not realistic or feasible to destructively sample shade trees and coffee bushes from the selected sampling sites. However, the regression equations used (from Suárez Pascua, 2000) were developed by the destructive sampling of trees and coffee bushes in coffee agroecosystems displaying similar conditions and employing similar shade species to those encountered during this research. Thus this method provides the most accurate estimate of biomass for the systems investigated.

5.5 Calculating Carbon-Stock from Biomass Measures

According to the Intergovernmental Panel on Climate Change (IPCC, 1996) approximately one half (50%) of the oven-dry weight of organic matter is elemental carbon. Therefore, carbon storage density (t C ha^{-1}) is calculated by summing the biomass of all woody components per unit of land area, and multiplying by 0.5. Two dominant factors that affect carbon storage density are tree density (trees/ha) and diameter distribution. More specifically, carbon storage per hectare will generally tend to increase with tree density and/or increased proportion of large diameter trees (Nowak *et al*., 2002).

5.6 Criticisms of Using Biomass Estimations in Agroforestry Systems

Brown (2002) reports that experience to date with the development of generic regression equations has shown that measurements of diameter at breast height explain more than 95% of the variation in tree biomass even in highly species-rich tropical forests. Therefore, the need to develop species-specific or site-specific equations is not warranted. However, in many tropical forests, unique plants forms occur such as species of palms and early colonizers; in these cases, local regression equations need to be developed as the application of generic equations may lead to inaccurate biomass estimates. Moreover, since the size of individual tree canopies in a forest could be smaller than those found in an open agroforestry setting where trees have more access to space and light, the application of generic biomass regression equations developed from forest inventories may lead to errors in biomass estimates for open systems.

Estimating biomass of agroforestry systems is also difficult because these often involve the growth of multiple tree species of different ages in complex arrangements with annual or perennial crops. Trees in agroecosystems, particularly shade coffee, are often mis-shapen as branches are cut or pollared. In this way, biomass is removed from the system and, depending on its final use, carbon could be returned to the atmosphere through decomposition or burning. In the context of shade-grown coffee, it is likely that harvested material will provide a number of end products (fuelwood, forage, poles and construction timber) and that each product will have a different carbon-storage profile. This factor could lead to additional errors in biomass and carbon-stock estimates.

Lastly, in projects designed to sequester carbon, such as the promotion of increased shade cover over crops, changes in carbon-stocks being claimed need to be periodically measured and monitored. More specifically, this requires the establishment of quantifiable baseline data to accurately determine the amount of "additional" carbon sequestered by the project, and of permanent plots with well-marked trees for re-measuring and monitoring (Brown, 2002). However, this could be difficult to implement in smallholder communities due to the large number of landowners involved, their willingness to participate and the different time periods each is disposed to commit to. All these factors present additional challenges to quantifying the carbon dynamics of agroecosystems.

Although establishing the oven-dry weight of the woody components of an agroforestry system through destructive sampling yields biomass regression equations with high precision, this method is extremely time consuming and costly, and therefore is generally beyond the means of most projects. Nonetheless, despite the fact that many questions remain on how to accurately assess the biomass and carbon-stock of complex agroforestry systems, the implementation of smallholder-focused carbon sequestration projects is highly desirable from a carbon investment, conservation and sustainable livelihoods perspective. Since increased tree cover serves to augment a region's carbon budget while providing many socio-economic benefits to local communities, mechanisms to estimate baseline and incremental biomass data in agroforestry systems need to be refined and expanded. This will serve to facilitate the implementation of agroforestry projects for increased carbon storage, thus contributing to an overall reduction of greenhouse gases in the atmosphere.

CHAPTER 6: RESEARCH METHODS

6.1 Study Area

This study was conducted in the Las Nubes/Los Cusingos Biological Corridor of southern Costa Rica. The corridor is located on the wet pacific slopes of the Talamanca volcanic mountain range and is contained within the canton of Pérez Zeledón in the Río General valley (Figure 6.1). The sites surveyed ranged in elevation from approximately 700 to 1,000 meters. Annual rainfall in the area averages around 3,500 millimeters, with most rainfall occurring between May and November.[10] A short but pronounced dry season occurs in the mid-to-low elevations between the months of December and April (Figure 6.2).

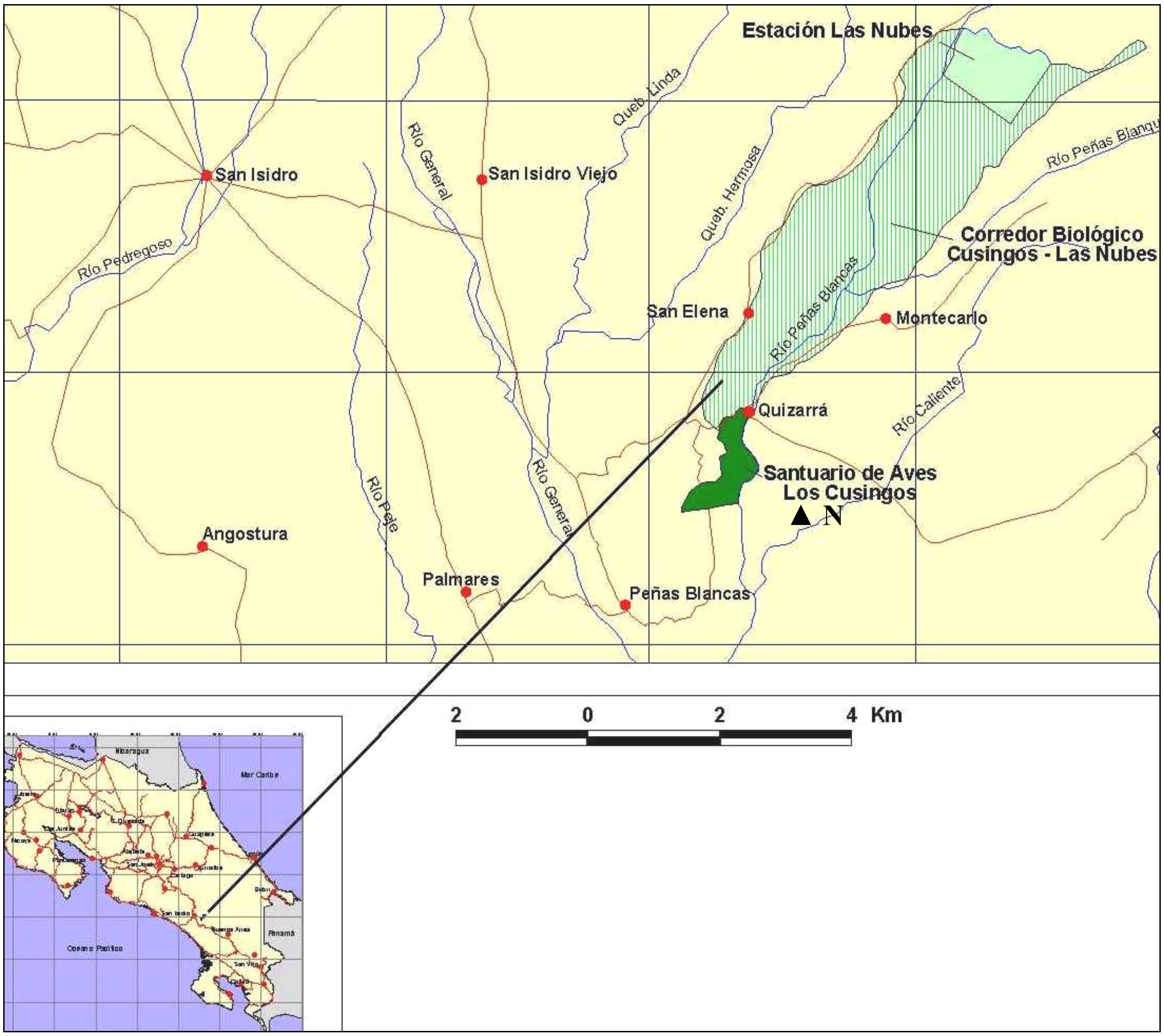

Figure 6.1 - Location of the Las Nubes/Los Cusingos Biological Corridor and communities in the study region (Source: Tropical Science Center, 2000)

[10] Dr. Joe Tosi, Tropical Science Center, June 2003. Personal Communication.

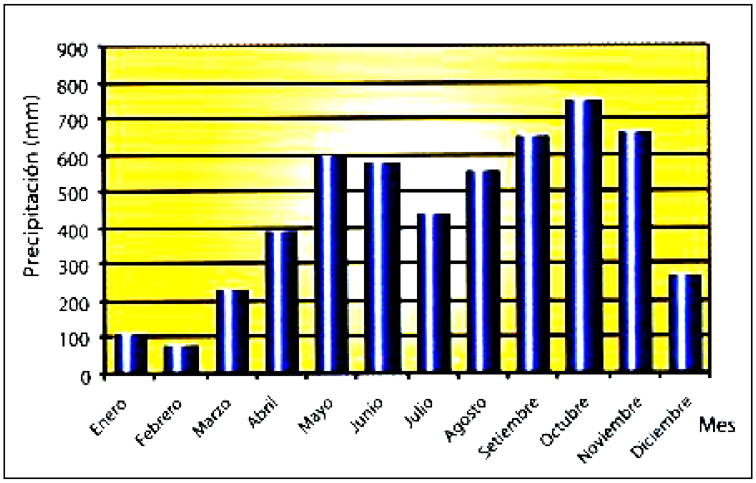

Figure 6.2 - Average monthly rainfall (2001) recorded at the Montecarlo meteorological station (Source: Chinchilla, 2002)

More specifically, the Las Nubes/Los Cusingos Biological Corridor is found between the two protected areas of Las Nubes and the Los Cusingos Neotropical Bird Sanctuary. Las Nubes (The Clouds) comprises of 124 hectares of pristine premontane rainforest, with its highest point found at 1,500 meters a.s.l. This property was donated to York University by Dr. Woody Fisher and is currently managed and administered jointly by the Faculty of Environmental Studies at York University and the Tropical Science Center of Costa Rica. To the northeast of the property is Chirripó National Park, which extends into La Amistad Biosphere Reserve, an international protected area shared between Costa Rica and Panama. This corridor of continuous upland protected forest represents the last unfragmented tract of tropical montane forest in Central America, contains great biological value and forms part of the Mesoamerican Biological Corridor – one of the world's largest conservation initiatives focusing on all Central American countries from Mexico to Panama (Evans, 1999).

The Los Cusingos Neotropical Bird Sanctuary comprises 78 hectares of tropical premontane wet forest and was the homestead of world-renowned ornithologist Dr. Alexander Skutch. The Tropical Science Center now protects and administers Los Cusingos as a bird sanctuary. In recent decades, the majority of lands surrounding Los Cusingos have been converted to agriculture, effectively isolating it from the upland corridor of protected forest that includes Las Nubes, Chirripó and La Amistad. The Río Peñas Blancas flows between Las Nubes and Los Cusingos. Its headwaters are found in Chirripó National Park and flow south to discharge into the Río General.

Three small communities reside in the corridor, the largest being the town of Santa Elena (Figure 6.1). Primary land-use systems in the region include a mixture of coffee plantations, sugar cane, cattle pastures and isolated forest remnants. Following the construction of the Pan-American Highway in the 1940s, this part of Costa Rica experienced a significant wave of immigration. More specifically, facing land shortages in the Central Valley around San José, many people moved to the Río General valley in search of land. As a result, Pérez Zeledón became one of the fastest growing coffee-producing regions in Costa Rica (Sick, 1999).

Due to increased land-use change in this region and, as a result, increased isolation of remaining forest patches such as Los Cusingos, one of the primary objectives of the York University-Tropical Science Center partnership has been to create a biological corridor between Los Cusingos and Las Nubes. This corridor will enhance tree cover and the restoration of original habitat in the region, thus facilitating the dispersal of animal and plant species between the lowlands of Los Cusingos and the highlands of Chirripó and La Amistad. Increased tree cover will also provide better habitat for biodiversity, serve to protect soil and the health of the Río Peñas Blancas watershed, and sequester carbon while moderating local climate.

One of the proposed strategies for achieving increased canopy cover in the corridor is through the promotion of more sustainable agricultural practices, particularly increased production of shade-grown coffee in the corridor's communities. Therefore, this region provides an attractive option for investigating the carbon-stock of existing coffee agroecosystems, as carbon storage may act as an additional incentive for farmers to convert to greater shade cover, thus contributing to the objectives of the Las Nubes Project.

6.2 Site Selection

6.2.1 Preliminary Interviews

Non-structured, informal interviews were conducted with coffee producers in the corridor prior to plot installment (see Appendix I). They provided insight on the size of the coffee fields, the variety and combination of shade trees employed, and the management strategies applied to the farms. Farmers were also interviewed on their reasons for choosing particular tree species for shade, what the use and products (if any) provided by the trees are, and whether they are aware of the carbon sequestration service granted by agroforestry systems. This information was used in conjunction with information from Znadja (2000) and Hall (2001) to choose specific sampling sites for the study. Coffee farms were sampled only with the permission of the landowner.

6.2.2 Coffee Farm Categories

Sampling sites (farms) for investigation were selected to represent the most common shade-grown coffee production systems in the corridor. More specifically, a gradient of structural complexity was created that includes five types of shade farms – those employing primarily poró (*Erythrina poeppigiana*), guaba (*Inga* sp.), banana (*Musa* spp.), eucalyptus (*Eucalyptus deglupta*), and a combination of species including timber trees such as amarillón (*Terminalia amazonia*) and cedro (*Cedrela odorata*). A secondary forest site at Los Cusingos was included to serve as a control, resulting in a total of 6 treatments. The coffee farm treatments were repeated twice respectively, for a total of 11 sampling sites.

As noted by Znadja (2000), the structure of the vegetative layers in the various shade-grown coffee farms of this region of Costa Rica do not lend themselves well to comparison with the classification presented in Chapter 4 (Figure 4.1). Specifically, rustic modes of production and traditional polycultures (or coffee gardens) do not exist in the communities of Santa Elena and Quizarrá. Moreover, true sun coffee (unshaded) monocultures are not characteristic of the region, as most farmers prefer to employ at least one leguminous shade layer to coffee.

The shade continuum observed in the study region more closely resembles that displayed in Figure 6.3. This classification scheme allows for the 11 sampling locations to be given a rank according to structural complexity, which includes:

- Rank 1: *Low shade cover,* or *shaded monoculture* (C in diagram). This system incorporates only one shade layer primarily composed of legumes such as *Erythrina poeppigiana* or *Inga sp.* Moreover, it is subject to intensive management including pruning for shade regulation.

- Rank 2: *Intermediate-low shade cover* (B in diagram). This system incorporates two layers, one with leguminous species and the second employing species that provide significant shade due to minimal pruning and abundant foliage. Species employed in this layer include *Musa* spp. and commercial species such as *Eucalyptus deglupta*.

- Rank 3: *Intermediate shade cover*, or *commercial polyculture* (A in diagram). This system employs a variety of shade species incorporated into three layers, including legumes, fruit trees and timber-yielding species such as *Terminalia amazonia* and *Cedrela odorata*. This system represents the highest structural diversity seen in the study region.

- Rank 4: *Natural forest* (Los Cusingos, not included in diagram).

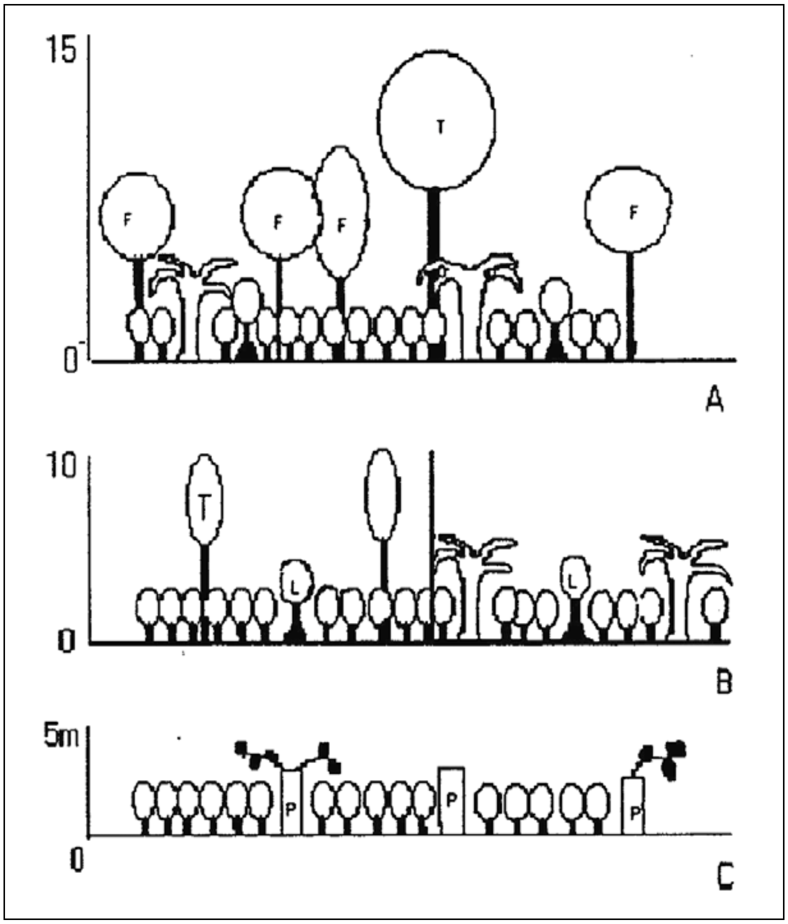

Figure 6.3 - Variety of coffee farms observed in the study region (A) Highest structural diversity with three layers, (B) Intermediate structural diversity with two layers, (C) Shaded monoculture, employing one shade species. T=timber, L=legume, F=fruit, P=Poró (Source: Znajda, 2000)

See Appendix II for photos of coffee farms described below.

Poró (*Erythrina poeppigiana*)

Poró is the most commonly employed shade tree in the study region. It is a deciduous broad-leaved legume that is usually vegetatively propagated with stakes. When allowed to grow freely, poró can reach heights of 30 m. However, it is common practice in Costa Rica to prune the tree branches in order to regulate shade. This results in a 3-4 m tree stump with one or two branches protruding from it. These serve to stimulate N-fixation, nodule formation in the roots, and root growth.

Both poró farms sampled were dominated almost entirely by this species. Careful attention was taken to select two farms where the poró trees had not yet been pruned, in order to capture a more accurate assessment of tree-carbon content that includes branches. Poró is most often employed in coffee farms for its ability to fix nitrogen, thus improving soil conditions and nutrient cycling in the farms. The pruned branches are often left on site to decay, thus providing soil protection and returning nutrients to the soil.

Guaba (*Inga* sp.)

Similarly to poró, guaba is often employed for its ability to fix nitrogen and act as a natural fertilizer. Farmers employing guaba for shade said they like the species for its ease of maintenance. More specifically, guaba does not need to be pruned as often as poró and the prunings provide good quality firewood. However, guaba also tends to dry out once trimmed, does not vegetatively propagate and tends to attract insects, such as termites.

The structure of this leguminous tree provides low and wide shade cover, 3.5 to 4 m in height. This, combined with the long and narrow structure of guaba leaves, provides good protection for soil due to both reduced drip damage and low canopy cover.

Banana (*Musa* spp.)

The farms investigated under this category employed a number of *Musa* spp., including bananito rosa, banano morado, banano críollo and plátano (plantain). The broad and thick leaves of banana trees provide good shade for coffee in the farms examined. Banana trees of different ages and stages of development were observed, with some trees in the flowering and fruiting stages. The fruits are used either as a household food supplement or as feed for domesticated animals. The two farms examined contained primarily *Musa* spp. in combination with other fruit trees – including naranja dulce (*Citrus sinensis*), mango (*Mangifera indica*), and avocado (*Persea americana*) – and poró and timber species such as *Eucalyptus deglupta*.

Eucalyptus (*Eucalyptus deglupta*)

Eucalyptus is a fast-growing exotic species with a multi-colored trunk and high canopy. Landowners said they employ this species for its fast growth and good production of timber. Most wood produced by the harvest of eucalyptus is used for the construction or repair of homes, or it is sold to other community members.

Eucalyptus trees in coffee farms are usually planted around the perimeter of the farm (live fences), or along walkways and pathways. Farmers interviewed expressed a preference for this since it allows for better shade-moderation. This translates into lower incidence of coffee pests such as ojo de gallo (*Mycena citricolor*), which tends to occur with an increase in humidity.[11]

<u>Amarillón and Cedro (*Terminalia amazonia* and *Cedrela odorata*)</u>

The two farms examined belonging to the intermediate shade category (Rank 3) employ three clear layers of vegetative cover. The first includes leguminous species, primarily poró, the second fruit trees such as *Musa* spp., mango and avocado, and lastly a layer characterized by timber species with diffuse foliage and heights up to 20 m. Species in the upper layer include amarillón and cedro, both preferred for their high-quality timber. Other species observed are maría (*Callophyllum brasiliense*), aceituno (*Simarouba glauca*), eucalyptus (*Eucalyptus deglupta*), guachipelín (*Diphysa robinoides*), ira marañon (*Ocotea tonduzii*) and muñeco (*Cordia collococca*), among others. Due to the diversity of shade trees employed, these two farms represent the most structurally complex shade-coffee production system observed in the study region.

Los Cusingos

The 78 hectares of forest protected by the Los Cusingos Neotropical Bird Sanctuary include a mosaic of primary, advanced secondary and secondary forest types. The sampling site established for this study was located in the advanced secondary forest portion. Three distinct tree strata were observed and the average height of dominants reached 40 m.

Los Cusingos was included in this study because it provides an ideal site within the region to investigate the carbon-stock of an advanced secondary forest, thus providing a good basis for comparison with that of coffee agroecosystems.

[11] Santa Elena coffee farmer. July 2003. Personal Communication.

Shade Category	Site	Rank	Size (ha)	Alt. (masl)	GPS (center pt)	CFH (m)	CFD (p/ha)	CNH (m)	CND (p/ha)	% in canopy
Poró	P1	1	9	737	N9 20.257 W83 37.977	1.9	6200	4-6	130	95
	P2	1	25	958	N9 22.116 W83 36.674	1.6	4300	3-4	100	99
Inga sp.	I1	1	2	891	N9 21.589 W83 36.830	1.6	4200	4	160	99
	I2	1	13	922	N9 21.761 W83 36.711	1.8	5100	3-3.5	160	95
Musa spp.	M1	2	13	893	N9 21.597 W83 36.689	1.9	6000	4-6	230	60
	M2	2	8.5	831	N9 21.138 W83 37.135	1.9	5500	4-5	245	65
Eucalyptus	E1	2	8	820	N9 21.127 W83 37.344	1.9	6500	15-20	70	75
	E2	2	7	806	N9 21.063 W83 37.379	1.8	5000	15-20	80	65
Diversified Shade	DS1	3	22	711	N9 19.633 W83 37.491	1.7	5000	15	100	NA
	DS2	3	18	800	N9 21.188 W83 37.999	1.9	6100	15-18	90	NA
Los Cusingos	LC	4	78	732	N9 20.087 W83 37.650	NA	NA	40	1400	NA

Table 6.1 - Characteristics of the eleven sampling sites examined for carbon storage in the Santa Elena andQuizarrá communities (CFH=average coffee height (m), CFD=coffee density (plants/ha), CNH=approximate canopy height (m), CND=canopy density (shade trees/ha), % in canopy=portion of canopy dominated by the shade category species)

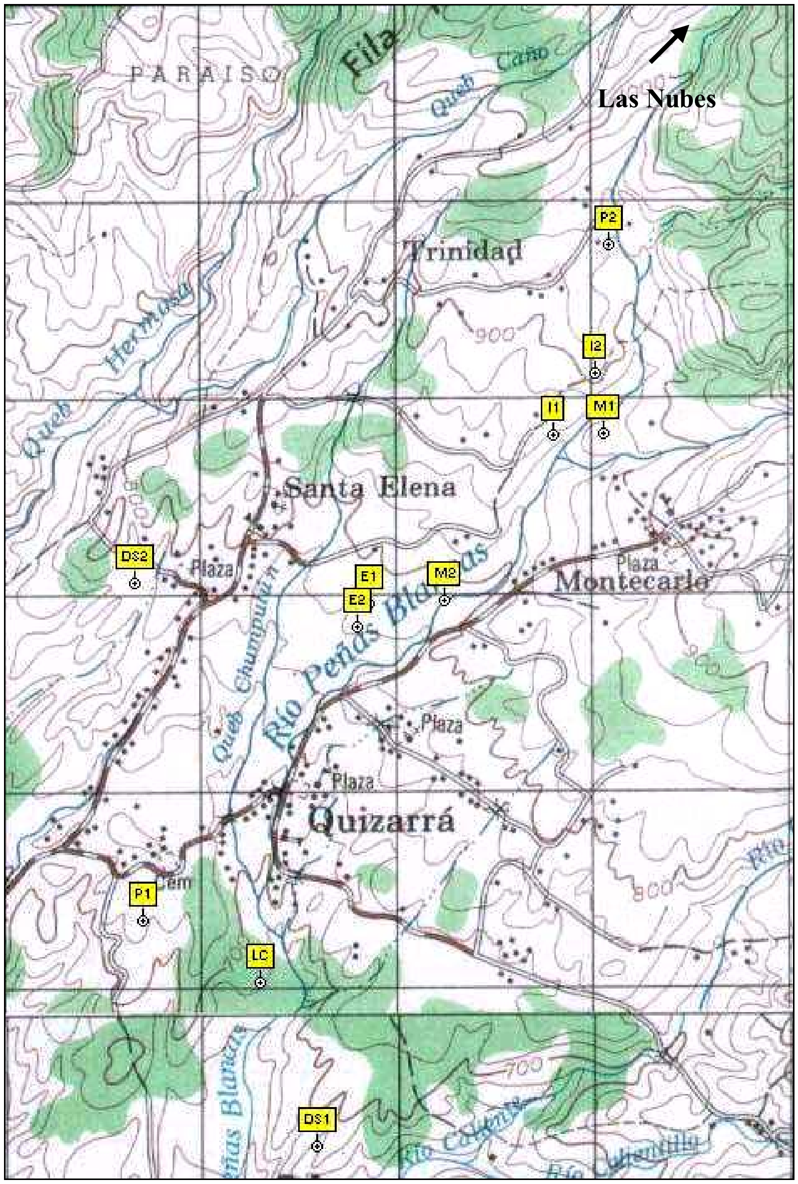

Figure 6.4 - Location of sampling sites P1,2 = Poró, I1,2 = *Inga* sp., E1,2 = Eucalyptus, M1,2 = *Musa* spp., DS1,2 = Diversified Shade, LC = Los Cusingos (Scale 1:50 000) (Source: Instituto Geografíco Nacional Hoja 3444 II, San Isidro and Hoja 3443 I, Repunta, Costa Rica)

6.3 Plot Installation and Measurement

6.3.1 Coffee farms

For each selected farm, a representative 50 m x 50 m (half-hectare) plot was delineated. GPS coordinates were recorded at the four corners and at the center of the plot. The diameters of all shade trees in the subplot with a diameter at breast height (dbh, 1.3 m above soil surface) greater or equal to 5 cm were measured and species recorded (Brown, 1997). For *Inga sp.* heights were recorded at 0.3 m, since the tree trunk often branches near the surface (Brown, 1997). Tree heights were measured using a clinometer.

The coffee bushes in the plot were counted and the height and dbh (at 15 cm) of each bush in every other row was recorded. The average height and dbh was calculated.

From the center of each plot, four points were established by walking 10 m in each direction (north, east, south, west). At these four points, herbaceous vegetation (dbh less than 5 cm) and litter (all organic matter above the surface that is not soil) samples were collected. These were obtained by placing a 50 x 50 cm quadrant at each sampling point. To minimize damage to farmers' fields, neither juvenile trees nor crops within the quadrant were destructively sampled. This missing biomass was not estimated since the situation occurred infrequently and the herbaceous component contains only a small fraction of the total carbon-stock of a forest-based land-use system (Brown, 1997). The fresh weight of each sample was determined in the field and a 250g sub-sample was extracted and sent to the ICAFE laboratory in Rivas for moisture content determination.

6.3.2 Los Cusingos

A representative one-hectare plot (100 x 100 m) of advanced secondary forest was selected within the Los Cusingos Neotropical Bird Sanctuary. GPS coordinates were recorded at each corner and center. Thereafter, the parcel was subdivided into one hundred squares of equal size (10 x 10 m). Twenty squares were chosen by random number selection in order to control for sampling bias. Within these, the diameter and height of all trees with a dbh greater than or equal to 5 cm were recorded. Diameters of down but intact trees, either living or dead were also recorded.

Four herbaceous and litter sub-samples were collected 1 m north, east, south and west of each plot's center by using a 50 x 50 cm quadrant (understory seedlings with a dbh less than 5 cm were not destructively sampled). The fresh weight of each sample was determined in the field and a 250g sub-sample was extracted and sent to the ICAFE laboratory in Rivas for moisture content determination.

6.4 Estimating aboveground biomass and carbon-stock

6.4.1 Shade Trees

To estimate the biomass (kg) of the shade trees employed in the sampled farms, the following regression equation was used:

$$\text{Log}(B) = -0.9578 + 2.3408 * \text{Log}(D) \qquad [1]$$

Where B = biomass per tree (kg)
D = dbh (cm)

This equation was developed by Suárez Pascua (2002) of CATIE ($R^2 = 0.95$, $P<0.01$) for a similar study conducted in Nicaragua. This equation was chosen because it was developed by destructively sampling 35 shade trees from coffee plantations with similar characteristics and employing similar shade species to those examined in this study. The most accurate method to estimate the biomass of trees in a given region is to destructively sample a significant number of them and oven-dry their components (Brown, 1997). However, this was not realistic in this study; instead, a biomass estimate was obtained by applying Suárez Pascua's equation (see Appendix III for details of the model).

Due to the low wood density of *Musa* spp., their biomass (kg) was estimated by applying equation [1] and multiplying the output by 0.5. (Brown, 1997). The total biomass of shade trees in a given farm (t ha^{-1}) was converted to C-stock (t C ha^{-1}) by applying the following equation:

$$C = B \times fC \qquad [2]$$

Where C = carbon stored by trees (tC ha^{-1})
B = biomass of trees (t ha^{-1})
fC = fraction of carbon in biomass (assumed at 0.5 (IPCC, 1996)).

6.4.2 Coffee Bushes

The biomass of the coffee bushes (kg) was estimated by applying the following equation:

$$LN(B) = -2.39287 + 0.95285 * LN(D) + 1.2693 * LN(H) \quad [3]$$

Where B = biomass per plant (kg)
D = dbh (cm at 15cm height)
H = height (m)

This equation was developed by Suárez Pascua's (2002) (R^2=0.89, $p<0.01$) by destructively sampling 102 coffee bushes and oven-drying their components. Again, this equation provides the best method for estimating the biomass of coffee bushes sampled in this study, since coffee variety, density of planting and management conditions are similar among the two studies (see Appendix IV for details of the model). The biomass of coffee bushes (t ha^{-1}) was converted to carbon-stock (t C ha^{-1}) by applying equation [2].

6.4.3 Leaf Litter

Each of the leaf litter sub-samples collected was oven dried to constant weight at 105^{o}C. Their dry-weight was established and a ratio of oven-dry-to-fresh weight was calculated.

The total fresh weight of each sample was multiplied by the calculated ratio resulting in an estimate of the dry weight, or biomass, of each sample. The average biomass of the four samples collected at each farm was calculated and converted to t ha^{-1}.

Leaf litter biomass (t ha^{-1}) was converted to carbon-stock (t C ha^{-1}) by applying equation [2].

6.4.4 Trees at Los Cusingos

The biomass of trees (kg) at Los Cusingos was estimated by applying a general biomass regression equation for tropical trees in wet zones, formulate by Brown (1997) (R^2=0.92):

$$B = 21.297 - 6.953(D) + 0.740(D^2) \qquad [4]$$

Where B = biomass per tree (kg)
D = dbh (cm)

The biomass of trees (t ha^{-1}) was converted to carbon-stock (t C ha^{-1}) by applying equation [2].

6.5 Qualitative Information

Various experts from the Ministry of the Environment and Energy (MINAE), the National Forestry Fund (FONAFIFO), the Costa Rican Office on Joint Implementation

(OCIC) and the Foundation for the Development of the Central Volcanic Mountain Range (FUNDECOR) were consulted in order to gather information on Costa Rica's Environmental Services Payment (ESP) programme and details on carbon trading agreements and carbon sequestration projects already implemented in this country. Moreover, consultation with researchers from the Centre for Investigation and Teaching in Tropical Agronomy (CATIE), the Costa Rican Coffee Institute (ICAFE) and the Tropical Science Center (CCT) was invaluable in assessing the methods available for determining forest-based carbon-stocks and designing the final methodology of this study. Lastly, conversations with various members and officials from the local agricultural cooperative (CoopeAgri) provided insightful information on the role that this organization could play in the implementation of carbon sequestration projects in the region (see Appendix V for a list of individuals and organizations consulted).

CHAPTER 7: RESEARCH RESULTS

7.1 Coffee Production and Management Strategies

Landowners were informally interviewed to acquire data on coffee production practices and management strategies applied to each farm. Particularly, the interviews provided insight and background information on coffee farming and on factors that potentially influence the carbon-stock of a coffee agroecosystem. The results of this qualitative analysis are not reported on an individual farm basis, but rather as general trends that pertain to most of the sampling sites.

7.1.1 Shade Trees Employed

The diversity of shade tree species employed in coffee production and the services/products they provide are presented in Table 7.1. Overall, 34 different tree species were observed. The Poró and *Inga sp.* farms display the least structural diversity, with these species comprising approximately 95% of the canopy cover, resulting primarily in a uniform shade layer (Rank 1). The Eucalyptus and *Musa* spp. farms display intermediate diversity, employing one leguminous shade layer and one layer usually composed of timber and fruit-yielding trees (Rank 2). Lastly, the Diversified Shade farms display the greatest diversity of species that are incorporated into three distinct layers (Rank 3).

Common Name	Latin Name	Reported Use
María	*Callophyllum brasiliense*	Timber
Poró gigante	*Erythrina poeppigiana*	N-fixation, green mulch
Amarillón	*Terminalia amazonia*	Timber
Ira marañon	*Ocotea tonduzii*	Timber
Guachipelín	*Diphysa robinoides*	Timber
Cacique	*Piratinera guianensis*	Timber
Cedro amargo	*Cedrela odorata*	Timber
Plátano	*Musa spp.*	Fruit for household or livestock
Bananito rosa	*Musa spp.*	Fruit for household or livestock
Bananito criollo	*Musa spp.*	Fruit for household or livestock
Bananito negro	*Musa spp.*	Fruit for household or livestock
Banano morado	*Musa spp.*	Fruit for household or livestock
Llama del bosque	*Spathodea campanulata*	Timber
Cerillo	*Symphonia globulifera*	Timber
Muñeco	*Cordia collococca*	Timber, N-fixation
Guaba	*Inga sp.*	Fertilizer, N-fixation, firewood
Higuerón	*Ficus insipida*	Timber
Palo de leche	*Brosium utile*	Timber
Pejibaye	*Ananas comosus*	Food
Guatimol	*Musa spp.*	Food for household or livestock
Guineo rosa	*Musa spp.*	Food for household or livestock
Guineo negro	*Musa spp.*	Food for household or livestock
Itavo	*Yucca elephanitipes*	Live fences, eatable flowers
Lengua de vaca	*Conostegia xalapensis*	Live fences
Limón acido	*Citrus aurantifolia*	Fruit
Limón dulce	*Citrus limetta*	Fruit
Mandarina	*Citrus reticulata*	Fruit
Mango	*Mangifera indica*	Fruit
Naranja dulce	*Citrus sinensis*	Fruit
Grapefruit	*Citrus paradisi*	Fruit
Eucalypto	*Eucalyptus deglupta*	Timber, live fences
Aguacate	*Persea americana*	Fruit
Aceituno	*Simarouba glauca*	Timber, live fences
Madera negra	*Gliricidia sepium*	Live fences

Table 7.1 - Shade tree species identified in coffee farms and their reported uses

Many of the farmers interviewed reported that they plant poró and *Inga sp.* on their farms because of their capacity to fix nitrogen and maintain soil fertility. As well, many farmers choose to employ timber-yielding species such as eucalyptus, cedro and amarillón for the extra household income they provide. A common concern among farmers is the low price received for the coffee harvest and unpredictable fluctuations in world coffee prices; therefore, timber-yielding trees provide additional income security. Harvested logs are sold or used as construction materials for houses and furniture (no wood is used for charcoal production). One farmer reported harvesting his timber trees every fifteen years and replacing them with naturally generated seeds or purchased ones.

Farmers also explained that fertilization costs are reduced in farms employing shade, particularly leguminous species. However, a common concern is that excessive shade decreases productivity, and that cost-reductions in fertilization are not sufficient to counteract productivity losses. As a result, farmers expressed an interest in accessing niche markets where they would receive a premium for the coffee produced (i.e. shade-grown) that will compensate for potential losses in productivity.[12]

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[12] Since the time of this writing a sustainable coffee project was implemented in the Las Nubes/Los Cusingos Biological Corridor of Costa Rica. Through this project, local farmers are receiving a price for the shade-grown coffee they produce that is higher than that of Fair Trade.

7.1.2 Pruning Practices

Coffee bushes

Farmers prune coffee bushes once per year, in a sequential rotation pattern. More specifically, for every three rows of coffee bushes, the first is pruned the first year, the second the second year and the third the third year. This ensures that some of the coffee is always in production and results in a complete revitalization of the field.

Coffee bushes increasingly lose their bottom foliage with age, and thus decrease in productivity. They are cut to a height of 30 - 40 cm every three years to maintain yields. The pruned material is left on the farm's floor to act as organic fertilizer and provide soil protection. In all farms sampled the coffee bushes were planted in pairs, as is common practice in Costa Rica.

Shade trees

Leguminous shade trees such as poró and *Inga sp.* are pruned frequently. A formation pruning for poró is usually carried out approximately 4 to 6 months after planting to remove the lower branches. Normal pruning management usually starts within a year, when all or most branches are cut at the top of the bole leaving a trunk stump 2.5 to 3.0 m in height (see Figure 2, Appendix II). Trees are pruned twice or three times annually, usually prior to flowering and ripening of the coffee berries, in an attempt to stimulate these events through intense exposure to sun. Farmers also prune poró during prolonged periods of cloudy weather or rain in order to moderate moisture buildup in the farm. The cuttings are allowed to fall between coffee rows and are not usually removed from the field. Timber species such as eucalyptus and amarillón are not usually pruned, unless branches generate too much shade or create obstructions.

7.1.3 Chemical Inputs

Most farmers interviewed reported applying some synthetic chemicals to their fields, including fertilizers, pesticides and herbicides.

Fertilizers are applied three times per year – May, June and November – to coincide with the flowering, fruiting and post-harvest stages of production. The solutions are applied at the base of the coffee bushes by using hand-held spray pumps. The reported purpose of fertilization is to stimulate plant growth and fruit development.

Some farmers use herbicides to control the emergence of weeds in coffee fields. However, others use shade trees to limit their incidence, or to shift their character to less aggressive varieties, thus reducing dependence on synthetic inputs for weed control.

Pesticides are applied to coffee farms several times a year to limit the incidence of pests such as ojo de gallo (*Mycena citricolor*) and la broca (*Hypotenemus hampei*). Ojo de gallo is a fungus that attacks coffee plants subject to high humidity and low temperatures. It causes the coffee leaves to fall and affects coffee harvest especially in the months of September to November when rainfall is high and daytime sunlight is limited. In drier months, the fungus remains in a dormant state. La broca is a small black insect that attacks green and ripe coffee fruits causing them to fall, thus reducing the harvest. Excessive shade is also believed to cause increases in populations of la broca (Chinchilla, 2002).

To control the incidence of pests, farmers also moderate shade levels (especially during the rainy season) to allow for light and ventilation to penetrate coffee farms, build drainage systems to carry away excess water, and prune coffee bushes every 3 - 4 years to ensure their maximum strength and health.

7.2 Biomass and Carbon-Stock

7.2.1 Biomass and Carbon-Stock of Shade Trees

The carbon-stock in the shade tree component of the farms examined ranges from 33.2 t C ha^{-1} in the Diversified Shade farm DS2, to 6.8 t C ha^{-1} in *Inga sp.* farm, I2. Overall, the Diversified Shade and Eucalyptus farms display the greatest carbon storage in shade trees. On average, these two systems store approximately 50% more biomass in their shade trees than other systems. Although the Diversified Shade and Eucalyptus farms display fewer trees per hectare than the other systems examined (see Table 6.1), their shade-tree component contains a higher carbon-stock because of the trees' larger dbh, height and wood density.

The difference in shade tree carbon-stock between DS1 and DS2 can be attributed to the lower average dbh of trees in DS1. Although DS1 contains more trees per hectare than DS2, the trees in DS1 are younger than those observed in DS2 and their height and dbh are lower, thus resulting in lower biomass and carbon-stock values. Similarly, the carbon-stock of trees in P1 and P2 differ significantly. This is attributable to a higher poró-tree density in P1 as compared to P2 (see Table 6.1). Moreover, the average dbh of poró trees in P1 is higher than that of P2.

Shade Farm		**Biomass**	**Carbon**	**Average Carbon**
Type	**Number**			
Diversified Shade	DS1 DS2	33.8 66.3	16.9 33.2	25.0
Eucalyptus	E1 E2	43.3 47.5	21.7 23.8	22.8
Poró	P1 P2	31.9 17.1	16.0 8.6	12.3
Musa spp.	M1 M2	19.0 20.8	9.5 10.4	10.0
Inga sp.	I1 I2	16.9 13.6	8.4 6.8	7.6

Table 7.2 – Biomass and carbon-stock of shade trees (t ha^{-1})

These results fall within the range reported by Kursten *et al*. (1993) for the carbon-stock of shade trees in agroecosystems, namely 3 to 25 t C ha^{-1}. Alvarado *et al*. (1999) report that the average carbon-stock of shade trees in coffee agroecosystems of Guatemala is 15.82 t C ha^{-1}. This figure compares favorably with the poró carbon-stock reported in this study, however, Alvarado *et al*. do not specify species type or density of planting for their study. Similarly, the results reported in this study compare favourably with the shade tree carbon-stock range of 1.9 to 31.8 t C ha^{-1} reported by Suárez Pascua (2002). However, a study of coffee grown under the shade of poró in Ciudad Colón, Costa Rica reports a shade tree carbon-stock of 24.2 t C ha^{-1}, higher than that reported for the Poró farms examined in this study (Fournier, 1996). This difference can be attributed to a higher reported density of poró trees per hectare in that study and different local conditions, including climate, soil and management practices influencing those coffee farms. According to the authors, these factors have a significant effect on the overall biomass-productivity of coffee farms.

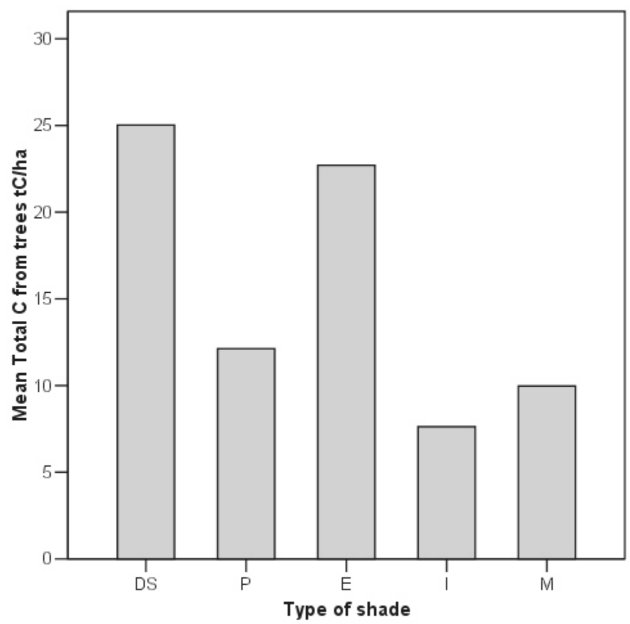


Figure 7.1 – Average carbon-stock of shade trees in the systems examined (DS = Diversified Shade, P = Poró, E = Eucalyptus, I = I*nga* sp., M= M*usa* spp.)

7.2.2 Biomass and Carbon-Stock of Coffee Plants

The carbon-stock of coffee bushes ranges from 1.4 to 3.5 t C ha^{-1}. The figures do not vary greatly among systems, as most display similar coffee-plant density, height and dbh (see Table 6.1). P2 and I1 display the lowest coffee carbon-stocks, a factor attributable to lower coffee-bush density in these farms.

Shade Farm		Biomass	Carbon	Average Carbon
Type	**Number**			
Diversified Shade	DS1	4.5	2.2	2.4
	DS2	5.1	2.6	
Eucalyptus	E1	7.0	3.5	2.9
	E2	4.6	2.3	
Poró	P1	5.8	2.9	2.2
	P2	2.9	1.4	
Musa spp.	M1	6.0	3.0	2.8
	M2	5.1	2.6	
Inga sp.	I1	3.8	1.9	2.2
	I2	4.8	2.4	

Table 7.3 - Biomass and carbon-stock of coffee bushes (t ha^{-1})

A number of studies have investigated the carbon-stock of coffee bushes in agroecosystems. Specifically, Suárez Pascua (2002) reports coffee carbon-stocks ranging from 0.2 to 2.8 t C ha^{-1}. Alpizar *et al.* (1985) report 3.93 t C ha^{-1} for coffee plants grown in association with *Cordia alliodora* in Turrialba, Costa Rica. Fournier (1996) reports 8.4 t C ha^{-1} in a coffee with poró system in the Central Valley of Costa Rica and Marquez (1997) 3.77 t C ha^{-1} in the coffee component of a study conducted in Guatemala.

The results of this study indicate that the type of shade, or structural complexity of the shade layer does not greatly influence coffee biomass. More specifically, shaded monocultures (Rank 1), such as Poró and *Inga sp.* farms, contain lower coffee carbon-stocks than those farms employing multiple shade layers. Therefore, these results indicate that increased shade diversity does not negatively affect the growth and development of coffee bushes, even though more complex shade limits the amount of sunlight reaching the coffee plants. Likewise, shade complexity does not significantly restrict density of coffee plants, thus resulting in similar coffee carbon-stocks between farms.

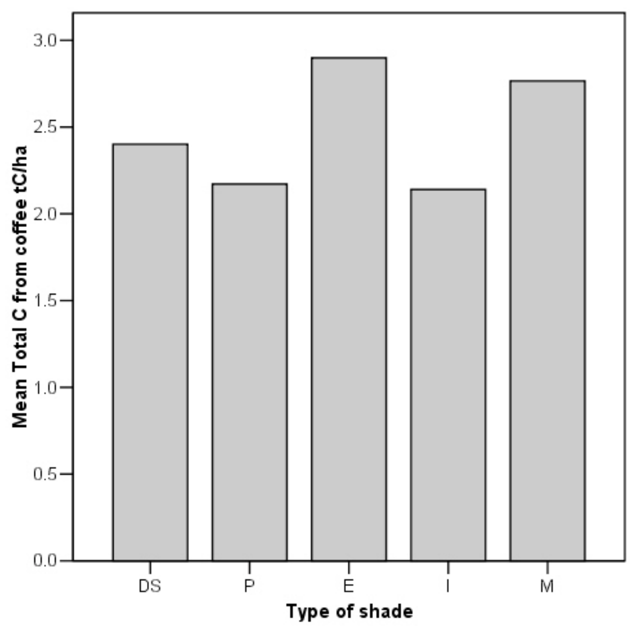


Figure 7.2 - Average carbon-stock of coffee plants in the systems examined (DS = Diversified Shade, P = Poró, E = Eucalyptus, I = I*nga* sp., M= M*usa* spp.)

7.2.3 Biomass and Carbon-Stock of Leaf Litter

The carbon stored in the leaf litter layer (dead leaves and twigs) of the coffee agroecosystems examined ranges from 0.7 to 4.5 t C ha^{-1}. On average, the Diversified Shade farms (Rank 3) displayed the greatest leaf litter carbon-stocks, due to the presence of large amounts of decomposing plant residue in between coffee rows. The eucalyptus and *Musa* spp. sites display "intermediate" carbon-stocks that are not very different from one another. The Eucalyptus E1 site exhibits greater litter biomass than its counterpart (E2) because the landowner had cut some shade trees a few days prior to sampling, resulting in the presence of more leaves and branches on the ground.

The Poró and *Inga sp.* (Rank 1) farms display, on average, the lowest leaf litter carbon-stocks. These shaded monocultures are well groomed and their trees minimally contribute to the litter layer. It must be noted that both Poró farms examined were surveyed prior to the pruning of tree branches, thus resulting in a shallow litter layer. However, Ruso (1983) reports that poró trees – when pruned twice per year and allowed to regenerate – can increase the carbon-stock of an agroecosystem by 5.9 t C ha^{-1} (generated from pruned material). Therefore the litter layer carbon-stock of farms employing poró will vary depending on pruning intensity and the time of sampling (provided that pruned materials are left in situ) (Ruso, 1983).

Shade Farm		Biomass	Carbon	Average Carbon
Type	**Number**			
Diversified Shade	DS1	7.6	3.8	4.1
	DS2	9.0	4.5	
Eucalyptus	E1	4.7	2.4	2.0
	E2	3.2	1.6	
Poró	P1	1.4	0.7	1.1
	P2	3.0	1.5	
Musa spp.	M1	2.5	1.2	1.8
	M2	4.7	2.4	
Inga sp.	I1	2.1	1.1	1.2
	I2	2.7	1.4	

Table 7.4 - Biomass and carbon-stock of leaf litter layer (t ha^{-1})

Suárez Pascua (2002) reports a leaf-litter carbon-stock range of 3.0 to 9.6 t C ha^{-1} in shaded coffee plantations of Nicaragua. Alpizar *et al*. (1985) report leaf litter carbon storage from 2.0 to 4.0 t C ha^{-1}, however they do not specify shade-type. Aranguren (1982) found that a coffee agroecosystem shaded by *Inga* sp. and poró contained 5.6 t C ha^{-1} in the litter layer. Generally, these studies report higher leaf litter carbon-stocks than those reported here. Variations in the leaf litter carbon-stock of a coffee farm can be attributed to the different management practices applied to each farm (particularly pruning practices) and the time of year in which the farms are sampled.

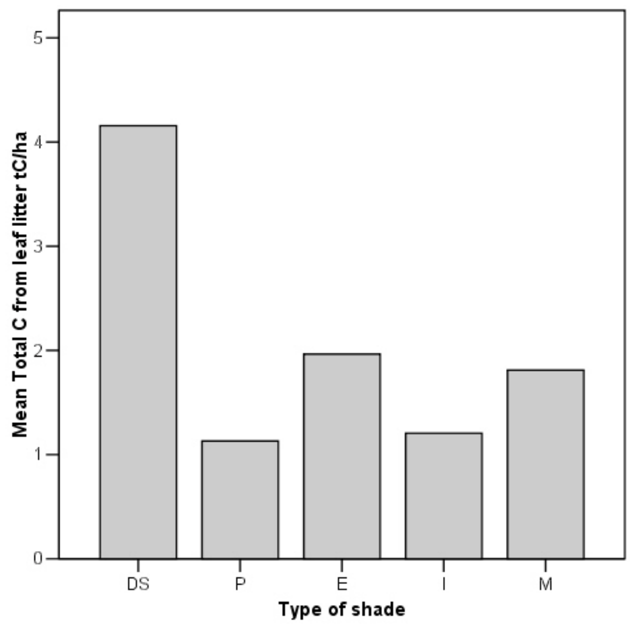


Figure 7.3 - Average carbon-stock of leaf litter layer in systems examined (DS = Diversified Shade, P = Poró, E = Eucalyptus, I = I*nga* sp., M= M*usa* spp.)

7.3 Total Aerial Carbon-Stocks and Comparison to Los Cusingos

One hectare of advanced secondary forest at Los Cusingos (Rank 4) contains a total aerial biomass (trees and leaf litter) of 394.2 tonnes and a carbon-stock of 197.1 t C ha^{-1}. The tree component of the system contains 192.3 t C ha^{-1}, or 98% of the total carbon-stock. The leaf litter component contains 4.8 t C ha^{-1}, or 2% of the total.

The total aerial carbon-stocks (trees, coffee and leaf litter) of the agroecosystems examined are presented in Table 7.5 and Figure 7.4. The Diversified Shade and Eucalyptus systems display the greatest aboveground carbon storage. The DS system contains approximately 50% (or more) carbon than that of the other systems examined (except Eucalyptus). Although the DS system contains more aerial carbon than all other systems, it only contains approximately 16% of the carbon stored in the aboveground vegetation at Los Cusingos. These results emphasize the important role forests play in climate change mitigation.

Agroecosystems shaded by eucalyptus display carbon-stocks comparable to those of DS farms, and 14% of the carbon-stock of Los Cusingos. Because of their fast growth, considerable height and dbh, eucalyptus trees are able to store large amounts of carbon. However, according to Resh (2002) eucalyptus tree farms do not support many native animal, plant and bird species leading to weak biodiversity in the environment. Moreover, this author reports that soil carbon-sequestration under eucalyptus shade is lower than that of mixed systems, particularly those employing nitrogen-fixers. All of these factors must be considered when planting eucalyptus trees for climate change mitigation purposes.

The *Musa* spp. and *Inga* sp. farms store less than half the overall carbon of the DS system. This is primarily attributable to the lower height, dbh and thus biomass of guaba and banana trees as compared to that of timber species such as eucalyptus, amarillón and cedro. Moreover, because the poró and *Inga sp.* farms are shaded monocultures comprised primarily of poró and guaba trees, the absence of larger tree species – that store more carbon – reduces their total carbon-stock. To illustrate, *Musa* spp. farms store more carbon than *Inga* sp. ones, although banana trees have a lower wood density. This is because in *Musa* spp. farms, only approximately 60% of the shade layer is comprised of banana trees; the rest is large timber species (Rank 2). This increases the overall carbon storage of the system.

Shade Type	Biomass	Carbon
Los Cusingos	394.2	197.1
Diversified Shade	63.2	31.6
Eucalyptus	55.2	27.6
Poró	31.0	15.5
Musa spp.	29.2	14.6
Inga sp.	22.0	11.0

Table 7.5 - Total aerial biomass and C-stock of systems examined (trees, coffee, leaf litter) (t ha^{-1})

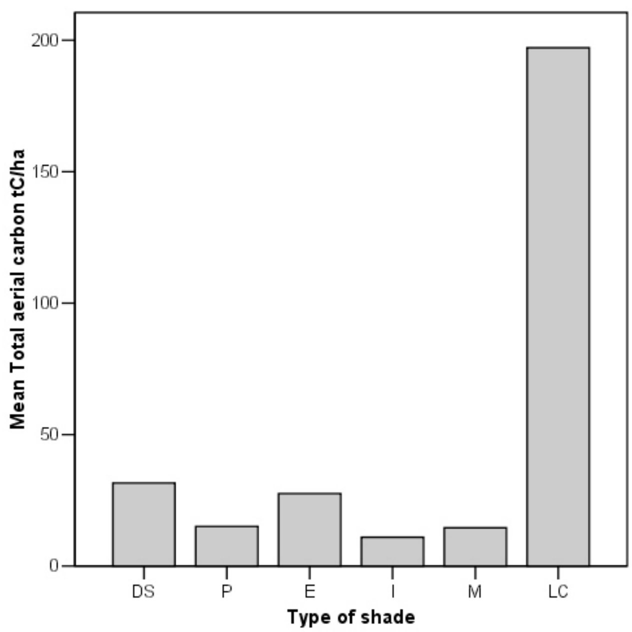


Figure 7.4 - Total aerial carbon-stock of systems examined (DS = Diversified Shade, P = Poró, E = Eucalyptus, I = I*nga* sp., M= M*usa* spp., LC = Los Cusingos)

Much variation exists between the total carbon-stocks reported in this study and those reported in the literature. Alpizar *et al*. (1985) report aerial carbon-stocks of 17.0 t C ha^{-1}

in coffee farms employing poró. This figure is similar to that reported in this study, however, Avila Vargas (2000) reports a total aerial carbon-stock of 10.57 t C ha^{-1} in farms employing poró in the Central Valley of Costa Rica, a figure lower than that reported by this study. Moreover, this author also reports aboveground carbon-stocks of 7.74, 12.29 and 15.53 t C ha^{-1} in three different systems employing coffee with eucalyptus.

In a similar study conducted in Nicaragua, Suárez Pascua (2002) reports aerial carbon-stocks of 27.3 t C ha^{-1} for a Diversified Shade system, 41.2 t C ha^{-1} for a system employing timber species (including eucalyptus) and 26.4 t C ha^{-1} for a system employing *Inga* sp. Suárez Pascua's (2002) reported values for Eucalyptus and *Inga* sp. farms are higher than those reported by this study, however, the carbon-stocks of the Diversified Shade systems are similar.

The variability in the results reported by this study and those of other studies can be attributed to differences in the age, density, height and management of both coffee plants and shade trees, and on the tree species employed in each system.

7.3.1 Breakdown of Total Aerial Carbon-stock by Components

The carbon-stock of each component of the systems examined is presented in Table 7.6. Figure 7.5 illustrates the percentage of the total aerial carbon that is comprised by each component of the system.

In all systems examined, the largest portion of the total carbon is stored in the shade trees. Almost all (98%) of the carbon stored in the secondary forest at Los Cusingos is found in the trees and the remaining 2% is in the leaf litter. Since the decomposition and recycling of fallen plant material occurs with great speed in the humid tropics (in comparison to northern coniferous forests) the leaf litter layer of tropical wet forests is often thin and stores much less carbon per hectare than the tree component (Kricher, 1997).

Shade trees play an important role in the carbon-storage of the Diversified Shade, Eucalyptus and Poró systems, where they contain approximately 80% of the carbon. However, in the *Inga* sp. and *Musa* spp. farms the shade trees contain a smaller portion of the overall carbon, namely 70%. In these systems, the coffee and leaf litter components play a more important role than they do in the others examined. This is attributable to the small stature of guaba trees and the low wood density and biomass of banana trees.

The carbon-stock of the coffee component is similar among all sites, ranging from 2.1 t C ha^{-1} to 2.9 t C ha^{-1}. This is because the density of planting, and the average dbh and height of coffee bushes do not greatly vary between systems. However, in agroecosytems with the lowest carbon storage (*Musa* spp. and *Inga* sp.), coffee bushes make a more significant contribution to the total carbon-stock than do those of systems where shade trees display large volumes and wood densities (Diversified Shade and Eucalyptus farms). In these cases the shade tree component of the system plays a more significant role.

The carbon storage of the leaf litter component is highest at Los Cusingos and in the Diversified Shade system, due to greater canopy density and complexity compared to the other systems. As noted above, the contribution of the leaf litter layer to the overall carbon-stock of Los Cusingos is minimal since the large trees play a predominant role in carbon storage. However, in the Diversified Shade system where shade trees display lower volumes, biomass and density than at Los Cusingos, the litter component plays a more significant role. The leaf litter layer also makes larger contributions to the total carbon-stock of the *Musa* spp. and *Inga* sp. *s*ystems, where shade trees store lower portions of the overall carbon.

Shade Type	**C from Shade trees**	**C from Coffee**	**C from Leaf Litter**
Los Cusingos	192.3 (98%)	--	4.8 (2%)
Diversified Shade	25.0 (79%)	2.4 (8%)	4.2 (13%)
Eucalyptus	22.8 (82%)	2.9 (11%)	2.0 (7%)
Poró	12.3 (80%)	2.2 (14%)	1.1 (6%)
Musa spp.	10.0 (68%)	2.8 (19%)	1.8 (13%)
Inga sp.	7.6 (70%)	2.1 (20%)	1.2 (10%)

Table 7.6 - Total aerial carbon-stock of each component in the systems examined (% of total)

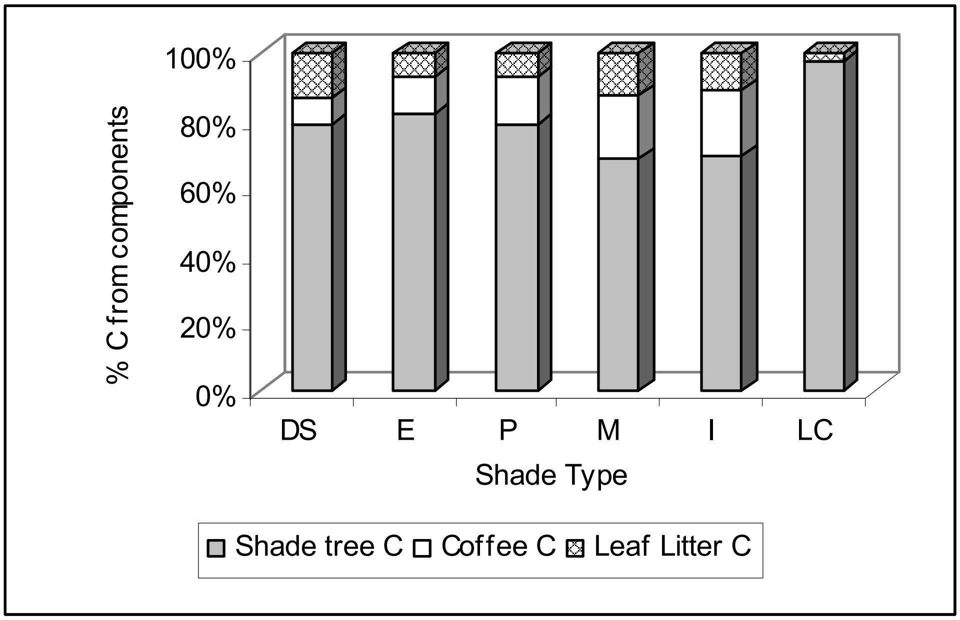


Figure 7.5 - Percentage of total carbon from components in the systems examined (DS = Diversified Shade, P = Poró, E = Eucalyptus, I = I*nga* sp., M= M*usa* spp.)

7.4 Valuation of Environmental Service

The aboveground carbon-stocks of the coffee agroecosystems examined in this study represent a baseline figure of the carbon that is currently stored in each system. If coffee growers were to be compensated for the "carbon storage" service provided by the shade trees on their farms, they would receive the following funding per hectare (crop component does not qualify for funding):

Shade Type	Aerial C (t C ha^{-1}) (trees and leaf litter)	Value in US $ (at US $10/ tC)
Diversified Shade	29.2	292.00
Eucalyptus	24.8	248.00
Poró	13.4	134.00
Musa spp.	11.8	118.00
Inga sp.	8.8	88.00

Table 7.7 - Revenue generated from a one-time payment for carbon storage of systems examined (shade trees and leaf litter components)

Assuming a price of US $10/ t C (as previously received by Costa Rica), the Diversified Shade system would provide the most revenue and greatest contribution to household income due to the higher carbon storage potential of this system. The difference in revenue generated by the Diversified Shade system (highest) and the *Inga* sp. system (lowest) is US $204.00 ha^{-1}. It follows that income-generation from the environmental service provided can be maximized by employing more diverse shade and converting additional land within each farm to shade-grown coffee production. For instance, assuming an average farm size of ten hectares in shade-grown coffee production a farmer could receive a one-time payment of approximately US $3000.00 for the carbon storage service provided. This would greatly supplement annual family income, given the currently low profitability of coffee production. Moreover, as previously discussed, employing shade in coffee production will reduce household expenses due to decreased dependence on synthetic fertilizers and pesticides and reduced labour inputs for weeding. Lastly, shade trees will provide products such as timber and fruit, which will further contribute to the income generation needs of local households.

If the carbon sequestration rate of shade-coffee farms of Santa Elena and Quizarrá is calculated, farmers could be compensated for the environmental service of "carbon sequestration" on an annual basis. However, the shade-coffee farms in the Las Nubes/Los Cusingos Biological Corridor are not currently eligible for funding under the CDM because they do not fulfill its "additionality" requirement. More specifically, the carbon storage and sequestration services currently provided by shade trees are not additional to those that would occur in the absence of a certified project activity. Therefore, for a CDM project to be implemented, shade cover and carbon storage would have to increase beyond the baseline amounts reported in this study. Nevertheless, compensation for the environmental services provided by coffee agroecosytems in southern Costa Rica would strongly contribute to household income generation needs, while simultaneously mitigating CO_2 accumulation in the atmosphere.

Lastly, the carbon-storage service provided by the forest at Los Cusingos is valued at approximately US \$2000.00 ha^{-1}. Although forestry activities eligible for funding under the CDM are currently restricted to those of afforestation and reforestation, thus rendering forest protection inadmissible, this value highlights the important role that the Los Cusingos Neotropical Bird Sanctuary plays in climate change mitigation and dictates its continued protection and expansion.

CHAPTER 8: SUMMARY, CONCLUSIONS AND RECCOMENDATIONS

Climate change is a multi-faced, global phenomenon. Addressing it requires the integration of several disciplines and co-operation among nations. This study presents an overview of the contributions that forest-based systems make to climate change mitigation and examines, in greater detail, the potential of coffee agroecosystems to remove CO_2 from the atmosphere and store it on land. Moreover, this study explores the CDM and related international mechanisms by which smallholders can access international carbon investment funds to convert low-biomass lands to productive tree-based systems with higher carbon-stocks. The results contribute to an understanding of the relationship between carbon-stock and the structural complexity of the shade layer in coffee farms of southern Costa Rica and, more generally, the contribution that increased shade cover could make to household generation needs and local livelihoods.

8.1 Aboveground Carbon-Stock of Coffee Agroecosystems

The aboveground carbon-stock of the coffee production systems examined ranges from 11.0 t C ha^{-1} to 31.6 t C ha^{-1}. The system that stores the most carbon is Diversified Shade, which employs a variety of shade species incorporated into three distinct layers including legumes, fruit trees and timber-yielding species. This system represents the highest structural diversity seen in the study region and the highest corresponding carbon-stock due to the greater potential of the shade trees employed for carbon storage (higher volume and wood density). Conversely, the system that stores the least amount of carbon is coffee grown with *Inga* sp. (guaba). This system represents a shaded monoculture mode of production, with low structural diversity and incorporating only one leguminous shade layer subject to pruning for shade regulation.

Intermediate systems, or those incorporating two shade layers, display different carbon-stocks depending on the shade species employed. More specifically, the *Musa* spp. system displays a carbon-stock comparable to that of shaded monocultures (*Inga* sp. and poró) and the Eucalyptus system to that of Diversified Shade. This is primarily attributable the low biomass and wood density of *Musa* spp. and the large stature and fast-growth potential of eucalyptus. Finally, the Poró system displays intermediate potential for carbon storage, attributable to the high density and intermediate stature of the poró trees observed on these farms.

In all cases, the largest portion of overall carbon is stored in the shade tree component of the system. Therefore, shade trees represent the largest and most important aboveground carbon pool in coffee agroecosystems. The carbon-stock of shade trees depends on the density of planting, species type and characteristics (including dbh, height and wood density). Therefore, carbon-stock is not only dictated by shade density and structural complexity, but also by the specific tree species involved. Projects aimed at increasing the aboveground biomass of coffee agroecosystems should not only focus on increasing the amount of trees per hectare, but also on strategically choosing tree species that store carbon efficiently, such as timber species. To illustrate, Corrales *et al*. (1998) (cited by Avila Vargas (2000)) report that pure silvicultural plantations in Costa Rica store 5.74 t C

ha^{-1} in their aboveground biomass. This figure is lower than that reported for the agroecosystems examined in this study, suggesting that high density of planting (characteristic of plantations) does not necessarily translate into higher carbon-stocks. On the contrary, trees may store more carbon when grown in an open agroforestry setting rather than a dense plantation, since in open systems more space is available for trees to branch out and fully develop.

Coffee bushes represent the second most important carbon pool, except for the Diversified Shade system where the leaf litter carbon-stock is larger than that of the coffee component. In this case, the leaf litter contribution to overall carbon storage is comparable to that of the secondary forest site at Los Cusingos. This indicates that increased structural diversity of the shade layer contributes positively to biomass accumulation in the litter layer. The carbon-stock of the coffee bushes did not vary greatly between systems, since the density of planting, dbh and height of coffee plants is similar among all farms.

Overall, of the coffee production system examined in the Las Nubes/Los Cusingos Biological Corridor of Costa Rica, the Diversified Shade system stores the most carbon per hectare in its aboveground biomass. Since this carbon pool is larger than that of systems employing less or no shade, payment for the "carbon storage" environmental service provided would yield an incentive for farmers to maintain shade, or even revert back to more traditional methods of coffee production that employ more shade than modern systems. This would in turn contribute to increased environmental health in the region and the diversification of household income while rendering coffee production more sustainable in the long-term.

8.2 Aboveground Carbon-Stock of Los Cusingos

The secondary forest site at Los Cusingos displays a carbon-stock significantly higher than of coffee agroecosytems. More specifically, one hectare of Los Cusingos forest contains 197.1 t C, most of which is stored in the well-established trees with large dbh and heights. These results illustrate the tremendous impact that tropical forests have on the global carbon cycle and the importance of preventing their conversion to less complex ecosystems, and hence release of carbon to the atmosphere. The results of this study and those of Hall (2001) and Znajda (2000) illustrate the importance of protecting the forest at Los Cusingos and expanding tree cover in its buffer zone in order to maximize the provision of environmental services, including habitat for biodiversity and carbon storage.

8.3 Payment for Environmental Services and Contribution to Local Livelihoods

In 2003, agroforestry activities became incorporated into the ESP programme of Costa Rica, thus compensating farmers for the environmental services provided by trees employed in the production of crops. This programme compensates a maximum of 3500 trees per farm and although contracts are initially limited to a three-year period, they can be subsequently renewed. Although designing, implementing and monitoring a property management plan is an involved and time consuming process, farmers who subscribe to the programme are able to supplement their household income generation needs by simply maintaining shade cover on their coffee farms.

The CDM is another financial instrument available to farmers for enhancing household income though increased shade cover in coffee production. Provided that the Kyoto Protocol comes into force, farmers could be compensated under the LULUCF component of the CDM for the carbon sequestration service provided; however, in order to fulfill its “additionality” requirement, farmers would have to increase shade cover beyond current levels. Therefore, the results presented in this study could serve as a baseline used to establish the difference in on-farm biomass between the “with project” and “without project” scenarios.

In previous carbon transactions, Costa Rica has been able to receive US $ 10 per tonne of carbon sold. Therefore, future carbon-sequestration projects implemented under the CDM should be able to secure at least this price per tonne of carbon traded. Alternatively, given the additional “soft benefits” provided by agroforestry systems, socially and environmentally conscious investors in industrialized countries may be willing to pay more for CERs produced by agroecosystems. Investors could also pay the project start-up costs by providing farmers with an up-front payment for CERs, thus farmers would subsequently owe carbon credits to investors. This would provide an incentive for farmers to become involved in climate change mitigation projects, since start-up and monitoring costs (i.e. renewal of CERs every five years) would incur upon investors.

Moreover, the cost of obtaining seedlings to plant in coffee farms of the corridor should continue to be supplemented by the local tree nursery in Santa Elena (recently expanded to include 6,000 seedlings for distribution to local farmers), and agronomy engineers at CoopeAgri, the farmers' cooperative, could provide technical assistance with planting and shade management as necessary. Therefore, in the case of the Las Nubes/Los Cusingos Biological Corridor of Costa Rica, a carbon sequestration project could provide farmers with a financial incentive and the technical information, inputs and expert consultation required to convert low-biomass coffee farms to productive tree-based systems.

Depending on the shade trees selected, increasing canopy cover in coffee production will provide landowners with access to additional products – fruit, timber, fuelwood and fodder – that serve to either supplement household income or reduce expenditures. Moreover, the on-farm production of trees may prevent the deforestation of other areas in the corridor, thus ensuring the continuity of environmental services provided by tree cover, including watershed protection, prevention of soil erosion and provision of habitat for biodiversity. Therefore, given the low profitability of coffee production in recent years (due to low world coffee-market prices), establishing a carbon sequestration project in this region of Costa Rica presents a viable opportunity to enhance smallholder livelihoods and increase environmental health.[13]

As indicated by the results of this study, most coffee farms in this region already do employ some form of shade. Therefore, if a carbon sequestration project were to be implemented in this region, "leakage" – the loss of carbon in outside areas due to changes in land-use practices at a project site – would be minimal or non-existent. More specifically, potential project sites (coffee farms) are already in coffee production, and simply increasing shade cover would not result in a displacement of farming activities and thus increased deforestation elsewhere. On the contrary, as mentioned above, increased shade cover may result in a reduction of tree loss elsewhere, due to on-site timber production. As previously stated, more problematic is the question of "additionality", since the willingness of farmers to increase tree cover is hampered by concerns with productivity losses and fungal diseases.

Lastly, since the individual coffee farms of the corridor are of limited size and by themselves store limited amounts of carbon, carbon sequestration projects in the region would have to be established on an aggregate basis, with all (or most) farmers in the corridor involved in project activities. However, projects that involve numerous landowners are more complex and have higher transaction costs. Therefore, special care must be taken to ensure that participants fulfill project commitments and that benefits are

[13] Since the time of this writing a sustainable coffee project was implemented in the Las Nubes/Los Cusingos Biological Corridor. Through this project local farmers are receiving a price for their coffee harvest that is higher than that of Fair Trade. A carbon sequestration project in this region could complement the sustainable coffee project and serve to further enhance the livelihoods of farmers in the Corridor.

fairly distributed. Since most farmers in the corridor are members of the CoopeAgri cooperative, this association could play a leading role in organizing farmers, project activities and the equitable distribution of benefits. Most importantly, the successful implementation of a carbon sequestration project in the Las Nubes/Los Cusingos Biological Corridor would serve as a model for other small coffee-producing watersheds in Costa Rica and Central America that are interested in accessing international carbon financing.

Although many questions remain not only concerning the fate of the Kyoto Protocol but also the implementation of smallhoder-focused carbon sequestration projects, the results of this study indicate that such projects are highly desirable from both a carbon investment and sustainable development perspective. More specifically, increasing shade cover in the coffee farms of the Las Nubes/Los Cusingos Biological Corridor would increase the region's carbon budget and provide many socio-economic benefits to its inhabitants thus contributing to the promotion of sustainable livelihoods. Further studies should be conducted to quantify the carbon sequestration and storage potential of other agroecosystems in the region and their contribution to local livelihoods.

8.4 Recommendations for Increased Shade Cover in Coffee Agroecosystems

As previously mentioned, coffee production is one of the primary land-uses in the communities of Santa Elena and Quizarrá. Because of this, increased shade cover in coffee farms would contribute to the creation of a biological corridor between the lowlands around Los Cusingos and the highlands of Las Nubes and La Amistad Biosphere Reserve. This corridor would allow for the dispersion of animal and plant species and facilitate movement for those that migrate between these areas, or spend a portion of their lives in both highland and lowland habitats.

Results from a number of studies indicate that increased shade density and complexity is beneficial for birds and beetles. Therefore, from a biodiversity perspective it is recommended that the diversity of tree cover in coffee farms be increased to benefit the greatest number of species. More specifically, studies from Znajda (2000) and Hall (2001) indicate that coffee produced with eucalyptus, poró and *Musa* spp. is able to support highly diverse communities of birds and beetles. The results of this study indicate that all three of these systems efficiently store carbon in their aboveground biomass, particularly the Eucalyptus system that contains a carbon-stock comparable to that of Diversified Shade farms. Thus these shade species should be further incorporated into coffee farming practices.

Moreover, given the instability in coffee prices, it is imperative that farmers in the region diversify their income sources while maintaining moderate production of high quality coffee. With respect to this, shade-grown coffee systems not only reduce the dependency on purchased chemical inputs, but also generate a variety of products that contribute to long-term household economic benefits. More specifically, the results of this study indicate that timber species such as amarillón and cedro can efficiently store carbon in their biomass due to their large stature and dbh. Since these can also provide farmers with good sources of timber and fuelwood they should be further employed in the production of shade-grown coffee.

Moreover, it is recommended that farmers incorporate more fruit-bearing species as shade for coffee, as these will provide a source of food, fodder and income to meet household needs. As the results of this study indicate, farms employing a variety of shade species (including fruit species) can store significant amounts of carbon in the aboveground vegetation. Moreover, although timber species are the most effective at storing carbon, fruit trees such as *Musa* spp. with large leaves contribute positively to carbon accumulation in the litter layer and act to protect the soil against erosion, while fertilizing it and providing more suitable habitat for soil fauna.

Lastly, dependence on chemical inputs for coffee production can be reduced by employing more diverse shade and nitrogen-fixing species, such as poró. More specifically, these have been shown to increase the organic matter reservoir in the soil and augment nutrient turnover, thus reducing reliance on synthetic fertilizers. Moreover, the use of shade also reduces the incidence of aggressive weeds, thus reducing dependency on herbicides. As the results of this study indicate, nitrogen fixers such as poró. can store intermediate levels of carbon in their biomass. It is recommended that these species continue to be used, due to the numerous environmental services they provide, but that they are increasingly interplanted with other species. More specifically, the shade layer in the shaded monoculture systems examined (Poró and *Inga* sp.) needs to be diversified in order to maximize carbon storage and the provision of habitat for biodiversity.

The overall management objective for ecologically sound coffee production in the communities of Santa Elena and Quizarrá is the sustained production of high quality coffee while maximizing the provision of environmental services to the greatest extent possible. This includes the maximization of carbon sequestration; an environmental service that farmers could be compensated for by accessing carbon markets created by international mechanisms such as the CDM. Therefore, while reverting to traditional methods of coffee production is both unfeasible and uneconomical, elements from traditional systems should be incorporated into current production practices in the region. These include increase in shade density and complexity, decrease in synthetic inputs and a more holistic approach to coffee production, one that contributes to environmental health and local livelihoods.

8.5 Recommendations for Future Research

Given that this study is the first of its kind in the region, and that studies on the carbon-stocks of agroforestry systems are generally lacking, there is much opportunity for further research in this field, both in Costa Rica and elsewhere.

It is recommended that further studies be conducted to quantify the amount of carbon that is stored in the soil pool of each of the agroecosystems examined. Previous investigation suggests that more than 80% of the total carbon found in coffee agroecosystems is stored in the soil (Suárez Pascua, 2002). Thus it is imperative for future research to attempt to quantify the carbon stored in the soil reservoir of these systems.

It is recommended that the carbon sequestration rate of the systems examined is investigated and classified according to tree species employed. More specifically, the results of this study provide a baseline amount of the carbon that is presently stored in the coffee agroecosystems of the Las Nubes/ Los Cusingos Biological Corridor; however, future researchers could monitor biomass increments over the years, thus establishing an annual sequestration rate (monitor yearly increments in dbh).

Studies should be conducted on the carbon-stock and carbon sequestration potential of silvipastural systems, in an attempt to promote and explore incentives for the afforestation of abandoned pastures in the region.

Once (and if) the Kyoto Protocol comes into force, an attempt should be made to access funding from the Community Development Fund and the Least Developed Countries Fund in order to establish a carbon-sequestration project in this region. Once again, the results reported in this study could serve as a baseline for measuring the fulfillment of the "additionality" requirement of the CDM.

Lastly, similar studies need to be conducted in other coffee-producing regions of the tropics and in other agroforestry systems, in order to refine sampling methods for measuring carbon-stocks and to better understand the role that agroforestry systems play in the global carbon cycle and in the mitigation of climate change and global warming.

APPENDIX I

Question set for non-structured, informal interviews conducted with coffee farmers in the Santa Elena and Quizarrá communities of Costa Rica.

1. What size is your farm? How many hectares of it are in coffee production?

2. Do you employ any shade trees on your farm? Why or why not?

3. What is (are) the primary shade tree species that you employ? What are your reasons for choosing the species?

4. What products (if any) do the shade trees provide your household with?

5. Do you allow for any trees to grow in your farm naturally, or are they all planted?

6. Approximately how old are the trees in your farm and how old are the coffee bushes?

7. What management practices do you apply in your farm? How often (if ever) do you prune the trees or coffee bushes?

8. What do you do with the pruned materials?

9. Do you ever remove any wood debris or fallen trees from your farm? Why?

10. Do you fertilize your farm and if so, how?

11. Are you aware of the national Environmental Services Payment programme? What is your opinion of it?

12. Are you familiar with the Clean Development Mechanism of the Kyoto Protocol? Would you be willing to increase shade in your coffee farm for climate change mitigation purposes, or to have access to specialty coffee markets?

APPENDIX II

Photos of the various coffee farms sampled in the Santa Elena and Quizarrá communities of Costa Rica.

Figure 1 - Coffee with unpruned Poró

Figure 2 - Coffee with pruned Poró

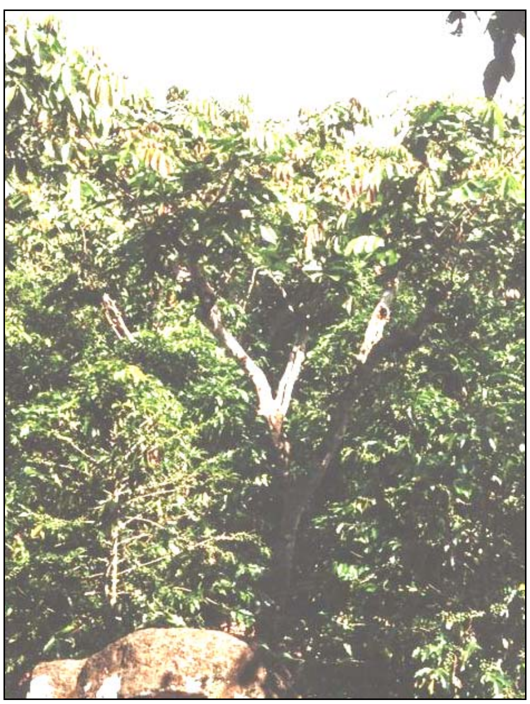


Figure 3 - Coffee with Guaba

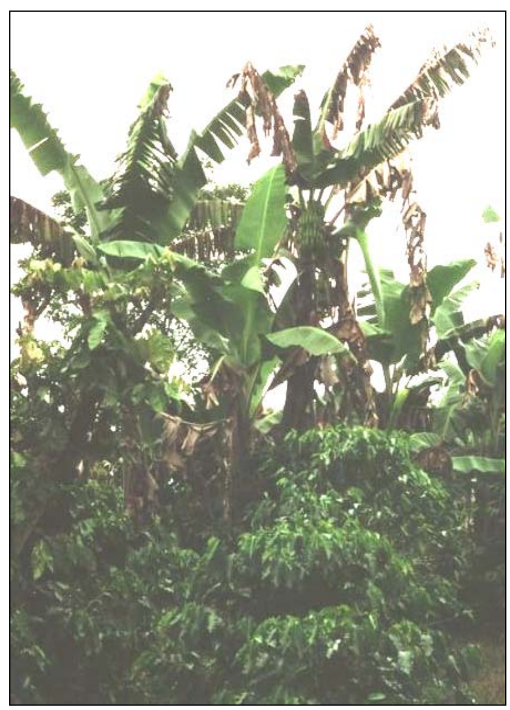


Figure 4 – Coffee with Banana

Figure 5 - Coffee with Eucalyptus

Figure 6 – Coffee with diversified shade

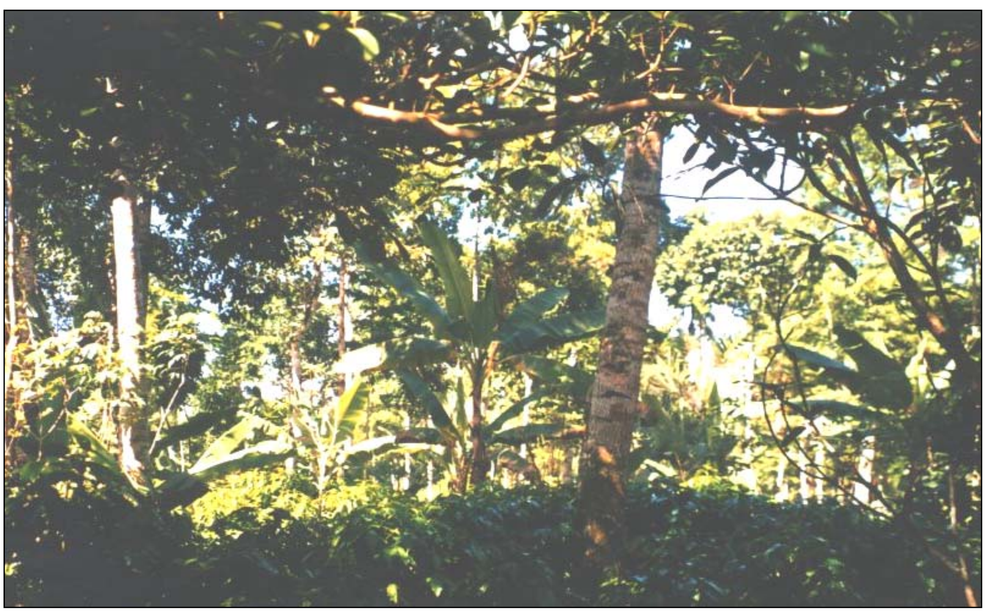


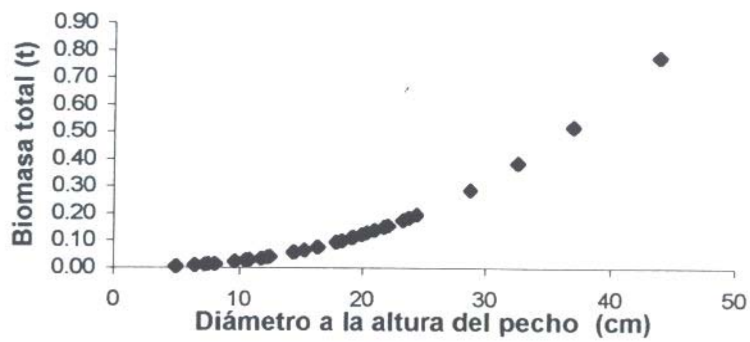
Figure 7 – Coffee with diversified shade

APPENDIX III

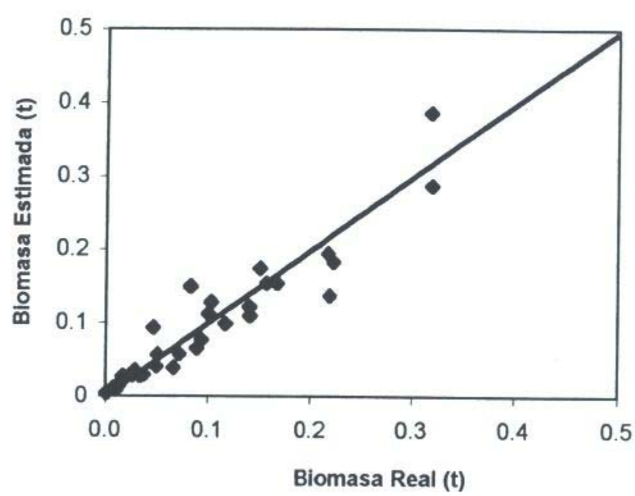
Model for the estimation of shade tree biomass, as developed by Suárez Pascua, 2002.[14]

Model	R^2	CV (%)	SE	Sign.T
Log (B) = -0.9578 + 2.3408 * Log (D)	0.95	6.67	0.015	0.0001

B = biomass (kg), D = dbh (cm), n = 35



Relationship between biomass (t) and dbh (cm) of shade trees



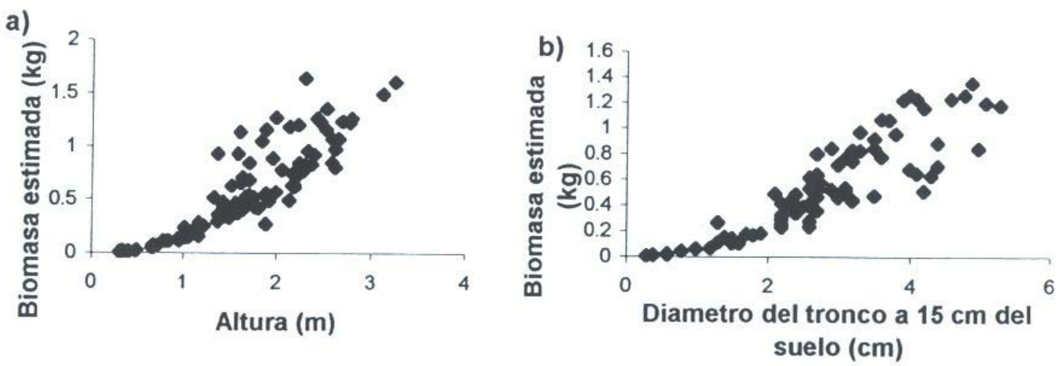
Relationship between actual biomass of shade trees and that estimated by the model

[14] For further details on the model and its development please refer to Suárez Pascua (2002)

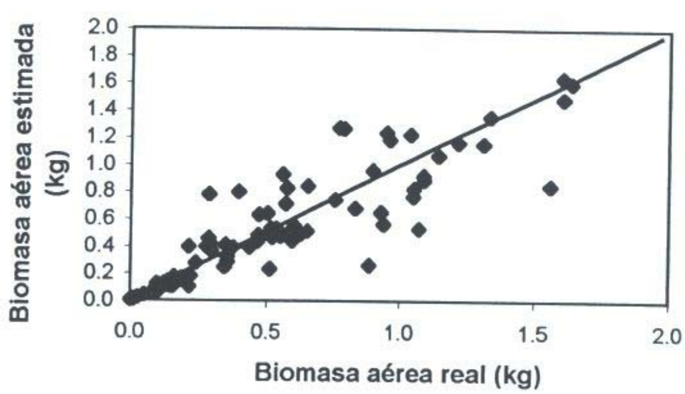
APPENDIX IV
Model for the estimation of coffee bush biomass, as developed by Suárez Pascua, 2002.[15]

Model	R^2	CV (%)	SE	Sign.T
LN (B) = -2.39287 + 0.95285 * LN (D) * LN (H)	0.89	53.6	0.237	0.0001

B = biomass (kg), D = dhb (cm), H = height (m), n = 102



Relationship between biomass (kg) and height (a) and dbh (at 15 cm) (b) of coffee plants



Relationship between actual biomass of coffee plants and that estimated by the model

[15] For further details on the model and its development please refer to Suárez Pascua (2002)

APPENDIX V

Costa Rican individuals and organizations interviewed between May and August, 2003

CENTRO CIENTÍFICO TROPICAL (CCT)
Tropical Science Center (TSC)
Ing. Enrique Ramírez. Executive Director.
Dr. Joseph Tosi. Researcher and co-founder.
Ing. Vicente Watson. Researcher.
Ing. Rosa Elena Montero. Director of small reserves
(plus various other CCT researchers).

LOS CUSINGOS
Edén Chinchilla Sánchez, Administrator

INSTITUTO DEL CAFÉ DE COSTA RICA (ICAFE)
Costa Rican Coffee Institute
Ing. Victor Chaves. Researcher at ICAFE-Heredia.
Dr. Olger Borbón. Coordinator of Programa Nacional de la Broca, ICAFE-Heredia.
Ing.Henry Rojas Castro. Coordinator of ICAFE-San Isidro.

CENTRO AGRONÓMICO TROPICAL DE INVESTIGACIÓN Y ENSEÑANZA (CATIE)
Centre for Investigation and Teaching in Tropical Agronomy
Ing. F. Milena Segura. Coordinator of Projecto Cambio Uso de la Tierra y Flujos de Carbono para Centroamerica, CATIE-University of Helsinki.
Ing. F. Hernan Andrade. Researcher at CATIE
(plus various other CATIE graduate students).

COOPERATIVA AGRÍCOLA INDUSTRIAL Y DE SERVICIOS MÚLTIPLES (CoopeAgri)
Agricultural Cooperative
Lic. Roger Zuñiga. Research and product development.
Ing. Agr. Mariano Ruíz Albarca. Manager of agricultural operations
(plus various other technicians who work at Finca La Prensa).

MINISTERIO DE AMBIENTE Y ENERGÍA (MINAE)
Ministry of Environment and Energy
Lic. Yamileth Cordero Barquero. Administrator of ESP programme, MINAE-San Isidro
(plus various other MINAE officials).

FONDO NACIONAL DE FINANCIAMIENTO FORESTAL (FONAFIFO)
National Forestry Fund
Ing. José Cubero Maya. Administrator of ESP programme-claims, San José.

OFICINA COSTARRICENSE DE IMPLEMENTACIÓN CONJUNTA (OCIC)
Costa Rican Office on Joint Implementation
Lic. Paulo Mansa, San José.

FUNDACIÓN PARA EL DESARROLLO DE LA CORDILLERA VOLCANICA CENTRAL (FUNDECOR)
Foundation for the Development of the Central Volcanic Mountain Range
Ing. F. Jorge Escribano. Forestry engineer at Puero Viejo de Sarapiquí research station.
Ing. F. Carlos Porras. Forestry engineer at Puero Viejo de Sarapiquí research station.
Ing. F. Pedro Uñiga. Forestry engineer at Puero Viejo de Sarapiquí research station.
Ing. F. Luís Aguilar. Forestry engineer at Puero Viejo de Sarapiquí research station.

INSTITUTO TECNOLÓGICO DE COSTA RICA (ITCR)
Technological Institute of Costa Rica
Ing. Edgar Ortíz Malavassi. Research on biomass expansion factors.

COMITÉ PARA LA CONSERVACIÓN FORESTAL (COCOFORES)
Forest Conservation Committee
Mario Ganados, Santa Elena.
Marvin Arias, Santa Elena.
Luís Angel Rojas, Quizarrá.
Humberto Guzmán, Playa Verde, Santa Elena.

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