FRUIT-TREE-BASED AGROFORESTRY IN THE WESTERN HIGHLANDS OF GUATEMALA: AN EVALUATION OF TREE-CROP INTERACTIONS AND SOCIOECONOMIC CHARACTERISTICS

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

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Worldwide, fruit-tree-based agroforestry systems have been only modestly studied, especially in terms of the quantification of biophysical interactions occurring in mixtures of fruit trees and crops. Agroforestry systems based on apple *(Malus* spp.), peach *(Prunus* spp.), and pear *(Pyrus* spp.) are common in northwest Guatemala as low intensity homegardens. The first portion of the study evaluated the productivity of mixed cropping of fruit trees with annual crops as influenced by biophysical mechanisms. The second portion of the study investigated the potential for adoption of fruit-tree-based agroforestry by resource limited farmers in the region using ethnographic investigation and linear programming simulations.

The on-station experiment included the following: sole crops and additive intercrops of maize (*Zea mays*) and fava (*Vicia faba major*), and clean weeding without crops as understory treatments, and eight-year-old pear trees or artificial shade structures as overstory treatments. Growth and yields of all components were measured during 2002 and 2003.

Mixed cropping of fruit trees + annuals showed significant yield advantages over maize + fava intercropping, which was superior to sole cropping of the same species. Annual-crop yields were generally unaffected by overstory treatments making fruit yields an additive benefit. Pear + fava mixed cropping improved yields of top-grade pears with no reductions in fruit quality. The results suggest small farm productivity and fruit quality can be increased through careful association of fruit trees with annual crops. Increased capture of growth resources (radiation and precipitation) by the fruit-tree + crop mixture suggests that the resources are not efficiently used by the sole crop stand and the increased resource use was at least partially responsible for the realized gains.

On-farm studies indicated that fruit-tree-based agroforestry was potentially more attractive to relatively prosperous families or those with larger land holdings. The inability to meet annual food security needs, poor fruit quality, and lack of market infrastructure were identified as factors that limit adoption. The complementarity of production with the dominant maize crop, home consumption of fruit, and the potential to generate additional cash on limited land holdings were identified as promoting adoption of fruit-tree-based-agroforestry within some groups.

CHAPTER 1
INTRODUCTION

Agroforestry, the relatively new name for the old practice of growing trees and crops in interacting combinations, is now recognized as an approach to increasing farm productivity in low-external-input, resource-limited situations. Many, if not most, agroforestry systems have developed over long periods of time in response to interactions between agroecological conditions, plant diversity, and farmer resources and needs. As Nair (1998) notes, much initial research in agroforestry was descriptive or applied, and prototype technologies were developed to address specific production limitations in development “hot spots.” More recent studies in agroforestry seek to understand the functioning of interacting components and the mechanisms by which relative advantage occurs through interactions. Being able to better understand the potential benefits and limitations of extant systems provides a basis for using proven principles to address perceived limitations in non-optimal systems.

Agroforestry in many instances addresses a basic issue in agroecology: the scarcity of productive land for agricultural pursuits. Were land quality and availability not overwhelming limitations, numerous issues such as crop yields, nutrient availability, conservation and ecological service functions, and fuelwood and timber production would become moot. As is readily apparent, strong tension exists between land that is managed for agricultural production, where resource capture and accumulation are streamlined to produce human-oriented goods and services, and land that is not currently in production. The natural resources such as carbon and other elements that are stored in ecosystems such as forests and grasslands are now being extracted and exploited, and the land that becomes depleted of its original vegetation is then used either to try and produce commodities for human needs, or are abandoned as wastelands. One resolution of this continuing degradation is to maintain and enhance the functions of woody perennials within a simplified agroecosystem while improving the total productivity of the system.

Numerous benefits of agroforestry have been reported and substantial effort has gone into quantifying the underlying processes. Species-level biodiversity and ecosystem processes in the subtropics are better maintained with partial canopy cover of a limited number of species in the overstory (Perfecto et al., 1996, Michon and de Foresta, 2001) compared to monocultures (Gallina, Mandujano, and Gonzalez-Romero, 1996). It has also been well documented that fruit-tree-based agroforestry systems in the north temperate zone are able to provide the public environmental services better than monocultured annuals or intensively managed orchards (Herzog, 1998). Additionally, agroforestry technologies may improve nutrient cycling (Glover and Beer, 1986; Nair et al., 1999; Schroth et al., 2001), buffer understory temperature extremes (Barradas and Fanjul, 1986), or enhance soil water balance while reducing erosion (Rao et al., 1998).

One central agroforestry hypothesis is that trees provide benefits to farmers and to ecosystems by capturing and using water, light, and/or nutrient resources that would remain unexploited in tree-less systems (Cannel et al., 1996). In defining relations between competitive and noncompetitive resource capture, these authors note that the value of the tree-component yield relative to the value of the crop-components yield directly affects the importance of the resources that are captured by the tree that the crop would never access. The greater the value of the tree-component yield is relative to the crop yield, the less important the resources lost to the crop become. Due then to the importance of the contribution made by the system in assessing the importance of the resulting competition, the relative merits of biological-nitrogen-based, timber-based, and fruit-tree-based agroforestry systems are briefly reviewed below.

A major focus of most studies of tropical agroforestry systems has been either the role of multipurpose trees in increasing or maintaining soil fertility. Trees that are used primarily for maintenance or enhancement of soil fertility in agroforestry systems, can be extremely competitive with the crops grown under or near them (Van Noordwijk, 1996). Most agricultural production has been founded on meeting year to year nutrient requirements through the extraction of previously-existing fertility stores without sufficient consideration for maintaining soil fertility levels as the crops are grown (Buresh et al., 1997). When fertility is reduced, production moves elsewhere or fertilizer is applied to directly support declining yields. A major claim about the advantage of agroforestry systems is the production of biological nitrogen, for example through symbiotic fixation by tree legumes. But, in low-input, limited-resource systems, the production of such biological nitrogen needs to be valued against free nitrogen, because "extraction" of whatever available nitrogen (rather than external application) is the norm. In such a scenario, the advantage of the tree component in agroforestry is actually rather small and of lesser value than often claimed. The lower "real" value of contributions by biological-nitrogen-based systems magnifies the importance of crop losses due to competition for nutrients. Thus, inter-component competition is of great importance to farmers, and it may be a leading reason for low levels of adoption of this type of agroforestry technology in many areas.

A second substantial thrust of agroforestry research has been on the inclusion of timber species into agricultural systems. De Foresta and Michon (1997) have suggested that in an acceptable (sustainable) agroforestry system, the majority of yields would be available for harvest or use on a “daily or monthly basis” and that some products of the system should be for household consumption. Systems that emphasize the production of even short-rotation timber as a principal focus will be hard pressed to meet these criteria, particularly as the timber matures (Sumitro, 1983; Barbier, 1990). While substantial value may be accumulated through annual increments, this value is inaccessible to farmers for a considerable time period, and again the importance of crop losses due to resource competition will be increased.

In contrast to the previous lines of research where much has been accomplished, Nair (2001) raises the question of why more progress has not been made in homegardens. Fruit producing species are so commonly part of homegardens that they are the best studied example of intensive fruit-tree-based agroforestry. While the literature is replete with descriptions and inventories of tropical and subtropical homegardens (Fernandes and Nair, 1986), little mention of the ubiquitous nature of homegardens from the equator to the northern temperate zones has been made. In a recent review describing and defining temperate agroforestry (Lassoie and Buck, 1999), the authors fail to mention homegardens or productive trees around households. These fruit-tree-based systems, which clearly meet their criteria for agroforestry systems, are undeniably more common though perhaps less intense than the six systems they examined. Frequently, the temperate homegarden may be less diverse (Long and Nair, 1999) and less intensive than the better characterized tropical version. This little-explored observation is well supported by ecological principles that link species diversity with evapotranspiration rates and total energy availability (Currie and Paquin, 1987). The low diversity and less intensive management of temperate fruit-tree-based agroforestry when compared to the complex multistrata systems of the lowland tropics make them harder to recognize and delineate.

The descriptions and inventories that past researchers have provided illustrate that homegardens, whether complex with numerous strata and diverse species of crops that provide a legion of products for use or sale (Fernandes and Nair, 1986; Kumar and Nair, 2004) or simple temperate gardens composed of an understory of annuals under dispersed overstory perennials, have a common thread linking them. In all of them, the tree components overwhelmingly produce consumable or saleable products on a regular or seasonal basis. Thus, within fruit-tree-based agroforestry systems, the importance of competitive resource losses to crops is likely to be diminished because the tree component produces a valuable good in exchange for its competitivity with the crop over a similar time scale.

Surprisingly, in comparison to other types of trees, the research conducted on fruit trees in areas such as tree-crop interactions and the appropriate horticultural and agronomic management regimes needed to optimize yields in the particular biophysical and social environment are extremely scarce. An exception is for those fruit trees such as *Coffea* spp. or *Theobroma* spp. grown as understory species where the tree is treated more like the annual crop component and the tree component is more frequently from the timber category (Bellow and Nair, 2003). In order to optimize fruit-tree-based systems and produce a suitable balance of annual- and perennial-based yields to meet farmer goals, research similar to historical agronomic and horticultural research is needed to identify optimal stand densities, fertilization regimes, and planting and management practices.

This study examines the biophysical interactions between trees and crops in fruit- tree-based agroforestry systems, as well as the relevance and performance of these systems in meeting the needs of subsistence farmers in low-input and limited-land situations in the western highlands of Guatemala.

Statement of the Problem

The limited area suitable for cropping, frequently less than 0.5 ha per farm in the Guatemalan highlands, is a major limitation to farm production (Instituto Nacional de Estadísticas, 1994). Historically, this has led to the progressive conversion of primary and secondary forest to agricultural land, often with a loss of many environmental services (Colchester, 1991). Agroforestry frequently promotes increases in land-use intensity, and evaluation of the use-efficiency of incident solar radiation and annual precipitation is critical to identify areas where productivity can be enhanced. Mixed systems of maize (*Zea mays*), broad bean (*Vicia fava*), common bean (*Phaseolus vulgaris*), and apple (*Malus* spp.), plum and peach (*Prunus* spp.) and pear (*Pyrus* spp.) are common in the study region. Intercropping or mixed cropping in small plots may have potential to increase total yields above those of monocropping using the same resource base (Mead and Willey, 1980; Hiebsch and McCollum, 1987). Land equivalency ratios (LER) >1.0 have been demonstrated for the maize-broad bean association at lower elevations in semiarid conditions (Li et al., 1999), yet the systems have not been evaluated under other conditions or in association with deciduous fruit trees. The evaluation of cropping efficiency through land equivalency ratios has also not been extended to consider mixed annual and perennial systems. Furthermore, economic yields may be increased by more efficient temporal partitioning of farm resources into crops and trees (Hiebsch and McCollum, 1987). It is currently unclear how to achieve optimal yields in these small plots on a continuous basis within the biophysical and social constraints experienced by the farmers.

Competition for nutrients and moisture have been identified as potential limitations in some tropical agroforestry systems (Ong et al., 1991), but have not been reported in subtropical highlands or fruit-tree-based systems. Climatic variability, both within and between seasons is a major constraint on agricultural productivity in western Guatemala (Redclift, 1981). The critical issue is to understand the interactions between trees and crops on overall water use, radiation capture, crop growth and development where fruit production is emphasized. Few studies have incorporated cropping patterns and yield variability into assessments of effects on farmers, and none have been conducted in this region.

The current research project provides explicit support for the current theory that farmers in land-scarce situations can directly benefit by incorporating fruit trees into an otherwise treeless agricultural landscape. This has relevance for subsistence farmers in high mountain areas worldwide. It further addresses the hypothesis that these anticipated benefits are realized because mixed tree and crop systems make use of biophysical resources that are not captured or used efficiently in agricultural fields without woody perennials. Some studies have examined these questions in relation to timber-producing or nitrogen-fixing trees. Fruit trees, however, enjoy greater popularity among subsistence farmers and provide benefits in less time. Yet, answers to several important questions are not available. For example, a) how competitive are small fruit trees and annual crops in mixtures and b) what are the critical factors that can lead to adoption of these systems as a land management alternative in tropical highlands?

Hypothesis

This study tests the validity of the hypothesis that fruit-tree-based agroforestry systems produce benefits for farmers by using resources that would not be exploited in non-agroforestry systems. Fruit-tree-based systems, practiced in the subtropical highlands of Guatemala at elevations between 2500 and 3000 meters above sea level, provide an excellent case study for the potential of fruit-tree-based systems to address the needs of limited-resource farmers in marginal highland areas worldwide.

Objectives

Objective One: Interactions at the Tree-crop Interface

The first objective was to evaluate the use of photosynthetically active radiation (PAR) and precipitation by fruit trees and crops in common associations, using controlled on-station experiments. The differences in PAR and water usage were related to measured tree and crop growth, rates of development, and final yields.

Objective Two: Socioeconomic Impact of Mixed Cropping in the Guatemalan Highlands

The second objective was to assess the potential impacts of farm management choices using realistic yield estimates while considering the real social and economic limitations of the farmers. Ethnographic linear programming was used to estimate the roles of farm and family size, crop yields, and fruit yields in the optimal allocation of resources.

Study Overview

This study is presented in five chapters. Chapter 2 provides a review of the literature to explain the historical role of fruit-tree-based agroforestry in the world. Farmers' preferences in tree planting on their farmlands and their reasons for their tree choices are covered. The performance, both biophysical and economic, of fruit-tree-based agroforestry systems drawn from the limited research available is evaluated and a broader context for the study provided.

Chapter 3 provides the results of a two-year study of the interactions between pear trees (*Pyrus communis* var. Ayres and Bartlett) and two annual crop components, maize (*Zea mays*) and fava bean (*Vicia faba*). After a brief review of the literature on annual-perennial competition with an emphasis on deciduous fruit trees, the chapter describes the details of experimental methodology, and then presents and discusses the results.

Chapter 4 examines the economic role of fruit trees and fruit-tree-based agroforestry in two communities in Guatemala's western highlands. A brief review of the region's agricultural landscape and the use of linear programming to evaluate agroforestry technologies, is followed by the results of on-farm survey and cropping evaluation studies. The chapter concludes with the results of linear programing simulations of some socioeconomic factors and their influence on the adoption of fruit-tree-based agroforestry.

Chapter 5 gives a synthesis, conclusions, and some recommendations for future research and development efforts.

CHAPTER 2
REVIEW OF LITERATURE

This study addresses important questions related to the relevance of fruit-tree-based agroforestry to meet the needs of subsistence farmers in low-input and limited-land situations. The available literature on the types of trees farmers prefer, the purposes for which they choose to plant trees, the economic benefits of fruit tree-annual intercropping, and an analysis of the yields in such systems are reviewed in this chapter.

Fruit-Tree-Based Agroforestry Systems

While analyses of harvest indices (HI) have not yet been successfully applied to most perennial crop species, it is possible to surmise that perennials may exhibit a fundamental advantage over annuals in that many of the necessary structures to produce a yield – roots, stems, and canopy parts – are carried over from year to year. It is reasonable to expect that a harvest index calculated on the annual growth and yields of many of these species would show production efficiencies comparable to or greater than those of many annual cultivars. Those trees producing non-timber forest products such as fruits, nuts, or spice crops form the basis for many of the most vibrant and sustainable systems.

Surprisingly, in comparison to other types of trees, the research conducted on fruit trees in the areas such as tree-crop interactions and the appropriate horticultural and agronomic management regimes needed to optimize total yields of mixed systems in particular biophysical and social environments are extremely scarce. An exception is for those fruit trees such as *Coffea* spp. or *Theobroma* spp. grown as understory species where the tree is treated more like the annual crop component and the tree component is more frequently from the timber category (Bellow and Nair, 2003). Research similar to historical agronomic and horticultural research is needed to identify optimal stand densities, fertilization regimes, and planting and management practices in fruit-tree-based agroforestry systems in order to maximize the benefits that these systems will produce.

What Trees Do Farmers Want to Plant?

The existing research provides ample evidence that farmers prefer to plant and maintain fruit trees (hereafter referring as well to trees with nuts as their primary yields) than other species. The permanent crops most commonly found in the "Sloping agricultural land technology - SALT" suite of technologies developed in concert with local Filipino farmers were fruit-bearing perennials mixed with annuals (Tacio, 1993). Farmers preferred to incorporate numerous fruit trees amongst the faster growing multipurpose trees when establishing hedgerows to control erosion. Of the top 10 farmer-preferred species in the Multipurpose Tree (MPT) Network's survey of seven Asian countries, the top three were well-known fruit trees, and only three of 10 did not produce a food item (Raintree, 1992). Similarly, 11 of the 15 most-preferred trees by farmers across four countries in West Africa were fruit trees and the top five trees had food as their principal product (Franzel et al., 1996). In Northern Laos, upland farmers commonly plant fruit trees in concert with their slash-and-burn agriculture, particularly on steep slopes where continuous annual cropping is difficult. While farmers expressed concerns about the limitations of inaccessible markets, fruit trees were the most commonly planted perennials in the study area (Roder et al., 1995). In eastern Madagascar, exotic fruit trees were identified on 100% of farms involved in the study and indigenous fruit trees were managed on 60% of the farms. Farmers expressed a desire to further expand their fruit production practices to increase self-sufficiency (Styger et al., 1999). A study in Cameroon shows that most of the most popular tree species with farmers have non-timber forest products, often fruit, as one of their principal products (Ayuk et al., 1999). In Southern Uganda, *Musa* spp. was the dominant perennial managed on farms and farmers generally allocated land to this herbaceous perennial in a ratio of 2:1 versus annual crops such as maize (*Zea mays* L.) and bean (*Vigna* and *Phaseolus* spp.) (Briggs and Twomlow, 2002). Farm-scale tree evaluations in Zimbabwe revealed that, of the trees planted or maintained on-farm, the majority were fruit-producing. Most of those trees were exotic fruit-producing varieties in comparison to indigenous trees, and the only indigenous species that were planted were fruit-producing. Additionally, this study showed that only fruit-bearing trees remained on the farm with increasing length of tenure (Price and Campbell, 1998). Allen (1990) reported that demand for fruit trees for planting in Swaziland was “very high,” but fruit from existing trees was of mediocre quality due to “difficulties in obtaining quality material.” While firewood species were characterized as appearing in woodlots of specific sizes, no information was provided on the arrangement of fruit trees. Excluding bananas, each Swaziland household had on average less than 10 fruit trees that were dispersed on farms, but wealthier residents and older homesteads had fruit trees in more regular plantings.

Farmers in Jamaica's Blue Mountains reported interest in planting trees on their farms; their preferred trees were described as multipurpose trees with fruit as one of their products and the majority of existing trees were fruit trees (McDonald et al., 2003).

Based on this brief review, it can be surmised that farmers are likely to be more receptive to the idea of tree planting when the perennials are fruit trees. Therefore, fruit trees have a better chance in programs that aim for integration of perennial and annual crops to maintain ecological services and to improve overall productivity in resource-limited environments. An important question to examine is what purposes do fruit trees serve on farms.

Why Do Farmers Plant Fruit Trees?

In a large study spanning 31 sites in seven Asian counties, the MPT Research Network found that food production was the primary characteristic of importance to farmers (Raintree and Wickramasinghe, 1992). Production of useful firewood or timber was valued secondarily in most cases and more than 50% of food-producing species valued by farmers had an important post-productive function. The authors noted that problems occurred with fruit producing species being excluded as not being multipurpose in at least one site or country (Raintree and Wickramasinghe, 1992). Wickramasinghe (1992), working with the MPT tree breeding project, found that Sri Lankan farmers valued the tree's ability to produce food, medicinals, or oil-rich seeds. Farmer responses to questions about their interest in planting *Tectonis grandis* (teak) in northern Laos further reveal the critical role that fruit trees play. Farmers who had planted teak generally possessed greater resources (rice lands, draft animals, and excess labor) than those who had not. Smaller-scale farmers were understandably reluctant to invest their land and labor resources in a crop that would give no return for 15 years (Roder et al., 1995). Farmers in Bangladesh gave income generation and household consumption as the two most important reasons for planting trees (no distinction was made as to type). Food production from trees was categorized as “not important” by only 15.1 % of farmers in this study while generation of household income was cited as very important by 87.8 %; ecological functions of trees in the landscape were scarcely considered. The availability of labor to establish and care for trees and the potential conflict between agricultural production and tree establishment were noted as important constraints (Salam et al., 2000). In the highlands of Northern Thailand, 62.4 % of fruit tree plantings were actively intercropped with annual crops. The existing systems were functionally classified and nearly all forms of fruit cultivation had a home consumption component, including those systems classified as conventional pure orchards (Withrow-Robbinson et al., 1999).

In Tanzania, farmers managed fruit trees in their fields and around their homes because the trees provided both income and fruit for home use. Additionally, the trees were useful in maintaining tenure of the lands. Large-scale orchards were extremely uncommon. Farmers perceived fruit trees as requiring very little labor and modern horticultural management was uncommon. Farmers’ explanation of the purpose of the fruit trees was their home consumption value, because without them there would be no source of fruit. Three quarters of growers surveyed also expressed the importance of market sales with an estimate that half of the harvested fruit was sold (Delobel et al., 1991). In western Africa, roughly half the production of *Irvingia gabonensis,* a popular tree-fruit, is for home consumption, and the remainder for cash sale in local markets (Ayuk et al., 1999).

In Soqotra island, a remote location near the Yemeni coast, the presence of fruit trees appeared to be most closely related to subsistence, as opposed to market gardening. The number of large fruit trees declined as the importance of crops destined for the market increased, highlighting the potential importance of the income generating aspects of fruit-tree management (Ceccolini, 2002) and the relative value of the various products.

Studies in Costa Rica (Marmillod, 1987) and Honduras (Hellin et al., 1999) have reported farmers' preference for fruit-producing rather than multipurpose- or timber trees on their farms. The high returns to labor (low labor inputs) were seen as an advantage and the relatively free availability of forest-based timber- and fuelwood products as a limitation. Mendez et al. (2001) found that Nicaraguan homegardens had 37% of their total space allocated to fruit producing species, on average; moreover, 85% of the fruits so produced were for home consumption and the remainder for marketing. When farmers in Jamaica were questioned as to the importance of trees, fruit was given as the second most important product following timber (McDonald et al., 2003).

Limited-resource farmers are undeniably interested in incorporating trees onto their farms when the trees produce a valuable resource that is in demand within the farm household; for example, food. The regular production of the valuable resource on a seasonal or monthly basis also seems to be a further important characteristic. In addition, the existence of a market for excess production may increase the number of trees or the intensity of management that farmers perform.

These examples clearly establish the importance farmers attribute to fruit trees on their farms for both consumption and income generation. It is paradoxical, however, that in spite of this and although biophysical interactions between trees and crops in agroforestry systems have been relatively well studied (Rao et al., 1998), such interactions between annual crops and fruit trees have seldom been studied. Nevertheless, economic performance and relative yields of mixed annual-fruit tree systems have been better studied and reported.

How Do Trees Perform With Crops?

Economic Responses of Fruit Tree - Annual Mixed Cropping

Based on a study of farmers in Dauphiné province in southeastern France, Mary et al. (1999) reported that farmers considered agroforestry as a significant aspect of walnut (*Juglans regia*) production. Annual crops such as maize and soybean (*Glycine max*) were frequently cropped among the growing trees. Additionally, farmers frequently grew numerous other fruits, such as apple (*Malus domestica*), currants and gooseberries (*Ribes* spp.), and grapes (*Vitis vinifera*) during the pre-production period. Mechanical harvesters and the lack of appropriate equipment for intercrops were cited as primary limitations of mixed cropping of annuals and perennials. The potential advantage of producing a high-value crop in place of often-costly groundcover-management was seen as a factor in favor of mixed cropping. A combination of perverse subsidies and a need for short-term financial returns dissuade many growers from agroforestry-based management.

Fruit-tree-based agroforestry, known locally as *streuobst*, has been a traditional activity throughout Europe, but has declined in extent since the advent of industrial agriculture in the 1930s (Herzog, 1998). The system consists of “tall” fruit trees irregularly dispersed throughout croplands, pastures and meadows. Temperate fruits, such as *Malus, Pyrus, Prunus, Juglans* and *Castanea* spp. are the most common tree components. The development of these systems was supported by a purposeful, government-based program promoting fruit tree planting. The principal disadvantage of *streuobst* compared to intensive orchards is labor productivity and currently it enjoys greater popularity where labor is a less limiting factor (Herzog, 1998).

In the northwest hills region of India, researchers reported that the returns from intercrops with temperate fruit trees are negligible but did not elaborate on whether they were unproductive or simply contributed little cash earnings to the system (Azad and Sikka, 1991). The results showed that fruit production was more profitable than comparative areas of annual crops. The farm to market link was described as the most tenuous and problematic in the production chain. Generally, growers were not able to profit from higher market value for their fruits because value was withheld at the farm gate by middlemen.

In the Bhopal region of central India, fruit-tree-based systems were found to have higher benefit to cost ratio (BC ratio 2.7) than agroforestry based on non-fruit trees (BC ratio 1.8). When cash crop systems were assessed, fruit-tree-based agroforestry had BC ratios of 2.9 versus 1.8 for timber and cash crops (Appropriate Technology Centre, 2003).

Farmers preferred a fruit and fodder system incorporating *Ananas comosus* (pineapple) and *Psidium guajava* (guava) with *Morus alba* (mulberry) for sericulture over a system of *Morus* with vegetables or rice in Meghalaya in northeastern India. The fruit-tree-based system was highly profitable, but detailed economic analysis was only performed on systems preferred by forestry officials (Dhyani et al., 1996). Mixed systems of *Prunus* spp. with *Lens culinaris* (lentils) and *Triticum aestivum* (wheat) showed an economic advantage compared to cropping systems without fruit (Ashour et al., 1997). There, BC ratios of sole peach (1.19) and mixed peach-annual crops (1.56) were observed. Another evaluation of economic returns of *Sorghum bicolor* and *Vigna mungo,* cropped with *Psidium guajava* (guava), and alley-cropped with *Leucaena leucocephala* in Andhra Pradesh, India, showed BC ratios ranging from 1.52 for crops with *Leucaena* to 2.16 for crops with guava (Das et al., 1993).

Key areas of biophysical interaction including competition between fruit trees and crops grown together have not been adequately addressed. While it appears very likely that the value of fruit tree yields relative to annual crop yields are substantial to farmers, the question of the resources that are lost to crops through competition vs. resources that are non-competitively acquired remains virtually unaddressed. Without knowledge of both these aspects, it is difficult to quantify the overall merit of a mixed fruit-tree + crop system.

Yield Responses of Fruit Tree - Annual Mixed Cropping

In Andhra Pradesh, India, systems based on annual crops with timber producing, fruit producing, and biomass-biological nitrogen producing trees were studied. Sorghum (*Sorghum bicolor*) and black gram (*Vigna mungo*) with *Acacia auriculiformis* (auri), with *Psidium guajava*, and with *Leucaena leucocephala* as alley-crops were evaluated on infertile, rainfed, alfisols. For all forms of mixed cropping, relative yields of sorghum and black gram were reduced compared to yields where trees were absent. Within the mixed systems, sorghum performed best with guava where its yield relative to sole-cropped sorghum ranged from 55 to 100%. Black gram in mixed systems produced best with guava or *Leucaena* with yields from 22 to 32% of sole-cropped black gram. Both crops performed poorly when associated with *Acacia auriculiformis*. Runoff measurements during the four years of the study showed that runoff losses were lowest in the fruit-tree-based system (4.9% of total precipitation). It should be noted that the guava system produced substantial quantities of fuelwood (300 t ha^{-1}) after 15 years as compared to (500 t ha^{-1}) for *Acacia auriculiformis* (Das et al., 1993).

A study of mixed cropping of *Lens culinaris* (lentils) and *Triticum aestivum* (wheat) with *Prunus* spp. (peach) in the arid northern Sinai of Egypt, showed that seed yield and harvest index of *Lens* and *Triticum* under mixed cropping increased over those under sole cropping (Ashour et al., 1997). Tillering and spike number of wheat were also increased in the mixed system. Peach yield increased marginally when grown with lentils, but not with wheat. Soil moisture was greater in the mixed annual-perennial system than in the sole crops. Several crucial experimental details of this study were not reported, for example irrigation amounts could have been limiting to sole crops.

In an intercropping study of banana with annuals in St. Lucia, The Caribbean, Rao and Edmunds (1984) found that intercropping various annuals with *Musa* spp. resulted in a decrease in weight per fruit but no loss in total bunch yield. Duration to maturity of banana was prolonged with underplanted annuals as compared to sole-cropped bananas. The study did not report any assessment of yield differences in annuals, however. The mixed stand of banana with annuals was stated as providing greater overall yields and more uniform distribution of income.

Cropping *Zea mays* or *Vigna mungo* with coconut palms (*Cocos nucifera*) produced yields roughly linear with the PAR intercepted below the coconuts. Simulation modeling of coconut PAR interception suggested that fruit-tree stand density could be adjusted to balance the yields of the different components and meet individual farm goals. Additionally, it was observed that crop variety had a large impact on crop yield, showing that screening at the varietal (sub-generic) level will be necessary to optimize many mixed cropping systems (Dauzat and Eroy, 1997).

Mixed cropping systems based on *Theobroma grandiflora* (cupuaçu) and *Bactris gasipaes* (peach palm) with a legume understory (*Pueraria phaseoloides*) in central Amazonia showed that nitrogen competition between the trees and the crop was spatially limited and the trees did not appear to be utilizing biological nitrogen from the legume (Lehman et al., 2000).

While the previous findings indicate potential for successful integration of fruit-trees with annual crops in the tropics, studies in the temperate zones are not so numerous. Several studies indicated that the management of the annual and perennial components may be decisive in the overall performance of these mixed systems. Near Montpellier, France, growth of young *Juglans nigra* (walnut) was superior with intercrops of *Medicago sativa* (alfalfa) or *Onobrychis sativa* (sainfoin) than in controls consisting of spontaneous weed growth, but differences in the relative competitiveness of the three associated crops varied with yearly precipitation effects and tree growth was not always superior with sainfoin compared to with weeds (Dupraz et al., 1999). In a separate study, walnut-based agroforestry systems were compared against annual cropping or pure walnut plantations.

A simulation study of intensive management of line-planted walnuts (*Juglans nigra*), in the central Midwest of the United States of America, which included mechanical root pruning to limit water competition between rows, was conducted. Walnut stands produced the greatest net present values when mixed with *Zea mays*, *Zea mays* + *Glycine max*, and *Zea mays* + *Glycine max* + *Triticum aestivum*. Pure walnut stands were superior to walnut-tree-based agroforestry systems where tree spacing was 8.5 m vs. 12.2 m between rows, essentially limiting annual crop production (Benjamin et al., 2000).

In many of the reported studies, fruit-tree-based agroforestry systems outperform sole crop systems economically. Biologically, however, results vary with both yield enhancement and yield suppression occurring depending on complex component by environment interactions. Generally, it appears that the combined yields of all the system components is frequently greater in mixed systems than by the same components under monoculture. In order to permit these systems to be optimized and to produce a suitable balance of annual- and perennial-based yields to meet farmer goals, further research is needed to quantify the nature and extent of competitive interactions. Additionally, clarification of the resultant benefits to farmers is required given their social and economic constraints.

CHAPTER 3
TREE-CROP INTERACTIONS IN A PEAR + ANNUAL CROP AGROFORESTRY SYSTEM IN THE WESTERN HIGHLANDS OF GUATEMALA

Introduction

Fruit-tree-based agroforestry systems are regionally common in the *altiplano* of northwestern Guatemala. The systems are difficult to classify by traditional groupings as they range from dispersed trees in crop fields or annual crops in semi-managed orchards to homegarden systems. The most common fruit-tree species in the study area were apple (*Malus domestica*) and peach (*Prunus domestica*), with substantially smaller numbers of numerous other species. Production and quality of both apple and peach suffer from sub-optimal management and adverse environmental conditions. A study in the region on management improvement in peach showed that significant improvements in vegetative growth, fruit size, fruit appearance, and total yields could be achieved with moderate improvement in pruning and fertilization (Williams et al., 1992). Irrigation was also applied in the study although this recourse is normally unavailable to small holders. The lack of properly developed fruit-tree varieties for the region further exacerbates the problem of low productivity encountered by growers. Farmers frequently grow trees interspersed with annual crops, but no scientific studies have been reported on either the optimal agronomic or horticultural practices for these conditions.

Pyrus calleryana (European pear) has been introduced into the region, but it is not widely adopted by farmers. If farmers' sentiments are any indicator, this is mainly due to the non-availability of planting materials. Observation of farmers' fruits in 2001 indicated that the pears produced in the highland environment appear to be of good quality under limited management, whereas that was not the case with apple, which suffered from numerous defects. In local markets, pear received equal or higher prices than apple. Thus pear seems to have good, yet unrealized potential for the region. Because of these reasons, pear was chosen as the fruit-tree species in this study.

While these systems contribute to the overall viability of small farms in the highlands of Guatemala, they have been little studied in terms of their biophysical interactions with maize (*Zea mays)* or fava bean (*Vicia faba),* or with respect to their contributions to farm households. Worldwide, fruit-tree-based agroforestry systems have been only modestly studied in respect to the quantitative effects that are realized through mixtures of fruit trees and crops (see review below). Most frequently, these systems have been studied under the headings of alley cropping, homegardens, or simply trees on farms. Numerous effects have been documented for mixtures of trees and annual crops, but the extent and magnitude of these effects in fruit-tree-based systems remain basically unknown. With this background, this study was undertaken to characterize system productivity and evaluate component interactions. Sole cropping (a single species cultivated), intercropping (more than one annual species cultivated), and mixed cropping (annual and perennial species cultivated) of maize, fava, and pear were contrasted as three alternatives available to farmers. Mixed cropping of maize, fava, and maize + fava beneath artificial shade structures was also evaluated to differentiate shading (above ground) effects from moisture and nutrient competition (belowground). This chapter presents component and system yields in terms of land-use efficiency, economic values, and harvested yields measured as glucose equivalents of production.

Review of Literature

As stated previously, there is limited specific research on tree-crop interactions in agroforestry systems involving fruit trees. Therefore, the literature review is extended to interactions between trees and annual crops in a general manner. The interactions are presented as those related to canopy processes and occurring in the aerial environment or at the soil surface and those that involve root interactions occurring within the soil profile.

Canopy Effects

Temperature

Overstory trees can reduce the understory temperature by reflecting shortwave radiation or absorbing incident shortwave and longwave radiation and re-radiating it as longwave radiation into the above-canopy environment. Additionally, evaporation of transpired water or precipitation intercepted by the canopy may further contribute to understory temperature reductions.

A related effect is the protection against radiational frosts and lower night time temperatures that can occur. No previous studies were found that could provide insight into the temperature effects provided by deciduous fruit trees, however agroforestry systems with *Inga jinicuil* and *Coffea arabica* moderated the average diurnal temperature range by 7.1° C compared to full sun (Barradas and Fanjul, 1986) in Veracruz, Mexico at a mid-elevation site (1225 m) where the average temperature was 18.5 °C. In the Garwhal district of the Indian Himalaya, a mixed plantation comprising nine tree species (*Albizzia lebbek*, *Alnus nepalensis*, *Boehmeria rugulosa*, *Celtis australis*, *Dalbergia sissoo*, *Ficus glomerata*, *Grewia optiva*, *Prunus cerasoides,* and

Pyrus pashia) allowed comparisons of temperature buffering between pruned and unpruned canopies. A positive relationship between the extent of pruning and mean air temperature in the understory resulted in a mean difference of 2.1 °C between unpruned and 75 % pruned stands (Semwhal et al., 2002).

In Burkina Faso, Jonsson et al. (1999) found that the dominant fruit trees in the region, *Parkia biglobosa* (néré) and *Vitellaria paradoxa* (karité) reduced mean understory soil temperatures 1 to 2 degrees. An important effect of shading was that the amount of time when the understory temperature was greater than 40 °C was reduced from 27 hours per week in full sun to between 1 and 9 hours in shaded conditions.

High leaf temperatures can increase respiration and decrease net photosynthesis. Reduced temperatures may slow development and increase duration of grain or alternately, where temperatures are excessive, development rates may increase over those of plants experiencing temperature extremes. Both possibilities may be important advantages depending on the environment and specific physiology of the crop. In Tunisia, increased yields of *Vicia faba* were observed as an effect of sheltering by trees (a windbreak) with grain yield increases up to 17%, and as much as a 39% increase in pod number compared to unsheltered crops (Ben Salah et al., 1989). These beneficial results may reflect either temperature buffering effects, changes in evaporative demand or a combination of the two. A further consideration is the development of a larger canopy boundary layer associated with a reduction in wind speeds at the canopy surface.

<u>Humidity and evaporative demand</u>

Within and beneath the canopy of trees associated with crops, relative humidity is often increased above unshaded conditions and evapotranspiration rates decreased

(Gutierrez and Meinzer, 1994; Srinivasalu and Jaganatham, 1992). Both transpiration from tree leaves and modifications in the effective boundary layer of the crop canopy contribute to this effect. Li et al. (2002) measured the transpiration of *Malus domestica* by the heat pulse method and evaluated it in relation to a variety of environmental parameters in orchard settings in Israel. Transpiration increased with temperature and vapor pressure deficit, and decreased with increasing humidity. Additionally, with reduced air temperature and no change in absolute humidity, declines in vapor pressure deficits and relative humidity may occur. This can result in greater water use efficiency in some situations.

Tree canopies can contribute to reductions in windspeed at the crop canopy surface thus reducing the bulk transfer of moisture (Ben Salah et al., 1989). Additionally, where tree canopies develop earlier than crop canopies, the shade may help conserve moisture in upper soil layers that later can be used by crops. It is however expected that the presence of trees places an additional demand on soil moisture and will likely have an overall effect of reducing the total available moisture for associated crops.

Light

When crops are grown with trees or shrubs, competition for light is an obvious concern. Trees and shrubs with their woody stems and perennial growth habit often overtop crop species with their canopies and may capture a greater amount of the incident light. This, however, is a function of canopy size, elevation, and tree density or canopy coverage. Where soil nutrients, water, temperature, or pests are not limiting, the growth of the associated crop and its biological yield are closely related to the amount of incident photosynthetically active radiation (PAR) intercepted throughout the growing season (Monteith, 1977). This simplistic relationship is complicated by a number of factors. One critical issue, reviewed by Black and Ong (2000) is that radiation use efficiency can vary substantially depending on when it is measured, the degree to which appropriate measures of interception are used, and the nature and extent of other limiting factors.

Mixed fruit-tree + crop systems may, like other agroforestry systems, intercept greater fractions of incident radiation when the perennial canopy is present during the early stages of crop growth, when canopy cover is low, or during late- to post-crop stages when interception is primarily by non-photosynthetically active tissues. Unlike other types of trees, fruit trees are often actively managed to present an open canopy allowing light and air penetration to fruiting sites and subsequently the crops beneath them. Pear trees are frequently pruned to a central leader or pyramidal form which may increase the relative amount of PAR transmitted to the understory compared to forms common to apple or plum (Horn, 1971).

The only reported study that was located on mixed cropping of pear with annual crops, evaluated the photosynthetic light environment within a mature pear orchard in the United Kingdom (Newman, 1983). The mature trees had been maintained with an overall crown height of 3.0 m and a mean crown diameter of 3.0 m. The orchard was square planted at a distance of 4.6 x 4.7 m. This would give an approximate canopy coverage of 68%. Mean PAR transmitted through the orchard canopy was 70%. Transmittance of individual tree canopies (more indicative of below-crown light levels) was in the range of 40 to 60% incident PAR. This study, with radishes (*Brassica* spp.) as the understory crop, provided land equivalency ratio (LER: equation 3.2) values of 1.5

to 2.01 for saleable radishes. No yield depression of the pear was observed during the two-year study (Newman, 1983). Another study of pear, focused on water use, noted that canopy radiation interception within the orchard at mid-day was approximately 38% of incident (Marsal et al., 2002).

Working with other types of trees, several researchers examined mixed cropping systems. Intercropping of several annual crop combinations with *Taxodium acendens* resulted in LER values greater than 1.0 in all instances. Crop yields were substantially depressed as the trees grew. The depressive effect was not equal among crop species, illustrating that crop species differ in their ability to perform adequately in shaded conditions. Also, an increase in humidity and a reduction in wind speed were reported from this study (Huang and Xu, 1999). Another study evaluating mixed cropping of *Mangifera indica* (mango) and vegetables indicated that vegetative yield was unaffected by distance from trees, so long as water was not limiting. However, since light levels beneath the mangos were not reported, it is not possible to comment on the importance of that aspect (Emebiri and Nwufo, 1994).

A limited review of canopy effects indicates that the effects are varied by both crop and overstory species. In some situations, tree associates appeared to have facilitated improved crop growth while in others, yields were depressed. Crops differed at both the species and varietal levels in their ability to perform with perennial overstories. Tree overstories are expected to buffer temperatures for crop growth while reducing radiation availability. The overall effect of reduced radiation transmission on soil moisture levels remains unresolved.

Competition for Soil Water

The root zone effects principally involve soil-water and nutrient availability. Few studies have been identified where deciduous fruit trees, including pear, have been evaluated for their belowground competitivity with annual crops. What is known is drawn from tropical alley cropping, orchard floor management, and studies of non-fruit producing trees. In mixed fruit tree-crop systems, like other agroforestry systems, complementarity in root distribution and access to soil water and nutrients is a critical factor in determining the degree of competition and resultant advantages in the system (Ong, 1995; Van Noordwijk, 1996). Several studies have shown that most tree roots, especially those of fast-growing species, exploit the same soil depths as crop roots, regardless of whether they also explore deeper horizons (Daniel et al., 1991; Jonsson et al., 1988; Van Noordwijk et al., 1996). *Gliricidia* and *Grevillea* (both fast growing) were highly competitive with maize for root space in a Kenyan experiment (Odhiambo et al., 2001). The implication of these findings is that the studied species are expected to exhibit highly competitive belowground interactions with associated crops.

In contrast, fruit trees in temperate orchards do not compete successfully with weeds or turfgrasses for nutrients and water (Hogue and Neilsen, 1987; Arnold and Aldrich, 1980; Lord and Vlach, 1973), potentially due to their comparatively low root density (Atkinson, 1980). Studies within apple orchards have shown that fruit trees exploit potential crop root space (Green and Clothier, 1999), however the extent to which this would be limited by crop cultivation practices is unknown.

Several studies have reported that annual crops are frequently unable to utilize all the soil moisture that is available during the cropping season. This shortcoming may waste as much as 60% of total available precipitation (Rockstrom, 1997; Ong et al., 1992). Fruit-tree-based agroforestry systems have the potential to make better use of available precipitation. The extended period of canopy cover that is possible due to inclusion of the perennial component may permit greater growth and productivity using excess moisture prior to or which remains following the harvest of annual crop components (Anderson and Sinclair, 1993; Lott, et al., 2003). In general, it is expected that trees, once established, will compete for soil moisture to the detriment of annual associates. Yet, studies have identified situations where the presence of trees may improve the availability of soil moisture for associated annuals.

Hydraulic lift, or the redistribution of soil water by way of perennial roots in response to differences in water potential, has been documented for numerous species (Caldwell et al., 1998) and may provide benefits to associated plants (Caldwell and Richards, 1989; Caldwell, 1990; Dawson, 1993). This phenomenon also may increase soil health by maintenance of soil organisms (Duncan and Elmorshedy, 1996). The extent to which this may occur in fruit-tree-based systems is unknown.

Establishment of trees can result in increased soil moisture levels at the soil's surface compared to bare soil. Arachi and Liyanage (2003) found that soils under four nitrogen-fixing tree species were all superior to bare soil at maintaining higher surface moisture levels in Sri Lanka. It seems reasonable to surmise that trees that prevent water losses or maintain higher moisture levels in upper soil layers may be more compatible with annual crops than other types. However, it is important to consider the overall effect of trees on the soil water table, particularly as many crops may exploit water resources from well below the surface horizons.

Agroforestry systems of eucalyptus and *Leucaena* with maize and wheat have shown higher water use efficiencies since a greater percentage of water was used for plant growth versus surface runoff at the Central Soil and Water Conservation Research Farm in Dehradun, India (Narain et al., 1998). Jackson et al. (2000) reported that *Grevillea robusta* + maize mixed cropping resulted in greater use of available soil moisture compared to sole crops or trees in semiarid Machakos, Kenya. Since it can be assumed that water not used during the cropping season will be lost to evaporation or drainage, this equates with a more efficient use of available water resources (Jackson et al., 2000). A similar study of *Grevillea robusta* + maize in the same location also showed that greater capture of precipitation was possible compared to sole cropping of either component, however; here maize yields were depressed with *Grevillea* making the overall effect negative (Lott et al., 2003).

Unlike many agricultural crops, where harvest index may be more conservative and final yields closely related to total production, conditions that promote maximal growth may not produce the highest yields in deciduous fruit trees. In Spain, reduced irrigation levels (regulated deficit irrigation), relative to evaporative demand as calculated by FAO (1993) resulted in greater yields and higher fruit numbers in pear trees. However, the yield of high-grade fruits (size based) was reduced, highlighting the need for adaptive management in order to obtain optimal economic yields (Marsal et al., 2002).

<u>Competition for Nutrients</u>

When considering competition effects with fruit trees, it is important to take into account the multi-year nature of growth cycles and responses. For pear, it was shown that N taken up at or after harvest was preferentially used during the following year for growth and fruiting (Quartieria et al., 2002). Fertilization early in the year was much less effective at increasing reserves and tended to be used in the current year's vegetative growth. This finding suggests temporal differences in the need for N between crops, which may need N early, and fruit trees that make better use of N that is available later. Perhaps trees are effective at taking up additional N that crops would not take up and thus can act as a safety net. Autumn fertilization has been shown to increase fruit set in pear the following year by increasing the period of receptiveness for pollination (Khemira et al., 1998). Flowering in pear is mainly supported using remobilized N from the prior year, however by the time fruit expansion begins, N is being supplied by uptake from the soil (Tagliavini et al., 1997; Sanchez et al., 1990, 1991). It has also been reported that excessive N availability during fruit development may lead to increased susceptibility to fungal damage and reduce the storability and transportability of the harvest (Sugar et al., 1992). While of interest, these findings were based on cold post-winter soils and the resultant poor natural N availability, so their relevance in subtropical highlands is unknown.

In a tropical setting, mixed cropping of an herbaceous legume failed to improve the N nutrition of two tropical fruit species, *Theobroma grandiflora* and *Bactris gasipaes.* The fruit trees primarily took up N from beneath their own canopies and not from between the tree rows (Lehman et al., 2000). On the surface, it appears possible that fruit trees could exhibit a high degree of compatibility for nutrients with annual crops. Excessive vegetative growth is undesirable and therefore early fertilization or high levels of nutrient availability for trees during the period of crop development unnecessary, while residual fertility and late applications after the period of crop uptake are perhaps less likely to be lost if fruit trees are present.

Little research has been conducted on interactions between fruit trees and annual crops. It appears that available resources (water and light) are not efficiently utilized in many systems and that potential exists to increase productivity through greater resource use. This would support the agroforestry hypothesis of benefits through greater resource capture. Fruit trees may have characteristics related to phenology and synchrony that make them more suited to mixed cropping than fast growing multi-purpose tree or timber species.

Objective and Hypothesis

The objective of this study was to evaluate and compare the performance of systems of *Pyrus* spp., *Zea mays*, and *Vicia faba* in terms of their efficient use of land area, their economic output, and the yields as measured in glucose equivalents of production. The annual crops are important components of many highland farms and are likely associates where fruit trees are desired. *Pyrus* spp., while less common, show high potential as a candidate for integration. I hypothesized that integrating pear with maize and fava would produce yield advantages over the monoculture alternatives and that additional, previously underutilized PAR and soil water would be used by the agroforestry alternative.

Methods and Materials

Study Area

This study was conducted at the Labor Ovalle Research station in Olintepeque, in the department of Quetzaltenango, Guatemala (14° 30' 50" N, 91° 30' 50" W) at an altitude of 2390 m above sea level. Annual mean temperature is 13.8 °C (Figure 3.1). The mean daily maximum was 21.9 °C with a mean daily minimum of 6.0 °C (1971-2002). The mean frost free growing period (defined as T > 0.0 °C) was 210 days per year. Frost free seasons from 1971 to 2001 ranged from 119 days in 1978 to 277 days in 1999. Total solar radiation during 2002 was 7223.7 MJ $^{-2}$ year^{-1} (Figure 3.2). Mean annual precipitation is 815.7 mm year^{-1} (Figure 3.3); during 1971 through 2002, the maximum was 1084.9 mm in 1998 and the minimum occurred in 1987 with 623.2 mm.

The local relief is a mountainous valley bottom surrounded by rugged ridges and ravines. The previous natural vegetation was subtropical lower montane semi-humid forest (Holdridge, 1947). The soils are entisols in the Quetzaltenango series (Simons and Taramo, 1959). Fields are heterogeneous clay loams with good drainage. Thirty years of mechanized agriculture has left an obvious plow pan in most fields. The experiment was conducted during 2002 and 2003 in a field known as El Tecolote that had previously been used for fruit tree varietal trials and semi-commercial fruit production.

In the fall of 2001, prior to establishment of the experimental treatments, an analysis of soil macro- and micro-nutrients was made. Soil was collected from each of the fifty treatment plots in El Tecolote and prepared at the extension soil testing laboratory at the University of Florida, Gainesville, Florida. The Mehlich-1 extraction was done and soil nutrients measured using a plasma spectrometer. The resulting measures were statistically analyzed and means separation of block means using Tukey's HSD at α=0.05 made for the P, K, Ca, Mg, Zn, Mn, and Cu (Table 3.1).

Materials Selection

Maize and fava bean were selected as the two annual crops for this study. European pear was chosen as the deciduous fruiting-producing perennial. The species characteristics and varietal selections are described below.

Maize

This study was conducted in or near the center of diversity for *Zea mays* L. in highland Mexico and Guatemala. Known commonly as corn, maíz, maize, tomorokoshi or milho, it is an annual grass with broad variations in climatic adaption. Maize is grown from the lowland tropics through the northern temperate zones. Throughout the remainder of this paper the common name maize will be used to refer to *Zea mays* L. without distinction to subspecies differences. The highland maize varieties differ substantially from varieties grown in lowland tropics or temperate zones. In general they are taller with a greater number of leaves at flowering. These varieties are often weakly rooted and are inclined to produce multiple ears pers stem. Morphologically, the leaves are long, broad, and droop substantially compared to more upright, short-leaved selections. Leaves and stalks are often densely pubescent and contain substantial quantities of anthocyanin lending them a purple color. Physiologically, highland varieties are thought to have lower optimal and base temperatures for growth and development (Ellis et al., 1992; Newton and Eagles, 1991).

The specific variety chosen for this study was released in 2003 as San Marceño Mejorado. Developed by CIMMYT, Guatemala in cooperation with ICTA; it is a yellow, open pollinated population selected from crosses of San Marceño and Chivaretto, each selections from locally collected landraces, for increased yields and reduced height. In 2002, under common local management regimes, San Marceño Mejorado yielded 5200 kg ha^{-1} from a stand with an average height of 2.65 m to the base of the tassel. The crop required 217 days from planting until the ears reached the low moisture contents favored for harvesting.

Fava bean

Vicia faba L. var. faba has a center of genetic diversity from the Near East (Cubero, 1973) or Central Asia (Ladizinsky, 1975). The list of common names is diverse including; field bean, horse bean, broad bean, faba bean, fava bean, windsor bean, *gourgane* and *haba* among others (Weisema and León, 1999). Throughout this paper, the common name fava bean is used to refer to *Vicia fava L.* varieties grown in the Guatemalan highlands which are known locally as *habas*. The crop has a long history of cultivation and selection in the highlands since it was introduced.

Fava bean is a semi-hardy annual with a deep tap root and an upright indeterminate habit that grow well in cool conditions. Favas show strong sensitivity to water stress throughout their life cycle with particular emphasis during flowering (Day and Legg, 1983). Fixation of biological nitrogen by symbiosis with *Rhizobium leguminosarum* v. viciae may be substantial with fixation rates >120 kg ha^{-1} occurring concomitantly with high yields of dry matter and seeds (Silim and Saxena, 1992).

The fava variety used was previously released as a higher yielding selection from a broad range of local landraces collected from regional markets. Currently it is produced as *ICTA Blanquita*, with a cream colored seed and contains a low percentage of yellow or purple colored beans. The individual beans are described as larger than "unimproved" varieties with a 1000 seed mass of 1.9 kg. Under management regimes common to highland Guatemala, the cultivar develops a leaf area index (LAI) of approximately 2.5 to 3.0. At maturity, ICTA Blanquita may have upwards of 12 tillers and a height >2.0 meters. In 2002 the fava crop required 162 days (175 days in 2003) from planting until harvest.

Pear trees

Pyrus communis was chosen as the perennial component for the system. Known by the common names pear, pera, peral, seiyo-nashi, or birne, their origins can be traced to Central Asia, Eastern Europe, and Northern Africa. Two varieties were included in the study, Bartlett or *Pera de jugo* and Ayres (also known as Tennessee); these will hereafter be called ‘Bartlett’ and ‘Ayres.’ Both varieties had been grafted to *Pyrus calleryana* rootstocks. In the remainder of this paper, the common name pear or the varietal names are used to refer to a grafted combination of *Pyrus calleryana* with *Pyrus communis*.

Without management, the upright trees can grow to 14 to 16 meters. Under management the trees rarely are allowed to exceed 4 to 6 meters. The varieties used in this study have a long history in Guatemala and the details of their original introductions are unknown. Little previous characterization of the varieties’ performance has been done. Trees were eight years old at the time of this study. The trees were being managed with a grass and weed understory and had been fertilized and ring-weeded annually. Additionally, lime slurries had been applied to the trunks each year during the Nov. through April dry season.

Experimental Design

A complete random block design was established to incorporate previously planted pear trees with annual intercrops and artificial shade trees (Figure 3.4). Plots were laid out such that each contained four pear trees and each block contained each treatment one time. Tree-crop interaction and tree-control plots were assigned randomly to plots containing trees. The remaining treatments were assigned randomly to the remaining six plots in each block. In order to create the design as shown, pear trees that had been growing in the non-fruit treatment plots were removed before establishment.

Establishment

Prior to plot establishment, the field was adapted for the planned experiment. The grasses and weeds were removed by hand and the five blocks were hand-hoed to a depth of approximately 20 cm. Trenches to divide the blocks and the experiment from the surrounding fields were dug to 1.0 m depth. Cables to facilitate data collection were installed in the trenches and buried. The area used for sole crops and crops with artificial-tree treatments previously contained pear trees, which were removed and relocated outside the experimental area.

The annual crop treatments were established on 13 May 2002 and 10 April 2003. Fifty plots, each 8.0 m long and 5.0 m wide (40.0 m^2), were established with alleyways between them. Each plot contained four pear trees, two of each variety at a spacing of 2.5 m in a square pattern. Within individual plots, planting sites were established at the distance of 1.0 m between rows and 0.6 m within rows. To prepare planting sites, the surface layer of soil was removed and a planting hole was dug. For planting in sole maize treatments, each hill received 5 seeds (81,000 plants ha^{-1}). Sole fava treatments received three seeds at each hill (48,700 plants ha^{-1}). Intercrops treatments received 5 seeds of maize and three seeds of fava in each planting site. Planting sites were filled in so that the new soil surface remained approximately 8.0 cm lower than the surrounding ground. Within fruit tree only treatments, planting sites were opened in an identical fashion and then were closed without planting seeds.

Artificial trees with a conical form were constructed based on measures of the existing live trees in the experiment. Artificial trees were 262 cm and 276 cm in height and 80 cm and 110 cm in diameter for Ayres and Bartlett respectively (Figure 3.6). Mean canopy height, crown base height, and mean maximum crown extension were measured and calculated for each variety. Canopy height was measured from intersection of the trunk with the soil to the highest woody branch. Crown base height was the distance between the soil surface and the lowest canopy branch, and crown diameter was measured through the crown at the point where the crown appeared widest. A steel ring was mounted and the structure covered with 30 % shade fabric. Overlaps and doubling of fabric provided random variations in the optical porosity of this artificial canopy (Figure 3.6). During 2002, the artificial trees transmitted incident PAR at a mean of 23.2 % (s.d. 4.2) for the pseudo-Ayres and 24.6 % (s.d. 5.1) for pseudo-Bartlett. This compared to measured percent transmissions of PAR for real trees of 9.3 % (s.d. 3.0) in Ayres and 11.9 % (s.d. 2.3) in Bartlett.

Tree Management

Pruning and fertilization

At the beginning of the study, the root suckers were trimmed from all pear trees and this was repeated throughout the experiment at monthly intervals. Suckering was more prevalent beneath Bartlett than Ayres. Pruning was not conducted during the 2002 season because the trees had previously been trained to a central leader form, and their growth was deemed insufficient to require pruning. Trees were numerically tagged to permit easy identification.

All trees were painted with a slurry mixture of lime the first week of February (to follow the common practices in the region). In both 2002 and 2003, granular fertilizer (15-15-15) was applied at the base of each trunk at the rate of 0.25 kg per tree with an area based application rate of 250 kg ha^{-1}. Additionally, both mixed-cropping and sole-tree treatments received fertilizers as described under “Crop Management” sub-section below. Fruit set did not appear to be excessive and no thinning was conducted. Fruits that abscised before harvest were not collected, nor were they considered except in counts of fruit set.

<u>Weed and pest management</u>

Weeds that developed around the trunk were removed by hand when root suckers were cut. In the later part of the season, these weeds were removed as part of weed management for the associated crops. Sole tree plots received identical weed management as mixed-cropping plots. Developing shoots were attacked by aphids (*Aphidae*) during April and May 2002, when moisture may have been limited. The affected trees were spot treated with Thiodan (endosulfan) as soon as the incidence was noted. During the final 8 weeks prior to harvest, each tree was misted with water once per week to simulate the application of pesticides with the purpose of protecting the harvest from theft.

Crop Management

Fertilization

Crops were not irrigated at any point during the experiment. Fertilization was performed at 26, 60, and 85 DAP (days after planting). At 26 DAP, all plants were sprayed with a complete foliar fertilizer (Avantis complete liquid) containing the following formulation: N = 9 %, P_2O_5 = 9 %, K_2O = 7%, Mg = 0.01%, S = 0.16%, B = 0.01%, Cu = 0.01%, Fe = 0.01%, Mn = 0.01%, Mo = 0.005%, Zn = 0.005%, Inert - 74.78%. At 60 DAP, granular fertilizer (15-15-15) was applied at a rate of 360 kg ha^{-1}. Granular fertilizer was applied in a hole opened to one side of each planting site and the hole subsequently filled in. At 85 DAP, granular urea (45-0-0) was applied at 360 kg ha^{-1} to treatments containing maize by the same technique used at day 65. Granular 15-15-15 was applied to sole fava treatments in place of Urea. The application rates of granular fertilizer were at the upper range of the practices normally followed by local producers with total annual applications being 216 kg ha^{-1} N for maize and maize + fava combinations, 108 kg ha^{-1} N for sole fava crops and an additional 37.5 kg ha^{-1} N where annuals were mixed with pear trees. Foliar fertilizer is not commonly applied by small holders.

Weed-management

Plots were managed to be as weed-free as possible, with manual removal of weeds at approximately 20 day intervals. Above ground portions of weeds were severed from their roots and buried in the inter-row spaces. Inter-plot walkways and alleys were cleaned regularly with a walking tiller or by hand. Prior to 85 DAP, all plants were hilled-up by bringing soil from both the inter-row and between plant areas to form a mound around each planting site that effectively covered the lower internodes up to the third to fifth internodes. A final weeding was done at 188 DAP. Tree control plots received identical cultivation.

Meteorological Data Collection

In November 2001, a field meteorological station was established at the north-eastern corner of the experiment, approximately 700 m from the main station operated by the Institute of Seismology, Volcanology, Meteorology, and Hydrology (INSIVUMEH). The field station recorded temperature, precipitation, and solar radiation at 10 second intervals and 15 minute means were stored (Table 3.3). Data were recorded on an automated datalogger (Campbell Scientific CR7 Measurement and Control System, Logan, Utah) and stored on SM716 storage modules which were downloaded at 14 day intervals.

Soil Water Status

Within blocks one through three, a soil moisture probe was inserted in the center of each plot. $Echo_2$ soil moisture probes (EC1, Decagon Devices, Pullman, WA) have a length of 20 cm. The probes were inserted to a depth of 55 cm and integrated soil volumetric water content (VWC) along their length, between 15 and 35 cm below the surface in this study. Sensors were excited at 2500 mV and the response voltage measured. Sensors were excited every 15 minutes and 3 hour means were recorded for each plot. Sensors were calibrated for local soil conditions by sequentially drying from full saturation and weighing soil samples while simultaneously measuring sensor responses to soil moisture content.

Light Interception

Within blocks one, two and three, canopy light interception was monitored with sensor triplets sensitive to PAR for each net plot. Sensors were constructed using Gallium arsenide Phosphide photodiodes (Model G2711-01, Hamamatsu Photonics, Bridgewater, NJ) and low temperature coefficient shunt resisters (Model CMF 100 Ω, Vishay Dale Electronics). PVC female pipe ends were machined to allow the photodiode to be glued flush with the surface and the leads extended into the interior. Shunt resistors were mounted across the leads and cable extensions fed out the side of the pipe and sealed with flowable silicon (Figure 3.7). Sensors were tested and wired in parallel triplets, such that the three sensors produced a voltage output that represented a spatial averaging of PAR intercepted at the three sensors. Sensors were randomly placed in the plots within a 2.0 m diameter from the plot center. Output voltages for sensor triplets were calibrated against a LI-190SA Quantum sensor. Calibration equations are given in appendix C. Canopy reflection was measured at 75 DAP. Equation 3.1 was used to calculate PAR absorbed by the canopy (PAR_{abs}) canopy interception where PAR_I is incident, PAR_T is transmitted, and PAR_R is reflected.

$$PAR_{abs} = (PAR_I - PAR_T - PAR_{reflected}) \qquad \text{Eq. 3.1}$$

Fruit Tree Growth and Yield Measures

Diameter growth

To facilitate the precise measure of tree diameter growth, 1.0 cm^2 squares of plexiglass were epoxied to opposite sides of the trunks at a height of 22 cm. Monthly measures of each tree were taken using digital calipers which provided a reading to 0.01 mm.

Height growth and crown diameter

Tree heights were measured using a 4.0 m pole. The height was measured 3 times during the season; early, middle, and end. Measures were made from the trunk base to the highest branch tip. Cultivation introduced some error into this measure as the soil surface relative to the trunk was not constant, however care was taken to minimize error. The direction of maximum crown extension was also estimated and the crown diameter measured through the line of the trunk.

Vegetative and floral development

Vegetative bud break and flowering were observed to provide correlative information on the phenology of the two varieties. Trees were observed weekly and were noted with < 5 fully expanded leaves or > 5 leaves. The presence of recognizable, no longer quiescent, floral buds was noted. Open flowers were defined as those at all stages from when the reproductive parts were visible in the center of the expanding petal whorl until all petals had abscised. The number of flowers was recorded weekly for each tree.

Fruit set

As part of the phenological observations, the presence of fruit was recorded. Fruit in which all petals had separated from the calyx and the ovary had swollen to the size of approximately 5 mm were recorded each week from the beginning of flowering until flowering had ceased and fruit number became stable. Each crown was marked, and a systematic count made in a circular pattern around the tree. For the final two counts, all fruit were marked with a permanent marker to ensure that stability had been achieved and that final fruit set counts were accurate.

Fruit yield

At harvest, all fruits were picked and no opportunity for differential development was permitted. Fruits from a single tree were bagged, labeled, and taken for sorting and measurement. Fruits were sorted into three classes based on size. Representative minimum sized fruit for each class were selected and sorting was performed by a single person with experience in local fruit grading practices who completed all samples in a single day. Fruit mass for each class size was recorded for each tree and a representative fruit from the large and medium classes selected from each sample for further analysis.

Selected fruits were stored at room temperature for 8 days after which the sugar or soluble solids content (% brix) of expressed juice and the firmness of the flesh were measured. Firmness was measured with a McCormick fruit penetrometer (McCormick Equipment, Yakima, WA). Two penetrations were made on each fruit and the mean firmness recorded. Juice was expressed from the resultant hole. Brix was measured with a temperature compensated refractometer (Model 30387, Ben Meadows Company, Janesville, WI). The refractometer was rinsed with distilled water between measurements.

Crop Responses

Yields of each component were assessed under mixed and sole cultivation to determine the effects of the agroforestry alternative. Additionally, yield differences were examined as subsamples to examine the effect of distance from the tree trunk. Two measures of yield were made in the annual crop components. The first was a distance-dependent measure based on planting location. Two planting sites (1.2 m^2) from the center of the net plot (sites a, Figure 3.5) were harvested and labeled as ‘far’ samples. Two more sites were harvested (sites b, Figure 3.5) from near the site of two fruit trees. These ‘close’ sites were generally within the canopy or at the canopy edge of the trees.

For fava bean plots, the pod numbers from each pair of close and far sites were recorded. Pods were air dried 10 days and shelled. Pod and seed masses were recorded and seed moisture content was calculated using a Dole 400 moisture meter with the soybean scale. The remainder of the 33 sites in the net plot were harvested in bulk. Fava bean was harvested in a single pass on 1 Nov. 2002 (162 DAP) and 29 Sept. 2003 (175 DAP). At this point, all pods were dried and brown, however, pods had not shattered appreciably. Fava pods were air-dried as bulk samples and shelled. Total seed mass was calculated and normalized to 12% moisture. Seed yields from close and far subsamples were added to each net plot yield with normalized 12% dry mass.

Maize was not mature at the time of harvesting of fava crops. Maize was harvested on 3 Dec. 2002 (215 DAP) and 10 Nov. 2003 (217 DAP). At this point all ears showed block layer at the base of the kernels and drying of stalks and ears had been progressing for several weeks. As with fava, both close and far sites were subsampled for distance dependent yield analysis. Ears were air dried for 16 days before shelling. Cob and grain mass were recorded and grain moisture content recorded. All values for maize yield are reported at 12% moisture content. The remainder of the net plot was harvested and husked ears were air dried for 16 days before shelling. Cob and grain mass were measured and grain moisture percentage calculated. Net plot maize yields include yield from close and far subplots at 12% moisture.

Data Analysis

While the experimental design was a random complete block design, because of the intercropping nature of the experiments, the complete design reduces to a series of factorial experiments for analysis. When structural or intentional effects due to the nature of the treatments are considered, yield effects in maize and fava were analyzed as factorials (2 x 3) with two levels of crop associates (sole maize or maize + fava intercrops) and three levels of environmental conditions (without trees, with pear trees, and with artificial shade structures). In assessing crop effects on fruit tree performance, the effects were analyzed as a factorial (2 x 4) with 2 levels of variety (Ayres and Bartlett) with 4 levels of environment (sole maize, sole fava, maize with fava, and clean cultivation). Standard statistical norms of $\alpha < 0.05$ were used in all analyses and multiple comparisons of means were made with Tukey's HSD to maintain acceptable and conservative confidence levels. SAS statistical software (SAS Institute, Cary, North Carolina) was used for all ANOVA and means separation tests.

Using the land equivalency ratio (LER), developed at the International Rice Research Institute (IRRI, 1974) and the area time equivalency ratio (ATER) of Hiebsch and McCollum (1987), the relative yields of maize + fava, pear + maize, pear + fava, and pear + maize + fava systems were assessed. LER was used to verify the existence of a yield advantage due to more efficient use of land area (Equation 3.2, where subscripts s and I indicate sole and intercrop yields) and ATER identified advantages due to factors that are not explained by land use duration, (Equation 3.3, where subscripts s and I indicate sole and intercrop yields (Y) and crop durations (t)). Superscripts 1 and 2 indicate the individual system components or crops.

$$LER = \frac{Y_i^1}{Y_s^1} + \frac{Y_i^2}{Y_s^2} \qquad \text{Eq. 3.2}$$

$$ATER = \left(\frac{t_s^1}{t_i^1}\right)\left(\frac{y_i^1}{y_s^1}\right) + \left(\frac{t_s^2}{t_i^2}\right)\left(\frac{y_i^2}{y_s^2}\right) \qquad \text{Eq. 3.3}$$

Further evaluation of relative yield ratios (the component ratios of LER) was graphically made to evaluate the nature of productive coexistence in mixtures with LER > 1.0. Relative yields for pear, maize, and fava bean were calculated using the yields of each component as sole crops and their yields as either intercrops or part of a mixed crop system. The components were systematically graphed and the interaction effects of each component pair in each cropping regime were analyzed.

Economic valuation of fruit-tree-based and intercropping systems was calculated using measured yields for each component and market prices for 2003. Economic values indicate likely values of harvested products and did not include labor or input costs. To compare mixed, intercropping, and sole crop systems, yield values were calculated based on 1.0 ha of the system. For sole crop comparisons, this assumes 50 % land allocation to each component for intercropping or 33 % allocation for mixed cropping. Therefore, a 1.0 ha intercrop of maize + fava is compared to the sum of 0.5 ha each of sole cropped maize and fava.

Direct comparisons of biological yields provided an alternative method to compare the disparate outputs of the alternative cropping options. Here valuation of yields was made by conversion of component yields to their glucose-equivalent production costs (Penning de Vries et al., 1983). The measured composition of each type of yield (maize, fava bean or fresh pear) was converted to percentages of dry weight found as proteins, lipids, carbohydrates, and ash (USDA, 2003). The prior work of Penning de Vries et al. (1983) provides a basis to estimate the material costs and the energy requirements to manufacture each component and calculate the equivalent amount of glucose per unit yield. These calculations provided a uniform basis for comparisons of the "biological yields" that were harvested as their glucose equivalents of energy content. This method does not consider crop by-products such as root remnants, maize and fava stover or tree biomass and therefore it should not be construed as an adequate measure of overall system productivity.

Results

Fruit Tree Responses

Tree flowering phenology and fruit set

Marked differences were observed in the pattern of flowering and fruit set between the two pear varieties in 2002 and 2003 (Figure 3.8). In 2002, the peak of flowering in both varieties occurred simultaneously with Ayres showing a long pattern of flowering before the peak and Bartlett an extended period following the first intense epoch of flowering. In 2002, there were no severe frost events following the start of flower blooming in Ayres. In 2003, the peak of flower bloom in Ayres occurred slightly earlier than the previous year. The potentially similar pattern was interrupted by a series of strong frosts, followed by an un-reversed decline in flowering by Ayres and a failure to reach levels of the prior year. In Bartlett, flowering was delayed in 2003 compared to 2002, however, a strong peak in blooming was observed over an extended period. Flowering in Bartlett was not affected by frost events beyond the potential delay in the start of flowering evident in the graph (Figure 3.8). Fruit set in 2002 and 2003 initiated and completed earlier in Ayres than in Bartlett. During both years, the number of fruits per tree for Bartlett eventually surpassed that of Ayres (Figure 3.9).

Tree diameters and heights

Trunk diameter increment was not affected by crop or crop assemblage associated with the trees; however, Ayres showed significantly greater diameter increase than Bartlett during both years (Table 3.4). Tree height increase was affected by the intercropping treatments that were applied during 2002, but not in 2003 (Table 3.5). In 2002, height increase was greater where pear was cropped with either sole maize or sole fava as compared to intercropping of maize with fava or clean cultivation beneath the trees. In both years, mean height increase was greater for variety Ayres than for Bartlett (Table 3.5).

Fruit yield

The total fresh fruit mass per tree in the autumn of 2002 was not significantly affected by the understory conditions that were imposed in the spring of 2002. During the second year of the study, fresh fruit mass per tree was significantly higher where sole fava was cropped in the understory as compared to where maize had been planted. Fruit yields with fava associates were not significantly higher than under clean cultivation (Table 3.6). Differences were detected in total fresh fruit mass per tree between the two varieties, where Bartlett produced a significantly higher fresh mass of fruit at harvest than Ayres during both years (Table 3.6). It can be inferred that the harvest index (HI), while not normally calculated for perennial fruits, was greater in Bartlett due to lesser vegetative height and diameter growth with greater fruit yields than in Ayres.

Fruit number

The total number of fruits carried to harvest was not significantly affected by the cropping conditions in the understory during 2002 or 2003 (Table 3.7). While crop associates had no effect, the fruit variety was a significant effect in both seasons. The variety Bartlett carried significantly more fruit to maturity than the variety Ayres (Table 3.7).

Fruit size

The percentage of fruits graded as first (largest sized) for commercial purposes was significantly reduced where pear was cropped with maize as compared to treatments containing fava or clean cultivation (Table 3.8). The highest fraction of grade 1 fruits occurred with fava associates in both years, however the fraction was not significantly greater than in the control or maize + fava intercropping in 2002. In 2003, the fraction of first-grade fruits in treatments with fava associates was superior to treatments including maize but not significantly better than clean cultivation. Additionally, the variety Bartlett produced significantly higher fractions of grade 1 fruits under all treatment conditions than the variety Ayres did during both 2002 and 2003 (Table 3.8).

Soluble solids content

Soluble-solids content of fruits seven-days after harvesting was unaffected by the crop associates that had been grown with the trees in 2002 (Table 3.9). At the end of the second year of study, soluble solids were significantly higher in the control treatment than in treatments containing maize. Soluble solids levels in fruit grown in treatments with favas were intermediate between the lower levels of fruit grown with maize and the higher levels exhibited in the control fruits, but no significant differences were detected between fava and control treatments or between fava and maize treatments. In 2002, no differences in soluble solids levels due to fruit variety were detected. Ayres had higher mean soluble solids than Bartlett at harvest in 2003 (Table 3.9).

Crop Responses

Maize yields

Grain yield was not significantly affected by any of the three overstory environment treatments that were established prior to sowing in 2002 (Table 3.10). In the second year, the control treatment had significantly higher yields than crops among pear trees. Crop yields beneath the artificial overstory were similar to those beneath pear and the control treatment. Where maize was associated with fava bean, significantly higher yields were produced regardless of overstory environment when compared with sole crop in 2002; however no differences due to cropping treatments was observed in 2003 (Table 3.10).

The effect of planting distance from the tree was significant in the first year of the study (2002), when higher maize yields were produced at far sites compared with sites beneath the overstory; however there were no observed differences due to the type of overstory (fruit tree vs. shade structure). In the second year of the experiment, the distance-effect was not significant even though yields remained nominally higher at the distant sites. In 2003, fruit-tree overstory, but not the artificial shade structure, had a negative effect on maize grain yield (Table 3.12).

The number of ears harvested per m^2 was not significantly affected by the type of overstory environment in 2002, but in 2003, fruit trees reduced ear numbers as compared to artificial shade. Irrespective of the nature of overstory (live tree vs artificial structure), the site distant from the overstory had a greater number of harvested ears when compared to the site beneath or within the overstory canopy in 2002, but no such effect was noted in 2003 (Table 3.13). The presence of *Vicia faba* as an associated intercrop did not significantly influence the number of ears produced by maize.

Fava yields

The overstory treatment did not exert a significant influence over fava grain yield during the first year of the study. During the second year, however, there was a significant interaction: When fava was the only crop beneath the overstory, fava yields were depressed beneath pear trees when compared with artificial shade structures or no overstory, the yields being the highest beneath the overstory of artificial shade structures during both years. The effect of cropping fava and maize as the understory crop was a significant decrease in the dry seed yields of fava (Table 3.14), regardless of the overstory environment or the year.

When the effect of planting distance from the overstory was examined, neither the type of overstory nor the distance from the overstory tree or structure exerted any significant influence over dry seed yields. The effect of intercropping with maize again produced a significant decrease in fava seed yield at both close and far sites (Table 3.15).

The number of fava pods at harvest was unaffected by the presence of an overstory comprised of either fruit trees or artificial shade trees. The pod number was equally unaffected by the distance of the plant from the fruit tree or shade structure. The intercrop of fava + maize significantly reduced the number of pods at harvest as compared to pod numbers in sole fava stands (Table 3.16).

Canopy Light Interception

Canopy reflection of PAR was not significantly affected by the type of overstory environment (Table 3.17). The annual cropping pattern had a significant effect in canopy PAR reflection. Among the mixed crops, reflection was greatest in pear + fava and was significantly higher than that of maize + fava intercropping. Reflection by plots with no overstory was greatest, but not significantly different from tree- or artificial shade overstories.

Repeated measures analysis of daily PPFD during 72 to 231 DAP of the cropping season showed that PAR capture by pear trees with clean cultivation was lowest (Table 3.18). The greatest PAR capture occurred with maize and fava intercropping with artificial shade structures or without any overstory (Table 3.18). Maize culture captured more PAR on average than did sole fava bean, which was the lowest of systems with annual crops. Figures 3.10 through 3.14 show the seasonal course of PAR capture. The clean cultivation of pear never intercepted more than 20 % of the available PAR during the cropping period. The planting of *Vicia faba* in an additive arrangement with the pear increased the system's PAR capture almost 100 %

during the majority of the fava's season (Figure 3.10). The incorporation of either maize or maize-fava intercrops with the pear increased the system's PAR capture to greater than 70 % of available PAR for over half of the maize cropping season.

The use of artificial shade to modify the overstory environment and compete for light capture with the associated annual crops resulted in an increase in PAR capture by associated plantings of fava. There was no similar effect for intercrops or for maize (Figure 3.11). Intercrop PAR capture was consistently higher than sole maize with this overstory environment.

Associated plantings of maize or maize intercrops captured similar quantities of PAR regardless of the overstory environment. PAR interception by plantings associated with pear was depressed in the earlier portion of the observation period. This effect was more noticeable with pear + maize mixed plantings compared to pear + maize + fava mixed crops (Figure 3.13). At the point of maximum PAR interception by maize and maize intercrop canopies (116 DAP through 150 DAP), little difference was observed due to overstory environment.

Fava showed greater PAR capture when beneath artificial shade, either when cropped with maize or alone, as compared with fava or fava + maize with no overstory. The effect of pear overstories was to reduce total PAR capture by fava and fava intercrops (Figure 3.14).

Land Equivalency and Area Time Equivalency Ratios

Calculations of LER and ATER based on observed yields during 2002 and 2003 suggested that intercropping and mixed cropping systems at the El Tecolote site provided a substantial advantage over similarly managed monocultures. The greatest relative yield advantage occurred in mixed cropping of pear + maize + fava with an LER of 2.98 in 2002 and 3.03 in 2003 (Table 3.19). All mixed crops and intercrops showed a large yield advantage. The simple additive intercrop of maize with fava showed the least advantage, 1.45 in 2002 and 1.37 in 2003.

More detailed analysis of these results using ATER to remove yield advantage that was due solely to increased duration of exploitation of available crop area showed similar results. The studied systems maintained their yield advantages relative to monocultures and with respect to each other. The greatest advantage was observed in mixed cultivation of pear with maize and fava bean where the advantage was 99 % in 2002 and 93 % in 2003. The least advantageous system was again maize + fava bean intercropping with advantages of 37 % in 2002 and 18 % during 2003 (Table 3.19).

Examination of relative yield ratios of the individual crop components, as calculated for LER, indicated that the maize component did not suffer substantial negative impacts (declines in yield relative to sole crop performance) from either fava or pear as associates. However, mixed cropping with pear trees did not provide positive facilitation of maize yields in pear + maize or pear + maize + fava mixed cropping.

Fava bean were associated with overyielding by maize in maize + fava intercropping, but the facilitative effect was diminished in the presence of pear. Fava suffered negative effects due to competition with maize, however the effect of pear was neutral to slightly positive when maize was not present (Figures 3.15 and 3.16). Responses of pear to maize and fava mixed crops were variable, in that maize generally was competitive with pear and reduced its yields relative to sole cropped pear, however, favas in pear + fava mixed cropping were mildly facilitative (Figures 3.15 and 3.16).

Economic Response of Fruit-tree-based Agroforestry

Mixed-crop (annuals + perennials) and intercropping (multiple species of annuals) systems are difficult to compare directly with their sole crop (single species of annual or perennial) counterparts since conversions must be made between the alternative products produced. In this case, maize, fava bean, and pear yields must be converted to a common currency to allow direct comparisons of the magnitude of yield outcomes to be made. For comparison purposes, economic yields of maize (dry grain), fava bean (dry beans) and pear (fresh fruit) were valued at their approximate market value in late 2003 (Table 3.20). Since all treatments were additive, mixed cropping and intercropping did not entail any additional labor or input costs over sole cropping, rather labor and costs were reduced.

Mixed cropping of maize + fava + pear had the greatest economic return of the possible systems showing an economic advantage of 124.2 % over sole cropping of each of the three components. Sole cropping of maize had the lowest economic return.

Biological Response of Fruit-tree-based Agroforestry

Comparison of glucose-equivalent yields indicated that, mixed cropping of maize + fava + pear had the highest productivity for the economic yields harvested from the system. The lowest glucose-equivalent yields occurred in the sole cropping of pear (Table 3.21). Sole cropping of maize allowed the harvest of five times greater glucose-equivalent yields than sole cropping of pear, and was nearly twice as productive as mixed cropping of pear + fava. All mixed cropping or intercropping patterns with maize as a component were essentially equivalent in their productivity.

Discussion

In order to be successful, agroforestry systems that are designed for farmlands should produce their benefits by exploitation of additional available resources that are unused in tree-less systems. Other alternative pathways for benefits exist; however their mechanism is primarily the exchange of one type of product for another with a potential increase in value of the new suite. Of greater interest is an increase in the total output of the combined components from greater resource use.

It may be overly optimistic to expect that additional components can be inserted into an agronomic system with no overlap or competition for resources. Cannel et al., (1996) suggest that losses to one component due to competition will only be considered important by producers relative to the value of the additional products produced. The implication is that perennial components with high value yields over a time-frame acceptable to producers should enjoy greater adoption than lesser valued products or those with excessive delays before products are mature.

In the Guatemalan *altiplano*, deciduous fruit trees are valued for the potential for sale and/or home consumption of their fruits. Pear, being a more recent introduction, is not as widespread as apple or peach; however they are well known in the market, have greater values than apple, and do not suffer as much from skin defects as apple and peach when produced in low-input systems. Pear was used in this study because it was expected that they would have superior performance in the mixed cropping system and for their expansion potential as a component of mixed systems.

Maize cropping systems prevalent in the region will allow the integration of pear production with maize; however, farmers would be unwilling to abandon maize production in favor of fruit trees or other crops with fruit trees. The overall focus of this study was to examine if incorporation of pear trees into maize farming systems would allow better utilization of moisture and radiation present in maize fields. The results clearly confirm this possibility and thus support the hypothesis of Cannel et al. (1996).

Responses of Pear Trees to Mixed Cropping

During this study, evidence was found that fruit trees were negatively affected by annual crops with respect to fruit soluble-solids contents (Table 3.9), production of large grade fruits (Table 3.8), and total fruit mass (Table 3.6). The few studies that have been reported on impacts of understory vegetation on fruit trees primarily consider non-productive weeds and grasses or leguminous crops (Dupraz et al., 1999; Anderson et al., 1992; Lipecki and Berbec, 1997). In general, effects against seedling or immature trees have been found, at a time when it can be assumed that there is little to no differentiation in root or canopy space. However, mature fruit trees are also affected, potentially due to low root densities (Atkinson, 1980).

Vegetative growth

It was found that where annual crops were introduced among established trees, tree height initially increased more rapidly when the competition for light was moderate (i.e., pear + fava, or pear + maize). Where competition for light was greater (pear + maize + fava), trees did not make additional growth, possibly due to resource limitations (Table 3.4). The height growth of pear trees in pear + maize + fava mixed cropping was similar to clean cultivated controls. It was expected that competition for light would result in extensive growth of the components (Ritchie, 1997; Holbrook and Putz, 1989;

Scott et al., 1998) and this was observed where competition for light was moderate. No differences in tree height increase were observed after the second year.

It is known that moisture stress may favor fruit growth over vegetative growth (Chalmers et al., 1986; Mitchell et al., 1986). While the combined observations are somewhat suggestive that substantial moisture stress occurred where maize + fava were mixed with pear, the soil moisture data that was collected to verify this is not presented and the effect of water stress remains hypothetical. Two factors may have contributed to the differences observed between years one and two. I observed that precipitation was reduced during year two, potentially leading to increased competition for soil moisture. Additionally, height growth was much greater in both varieties in year two than in year one. It should be concluded that conditions were more favorable for tree growth under all treatment alternatives as compared to the previous weed understory. The enhanced conditions for growth may have offset tree-crop competition for below-surface resources. Not surprisingly, tree diameter growth was equally unaffected by crop treatments. Growth often relies on carbohydrate accumulation during the prior year. Treatments were not applied prior to year one and it must be assumed that a fraction of the observed response was due to the previous season's weather and the grass and weed understory that was present.

A tradeoff between reproductive and vegetative growth was clearly evident between the two varieties. Generally, reproductive growth was favored over vegetative in Bartlett during the two years of this study and the reverse true in Ayres. This observation is well explained by the interaction of early flowering in Ayres and local climatic conditions serving to limit reproductive potential in Ayres during the two years of this study. In 2003, it is possible that the number of freeze events negatively affected the progression of fruit set in Ayres, while fruit set in Bartlett did not appear to be affected by freeze events beyond a possible delay in fruit initiations well related to that observed in flowering initiation (Figure 3.9). Substantial root suckering was observed by Bartlett, reflecting scion-rootstock incompatibilities which potentially contributed to limitations in vegetative growth.

Fruit production

I found that the tree's ability to produce mature fruit was affected by the presence of annual crops. In the first year, no significant differences were apparent in the emerging pattern, however in the second year significant differences became apparent as the treatment effects emerged. The total fruit mass per tree was not significantly different between any of the crop treatments until the second year when yields were improved with fava associates or the control treatment compared to treatments with maize (Table 3.6). Again, the carry-over of stored reserves from the previous year may have influenced this finding in year one; yet year two clearly represents a depressive effect from maize components. The number of fruits per tree (a function of flowering and fruit set) was not impacted by understory cropping regimes and similar quantities of fruit were maintained by fruit trees subjected to the competitive regimes compared to trees with clean cultivated understories.

The distribution of fruit grades measured by size and mass of individual fruits was affected by associating annual crops with pear trees (Table 3.8). First grade fruits constituted a greater fraction of the total harvest from trees underplanted with fava as compared to treatments containing maize. This effect was not significantly greater than the results obtained where the understory was cleanly cultivated. Excessive competition for water should reduce fruit size owing to limitations in cell divisions and later in cell expansion (Caspari et al., 1994; Miller et al., 1998; Naor et al., 1999). I found that the largest fruits comprised a lower fraction of the total where maize had been associated with pear trees (Table 3.8). The competitive effects of grasses with fruit trees are well known (Kumar et al., 2001; Tworkoski and Glenn, 2001; Meyer, et al., 1992) and I could anticipate that, at the experimental densities under Guatemalan climatic conditions, maize associates are likely to result in reduced tree growth and diminished production of Grade 1 fruit owing in part to water stress. Data on soil water status in all treatments was collected in this study, and these results will be presented in forthcoming publications.

In contrast, fava bean associates may enhance growth and production of Grade 1 fruits compared to maize, however the advantage over clean cultivation was not significantly greater by Tukey (HSD) during the study (Table 3.8). Kappel (1989) reported that, canopy shading may also have contributed to reductions in fruit size in pear. The studied pear, where interplanted with maize, were shaded relative to diffuse, morning, and afternoon light over the same time frame that Kappel (1989) used. Therefore, the possibility that fruit size reductions were influenced by both light and water competition cannot be excluded, since in treatments with fava, no comparative shading occurred.

The effect of greater availability on nitrogen in treatments containing fava bean was not measured in the experiment. With equal applications of fertilizer, these treatments may have contained a greater pool of available N since favas were observed to be well nodulated. The observed tree responses are consistent with better N nutrition and the importance of this factor can not be confirmed or rejected without further study.

Fruit quality

Brix and fruit texture assess fruit quality, essentially how sweet and how crispy or mealy the fruit will seem to consumers. If carbohydrates are limiting during fruit filling, the limitation should be reflected either in decreased sugar content or decreased vegetative growth. Fruit quality, while unaffected by understory cropping choices in the first year, declined in association with maize treatments during the second year as compared to the control. While means separation was incomplete, % brix was greatest with the clean cultivated understory and lowest where maize was present as an associate (Table 3.9). The lower brix values within maize treatments are harmonious with the supposition that excessive competition occurred in these treatments. Additional data is needed to permit a clear conclusion of the presence of negative effects owing to mixed cropping with a maize component.

Response of Maize to Mixed and Intercropping

The presence of fruit trees or shade structures did not produce a significant decrease in maize grain yield or in the number of ears during 2002 (Tables 3.10 and 3.11). The high coefficient of variation for maize grain yields makes it difficult to detect differences between treatments. In 2003, clear differences in grain yield, though not ear number were observed due to the effect of fruit trees and to a lesser extent from artificial shade structures (Table 3.10). This is consistent with the expectation that moisture stress was a larger factor in the 2003 results. If the yields under trees or shade structures are in actuality lower than control treatments an estimate of the importance of the supposed yield loss can be made. From Table 3.10, there is a potential yield loss of 380 kg ha^{-1} associated with fruit trees or similar shading. On the farm scale, this translates to a loss of 16.8 kg *cuerda*$^{-1}$ (1.0 *cuerda* = 441 m^2, the standard measure for agricultural activities in the highlands). *Criollo* maize varieties have a mean percent shelling of 69 % and this loss would appear as approximately one half of the net sack used to transport unshelled maize from the field. It is likely that this approaches a difficult-to-detect level of loss in total yields, particularly if the field is not uniformly dedicated to fruit-maize mixed cropping. More likely, farmers' observations will be of barren canes and stunted ears on plants.

When the importance of distance from trees for maize yields was assessed, significant differences in grain mass were observed between plants growing beneath or directly next to overstory canopies compared to those growing at a greater distance from overstory influences during the first year (Table 3.12). In shaded treatments, maize plants at a distance outyielded plants closer to the shading object. In the second year this effect was not observed (Table 3.12). It is likely that the first year's performance was influenced to some extent by pre-existing differences based on the historical presence of the fruit trees during the previous seven years. Similarly, the number of ears was significantly reduced in close proximity to trees or shade structures in the first year and this loss could likely be recognized by farmers at harvest. In the second year, distance effects were not seen and in contrast, the effect of fruit trees was greater than that of shade structures which may provide further support to increased level of moisture competition affecting 2003 results.

Increased maize yields were found with additive intercropping of maize + fava without regard to the presence of trees or shading during the first year. Both grain yield and number of ears were higher in intercropping. This pattern was also evident when distance from shade structures was assessed. In all instances, intercropped maize outperformed sole-cropped maize by an average of 790 kg ha^{-1}. At the farm scale, this difference should be visible to farmers at harvest. However, in the second year of study, this facilitative effect by intercropping with fava was not observed. It must be concluded that the facilitative effects of intercropping maize + fava are influenced by factors such as soil nutrients or soil moisture levels that were not controlled in this study. These observed results are consistent with common observations in farmers' fields where crop growth is visually depressed in proximity to mature fruit trees. Inadequate or sporadic maintenance of soil fertility is suggested as the likely cause and that adequate nutrient supplies may contribute to reducing the phenomenon.

Response of Fava Bean to Mixed and Intercropping

In contrast to maize, fava yields were consistently and dramatically depressed in intercropping situations with intercrops yielding approximately 34% of sole crops. As expected, pod numbers were depressed where maize was associated with the fava crop. Responses to overstory environments suggest that fava yields were not greatly impacted by shading from fruit trees or shade structures while shading or other competitive effects were substantial with maize.

PAR Capture

The analysis of PPFD provided additional insights into crop and tree responses. Canopy reflectivity was lowest in maize + fava intercrops, and greatest within sole-cropped fava and within clean cultivated fruit trees (Table 3.17). This is likely due to greater reflection by bare soil compared to leaf and stem tissues and reveals an additional factor that contributed to the comparatively low rate of PPFD capture by these two systems. The greatest daily PPFD capture occurred in maize-fava intercropping beneath artificial shade structures and the lowest rates were realized within clean cultivated fruit trees (Table 3.18). It is likely that three GaAsP sensors per plot were insufficient to accurately characterize the PAR capture of the fruit trees, and that this measure is best interpreted as radiation unavailable in the understory of the fruit tree stands. Radiation capture is a conserved predictor of yields in the absence of other limitations, even within agroforestry systems (Bérnard et al., 1996; Monteith, 1972). On this basis alone, it could be anticipated that the greatest yields would occur in maize based systems without perennial overstories. During the 2002 season, the addition of fava within maize crops increased the weekly capture of PAR across all overstory treatments (Figures 3.10 through 3.12) and should produce superior total yields compared to sole maize and maize + pear. The addition of fava beneath pear trees produced a large increase in PAR capture until the harvest of fava around 172 DAP (Figures 3.10 and 3.14) when the performance of sole cropped pear was considered. This again foreshadowed a total yields improvement from pear cropping alone to mixed pear + fava cropping. The increase in PAR capture with maize as a component was much greater than with fava. Among systems with fruit trees, the radiation capture indicated that mixed cropping of maize + fava with pear should offer the greatest biological yields.

It seems evident based on these results, that with respect to PAR, it was indeed possible to capture additional resources using fruit-tree-based agroforestry technologies, at least in a controlled setting. The introduction of both sole crops and intercrops of maize and fava were efficacious in increasing PAR capture over clean cultivated pear trees. The difficulty with showing increased radiation capture where trees are introduced may be due mainly to sampling inadequacies for tree radiation capture.

Effects of Potential Water Competition

Combining the observations of fewer large fruits where maize was present (Table 3.8), lower vegetative growth where maize + fava intercrops occurred (Table 3.4), and the reduced rate of canopy development in maize crops associated with pear, particularly at the beginning of the intermodal dry period (Figure 3.14), the evidence suggests that competition for water was occurring with sufficient intensity to limit both annual and perennial components. Soil water content has previously been shown to be depleted more rapidly close to trees (Jackson et al., 2000; Jose et al., 2000). During this study, canopy growth of fava bean and Maize + fava appeared limited by association with pear trees (Figure 3.14). Recalling the lower harvest of favas in pear + fava mixed cropping in 2003 (Table 3.14), it appears possible that competition for water was also excessive with pear + fava mixed cropping. In systems of maize with black walnut (*Juglans nigra*) (Jose et al., 2000) or sugar maple (*Acer saccharinum*) (Miller and Pallardy, 2001) in the U.S., competition for water rather than light was the principal cause for reduced canopy leaf area. The same phenomenon seems to have been operating in this study. However, it apparently was insufficient to limit fruit production, particularly as tree canopies were fully expanded and fruit set had occurred previously.

Apple trees have shown to respond in 3 dimensions to greater water availability (Green and Clothier, 1999). It is likely that pear may have been able to access water from moister horizons as surface sources became depleted as was demonstrated for peach with fescue (*Festuca arundinaceae*) (Glenn and Welker, 1993).

Without analysis of additional data to at least partially disaggregate plant water use, it is not possible to conclude whether additional soil water was accessed. The current results are consistent with the possibility that water limitations occurred under mixed cropping during the intermodal dry period during the first half of the cropping season. Additional analysis of soil water and tree transpiration data not presented in this study may provide a better understanding of this issue.

Apparent Benefits from Mixed and Intercropping

The second issue implied by Cannel et al.'s (1996) hypothesis is that benefits are produced using the previously mentioned additional resources. The analysis of LER provides an initial response to this issue. Results presented in chapters four indicate that the limited area of smallholder farms contributes to low farm productivity, it is appropriate that the efficiency with which available land is used be addressed.

LER and ATER benefits

This study showed that intercropping and mixed cropping resulted in increased production compared to sole cropping of any of the three studied components with 8-year-old pear trees. Huang and Xu (1999) looked at wheat and beans with *Taxodium ascendens* in Jiangsu Province, China, where they noted that declines in relative yields began as early as year three, supporting the supposition that deciduous fruit trees may be less competitive components than the timber species. Mixed cropping of pear, maize and fava was extremely advantageous, producing 98 % to 103 % greater combined yields than could have been produced with sole cropping. This advantage was based on the total yield of the three components under mixed cropping compared to sole cropping at equal densities on the same land area. The least advantageous was intercropping of maize + fava where the overall advantage versus sole cropping of maize and fava was between 19 % and 45 % greater yields.

It is possible to further break down the observed advantages by removing any gains due solely to greater resource capture with additional days of growth. That is to say, if one crop grows for 100 days and a second for 200 days, it is self evident that an additional 100 days of resource capture should produce greater yields. The use of ATER allows direct comparisons between crops of unequal durations. Advantages remaining after ATER analysis are occurring during the period when all components are present and are due to increased resource use or improved use efficiency. The ATER showed that some benefits in each of the cropping options were due to increased duration of crops on the land area. The absolute amount was greatest within pear + maize + fava mixed cropping and least for maize + fava intercropping. Substantial improvements in relative yields to land area remained and must be considered as accruing on a daily basis. The ranking of the systems to each other was unchanged when the cropping duration had been accounted for.

<u>Relative yields totals of mixed and intercropping</u>

Comparisons of relative yield totals provided clear explanations of the source of the calculated advantages by LER and ATER. It appeared no facilitation of maize or fava occurred through the inclusion of pear trees as mixed crop components. This suggests that any improvements in understory light or temperature climates were less important than the competitive belowground interactions. Yields of both maize and pear were facilitated in the presence of fava; however the effect was notably less when three components rather than two were present. This again bring to light the potential impact of biological nitrogen on system performance. Li et al. (1999) found comparable responses of maize to fava. The effect was dependent on interactions between the root systems of each component. In contrast, in this study, the same facilitative effect was not consistently observed. This is likely due to differences in density and shading as their experiment had inter-row planting whereas this study evaluated intra-row plantings. Maize treatments facilitated pear yields in pear + maize mixed crops, but not as pear + maize + fava (Figures 3.15 and 3.16). Theoretically, it is possible to change proportions of crops, to realize increased relative yields to land, and yet produce an overall loss from the perspective of small farmers. A simplistic example would be the intercropping of maize with turf grass. Therefore it is insufficient to rely on LER and ATER alone to show benefits.

These differences are potentially related to the total availability of resources and alternations of niche differentiation when different components are present. As a thought experiment, I assessed other possible factors that might influence facilitation effects. I identified significant differences (Tukey's HSD) in soil nutrients (Table 3.1) specifically, greater levels of Phosphorus, Zinc, Manganese and Copper as well as lower levels of Calcium in the blocks where facilitation was taking place. Outside of these blocks, interactions were neutral to negative. Additional study is warranted to understand the significance of this important observation.

Valuation of economic yields

The production of varying proportions of three different types of yields complicates assessment of the benefits occurring within alternative cropping patterns. Evaluation of changes in the economic output of the systems and differences in the biological yield after harvest provide two contrasting methods to compare across type of yields. In the analysis of economic yields, I measured only the market value of the principal yield products; fresh pear, dry fava bean, and shelled maize. The value of stover as fodder, of husks as fodder and *doblador*, and of tree litter as organic matter recycled and potentially not extracted from adjacent forest areas were excluded. For this reason, I could expect the estimates of economic output to be slightly higher than stated. Additionally, I did not calculate labor and input costs. During the experiment, no crop management activities were identified that were exclusive or additional to intercropping or mixed cropping of a component and none were done. Equivalent amounts of inputs for each component were used regardless of its cropping status.

In contrast, the integration of tasks may have reduced total expenditures on labor in intercropping and mixed cropping alternatives. A clear example is the labor costs or herbicide expenses related to clean cultivation beneath fruit trees. Here, the presence of annual crops limited weed growth and reduced the amount of weeding required. My direct comparisons between economic outputs (Table 3.20) assume that labor and input costs remain constant with land area and rather than indicating farmer benefits, provide a measure of comparative economic potential of cropping choices.

The economic output of the systems supported the trend of the analysis of ATER where pear + maize + fava mixed cropping had the greatest yield potential and maize +

fava intercropping excluding sole crop alternatives the least (Table 3.20). Pear + fava mixed cropping was slightly better than pear + maize mixed cropping, however it is unwarranted to recommend one over the other on this basis. Further research is warranted to ascertain whether these relative advantages are stable at lower crop densities. The experimental conditions used in this experiment were at the upper limits for crop densities for maize and pear and high for fava intercrops. My findings are quite similar to the work of Benjamin et al., (2000) working in alley crops of maize, beans, and walnut. They also found increasing economic returns with increasing cropping intensity. Their study differed in that no consideration was given to the value of nut yields.

Biological productivity measured as glucose-equivalent yields

When measuring the biological output of crop yields, the biochemical contents of the economic yields were converted to equivalents of glucose. Here both the actual compounds present as well as the energy required to create them relative to glucose were considered. The yield potential of highland maize in the local environment was highlighted in as much as it was 160 % more productive than a comparable sole crop of fava bean and 400% greater than clean cultivated fruit trees at 1000 trees ha^{-1}. The top seven out of eleven alternatives included maize as a component (Table 3.21). Mixed cropping of pear + maize + fava was slightly better than either maize + fava intercropping (second) or pear + maize mixed crops (third). Surprisingly, sole cropped maize and intercrops of maize + fava were fourth and fifth respectively. In order for fruit-tree-based agroforestry to be biologically superior to sole cropped maize, it must include maize as a component. Mixed cropping of pear + fava is only superior when maize would not be planted.

The main objective of this study was to test the hypothesis that fruit-tree-based agroforestry in Guatemala would support the general hypothesis that benefits are produced by the exploitation of resources that would not be used in treeless systems. The results indicate that both economic and biological benefits were realized by fruit-tree-based agroforestry alternatives. I conclude that the general hypothesis was supported in pear-tree-based agroforestry with maize and fava crops and that further study is warranted to understand farmer adoption and potential limitations in the applicability of my findings. The on-station results imply that farmers could engage profitably in fruit-tree-based agroforestry that involves a maize and/or fava component.

Table 3.1. Soil nutrients from five experimental blocks in El Tecolote, Labor Ovalle, Guatemala.

	Soil nutrient contents (mg kg^{-1})						
Block	P	K	Ca	Mg	Zn	Mn	Cu
1	11.1 a	232.4	1475 a	144.4 ab	1.7 a	5.8 a	1.3 a
2	9.1 a	217.5	1463 a	147.0 ab	1.8 a	5.0 a	1.4 ab
3	15.0 ab	202.1	1254 b	134.3 b	1.7 a	5.3 a	1.7 bc
4	20.5 bc	218.3	1150 bc	132.8 b	1.8 a	5.8 a	1.9 c
5	21.9 c	168.6	1008 c	172.6 a	4.2 b	13.6 b	2.8 d

Nutrients extracted with Mehlich 1 technique.
Means separation for P, Ca, Mg, Zn, Mn, and Cu by Tukey (HSD) (α=0.05).
Means for an element followed by the same letter are not significantly different.

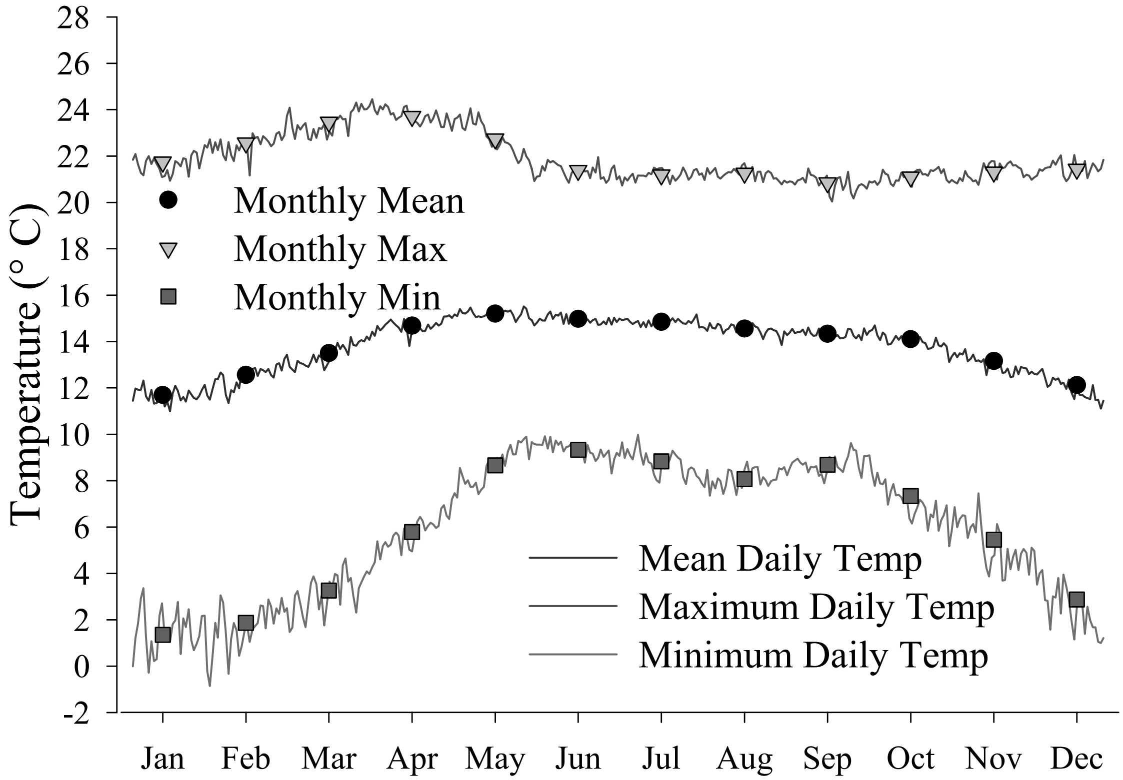


Figure 3.1. Monthly and daily mean, maximum, and minimum temperatures at Labor Ovalle Station, Olintepeque, Guatemala. Data from unpublished INSIVUMEH records (1971 to 2002).

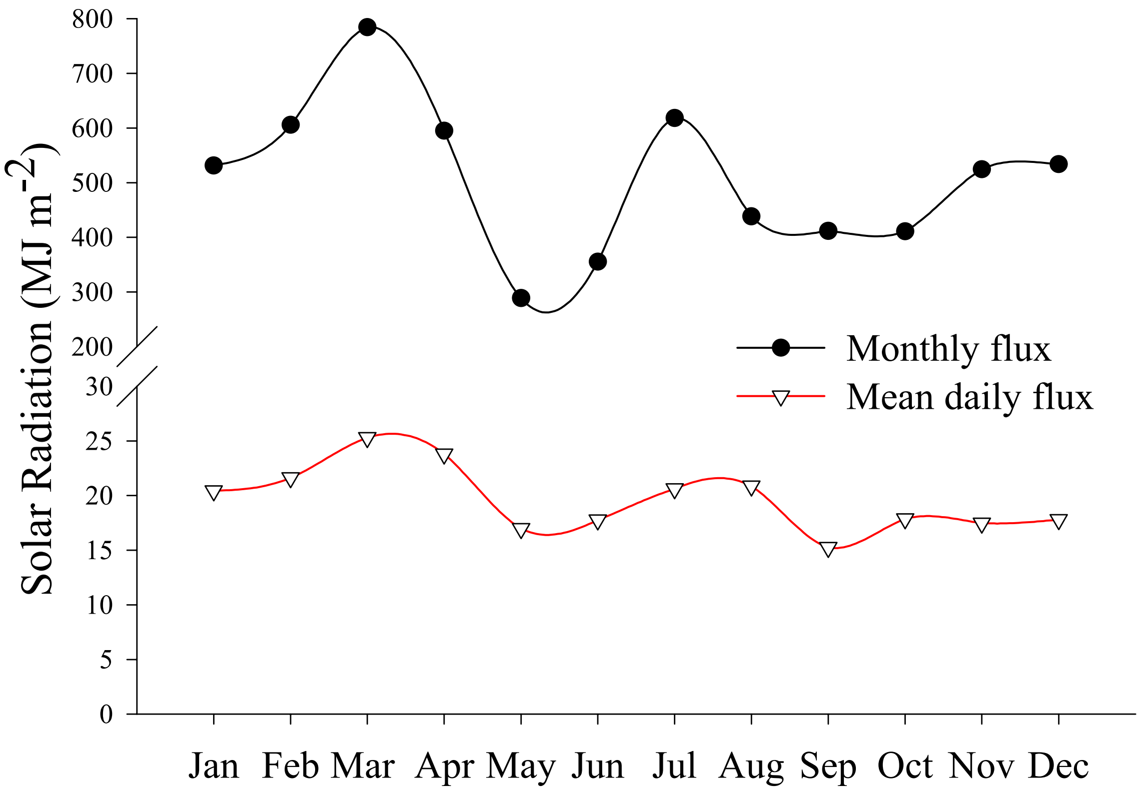


Figure 3.2. Monthly totals and daily means of incident solar radiation measured at Labor Ovalle Station, Quetzaltenango, Guatemala during 2002. Note break in Y-axis between 30 and 200 MJ $^{-2}$. Data from unpublished INSIVUMEH records (1971 to 2002).

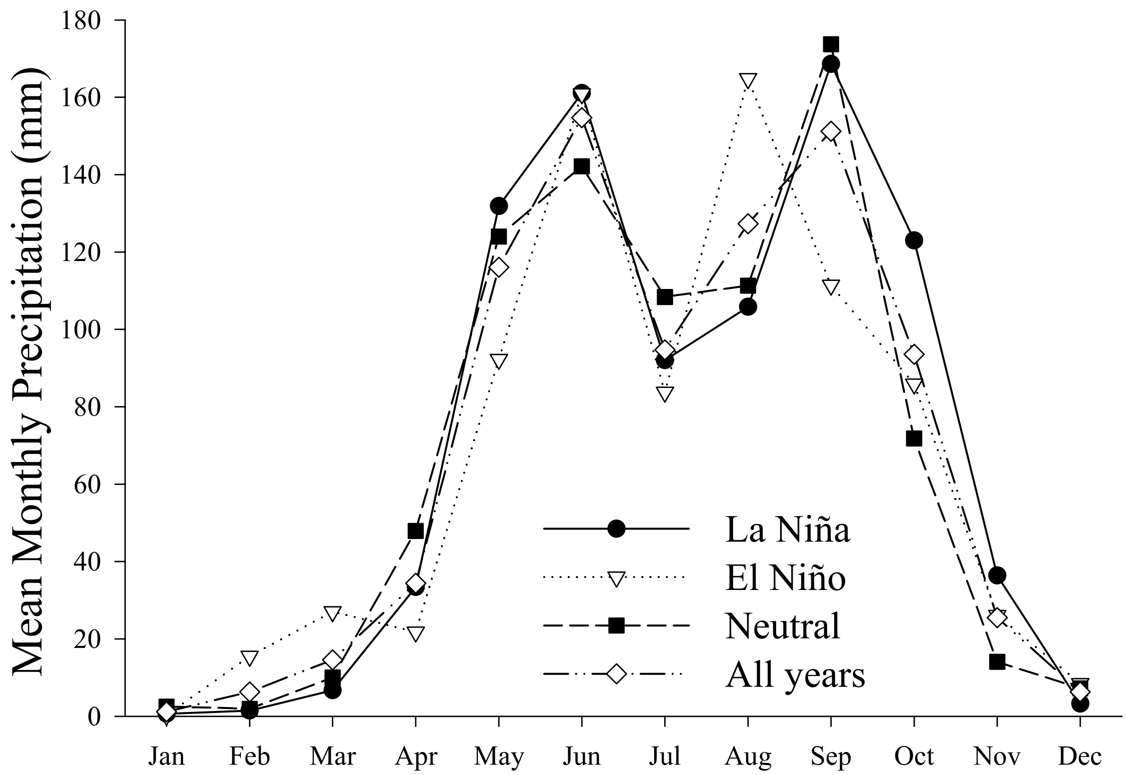


Figure 3.3. Mean monthly precipitation during La Niña, El Niño, neutral and all years at Labor Ovalle station, Olintepeque, Guatemala for the years 1971 to 2002. Data from unpublished INSIVUMEH records (1971 to 2002). La Niña, El Niño, and neutral years calculated using the definition of the Japanese Meteorological Society (JMA) (Trenberth, 1997).

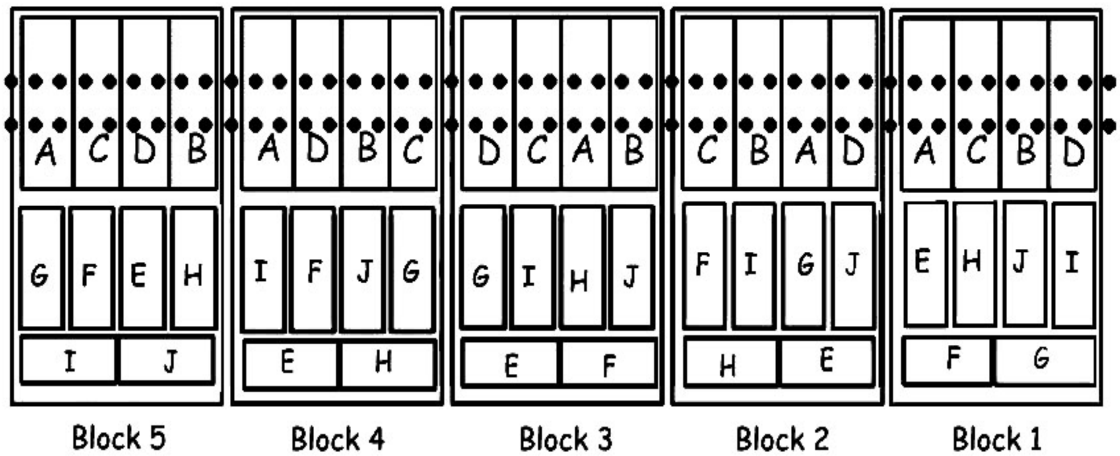


Figure 3.4. Experimental layout for dispersed orchard agroforestry with maize and fava. Trees were removed from non-tree plots to permit establishment of controls. A, B, C, … stand for the nine treatments as explained in Table 3.2.

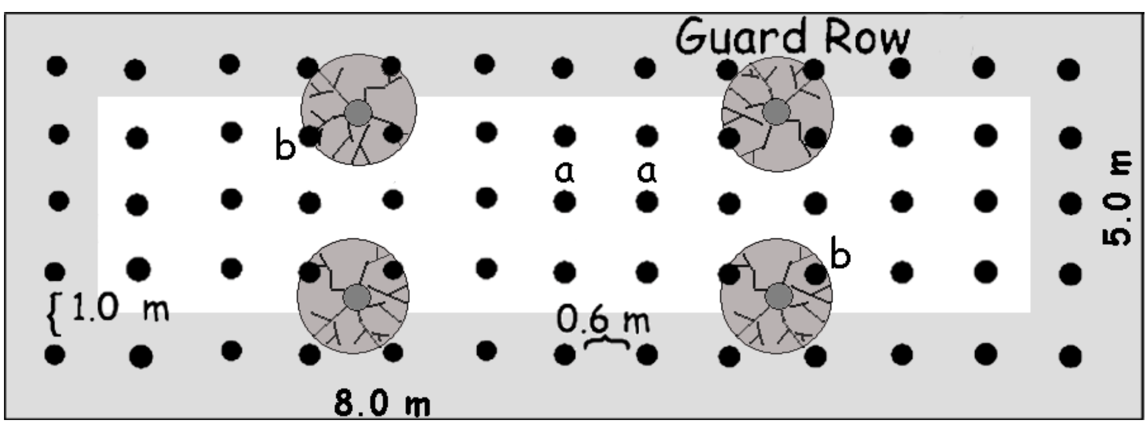


Figure 3.5. Single plot layout showing crop planting sites in relation to pear trees. Treatments with artificial trees were identically oriented. The dark, filled circles denote crops and the four large circles with drawings inside denote trees. The lighter area inside the plot was the net plot from which observations were recorded.

Table 3.2. Treatments for tree-crop interactions for tree-crop interactions experiment. Each treatment is replicated five times within a complete random block design.

Crops with pear	Code	Crops with shade structures	Code	Sole crops	Code
Pear + maize	A	Shade + maize	E	maize	H
Pear + fava	B	Shade + fava	F	fava	I
Pear + maize + fava	C	Shade + maize + fava	G	maize + fava	J
Pear control	D				

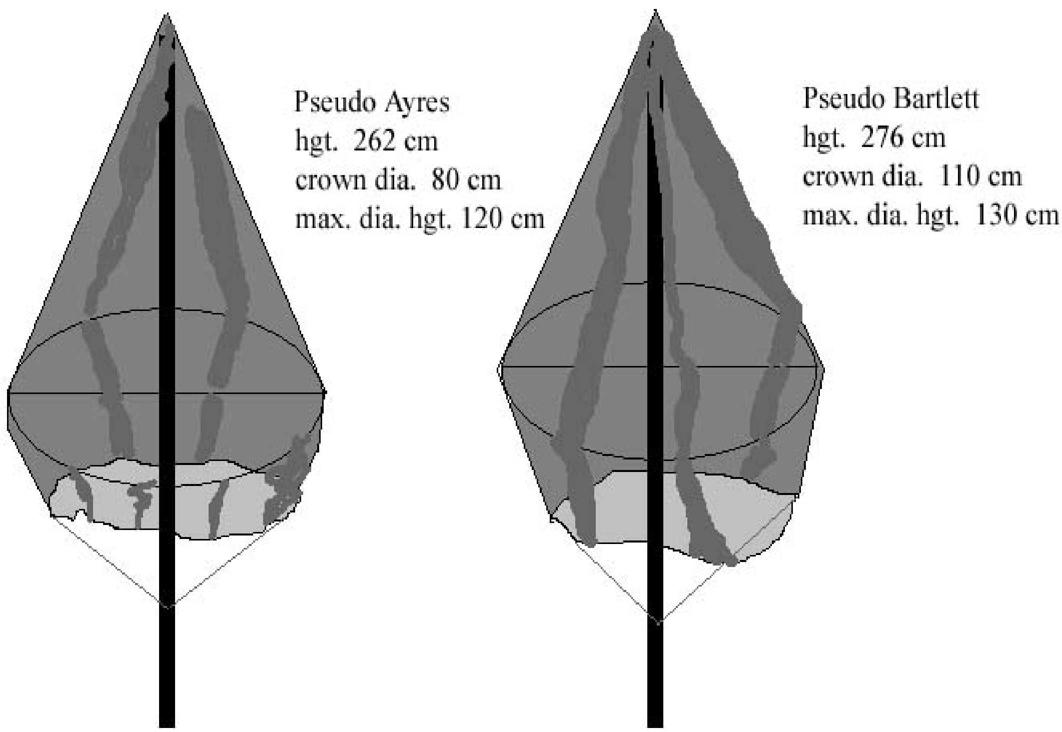


Figure 3.6. Artificial shade structures designed to provide similar shading conditions as real pear trees. Structures were covered with 30% shade fabric attached with wire clips.

Table 3.3. Micrometeorological measurements made during 2002 and 2003 at El Tecolote, Labor Ovalle, Olintepeque, Guatemala.

Parameter	Measurement technique	Measurement interval	Recording Time step
Temperature	Copper-constantan (CU-CO) thermocouples	10 seconds	15 min.
Max T	CU-CO thermocouples	10 seconds	daily
Min T	CU-CO thermocouples	10 seconds	daily
Precipitation	Tipping bucket gauge (0.254 mm minimum measurement value)	continuous	daily
Potential evaporation	Standard class-A pan	daily	daily
PPFD	Photosynthetic photon flux density with Li-Cor Quantum sensor (LI-190SA)	10 seconds	15 min.
Solar radiation	Solar radiation with Li-Cor Pyranometer (LI-200SA)	10 seconds	15 min.

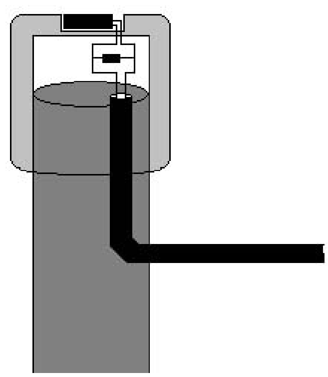


Figure 3.7. Construction details of PAR sensor using Gallium Arsenide Phosphide (GaAsP) photodiodes and shunt resistor embedded in a silicon matrix.

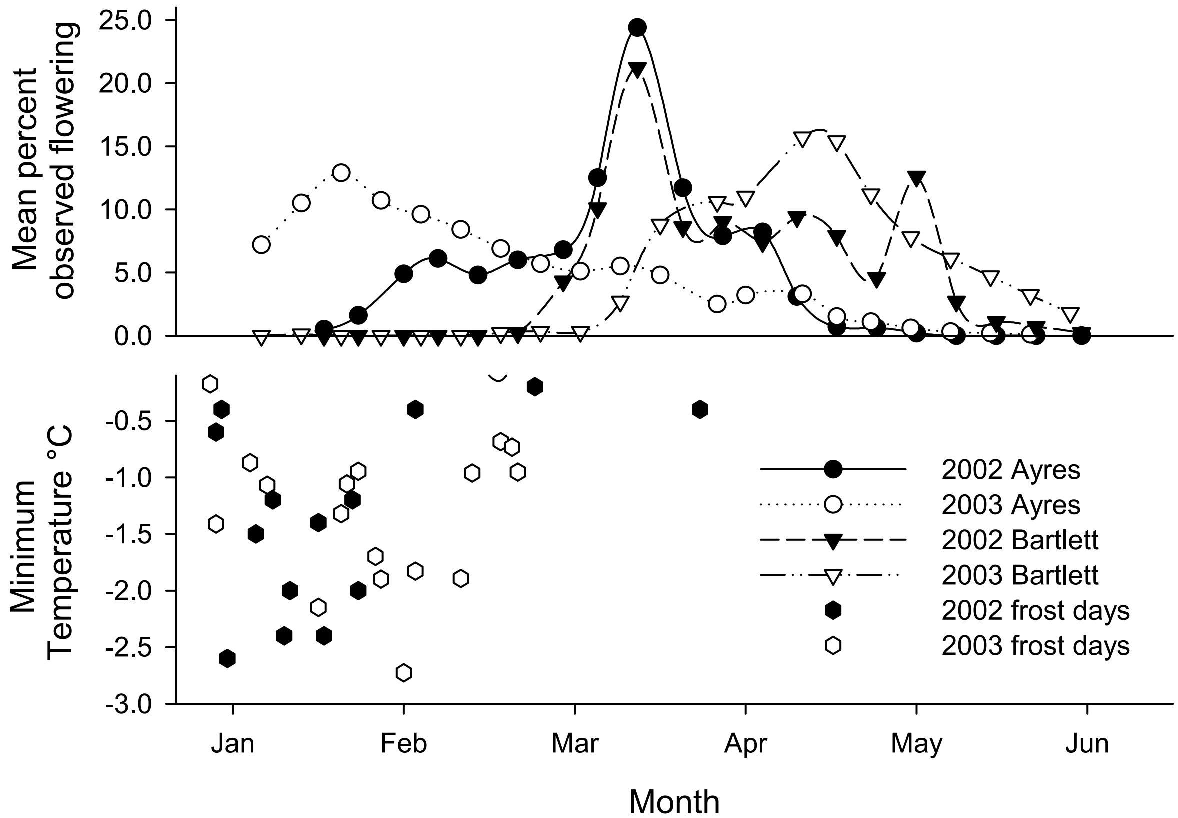


Figure 3.8. Flowering phenology of two pear varieties in 2002 and 2003 at Labor Ovalle, Quetzaltenango, Guatemala and its relation to sub-freezing temperatures occurring during both years.

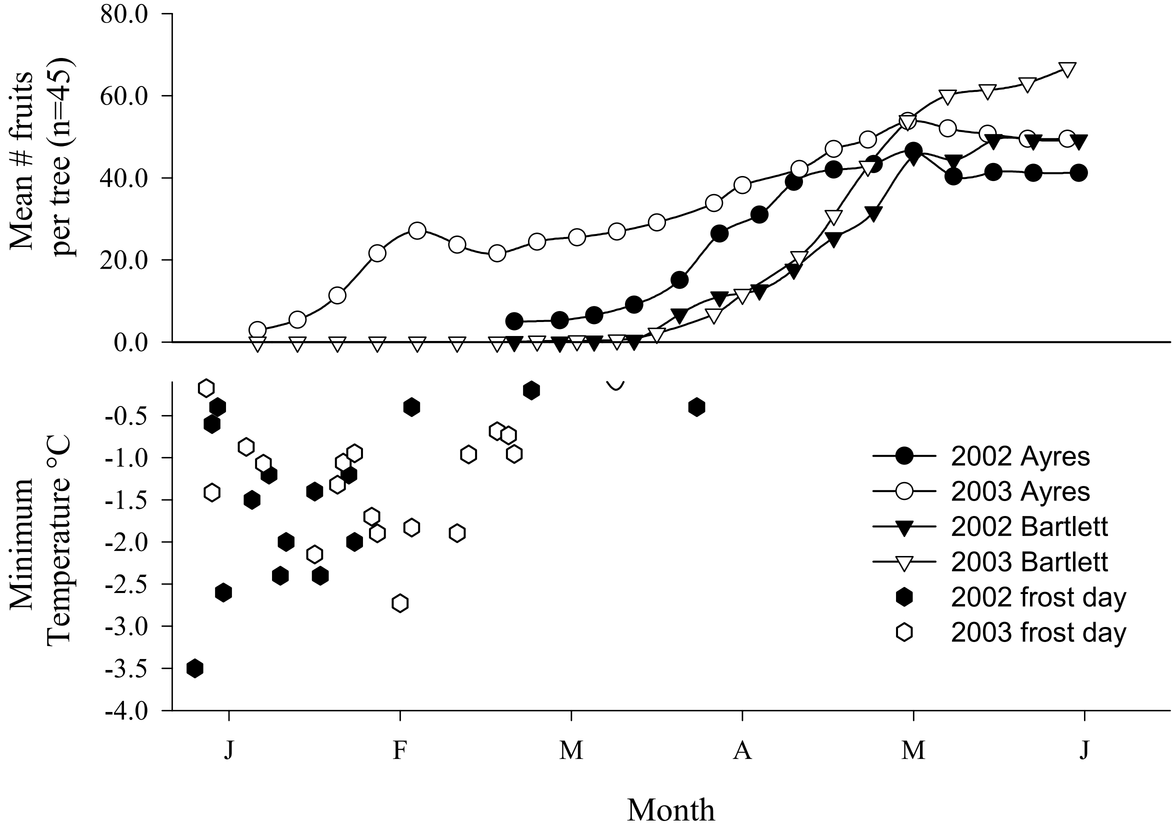


Figure 3.9. Fruit set on pear trees during 2002 and 2003 and frost events at Labor Ovalle, Quetzaltenango, Guatemala.

Table 3.4. Trunk diameter at 20 cm above ground and tree-growth increments of two grafted pear varieties in response to four understory management regimes comprised of clean cultivation and combinations of annual crops at El Tecolote, Labor Ovalle, Guatemala.

	Var. Ayres x *calleryana*				Var. Bartlett x *calleryana*				
	2002		2003		2002		2003		$\bar{x}$
Understory crop	Dia. (mm)	Growth (mm)	Dia. (mm)	Growth (mm)	Dia. (mm)	Growth (mm)	Dia. (mm)	Growth (mm)	Growth (mm)
Maize	51.9	7.4	59.7	7.8	47.9	4.0	52.4	4.5	12.1
Fava	49.1	9.0	56.2	7.2	48.1	5.2	51.5	3.4	12.5
Maize x Fava	52.6	8.1	58.9	6.4	46.8	4.4	51.1	4.5	11.5
Control	47.0	7.8	54.3	7.3	46.6	4.6	50.4	3.8	11.8
$\bar{x}$	50.2	8.1a	57.7	7.2y	47.4	4.5b	51.4	4.0z	

During 2002, the main plot growth (understory treatment) effects were not significant and sub-plot growth (variety) effects were significant ($p < 0.001$).
Means for annual diameter growth within a year followed by the same letter are not significantly different. Means separation for sub-plots effects by Tukey HSD (α=0.05).

Table 3.5. Tree foliated heights in two grafted pear varieties (sub-plot effects) during 2002 and 2003 in response to four understory management regimes (main plot effects) comprised of clean cultivation and combinations of annual crops.

	Var. Ayres x *P. calleryana*				Var. Bartlett x *P. calleryana*				$\bar{x}$	
	2002		2003		2002		2003		2002	2003
Understory crop	Hgt. (m)	Growth (cm)	Hgt. (m)	Growth (cm)	Hgt. (m)	Growth (cm)	Hgt. (m)	Growth (cm)	Height increase	Height increas e
Maize	3.0	6.4	3.1	16.7	2.9	3.0	3.0	18.4	4.7 a	17.6
Fava	2.6	7.0	2.8	23.0	2.9	3.2	3.0	18.7	5.1 a	20.9
Maize x Fava	2.9	5.1	3.2	34.7	2.8	1.4	3.0	16.1	3.3 b	25.4
Control	2.6	3.9	2.9	33.7	2.8	0.9	2.9	17.3	2.4 b	25.5
$\bar{x}$	2.75	5.6 y	3	27.0 a	2.8	2.1 z	3.0	17.6 b		

In 2002, main plot (understory treatment) effects for height growth were significant ($p < 0.001$) and subplot (variety) effects for height growth were significant ($p < 0.001$).
In 2003, main plot (understory treatment) effect were not significant and subplot (variety) effects were significant ($p < 0.001$).
Means separation for sub-plots effects by Tukey HSD (α=0.05). Mean height growth within a year followed by the same letter are not significantly different.

Table 3.6. Fruit yield (fresh weight) of two grafted pear varieties under four understory management regimes during 2002 and 2003 at El Tecolote, Labor Ovalle, Guatemala.

	Var. Ayres		Var. Bartlett			
	Fruit mass (g $tree^{-1}$)		Fruit mass (g $tree^{-1}$)		Fruit mass (g $tree^{-1}$)	
Understory management	2002	2003	2002	2003	$\bar{x}$ 2002	$\bar{x}$ 2003
Maize	5246	3290	8709	8615	6978	5952 a
Fava	4109	4890	8709	13464	6409	9177 b
Maize x Fava	4163	3360	7823	7747	5993	5553 a
Control	4146	4493	8064	9561	6105	7027 ab
$\bar{x}$	4416 a	4008 y	8326 b	9847 z		

In 2002, main plot (understory treatment) effects were not significant, sub-plot (variety) effects were significant ($p < 0.001$).
In 2003, main plot (understory treatment) effects were significant ($p < 0.001$), sub-plot (variety) effects were significant ($p < 0.001$).
Means separation within years by Tukey HSD (α=0.05). Yearly means followed by the same letter are not significantly different.

Table 3.7. Fruit number of two grafted pear varieties under four understory management regimes during 2002 and 2003 at El Tecolote, Labor Ovalle, Guatemala.

	Var. Ayres		Var. Bartlett			
	Fruit number tree^{-1}		Fruit number tree^{-1}		Fruit number tree^{-1}	
Understory management	2002	2003	2002	2003	$\bar{x}$ 2002	$\bar{x}$ 2003
Maize	51.1	39.9	66.2	65	58.6	52.4
Fava	35.6	41.3	56.4	87.4	46	64.4
Maize x Fava	42.5	36.9	55.3	56.5	48.9	46.7
Control	36.3	43.7	52.4	60.9	44.4	52.3
$\bar{x}$	41.4 a	40.5 y	57.6 b	67.4 z		

During 2002, main plot (understory management) effects were not significant, and sub-plot (variety) effects were significant ($p < 0.001$).
In 2003, main plot (understory management) effects were not significant, and sub-plot (variety) effects were significant ($p < 0.001$).
Means within each year followed by the same letter are not significantly different by Tukey HSD (α=0.05).

Table 3.8. First grade fruits of two grafted pear varieties under four understory management regimes during 2002 and 2003 at El Tecolote, Labor Ovalle, Guatemala.

	Var. Ayres		Var. Bartlett			
	First grade fruits (% of total)		First grade fruits (% of total)		First grade fruits (% of total)	
Understory management	2002	2003	2002	2003	$\bar{x}$ 2002	$\bar{x}$ 2003
Maize	21.8	6.6	40	53.6	30.9 a	30.1 a
Fava	35.6	28.8	48	86.1	41.8 b	57.5 b
Maize x Fava	20	13.3	45.5	48.4	32.7 ab	30.8 a
Control	31	29.6	50.6	68.3	40.8 ab	48.9 ab
$\bar{x}$	27.1 y	19.6 j	46.0 z	64.1k		

In 2002, main plot (understory management) effects were significant ($p < 0.05$), and sub-plot (variety) effects were significant ($p < 0.001$).
In 2003, main plot (understory management) effects were significant ($p < 0.001$), and sub-plot (variety) effects were significant ($p < 0.001$).
Yearly means followed by the same letter are not significantly different by Tukey HSD (α=0.05).

Table 3.9. Fruit soluble solids content of two grafted pear varieties under four understory management regimes during 2002 and 2003 at El Tecolote, Labor Ovalle, Guatemala.

Understory management	Var. Ayres Soluble solids (% brix)		Var. Bartlett Soluble solids (% brix)		Soluble solids (% brix)	
	2002	2003	2002	2003	$\bar{x}$ 2002	$\bar{x}$ 2003
Maize	11.33	11.94	10.46	10.95	10.9	11.4x
Fava	11.13	12.29	11.22	11.94	11.2	12.1xy
Maize x Fava	10.99	11.47	10.84	11.24	10.9	11.4x
Control	11.59	12.89	11.29	11.99	11.4	12.4y
$\bar{x}$	11.26	12.14a	10.95	11.53b		

In 2002, main plot (understory management) effects were not significant, sub-plot (variety) effects were not significant.
In 2003, main plot (understory management) effects were significant ($p < 0.001$), sub-plot (variety) effects were significant ($p < 0.001$).
Yearly means followed by the same letter not significantly different by Tukey (HSD) (α=0.05).

Table 3.10. Maize grain yield planted as two crop assemblages under overstory environments of pear trees and artificial trees, and no overstory (control) during 2002 and 2003 cropping seasons in El Tecolote, Labor Ovalle, Guatemala.

Overstory environment	Maize grain yield (kg ha^{-1}) Sole cropping		Maize + fava intercropping		$\bar{x}$	
	2002	2003	2002	2003	2002	2003
Pear overstory	5526	7085	5400	8227	5463	7656 a
Artificial overstory	5047	10990 x	5815	6952 y	5431	8971 ab
Control	5447	9769	6205	11035	5826	10403 b
$\bar{x}$	5340 a	9282	5807 b	8738		

In 2002, overstory environment effects were not significant, and cropping effects were significant ($p < 0.001$).
In 2003, overstory environment effects ($p < 0.05$), and cropping effects were not significant.
In 2003, an overstory x cropping interaction effect was significant ($p < 0.001$). Analysis at fixed levels of overstory environment revealed that sole cropped maize had higher yields than intercropped under artificial canopies.
Means within a year followed by the same letter are not significantly different by Tukey (HSD) (α=0.05).

Table 3.11. Maize ear number planted as two crop assemblages under overstory environments of pear trees and artificial trees, and no overstory (control) during 2002 and 2003 cropping seasons in El Tecolote, Labor Ovalle, Guatemala.

	Maize ear counts (ears m^{-2})					
	Sole cropping		Maize + fava intercropping		$\bar{x}$	
Overstory environment	2002	2003	2002	2003	2002	2003
Pear overstory	5.6	6	5.4	6.1	5.5	6.1
Artificial overstory	5.3	8.1	5.8	5.1	5.5	6.6
Control	5.8	7.2	6.1	6.9	5.9	7
$\bar{x}$	5.6	7.1	5.7	6		

In both 2002 and 2003, overstory environment effects were not significant, and cropping effects were not significant. Comparisons made only within years.

Table 3.12. Maize grain yields at two planting distances from overstory trees and artificial shade structures during the 2002 and 2003 cropping seasons in El Tecolote, Labor Ovalle, Guatemala.

	Grain yields (kg ha^{-1})											
	Sole cropping				Maize + fava intercropping				Close $\bar{x}$		Far $\bar{x}$	
	Close		Far		Close		Far					
Trt.	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
Pear overstory	4800	6845	5698	8079	4583	6321	5883	7761	4692	6583a	5790	7921 j
Artificial overstory	3898	9054	3913	8623	4485	8294	5786	9941	4191	8674 b	4850	9283 k
$\bar{x}$	4349 y	7950	4806 z	8352	4533 y	7308	5834 z	8852				

In 2002, overstory environment effects were not significant, cropping effects were not significant, distance effects were significant ($p < 0.05$).
In 2003, overstory effects were significant ($p < 0.05$), cropping effects were not significant, distance were not significant.
Means within a year followed by the same letter are not significantly different by Tukey (HSD) (α=0.05).

Table 3.13. Ear counts in maize as an effect of two planting distances from overstory shade caused by live trees, and artificial shade structures during 2002 and 2003 in El Tecolote, Labor Ovalle, Guatemala.

	Maize ear counts (ears $^{-2}$)											
	Sole cropping				Maize + fava intercropping				Close $\bar{x}$		Far $\bar{x}$	
Overstory management	Close		Far		Close		Far					
	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
Pear overstory	7.0j	8	7.6j	7.6	5.6	7	7.2	7.8	6.2 a	7.5 x	7.4 b	7.7x
Artificial overstory	4.8k	8.6	7.2k	8.8	6.6	7.2	7.2	9	5.7 a	7.9 y	7.2 b	8.9 y
$\bar{x}$	5.8	8.3	7.4	8.2	6.1	7.1	7.2	8.4				

In 2002, overstory environment effects were not significant, cropping effects were not significant, and distance effects were significant ($p < 0.05$). Analysis of overstory environment at fixed levels of cropping showed significantly greater ears counts beneath pear as compared to artificial overstories.
In 2003, overstory environment effects were significant ($p < 0.05$), cropping effects were not significant, and distance effects were not significant.
Yearly means followed by the same letter are not significantly different by Tukey (HSD) (α=0.05).

Table 3.14. Fava seed yield planted as two crop assemblages under overstory environments of pear trees and artificial trees, and no overstory (control) during 2002 and 2003 cropping seasons in El Tecolote, Labor Ovalle, Guatemala.

	Fava seed yields (kg ha^{-1})					
	Sole cropping		Maize + fava intercropping		$\bar{x}$	
Overstory management	2002	2003	2002	2003	2002	2003
Pear overstory	1516	1853 j	650	235 z	1083	1044
Artificial overstory	1898	2566 k	538	168 z	1218	1367
Control	1849	2483 k	578	154 z	1213	1318
$\bar{x}$	1754 a	2301 a	589 b	186 b		

In 2002, for overstory environment effects were not significant, and cropping effects were significant ($p < 0.001$).
In 2003, interaction effects were significant ($p < 0.05$), cropping effects were significant ($p < 0.001$), overstory effects were significant at fixed levels of cropping ($p < 0.001$).
Yearly means followed by the same letter are not significantly different by Tukey (HSD) (α=0.05).

Table 3.15. Fava seed yields at two planting distances from overstory trees and artificial shade structures during the 2002 and 2003 cropping seasons in El Tecolote, Labor Ovalle, Guatemala.

	Fava seed yields (kg ha^{-1})									
	Sole cropping				Maize + fava intercropping					
	Close		Far		Close		Far		Close	Far
Overstory management	2002	2003	2002	2003	2002	2003	2002	2003	$\bar{x}$ 2002 2003	$\bar{x}$ 2002 2003
Pear overstory	1768	1497	1792	2240	878	166	429	120	1323 832	1111 1180
Artificial overstory	2045	2119	2216	2169	376	142	508	99	1210 1131	1362 1134
$\bar{x}$	1907y	1808a	2004y	2204a	627z	154b	469z	110b		

In 2002 and 2003, overstory environment effects were not significant, and cropping effects were significant ($p < 0.001$). Yearly means followed by the same letter are not significantly different by Tukey (HSD) (α=0.05).

Table 3.16. Fava pods at two planting distances from overstory trees and artificial shade structures during the 2002 and 2003 cropping seasons in El Tecolote, Labor Ovalle, Guatemala.

	Fava pod counts (pods $^{-2}$)											
	Sole cropping				Maize + fava intercrop							
	Close		Far		Close		Far		Close $\bar{x}$		Far $\bar{x}$	
Overstory management	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003	2002	2003
Pear overstory	66.8	46.2	70	66	31.8	5.8	17	4.8	49.3	26	43.5	35.4
Artificial overstory	75	66.8	90.6	68.2	16.4	5.8	23.6	4	45.7	37.9	57.1	36.6
$\bar{x}$	70.9y	56.5a	80.3y	67.1a	24.1z	5.8b	20.3z	4.4b				

For 2002 and 2003, overstory environment effects were not significant, and cropping effects were significant ($p < 0.001$).
Yearly means followed by the same letter are not significantly different by Tukey (HSD) (α=0.05).

Table 3.17. Canopy PAR reflectivity at 75 DAP during the growing season as a response to four annual cropping patterns and three overstory environments.

	Reflected PAR (% of incident)			
Understory crop	Fruit trees	Artificial shade	No overstory	$\bar{x}$
maize	3.85	3.83	4.13	3.93 ab
fava	4.06	4.27	4.74	4.35 a
maize + fava	3.88	3.65	4.05	3.86 b
clean cultivation	4.37	n/a	n/a	4.38 ab
$\bar{x}$	4.02	3.92	4.3	

For overstory environment effects were not significant, and cropping effects were significant ($p < 0.001$).
Means followed by the same letter are not significantly different by Tukey (HSD), (α=0.05).

Table 3.18. Mean daily interception of PAR for four understory annual cropping alternatives and three overstory environments from 72 to 231 days after planting the crops in El Tecolote, Labor Ovalle, Guatemala.

	Photosynthetic photon flux density (mols m^2 day^{-1})			
Understory crop	Fruit tree	Artificial shade	No overstory	$\bar{x}$
maize	24.05	26.05	25.66	25.25 a
fava	11.73	15.38	12.28	13.19 b
maize + fava	24.58	27.51	26.27	26.12 a
clean cultivation	5.02		**34.91** (1)	5.02 c
$\bar{x}$	17.44	22.99	21.79	

Overstory effects were not significant and cropping effects were significant ($p < 0.001$).
Means followed by the same letter are not significantly different by Tukey HSD (α=0.05).
(1) Mean incident PPFD (mols m^2 day^{-1}).

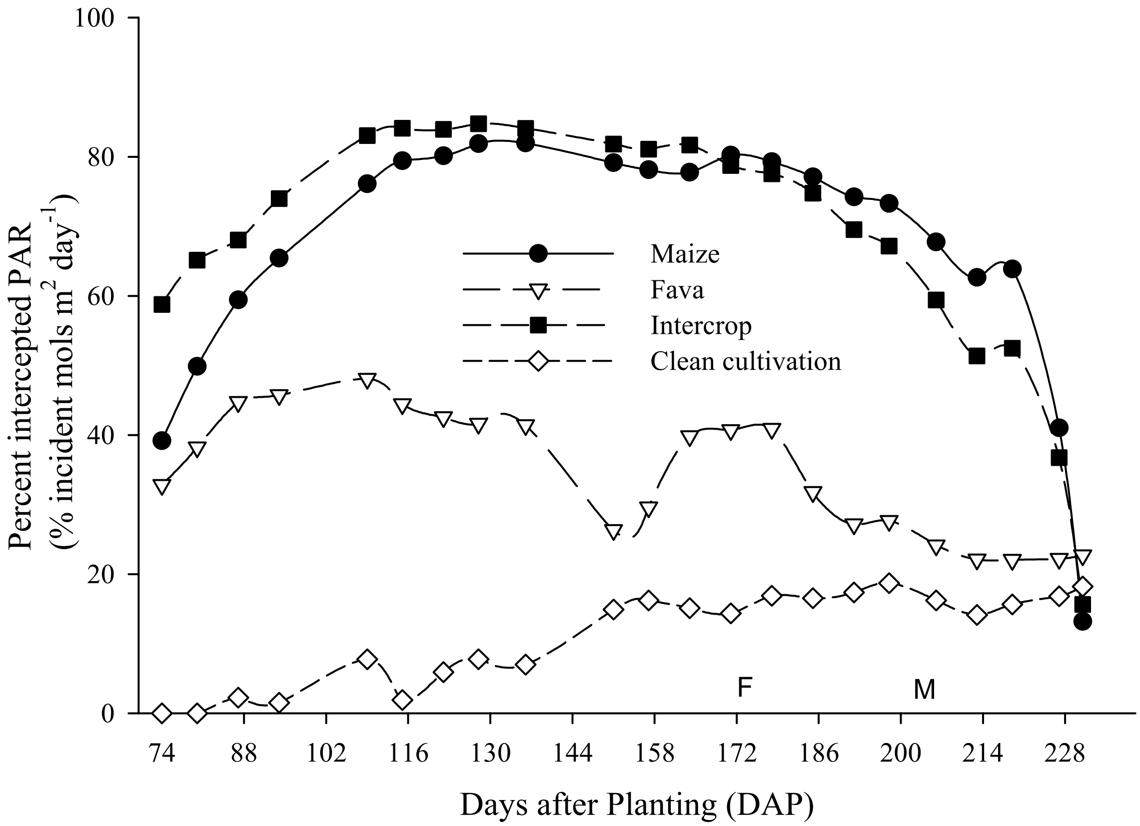


Figure 3.10. Canopy interception of mean weekly PAR for three mixed cropping regimes and a clean cultivated control beneath pear trees. The letters F and M indicate fava and maize harvest dates respectively.

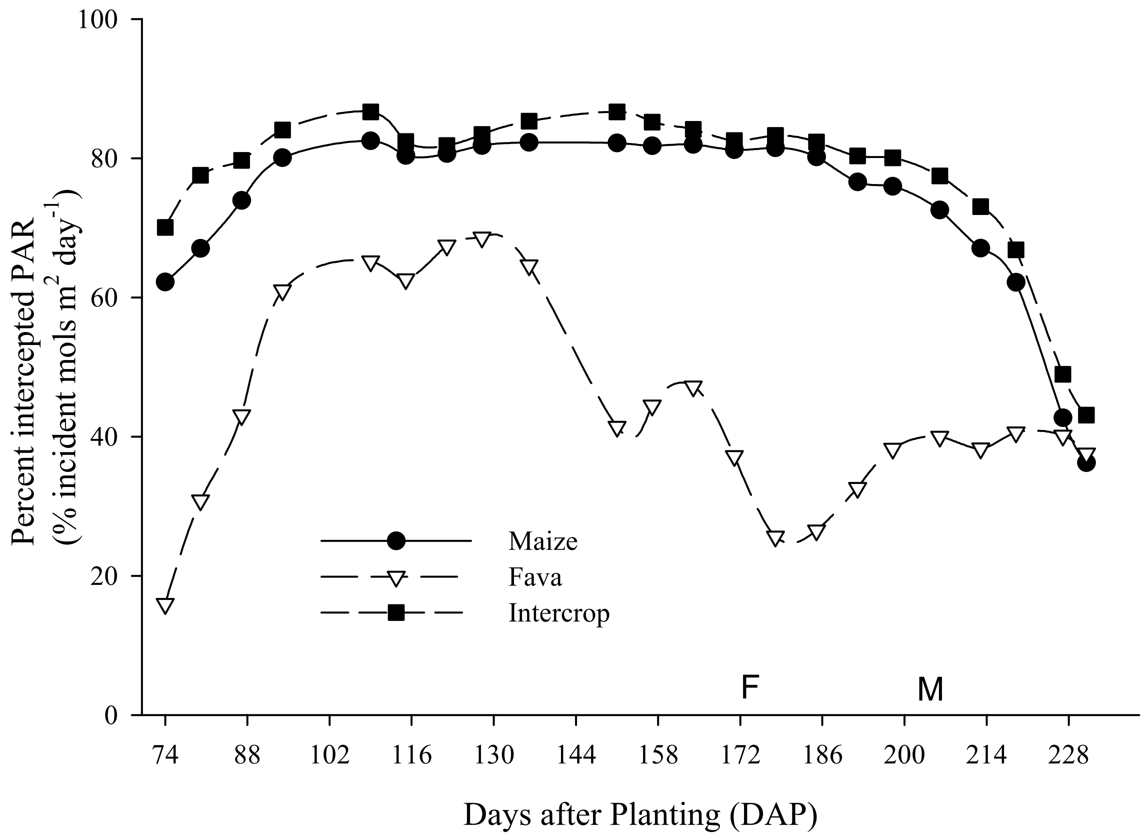


Figure 3.11. Canopy interception of mean weekly PAR for three mixed cropping regimes beneath artificial shade structures. The letters F and M indicate fava and maize harvest dates respectively.

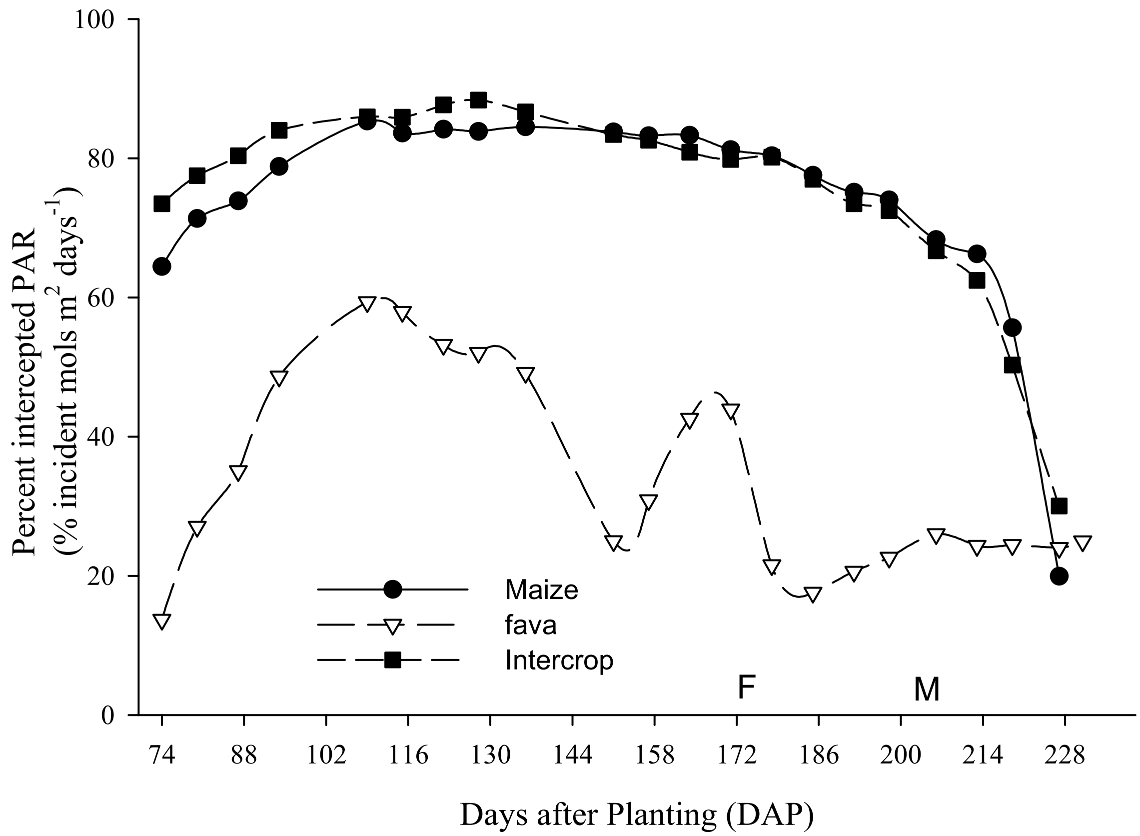


Figure 3.12. Canopy interception of mean weekly PAR for sole and intercropping regimes without shading. The letters F and M indicate fava and maize harvest dates respectively.

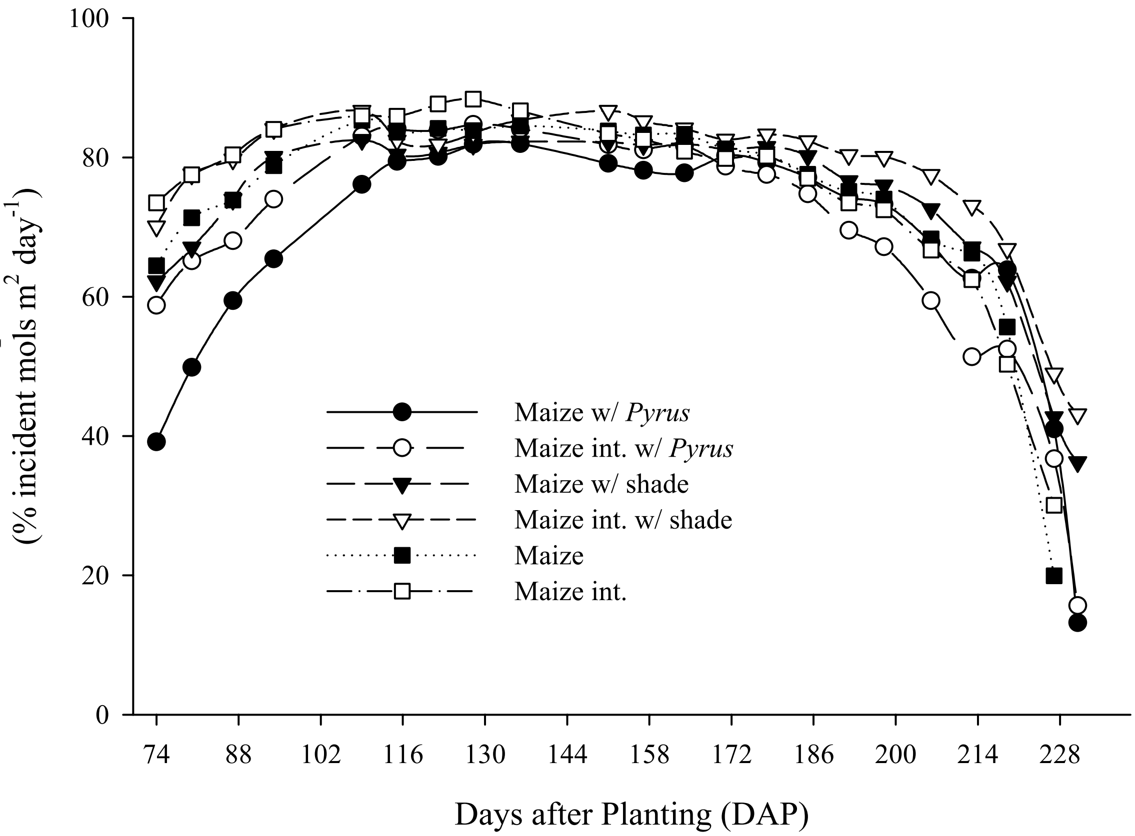


Figure 3.13. Canopy interception of mean weekly PAR for maize mixed cropping, sole cropping, and intercropping regimes beneath pear trees, artificial shade structures, or without shading. Maize was alternately sole cropped or intercropped with fava bean.

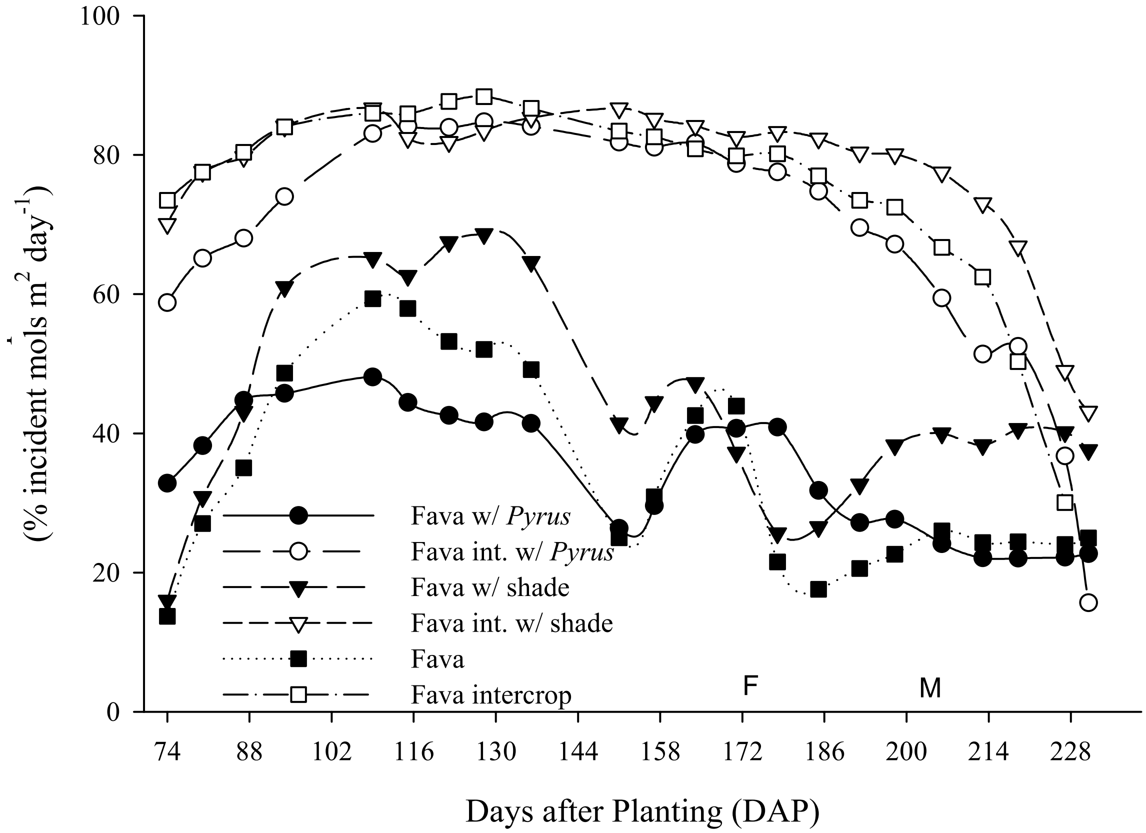


Figure 3.14. Canopy interception of mean weekly PAR for fava mixed cropping, sole cropping, and intercropping regimes beneath pear trees, artificial shade structures, or without shading. Fava was alternately sole cropped or intercropped with maize. Letters F and M indicate fava and maize harvest dates respectively.

Table 3.19. Land equivalency ratio (LER) and area time equivalency ratio (ATER) of mixed cropping, intercropping and sole cropping systems of pear, maize, and fava bean in on-station trials to evaluate agroforestry technologies in northwestern Guatemala during 2002 and 2003.

	LER		ATER	
	2002	2003	2002	2003
Maize + fava intercrop	1.45	1.19	1.37	1.18
Pear + maize mixed crop	2.16	1.59	1.74	1.29
Pear + fava mixed crop	1.87	2	1.41	1.61
Pear + maize + fava mixed crop	2.98	3.03	1.99	1.93

LER calculated with equation 3.2.
ATER based on 162 (2002) or 175 (2003) days for fava, 215 (2002) or 217 (2003) days for maize, and 365 days for pear using equation 3.3.

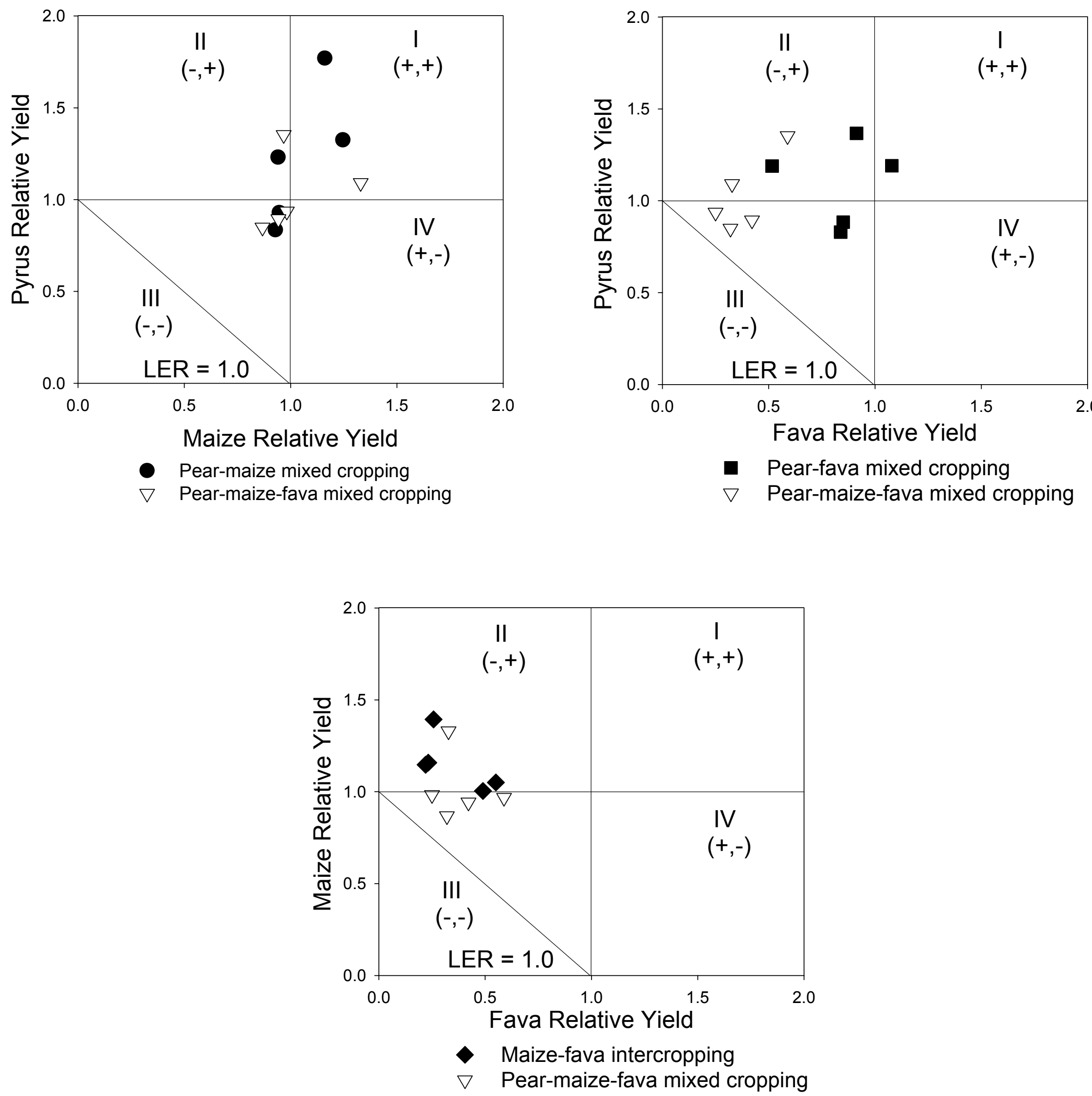


Figure 3.15. Relationships of the relative yields of three components during 2002 under mixed or intercropping patterns at high densities relative to regional practices. The four quadrants (I, II, III, and IV) represent possible interactions; with II and IV representing monopolistic competition by one of the system components. Quadrant I represents synergistic interactions and III indicates inhibitory interactions. The diagonal line (LER = 1.0) represents the limits of productive coexistence in fruit-tree-based agroforestry. Systems that are located to the left of the diagonal line are detrimental, whereas, systems to the right of the diagonal provide an advantage relative to sole cropping of the components.

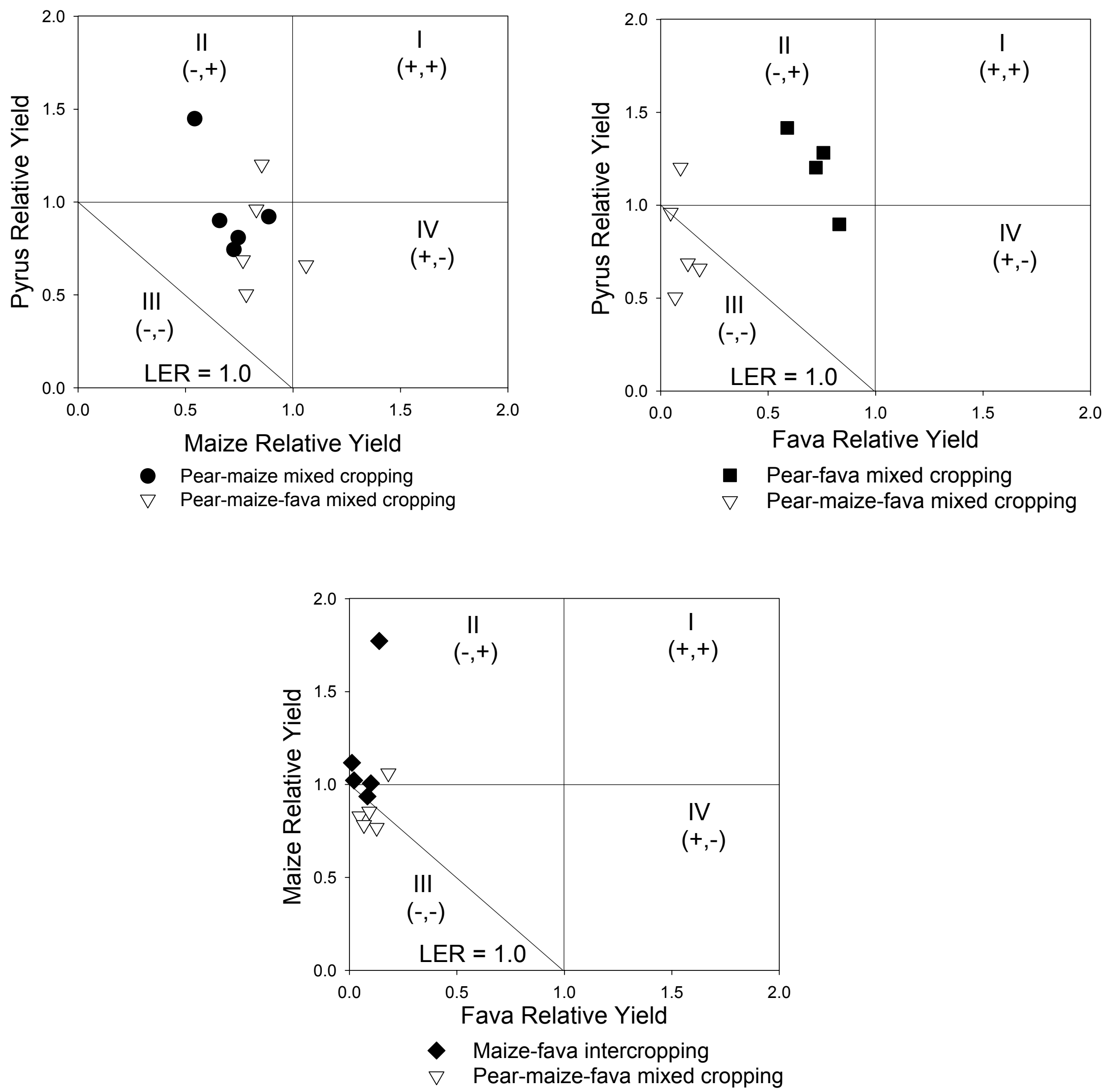


Figure 3.16. Relationships of the relative yields of three components during 2003 under mixed or intercropping patterns at high densities relative to regional practices. The four quadrants (I, II, III, and IV) represent possible interactions; with II and IV representing monopolistic competition by one of the system components. Quadrant I represents synergistic interactions and III indicates inhibitory interactions. The diagonal line (LER = 1.0) represents the limits of productive coexistence in fruit-tree-based agroforestry. Systems that are located to the left of the diagonal line are detrimental, whereas, systems to the right of the diagonal provide an advantage relative to sole cropping of the components.

Table 3.20. Economic outcomes from sole cropping, intercropping, and mixed cropping of maize, fava bean, and pear in 2002. Gross benefits measured in Quetzales (1.00 $US = Q 7.85).

Cropping system	Q kg^{-1}	Yields ($kg\ ha^{-1}$)	Gross benefits of economic yield As Intercrops ($Q\ ha^{-1}$)	As Sole crops ($Q\ ha^{-1}$)
Maize	1.87	5447		10187
Fava	7.70	1849		14233
Pear	11.00	1220		13420
Maize + fava		6205 maize 578.0 fava	16052	12210
Pear + maize		5526 maize 1395 pear	25679	11804
Pear + fava		1516 fava 1280 pear	25756	13827
Pear + maize + fava		5400 maize 650 fava 1198 pear	28283	12613

Economic yields based on cropping of 1.0 ha.
Sole cropping comparisons of intercrop systems based on 0.5 ha of each component and 0.33 ha for mixed cropping.
Fruit values based on 200 trees ha^{-1}.

Table 3.21. Glucose-equivalent yields analysis from sole cropping, intercropping, and mixed cropping of maize, fava bean, and pear in 2002 based on standard yield compositions.

Cropping system	kg glucose kg^{-1} product	Yields ($kg\ ha^{-1}$)	Material and growth cost of economic yield: As intercrops (kg glucose ha^{-1})	Material and growth cost of economic yield: As Sole crops (kg glucose ha^{-1})
Sole maize	1.49	5447		8117
Sole fava	1.69	1849		3124
Sole pear	1.30	1220		1586
Maize + fava intercrop		6205 maize 578 fava	10222	5620
Pear + maize mixed crop		5526 maize 1395 pear	10048	4851
Pear + fava mixed crop		1516 fava 1280 pear	4227	2355
Pear + maize + fava mixed crop		5400 maize 650 fava 1198 pear	10703	4276

Economic yields based on cropping of 1.0 ha.
Sole cropping comparisons of intercrop systems based on 0.5 ha of each component for 2 component systems and 0.33 ha for three component mixed cropping. Fruit tree values based on 200 pear trees ha^{-1}.

CHAPTER 4
SOCIOECONOMIC ROLE OF FRUIT-TREE-BASED AGROFORESTRY ON SMALL FARMS IN THE WESTERN HIGHLANDS OF GUATEMALA

Introduction

In the highlands of western Guatemala, a majority of inhabitants rely, at least partially, on the outputs from their crop fields for subsistence. As producers frankly explain, maize (*Zea mays*) is the preferred crop although they are aware of other, potentially more remunerative crops. There are two reasons for this preference for maize: first, it comprises the dietary basis of survival and second, other sources of cash income that could purchase maize are notoriously risk-laden. In the case of potatoes (*Solanum tuberosum*), potentially the most attractive of alternative crops, the current level of profitability is perhaps because it is planted extensively by only a few farmers and therefore the supply is limited. Large-scale adoption of potato cultivation will alter this situation: profitability will be marginal at best and crops will be unharvestable at worse. This phenomenon is regularly observed with annual variations in crop yields, areas dedicated to potato cultivation, and market prices. In the opinion of small-scale producers, this simple trend in market saturation generally holds for most horticultural crops.

Four principal types of farm production were previously identified within the greater region of the *altiplano*. They consisted of maize (*Zea mays*), potato (*Solanum tuberosum*), wheat (*Triticum aestivum*), and cool season vegetables (Table 4.1). It is noteworthy that the production of a subsistence crop such as maize was preferred by farmers with the smallest areas of land rather than a vegetable crop, such as broccoli (*Brassica oleracea*) or snow peas (*Pisum* spp.) that produces higher returns per area (Immink and Alarcon, 1993). This observation highlights the importance of risk avoidance to farmers of the region. Adopters of vegetable production experienced mixed outcomes. Overall, families with larger areas of farmland had a clear advantage as they could diversify crop production by including crops other than maize (*Zea mays*) which generally resulted in higher incomes. However, even with increased incomes that some situations engendered, food and nutritional security of the families were not improved (Immink and Alarcon, 1991).

Farmer emphasis on a specific main crop does not preclude inclusion of others; rather it was shown that crop preferences were linked with yield levels of each crop in a diversified system (Table 4.2). Thus, the land area available for crop production was expected to determine the choice of principal crop by farmers in the two communities studied in a similar manner. These data may provide a meaningful baseline for making a preliminary assessment of the validity of a farm systems model.

While these previous findings (Immink and Allarcon, 1991, 1993) may suggest some broad trends in the region, many significant changes have taken place in Guatemalan society since those studies were done. The most notable is the end of open civil conflict in 1996. In addition, the previous findings have not considered the role of productive perennials on the farm and lack sufficient detail to characterize potential relationships with land availability, family size, and resource allocation.

While the term "subsistence farmers" is often used, it is important to recognize that Guatemalan farm families do not survive outside of a cash-based economy, and that cash-earning endeavors, frequently based off-farm, are critical to the survival of indigenous producers (Smith, 1989). A broad range of activities is pursued to provide needed cash; consequently, like in many other highland areas, the time available to produce subsistence crops is often limited (Mahat, 1987; Mulk et al., 1992; Storck et al., 1991).

Agricultural land is marginal in the Guatemalan highlands, and climatic variability increases the risk of low yields (Redclift, 1981). Land holdings in productive areas are frequently small and fragmented (Tewolde, 1986) and a substantial portion of agricultural resources is dedicated to crops for domestic consumption. In this region, fruit trees are popular among farmers and often numerous on individual farms. However, market, infrastructure, and product quality limitations constrain commercial agricultural activity just as is the case in the highlands of many other areas (Tsongo, 1993). Delobel et al. (1991) provide a portrait of a remarkably similar highland community in Upper Mgeta, Tanzania. In addition to the limitations imposed by poor infrastructure, both regions have the distinction of having temperate temperatures in tropical to sub-tropical latitudes and the accompanying advantage of being able to supply deciduous fruit to their neighbors. Because of its similarity to communities in other marginal areas, the Guatemalan highlands provide insight into potential issues facing resource-limited producers in rural mountain farms worldwide; therefore, a further examination of adoption practices in the region is warranted.

In agricultural research, it is not difficult to identify technologies that can address perceived limitations in system productivity. Frequently, however, these alternatives have not been as widely adopted as anticipated due to a variety of factors (Current et al., 1995; Floyd et al., 2003; Lado, 1998; Morales and Perfecto, 2000). Adoption failure can often be traced to social or economic factors that influence the attractiveness of the new recommendations to potential adopters (Byerlee et al., 1981) rather than intrinsic failures of the technology to perform as anticipated. For these reasons, it is critical to better understand crop selection, resource allocation, and management by low-input small-holder farmers. Modeling farm systems with sensitivity to both the social and economic constraints of smallholders while incorporating realistic yield responses will contribute toward making better recommendations designed to improve productivity and reduce farmer risk in highland subsistence agriculture.

Linear programing (LP modeling) has been successfully used to evaluate the adoption potential of agroforestry technologies among smallholder farmers. Both socioeconomic characteristics of potential adopters (Mudhara et al., 2003) and the influence of broader scale economic policies (Kaya et al., 2000) have been examined. Linear programing methods have frequently been used to optimize the allocation of limited resources between several competing technologies and crops. This has been effective for small-farm planning (Garcia de Ceca et al., 1991; Kapp, 1998), for broader watershed to landscape scales (Knapp and Sadorsky, 2000; Nasendi et al., 1996; Njiti, 1988; Wirodidjojo, 1989), and to identify management strategies worthy of additional study (Wojtkowski, 1990). Linear programming is particularly useful in small-farm or resource-limited situations because it implies that particular resources will constrain farm productivity and that the further expansion of production is dependent on the optimal allocation of the resources that are available (Dorfman, 1953). The results of farming systems simulations are meant to be informative and, in concert with feedback from potential adopters, help to identify those situations that merit more detailed experimentation or to detect flaws or unforeseen constraints in proposed technologies.

Resources for fruit research and extension to smallholders in Guatemala are exceedingly scarce and generally limited to externally funded development projects. While there is a long history of varietal introductions and selections for fruit varieties that perform well in the unique environment of the subtropical highlands, the findings rarely have been disseminated to producers who will benefit from them. Limited development resources may be more efficiently allocated when the relative merits of competing strategies for enhancing productivity are better understood. Farm activities simulation permits the examination and evaluation of agroforestry technologies ex-situ and pre-transfer evaluation and adaptive modification that may increase adoption or help prioritize groups and regions where adoption is most likely.

Objective and Hypothesis

The objective of this investigation was to assess the potential for adoption of fruit-tree-based agroforestry by small-holder farmers in the northwest highlands of Guatemala. I hypothesized that fruit-tree-based agroforestry would be of interest to smallholder farmers, but differences in adoption rates could be linked with individual socioeconomic differences.

Methods and Materials

Site Description

This study was conducted in two small communities in the departments of Totonicapan and Quetzaltenango, in the western highlands region of Guatemala. The contrasting sites were intended to provide a representative case of the problems of rural mountain farmers world-wide. The western highlands overall are characterized by a lack of infrastructure, poor or non-existent education and health facilities, and high population density. Population density, ranging from over 300 to nearly 900 persons km^{-2}, is of great importance when the actual area of land suitable for annual agriculture (approximately 20% in Chuculjulup: Gramajo, 1997) is considered. The overwhelming majority of the population is comprised of indigenous Mayans who have historically been marginalized in educational and development initiatives. The extremely high levels of rural poverty, malnutrition, and illiteracy are diluted in national statistics by the relatively good conditions experienced by Ladino and Latino families in urban centers and by the historical failure of government censuses to adequately survey rural areas where most indigenous people live (Adams, 1998; Early, 1982). Many families are not food-secure throughout the year and they frequently migrate seasonally to find work. Market access for crops is limited by poor infrastructure and the majority of land held by smallholders is allocated to crops that are consumed on farm.

The landscape is characterized by rugged mountainous topography, eroded and steeply sloping agricultural lands, extremely fragmented fields, and limited access to markets for agricultural products. The land is primarily in forest or agricultural production, with small farms (< 1.0 ha) occupying the majority of farmlands. Elevations range from 900 to 4000 meters above sea level. Generally the soils on low sloping lands are deep and well drained; however, they are considered to be of low productivity due primarily to the long history of continuous cultivation (Gramajo, 1997). Irrigation infrastructure is limited, and most agriculture in the region is rain fed.

The two communities, Cabrican and Chuculjulup, where family and farm characteristics were investigated, were selected based on the historical presence of fruit-tree-based cropping systems. On the surface, Cabrican and Chuculjulup primarily differed in their demography and access to infrastructure support (Table 4.3). Additional important differences were later identified and are discussed below.

Cabrican is the most northerly municipality in the department of Quetzaltenango. Roads into the municipality are steep and unpaved, making the roads quite difficult-to-pass during the rainy season. Public transport is both limited and slow as well as monopolized by a small group of *Ladinos*, people of mixed heritage who are oriented toward the more urban Hispanic culture and who, as a group are generally more economically advantaged.

Chuculjulup is an *aldea*, or rural community within the municipality and department of Totonicapan. It is located approximately 5 km from the departmental capital of Totonicapan. Services and projects in the community are notable and extensive. Piped running water and electricity are ubiquitous and telephones are common. The road to the main highway is paved and the trip to the departmental capital is 15 to 20 minutes by private vehicle. The differences in wealth status between the two communities are broadly evident by the larger number of cinder block houses, steel laminate roofs, and private vehicles in Chuculjulup as compared to Cabrican.

Both communities are located at approximately 2600 m altitude above sea level. Observations of historical weather do not exist and detailed descriptions of the differences between the two communities or Quetzaltenango (2300 m), where the closest meteorological station is located, could not be made. Micro-meteorological stations were established in both communities to provide weather data that could help estimate potential agricultural productivity.

The majority of land in the two communities is dedicated to the cultivation of maize, whether as a sole crop or as intercrops with other annuals or perennials. Land holdings are small and frequently fragmented with small plots measured in units of several hundred square meters rather than hectares. Cultivation of these plots is entirely by manual labor, often with parties of five to eight family members and hired laborers working to complete a specific task in a short time. Soil fertility is augmented by the application of locally collected forest leaf litter, bedding and dung from livestock, or through the application of chemical fertilizers (15-15-15, 20-20-0,or 45-0-0). The Guatemalan Ministry of Agriculture (MAGA) provides a limited quantity of subsidized fertilizer to farmers. The fertilizer must be ordered through farmer cooperative groups and paid for in advance and then collected from a central distribution point. In practice, many families are unable to avail themselves of this source due to logistical impediments.

Farm families are able to purchase and market their farm products at least weekly. Most farm families appear to operate on a cash basis and neither community had formalized banking or credit institutions. Like rural families in many parts of the developing world, family wealth is often maintained in livestock, food surplus on the farm, and through informal credit between neighbors.

Fruit-tree-based agroforestry in Chuculjulup and Cabrican was extensive in comparison to many surrounding areas, yet obvious differences existed between farms over small spatial scales. It was necessary to characterize small farms in order to identify the crops being grown, the management regimes employed, and to begin to develop reliable estimates of average yields for principal crops.

Data Collection

Sondeos

Ethnographic information on farm families in the two communities was gathered using national and municipal data, published technical reports, field observations, semi-structured interviews, and an informal survey. Semi-structured interviews or *sondeos* were conducted with key informants from 15 randomly selected households per community (Hildebrand, 1986). Households were partially self-selected because households with members who were uninterested or unwilling to talk were replaced with others. At least three separate visits were made to each household during the *sondeo* process. During the *sondeos*, family size and gender distribution, land holdings, crop practices and animal husbandry were characterized. Additionally the presence and variety of fruit trees were noted. One of the visits generally included an examination of the families' closest field and/or orchard and a discussion of the performance and management of the crops.

Interviews were conducted as much as possible with a male-female interview team. On those occasions when a mixed gender team was unavailable, the principal investigator was accompanied by a member of the community. Between interviews, all findings were discussed by the interviewing pair and the details noted to enhance recall on the *sondeo* data sheet (appendix A). Data collected during the *sondeos* were used to parameterize and guide structural formation of a farming simulation model.

<u>Market surveys</u>

Farm product prices were collected from farmers and market surveys in both communities. To assess differences in local markets and quantify potential seasonal fluctuations in product value, the two markets most frequented by the communities were visited monthly to collect prices. For Chuculjulup, this was the Totonicapan municipal market and the Cabrican municipal market was visited for Cabrican. Due to differences in product quality and vendor behavior, prices were assessed based on produce which appeared representative of what was being offered, and thus the poorest and best quality examples were excluded. Additionally, for each product sampled, three separate vendors were queried and the highest price rejected. It remained evident that patronage, familial ties, and bargaining skills often produce substantial variations in market values. These prices were averaged quarterly to characterize value in each community.

<u>Validation survey</u>

The initial *sondeos* were conducted during the late autumn of 2001 and the spring of 2002, and participants in the on-farm yield assessments were selected from among those interviewed. This was primarily due to the heightened rapport that was established through multiple visits by the *sondeo* team. It became evident during 2002 that several areas of interest, including household expenditures and management of fruit crops, were inadequately characterized and that further investigation was warranted. Using the previous findings, a more structured but still flexible survey instrument was created (Appendix B). In the autumn of 2002, a broader segment of the population in each community was visited in a shorter context and interviewed about their household practices. Similar information was collected as during the *sondeos*. In the survey phase, two-person teams consisting of two local community members or one community member and the principal investigator visited the sites.

On-farm yields assessment

Crop yields as reported by families and in informal discussions within the community were highly variable. Farmers readily admitted to not knowing yield information except in the broadest sense. This was understandable in the context that, under common handling practices, dry grain was only shelled incrementally prior to being used. Farmers were readily able to provide information on the number of storage nets or *redes* (net bags containing between 35 and 55 kg) full of unhusked maize ears that were produced in a specific field. Subsequent evaluation of potential relations between full nets of ears and grain yield suggested that biologically relevant information would not be obtained and the approach was abandoned. Primary problems were high variation in the mass of full nets and high variation in fresh ear mass.

Additionally, farmer perceptions of their crop performance appeared to contain more holistic elements such as plant size and stand establishment characteristics that were not necessarily related to economic productivity. To gain greater insight, a series of test plots was established for the harvest of 2001 from a geographically diverse sample of cooperating farmers to evaluate their local varieties. Grain yields and dry mass accumulation were collected from 36.0 m^2 plots placed at random within the existing fields. Grain yields are reported as sun-dried grain mass after 15 days of drying.

During 2002, farmers were offered the unreleased San Marceño Mejorado, an improved open-pollinated population of yellow maize, and Blanquita, an improved population of white seeded fava bean (*Vicia faba*) for self-evaluation. One-half kg of maize and 2.0 kg of favas were supplied along with 15 kg of 15-15-15 fertilizer. Farmers were requested to plant the seeds in a single plot at least five rows wide. They were given the option to plant the favas as sole crops or intercrops. Further instructions permitted the farmers to supply whatever form of management they judged appropriate. Selected plots were marked to facilitate end of season sub-sampling on eleven farms in 2002 and thirteen in 2003. At harvest time, as determined by plot-owners, a 2.4 m^2 sub-plot was established at a random location and harvested. Ears were husked and sun-dried for 15 days prior to shelling after which measurements of grain and cob masses were made. Grain yields in 2002 were normalized to 12 % moisture content. It proved infeasible to measure fava yields in this manner and no data on fava yields could be collected. Observational evidence suggests that farmers did not, in any case, realize substantial harvests of fava bean in either year.

Weather records

Micro-meteorological stations were established in the two communities in order to collect climatic data and to assess the climatic variation between them and the nearest permanent weather station in Quetzaltenango operated by the Institute of Seismology, Volcanology, Meteorology, and Hydrology (INSIVUMEH). The community stations recorded temperature, precipitation, and solar radiation on a continuous basis. Data were recorded using a Campbell Scientific CR10 micrologger and stored on SM716 storage modules, and downloaded at regular intervals. Temperature was monitored at 10 second intervals using copper-constantan (type T) thermocouples mounted in radiation shields 2.0 m above the ground, and 15-minute means were recorded along with daily maximum and minimum. Precipitation was recorded using a tipping bucket style gauge with a minimum recording level of 0.254 mm; the total amount was calculated based on the number of tip events and the multiplier. Daily values for total precipitation were recorded at midnight.

Solar radiation was monitored with a Li-Cor Pyranometer (LI-200SA) for total shortwave radiation at 10 second intervals and 15 minute means were recorded. Daily flux values were calculated from the 15 minute means. A quantum sensor was not mounted permanently in either community, so a linear regression model was used to predict PAR from the radiant flux. Analyzed results and comparisons of microclimatic parameters are found in appendix C.

Model Formulation

A farm simulation-model for the general structure of smallholder agriculture in the two communities was developed using linear programming (LP) (Dorfman, 1953). While not all farm activities are well modeled by a linear function between inputs and outputs, the method is well established and provides a good first approximation of a complex process using mainly qualitative data. The model was developed to understand the role that family characteristics, land holdings, and market opportunities play in the establishment and maintenance of fruit-tree-based agroforestry systems in these marginal areas.

The model was structured to be temporally discrete with three-month periods beginning in February through April and terminating November through January which more accurately captures the passage of seasonally explicit labor requirements and harvests in the study area than a conventional January to December year. Initial model formulations operated on a monthly basis; however, they were not sufficiently flexible to allow for variations in the timing of agricultural activities. Labor and resources for individual activities were explicit for these quarterly periods, but family consumption of agricultural products and cash expenditures were calculated on an annual basis. Livestock feeding for cattle was disaggregated for dry (Feb. through Apr.) and wet (May through Jan.) feeding seasons to reflect the need to collect fodder to carry animals through the dry season. Poultry production was calculated on a six-month basis allowing two generations of poultry per simulation year.

Farm activities as modeled

Owing to extensive linkages between crop and animal husbandry activities and the importance of livestock on Guatemalan farms, both annual crops and livestock were characterized and simulated. Poultry, swine, sheep, and dairy cattle were included with both their consumptive and reproductive characteristics. Animals, their offspring, and their additional products (wool, eggs, and milk) could be bought, sold, or consumed on an annual basis as a function of the number of individual animals present. Animals required fodder or feed, that could be obtained through grazing or cut-and-carry operations, and concentrates or maize. Labor for animal husbandry was provided from female and adolescent labor with the exception of dry season (first q) fodder which had to be supplied by male labor. Linkages to cropping were based on the consumption of crop stover and maize and through the production of organic material (*estericol*) used for many cropping combinations. Organic matter for cropping could also be supplied through the allocation of male labor to collecting and applying litter, mainly from public lands.

Five variations of maize intercropping with climbing beans (*Phaseolus vulgaris*), fava (*Vicia faba*), and squash (*Cucurbita pepo*), monocropped fava bean, potatoes, wheat (*Triticum aestivum*), and oat (*Avena sativa*) were included as crop activity alternatives. For each activity, quarterly labor requirements were defined. Crop production activities required seed, fertilizers, organic matter, and chemical herbicides and pesticides in varying quantities. Crops produced yields of grains, pulses, or tubers and fodder based on the land area that was allocated to the activity. Seed for planting could be purchased or saved from the prior year's production. Fertilizers and chemical inputs were purchased with cash. Organic matter accumulated in livestock operations, or was collected from off-farm.

Crop production could be consumed on-farm by family members or livestock or sold. Modeled crop yields for the two communities were developed from on-farm measurements of maize yields during 2001 (*criollos*) and 2002 (selected population) and from yield expectations stated by farmers for potatoes, beans, favas, wheat and oats (Table 4.4). Because intercropping patterns and yields are extremely variable as an effect of differences in crop percentages, intercropping effects were patterned after the response seen between the selected maize population and fava bean during on-station trials.

Family composition was used to calculate food requirements on an annual basis. Based on the individual energy contents of the various food items, daily consumption needs for male and female adults, adolescents, and children were calculated in terms of maize, beans, potatoes, fruit bread, eggs, meat, and chicken. Annual family consumption could be satisfied through market purchases, the consumption of farm production (Table 4.5), or a combination of the two. Additionally, a linear regression model for each community (Equations 4.1 and 4.2),where E is estimated weekly expenditures (in Quetzales, 1 \$US = 7.85 Q) and F_s is family size, was used to estimate additional market cash expenses (sugar, salt, vegetables, oil) per family member which were deducted on an annual basis from family cash holdings. Finally, a cash expenditure requirement was stipulated to pay the costs of clothing, utilities, transportation, and miscellaneous expenses.

$$E = 77.98 + 5.0 \cdot F_S \quad \text{Eq. 4.1}$$

$$E = 76.89 + 8.1 \cdot F_S \quad \text{Eq. 4.2}$$

Total labor availability was calculated based on family composition. Adult males were considered to have 365 work days available or 100% of their time. While this seems excessive, it is commonly understood that each day in Guatemala contains roughly 1.5 labor days (12 hours). In practice, people may work on jobs off-farm during one labor day for wages and then one-half day on their own farm within a 24-hour period. However, this amount of labor was not included in the model structure of the year to allow for non-modeled time allocation such as being ill. Females were able to supply 50 % of male labor equivalents owing to limitations on their time for the other activities they are responsible for within the farm household which were not modeled. Male and female adolescents were able to contribute 20 % of male labor equivalents owing to their reduced capacity for work and that they should be in school during a significant fraction of time. Children were able to contribute 5 % of male labor equivalents, mainly to graze and feed animals. Child, adolescent, and female labor was summed to calculate labor available for female labor activities.

Necessary inputs, and likely yields for sole cropping, intercropping, and fruit-tree-based agroforestry were characterized for the identified crops and crop combinations prevalent in the communities. To account for potentially important interactions with cropping systems, the model also included simplified activities related to livestock husbandry, product marketing and consumption activities, and opportunities for off-farm or non-agrarian livelihood strategies. Model structuring is in essence a hypothesis that the activities are correctly characterized and cross-linked to accurately portray the principal options available to the farmers.

Objective function

The desire to achieve multiple goals was hypothesized for farm families and were incorporated to drive activity selection in the simulations. Some family goals were incorporated implicitly within the model structure. Model constraints stipulated that families were required to consume nutritionally adequate diets. Adequate cash expenditure to meet common annual expenses such as electricity and clothing was also incorporated as a constraint. The maximization of total cash available for discretionary spending at the end of the twelfth year, after family consumption has been met through production and purchases, was selected as the family objective for the simulations in this study. The sale of farm products and non-agricultural labor were the principal alternatives to meet this goal. The inherent difficulties in correctly incorporating non-economic drivers such as aesthetics, religious beliefs, social pressures, or moral values may limit the results of the simulation as family goals diverge from economic optimization.

Model variables and constraints

Land area, available cash, and labor availability (both family and hired) are the principal constraints of this model. Additional constraints include limits on starvation and availability of non-agricultural employment. The extent to which each of the modeled activities is undertaken represents model variables in the classic sense. The list of variables that may be included in the initial formulation of the model will be the choice and level of crop production, the number and type of livestock cared for, the amount of hired labor, and magnitude of off-farm labor. Off-farm labor activities were disaggregated by gender to represent the different activities and pay scales, but earnings were standardized within gender at 250 Q $week^{-1}$ for males and 125 Q $week^{-1}$ for females (1.00 US$=7.85 Q). The use of family labor on-farm was partially disaggregated for gender to signify that female labor is generally not available for land preparation, while females can and often may participate in planting, weeding, and harvest activities. Both women and children were considered to contribute labor for animal husbandry.

Simulations

Initially, a systematic exploration of the model was made and feasible combinations of labor availability, farm size, family composition, food security, and household expenses were examined. For this process, mean values for production in the two communities were used as model parameters. Two alternate scenarios were then examined using production values specific to the two communities as representative examples. The model was parameterized for each community and a deeper examination of several principal variables was made, with each evaluated while other variables were held constant. Labor availability, calculated as a function of family size and distribution, and agricultural land holdings, were evaluated by multiple simulations of typical family farms in the two villages in order to assess their impact on optimal numbers of fruit trees. It was not possible to hold the constraint on food security levels constant across all combinations of family- and land-holding- sizes. Finally, the model was parameterized to represent average families in each community, and the effects of tree competitiveness, fruit yields, and farm gate prices for fruit were examined in both scenarios.

Results

Farm and Farming Systems Characterization

Family size

Family size varied significantly between the two communities (Table 4.6) regardless of the data source. Families who participated in the semi-structured interviews had 2.2 more individuals (t-test with unequal variances, $p < 0.05$) living in the household in Cabrican than families in Chuculjulup. In the larger sample, families surveyed in Cabrican had on average 0.9 individuals (t-test with unequal variances, $p < 0.05$) more than those in Chuculjulup.

Consumption practices

In order to better understand what is needed by small holder families to survive, the consumption habits of the families were investigated during the household surveys during 2002. Total market expenses, including what was spent locally during the week

(Table 4.6) did not differ significantly between the communities. Regression equations were developed to predict market expenditures (Q) in each community based on family size. R^2 values for the regression equations indicate that their predictive power was poor in both communities (Eq 4.1 for Cabrican, $R^2 = 0.12$ and Eq 4.2 for Chuculjulup, $R^2 = 0.13$). Further breakdown of purchases into major food categories shows several differences between the communities (Figure 4.1) in expenditure allocation.

Surveyed families reported that weekly expenditures on vegetables were significantly higher (t-test with unequal variances, $p < 0.05$) in Chuculjulup (Q 35), than in Cabrican (Q 24). Purchases of whole grains and pulses (excluding maize) were significantly greater in Chuculjulup (Q 26) than Cabrican (Q 9) as well. Weekly purchases of meats were higher in Cabrican (Q 28) than in Chuculjulup (Q 26). Miscellaneous purchases which would include spices, oils, sugars etc. were also greater in Cabrican (Q 33) than in Chuculjulup (Q 17). No significant differences were detected in expenditures on breads.

Consumption of maize as tortillas or *tamalito*s is the dominant source of energy for inhabitants of both communities and previous surveys have indicated that it may provide on average 72% of total caloric intake (INCAP, 1971). Maize consumption per family was higher in Cabrican than in Chuculjulup (Table 4.5). Even considering that some families reported purchasing maize year around, maize shortfalls most commonly occurred from June to October. In Chuculjulup, 48 % of surveyed families reported purchasing maize during the year. In comparison, only 28 % of surveyed families in Cabrican reported maize purchases. The estimated average amount of maize purchased during the year was significantly greater (t-test with unequal variances, $p < 0.05$) in

Chuculjulup (313 kg) than in Cabrican (232 kg). Regression equations were developed to predict daily household maize consumption (kg) where S_f is family size. Model fit for Cabrican was $R^2 = 0.32$, (Eq. 4.3). In Chuculjulup, model fit was slightly better, $R^2 = 0.42$, (Eq. 4.4).

$$maize = 0.32 + 0.27 \cdot S_f \qquad \text{Eq. 4.3}$$

$$maize = 0.53 + 0.36 \cdot S_f \qquad \text{Eq. 4.4}$$

Wood is used for all cooking and whatever heating that is done during the winter; for heating, wood is burnt in ceramic or adobe stoves. Fuelwood consumption was reported as an average number of *tareas* consumed per month. The *tarea* is derived from *cargas* which are based on the amount of firewood an adult male can cut and carry out of the forest in a day, with 8 *cargas* per *tarea*. While highly variable, the *tarea* contains approximately 0.5 m^3 of wood. In Cabrican, families reported using 1.2 *tareas* per month with a value of Q 140. Among these families, 46.9 % stated that they purchased some quantity of firewood regularly. In Chuculjulup, 83.7 % of families needed to purchase firewood on a monthly basis. Purchase costs were similar in both communities, with a *tarea* having a value between Q 110 and Q 120. Respondents from Chuculjulup reported using an average of 0.98 *tareas* per month.

Market costs

Costs for a variety of products available at the weekly open-air markets in or near each community suggest that prices for agricultural products that can be produced locally do not differ significantly throughout the year (Table 4.7). For fava prices were significantly lower ($p < 0.05$) in Cabrican than in Totonicapan. Prices of all other surveyed products were not significantly different in the two markets.

Farm holdings

Farmers' stated land holdings per household were significantly higher in Cabrican than in Chuculjulup for both agricultural and non-agricultural land (Table 4.6). Analysis of the distribution of farm size shows that most families in Chuculjulup are at the lower end of the range of holdings for agricultural land (Figure 4.2). A small sample of families from both communities stated that they did not own agricultural lands. Non-agricultural land holdings were higher in Cabrican as well.

Land allocation to cropping systems

Farmers in the two communities used their agricultural lands in different ways. During the *sondeos,* twelve major cropping systems were observed and characterized within the two communities (Table 4.8). Of the twelve systems, five were maize-based variants, differing primarily in the associated crops; these were: 1) maize interplanted with one of several varieties of climbing bean (*Phaseolus coccineus* or *P. vulgaris*); 2) maize interplanted with climbing bean, fava, and squash (*Cucurbita pepo* and *C. ficifolia)*; 3) maize with climbing bean and fava; 4) maize with fava bean; 5) sole cropped maize. Within the five variants, there was substantial variation in cultivars. Cropping system six consisted of sole cropped fava. System seven, sole cropped climbing bean was observed one time in Cabrican on wooden supports, and was not investigated further. The cultivation of sole cropped potato comprised system eight. At least three varieties of potato were observed in the two communities. The cultivation of wheat and oats were characterized as systems nine and ten. No attempt was made to differentiate the cultivation of barley in this study from that of wheat. System eleven was defined to encompass any cropping system devoted to vegetable crops. The final system, twelve, was the cultivation of fruit trees in pure stands. Fruit trees as a mixed cropping component were the norm where present and fruit management practices were evaluated separately, however specific mixed cropping systems were not defined as fruit trees could be found accompanying any of the prior eleven systems and would have produced unnecessarily repetitive explanations. Detailed descriptions of the crop activities that were observed and recorded during the *sondeos* are found in appendix D.

On-farm yields assessment

Assessment of on-farm maize yields in the two communities studied shows higher mean yields in Chuculjulup than in Cabrican for local varieties during 2001 (Table 4.9). These higher yields were due to higher yields per stem and greater total ear mass harvested in Chuculjulup. While low by current standards, there was no difference in harvest indices between the two communities.

During 2002, an open pollinated maize population was distributed to selected farmers for self-assessment. Yields were not significantly different between the two communities when this variety was assessed. The only significant difference was that shelling percentages were higher in Chuculjulup for the improved variety. Planting densities were not significantly different between the communities or between years.

When comparing the performance of bulked local varieties in 2001 with the improved variety during 2002, planting densities were similar. The improved variety produced higher grain yields. The improved variety had higher per stalk yields and a higher shelling fraction in 2002 than the bulked local varieties in 2001 (Table 4.9).

Fruit tree practices

Due to the importance of fruit culture within both communities and its prevalence within all observed agricultural systems, management practices and end uses for fruit trees were evaluated separately from annual crop although they were frequently in mixed plantings. The percentage of families with fruit trees was higher in Chuculjulup than Cabrican (Table 4.10). From within the surveyed families who had at least one productive fruit tree, the percentage who had sold fruit the prior year was similar in both communities. In Cabrican, 25.1 % reported having sold their fruit to middlemen and 7.1 % to end users, while 67.6 % did not specify. In Chuculjulup, 58.6 % had sold to middlemen and 19.0 % to final consumers. Additionally, 4.3 % reported selling to both, while 18.1 % did not specify. Families who had fruit trees estimated having significantly more trees per family in Cabrican (23.2 trees household^{-1}) than in Chuculjulup (13.3 trees household^{-1}) (t-test with unequal variances, $p < 0.05$). Based on their estimates, apple (*Malus* spp.) was the most common, followed by peach (*Prunus* spp.) with pear (*Pyrus* spp.) a distant third (Table 4.10).

Those families who indicated that fruit trees were present in their fields characterized the management practices that they had used (Table 4.11). Farmers engaged in relatively low levels of the common management practices that might be undertaken such as pruning, application of calcium during the dry season, and the use of organic matter around the tree base as fertilizer and soil conditioner. These activities were more commonly stated as part of farmer practices in Cabrican than in Chuculjulup. The remaining management activities were realized at very low levels and differences in the fraction of farmers engaged in them were not significantly different between the communities. As is evident from Table 4.11, no single management activity was undertaken by more than half the families with fruit trees.

Animal husbandry

Farmers in both communities kept a variety of livestock within and around the homestead. Overall, livestock was a greater factor in the livelihood strategies of Cabrican families than those of Chuculjulup (Table 4.12). For all species studied, a larger fraction of surveyed families in Cabrican reported having at least one animal than in Chuculjulup. The mean number of cows (*Bos taurus*) kept by families with cows was significantly higher in Cabrican. More pigs (*Sus domesticus*), chickens (*Gallus domesticus*), and turkeys (*Meleagris gallopavo*) were raised per family tending these species in Cabrican (Table 4.12). There were no differences in the number of sheep (*Ovis aries*), ducks (*Anas domesticus*), or horses (*Equus caballus*) kept where these species were present.

Labor requirements for both genders for animal husbandry were identified through *sondeo* discussions with key informants who stated that women and children did most of the labor. Gathering dry season fodder was specifically identified as a male task (Table 4.13).

Non-agricultural livelihoods

The main economic character of the non-agricultural activities on a per day basis was developed from additional conversations during *sondeos* with participants. Individuals described a broad range of wage-earning endeavors not directly linked to their agricultural practices (Table 4.14). It was clear from discussions during *sondeos* that the opportunities for wage earning were extremely limited in Cabrican as compared to Chuculjulup. While numerous cottage industries and piecework activities were observed in Chuculjulup households, Cabrican informants were more likely to describe less continuous opportunities such as field work, sand or lime mining, or the lack of any activities at all.

Regardless of the income-generating activities that family members may engage in, the control of the income often remains primarily in the hands of the males in the families (Murray, 1989). While extremely difficult to explore with families, observed evidence suggests that in some families, women retain control over some of their own earnings and exercise discretion over how the money is used in some households but in others, women had little or no control. Where the topic was discussed, the opinion was nearly unanimous that the male was responsible for feeding the family and maintaining the household. It was impossible to develop any reasonable estimate of household cash holdings due to farmers' unwillingness and discomfort in discussing the issue.

Farm Demographic Simulations

Farm size

The two communities that were simulated differed in both their circumstances and their potential response to fruit trees based on differences in land holdings. In Chuculjulup, the response to increased land holdings was a strong increase in the optimal number of trees that would likely be managed. In contrast, the response under the conditions in Cabrican was much weaker and occurred only at much higher land holding levels than the equivalent response in Chuculjulup (Figure 4.4).

Further differences were observed in the levels of a representative selection of activities that were optimal at a given land holdings level between the two community scenarios. In the Cabrican scenario, no combination of activities was sufficient to permit family survival at the levels stipulated when farm size dropped below 0.35 ha. The amount of land allocated to variations of the *milpa* or maize cropping system increased steadily up to 0.71 ha at the largest simulated farm size (0.88 ha). In Chuculjulup, maize-based production reached a plateau at 0.53 ha, after which resources were invested in other activities. Potato production was not part of farm management in Chuculjulup, while in Cabrican, land allocated to potatoes increased moderately as farm size increased (Table 4.15). In Cabrican, increases in farm size were directly related to increases in the average amount of year end cash that a family could expect; however in Chuculjulup, average earnings in year seven reached a maximum at 0.53 ha. Poultry production in Chuculjulup was generally unaffected by farm size while it increased with larger farms in Cabrican. The response of large livestock husbandry was positive with increasing farm size, however, a plateau was reached in Chuculjulup. This is in direct contrast to Cabrican, where the increase was continuous across the simulated range.

Family composition

Increasing family size at the average levels of agricultural land holdings in the two communities had a strong negative effect on the optimal number of fruit trees that a family might manage in both communities. The magnitude of the effect was substantially greater in Cabrican (Figure 4.5). When the indicator activities were examined, increasing family size was positively related to the amount of land dedicated to maize-based systems and the size of livestock activities in both communities (Table 4.16). In Chuculjulup, larger family sizes resulted in declines in year-end cash, however, the reverse was true in Cabrican, where larger families achieved higher year-end cash values than small. Potato production was not selected in Chuculjulup and in Cabrican potato production reached its peak at family sizes below the community average. In Cabrican, families of eight or more members could not meet the constraints during the early years of the twelve-year model. Generally, the results reflect a slackening of food security among larger-sized families on smaller farm holdings and show the implicitly reduced security that can be achieved in those circumstances.

Fruit Production Characteristics

Fruit values

The effect of potential changes in fruit market values revealed that the response in the two communities differed substantially. In Chuculjulup, the optimal number of fruit trees increased marginally until fruit value reached 90 % of 2003 market values at which point it increased substantially. As values continued to rise, a second critical point occurred when simulated fruit values were 130 % of 2003 market values (Figure 4.6). Further increases had little effect on simulated fruit tree establishment. In Cabrican, the optimal number of fruit trees was maximized when fruit values ranged from 90 % to 120 % of market values. The number of fruit trees declined outside this range (Figure 4.6).

In Cabrican, the majority of indicator activities were unaffected by variation in fruit values. Only at the highest optimal levels of fruit tree establishment (90 to130 %) was the emphasis placed on maize-based cropping reduced (Table 4.17). In Chuculjulup, increasing fruit production tended to supplant maize-based options along the entire range of fruit market values. Additionally, emphasis on animal husbandry was affected negatively by increasing fruit values. Year-end cash values at the end of seven years were negatively related to increasing market prices for fruit (Table 4.17).

Tree yields

The effects of fruit tree yields on optimal adoption levels to maximum cash resources at the end of 12 years were similar to the effects of variations in fruit values. In Chuculjulup (Figure 4.4), increases in the optimal number of trees per family occurred when yields reached 90% and 130% of expected yields (Table 4.18). In Cabrican, optimal tree numbers increased from 70% of expected values until yields were 110% of expected values, after which further yield increases had little effect (Figure 4.7). The simulated potential for intensive fruit production was much greater in Chuculjulup, where trees could be expected to be established twice as densely when yields were 100% of expected compared to Cabrican. If yields were increased to 140% of expected, simulated tree establishment was four times greater per area in Chuculjulup than Cabrican.

Increases in fruit tree yields resulted in declines in the amount of land allocated to other crops in both communities. This effect was most apparent in Chuculjulup and only occurred in Cabrican at fruit yield levels > 160% expected (Table 4.18). Animal husbandry declined in Chuculjulup as tree yields increased, however, in Cabrican it was unaffected. There was no clear evidence that increases in fruit tree yields would enhance the year-end cash status of families in the seventh year of simulated adoption. While cash levels increased as yields increased above 100% expected yields, they also increased as yields declined below 100% (Table 4.18).

Tree competitive area

Increases in the magnitude of tree competition across the entire resource pool, simulated by increasing areas where associated crops yielded poorly, resulted in declines in the optimal number of trees per family that farmers would be likely to establish and manage. The two communities differed in the importance of this factor. Farmers in Chuculjulup were already affected when tree competition reached nominal levels (indicated by the arrow in figure 4.8). After the competitive area per tree had surpassed 10 m^2, adoption levels were minimal and little further change was observed. In Cabrican, there was no simulated response to increasing competition until tree competitive area had reached 20 m^2, at which point, adoption was greatly diminished.

The majority of indicator activities (Table 4.19) were unaffected by changes in tree competitivity in either community. In Chuculjulup, livestock management increased slightly as trees became a more competitive crop associate. There was no clear impact on year-end cash values due to differences in tree competitive area.

Overall Effects of Off-farm Employment Availability

Increases in the availability of off-farm employment for males showed a positive relationship with the number of fruit trees that were optimal for families of varying composition. When responses were averaged across land holdings, differences were observed between larger and smaller families as the families became progressively more mature. In larger families, the optimal number of fruit trees per family declined as the children matured. In sharp contrast, optimal fruit-tree numbers increased as smaller families aged (Figure 4.9). The positive relation between off-farm employment and fruit-tree number diminished as families matured and was very weak in mature families. The positive effect of increased employment was generally more pronounced in smaller families.

The effect of increased off-farm wage earning by females was generally positive for any of scenarios simulated (Figure 4.10). Regardless of scenarios, likely adoption was consistently higher in smaller families when compared to larger families. In smaller families, the effect of female wage earnings was negligible until children were in the oldest category and little difference was seen in likely adoption when children were infants through adolescence. This was true for larger families as well, where potential adoption was similar for large families with young and mid-aged children. As children reached maturity, female wage-earning potential was positively related to increased adoption and the highest predicted rates of adoption were achieved.

Discussion

Sondeo Investigations

With such small farm sizes (< 0.5 ha), excess family labor is available and necessary for many farm families to obtain income from off-farm activities rather than being a limiting constraint to on-farm activities. In fact, between the two communities, a broad range of off-farm labor activities was identified for both genders. Male labor activities were generally more highly paid on a daily basis. While not quantified, substantially more people in Chuculjulup earn a non-agricultural income than those in Cabrican. The majority of the occupations, particularly those that are best described as piece work (i.e. sewing, weaving, carpentry), exist primarily in Chuculjulup. Only calcium mining as a source of income was unique to Cabrican. Chuculjulup is located much closer to a major population center and its greater reliance on off-farm income is most likely due to need (less land and higher population density) as well as greater opportunity (closer to supplies and market).

The smaller family sizes (Table 4.6) and slightly higher maize yields (Table 4.9) in Chuculjulup appear to support survival with smaller land holdings. Cabrican families reported lower maize purchases to augment their on-farm production which was lower on a per area basis than in Chuculjulup, highlighting the importance of extensive versus intensive production in remote, low resource areas.

Families in Chuculjulup reported greater need to purchase fuelwood because of limited access to wooded non-agricultural lands. In Cabrican, greater access to wooded parcels allows families to augment their fuelwood purchases with collected wood to a much greater extent. No large differences in fuelwood costs between the communities were observed. This is a reflection of the similar, distant source for most purchased fuelwood in both communities.

Consumption

Larger average family size in Cabrican was well reflected in higher reported monthly maize consumption (Table 4.6). Weekly market expenses were higher in Cabrican, perhaps due to the remote location and difficulties in bringing products to market, but also potentially owing to greater family size. The lack of significant differences in total weekly expenses may be attributable in part to stated expenditures in Chuculjulup by several informants that were much higher on a per person basis than any other reported values. Certainly, a tendency to overstate one's economic status, particularly to visiting foreigners, cannot be discounted. In Chuculjulup, families reported allocating more of their food costs to vegetables and dry grains. This is reflected in the agricultural systems distributions (Figure 4.3) which shows that systems that include legumes or other grains are more prevalent in Cabrican and families are able to produce a greater fraction of their consumption needs. Meat expenses were higher in Cabrican and may reflect the remote location of the market and a restriction on meat availability. The actual costs in meat products were not tracked in market surveys though it was discovered post hoc that meat costs are a substantial fraction of food expenditures.

The low explanatory power of regression equations (Eq. 4.1 and 4.2) relating family size to market expenditures is most likely due to large variations in the actual level of consumption (wealth and/or nutritive status) of the various families. The greater slope of the equation in Chuculjulup suggests that food expenses increase more rapidly for additional family members than in Cabrican. A likely interpretation is that overall the greater land holdings and more diverse production in Cabrican may produce greater resilience in food security. Thus large family size remains more tenable in Cabrican then in Chuculjulup. This would tend to allow the reasonable survival of larger families in Cabrican or at least permit smaller families to satisfy many basic needs without resorting to off-farm income sources. An alternative explanation is that larger families in Cabrican are hungrier or purchase less food than those in Chuculjulup. Market prices in both communities were systematically recorded monthly to help with triangulation of the data to explain this important issue, however the market prices failed to show any strong differences that would help explain this issue.

<u>Land allocation</u>

Crop production is more diversified in Cabrican than in Chuculjulup. While the observed systems are similar to those described by Immink and Alarcon (1993), few families that were interviewed in either community were currently growing wheat or were engaged in field production of horticultural crops, and only 11 families in Cabrican had planted potatoes. Furthermore among potato planters, the crop occupied less than 20 % of their agricultural land. In contrast, Immink and Alarcon (1993) found no more than 50 % of farmers engaged in extensive maize production. It is well established that various subregions of the *altiplano* specialize in crops well suited to the area resulting in for example, intensive vegetable production in San Pedro Almalonga or the larger relative importance of potato in the department of San Marcos. These findings show that broader-scale studies such as Immink and Alarcon (1993) may be inadequate for characterization of individual subregions or communities.

Maize yields self-assessment

Maize production by farmers with land to cultivate was ubiquitous. All other cropping alternatives in the communities studied must be considered as ancillary. Farmers characterized the principal problems with maize production as lack of resources for fertilizer purchases, and damage to stands by late season winds. Favas (*Vicia faba*) were characterized as being particularly susceptible to fungal attacks to the extent that without fumigation, the crops could be a complete loss. Few farmers were growing sole favas and none were growing climbing beans (*Phaseolus coccineus*) in sole stands, presumably due to the necessity of either maize stalks or other structures to support the beans.

The findings from the on-farm yield trials suggests that substantial room remains for increasing production in these small homesteads (Table 4.9). The maize yield from a field of 0.3 ha planted to locally adapted varieties (about 900 to1250 kg) is extremely close to providing a full year's supply of maize for a family of 5 to 6 (including 2 adolescents) who are likely to consume between 900 and 1300 kg. Unfortunately, population density has already reduced mean farm sizes in Chuculjulup to 0.21 ha. This essentially ensures a produced-food shortage on the order of 60 to 400 kg or 1 to 4 months of maize for an average family and thus the need for small-holder farmers to purchase raw maize late during the production season is a prime indicator of food-insecurity.

LP Simulations

The simulations showed that the socioeconomic factors (that were included in the simulations) influenced potential adoption of fruit-tree-based agroforestry differently in the two study areas. This finding further reinforces the importance of evaluating the needs of potential technology users and involve smallholder-producers from the initial phases of technology development (Chambers, 1983; Nelson, 1994).

Land holdings

In general, larger land holdings by families in both communities were associated with greater numbers of fruit trees being established. Families in Chuculjulup were predicted to be much more responsive to farm size than those in Cabrican (Figure 4.1). Fruit tree establishment and management were predicted for families in both communities under most scenarios and it was the number of trees likely to be established that was used to gauge the response to changes in variables. Using this measure, it seems clear that fruit-tree-based agroforestry has greater potential in Chuculjulup under current socioeconomic conditions (2002) than in Cabrican. It is likely that differences in *milpa* productivity influence this observation. The amount of land dedicated to maize increased over the entire range of simulated farm sizes in Cabrican, suggesting a need for greater production area to meet family needs. In Chuculjulup, the higher yields resulted in a plateau in the land area used and suggested that the remaining resources could successfully be dedicated to fruit production. Families in Cabrican were predicted to engage in livestock and potato production as farm size increased (Table 4.3). These farmers probably engaged in higher profit, but potentially more risky farm activities owing to the extreme difficulty in surviving without substantial wage-earning opportunities.

Family composition

In both communities, the effect of increasing family size was to decrease the number of fruit trees that families were predicted to establish (Figure 4.5). This decline was also linked with a steady increase in the production of maize as families attempted to retain higher levels of food security with greater consumption needs. Thus it appears, based on simulation results, that there exists a potential tension between food security within farm households and adoption of fruit-tree-based agroforestry. Higher numbers of fruit trees were predicted where food security is more readily achieved, i.e., where sufficient land exists to grow larger maize fields in spite of low yields or where food consumption is lowered due to small family sizes.

There are several critical limitations, however, because of the structure of the model used to make these predictions. The first is in the constraint that existed to promote the cultivation of maize. It is well founded that for many highland farmers in the region maize cultivation is not purely an economic or food subsistence venture but contains spiritual or moral connotations (Aguilar, 1993; Terán and Rasmussen, 1995; Ucán Ek et al., 1982) that may drive otherwise uneconomical activities.

The LP model was driven by an economic maximization function while additional goals such as adequate diets and sufficient cash to pay reasonable expenses were met as boundaries on the possible solutions. Early formulations of the linear program indicated a strong economic advantage of potatoes over maize. However, in practice this was not observed among small-holder farmers and further inquiry revealed that farmers were perfectly aware of the earning potential of potato yet chose to plant the maize they would need for their families before considering what to do with any remaining land. Anecdotes relating large potato fields left unharvested when the required labor became uneconomic with low market prices, indicated that farmers perceived the activity as extremely risky.

Within the linear program this was modeled as a requirement that 80 % of household maize consumption be produced on-farm and effectively prohibited farmers from excessive speculation in cash crops. The limitation may be responsible for effects such as the negative relation between family size and fruit production. It is likely that in the absence of this cultural norm, for example with *Ladino* farmers, fruit-tree-based agroforestry might enjoy greater adoption. Yet it seems likely that food security, when defined as having the necessary food on hand rather than simply the means to procure any food that is available, is unlikely to be enhanced through fruit-tree-based agroforestry. The findings suggest that adoption of this technology is enhanced where other factors contribute to enhancing the security of the family first. This correlated well with observations made in the community *sondeos* that farmers who had large scale fruit-tree plantings frequently had clear sources of cash income such as small stores or other entrepreneurial activities.

Fruit tree characteristics

The effects of several possible types of interventions in fruit-tree-based agroforestry indicated that no single approach would be equally successful in the two areas. Potential strategies included those that would increase the price farmers received for the fruit they produced, interventions that would increase the yields of individual trees during their productive period, and techniques that would result in reduced tree-crop competition. These alternatives were examined with the simple expedient of introducing changes in the modeled outcomes from tree establishment, for example a 10 % higher harvest in a given year to indicate that an intervention had enhanced tree yields.

The model predictions indicate that neither community was particularly sensitive to small scale fluctuations in fruit prices. Of the two, farmers in Chuculjulup were predicted to respond strongly within the range of a 10 % decline or a 30 % increase in fruit values. Little response was predicted by the simulation outside this range. In Cabrican, a 20 % decline in fruit value reduced likely adoption to the same extent as in Chuculjulup (Figure 4.6). Differences between the communities were indicated with continued price increases. Adoption was predicted to be strongly favored in Chuculjulup above a 30 % increase. In Cabrican after a brief increase, adoption was predicted to decline as fruit values increased beyond 120 % and it is likely that this resulted from the modeling structure as explained below.

In both communities, the sales and purchase price of fruit in the market was linked to fruit values with the sales price being equal to fruit value and the purchase price 110 % of the sales price. During the simulations, Cabrican was characterized as a community where opportunities for off-farm wage income were strongly limited. However, consumption of fruit products within the household was proportional to family composition and during the initial years of the simulations fruit needed to be purchased with scarce cash. The only option that was included in the model was for the establishment of fruit trees in year one to begin yielding in year three, and therefore, if cash were scarce, families were predicted to generate cash in years one through three by other means but then were unable to adopt fruit-tree-based agroforestry resulting in observed decline in adoption.

Activities such as cooperative or direct marketing, or enhanced fruit quality that have potential, among other possibilities, to enhance fruit value were predicted to affect likely fruit-tree adoption differently in the two communities. Very little effect was observed by yield increases per tree beyond 40 % in Chuculjulup and beyond 10 % in Cabrican. Declines in fruit yield that might occur due to deficient management or excessive competition with crops appeared to be more important in Chuculjulup, where adoption was limited by a 10 % decrease in yields per tree. The effect in Cabrican was more gradual, and a 30 % decline was required to reduce the likely number of trees to the same extent (Figure 4.7).

While predicted tree number per family only differed by 10 to 12 at the highest adoption levels, the intensity of the activity was much higher on the farm in Chuculjulup because of the smaller land-holding, and would have the appearance of densely cropped orchards as compared to dispersed trees in fields. A substantial portion of the research that has been done on fruit varieties in the highlands region of Guatemala has emphasized the methods for establishment and management of commercial orchards

(Williams and Vasquez, 1990; Vasquez, 2000), however the simulation results suggest that intensive plantings will only be popular among farmers where maize yields are high or farmers are not dependent on maize production for cultural and economic survival.

The role of competition between trees and crops was much more important in Chuculjulup where potential tree establishment declined precipitously as the area of competition per tree increased (Figure 4.8). Management strategies that result in better use of available resources by trees and crops in association would be more useful in Chuculjulup than in Cabrican where increasing competition between crops and trees had little comparative impact on predicted establishment.

Off-farm employment opportunities

The availability of off-farm wage-earning opportunities for both males and females was related positively to fruit-tree establishment but those differences in adoption were minor as family members went from marginal to full-time employment (Figures 4.9 and 4.10). Additionally, when wage employment is available, it may be present in higher values than examined in this study. This should not eclipse the previous observation that families likely to be economically better-off such as smaller families, families with older children, or families with greater land holdings were predicted to establish greater numbers of fruit trees.

Despite the limitations of the simulations and the assumptions on which the study was based, the findings from this study suggest that adoption rates for fruit-tree-based agroforestry can be very high, but of different pattern, in the two communities studied. The numbers of trees that will be attractive to families varied based on their specific socioeconomic conditions; moreover, the technology appeared to be of greater interest to more affluent community members. The potential magnitude of the economic benefits that could be achieved through adoption was not clear, since fruit tree establishment often indicated foregoing other productive activities and a period of reduced annual cash availability. The findings that fruit trees were so frequently selected from the suite of livelihood activities in place of other crops such as potatoes or wheat suggests that the technology possesses characteristics that permit smallholders to improve their economic status over the alternatives.

Based on these findings, it is recommended that any extension activities promoting fruit-tree-based agroforestry or intending to enhance small farm fruit production in this region should be integrated with research to enhance the productivity of the associated or principal crops. Additional analysis is warranted, however, to examine the likely differences that would emerge if fruit trees were not available as a cropping alternative.

Table 4.1. Crop production emphasis relative to land holdings in Western Guatemala.

	Farmers' principal crop (N=786) (percentage of farmers)			
Land holdings (ha)	Maize (313)	Potato (190)	Wheat (120)	Vegetable (163)
Less than 0.5	50.2	18.4	10.8	17.3
0.5 to 1.0	20.3	34.7	25.8	24.1
1.0 to 2.0	17.7	27.9	28.3	26.5
Greater than 2.0	11.9	18.9	35	32.1

Source: Adapted from Immink and Alarcon, 1993.

Table 4.2. Mean crop yields depending on the growers' emphasis on principal crops in western Guatemala.

Crop type	Crop yield (kg ha^{-1}) based on Farmer's main crop (N=786)			
	Maize (313)	Potato (190)	Wheat (120)	Vegetable (163)
Maize (*Z. Mays*)	1800	1800	2200	1800
Beans (*P. Vulgaris*)	200	100	100	200
Potato (*S. tuberosum*)		12600	12000	13600
Wheat (*T. aestivum*)			1700	
Broccoli (*B. oleracea*)				8900
Cabbage (*B. oleracea*)				9900
Beets (*Beta vulgaris*)				12500
Carrots (*Daucus carota*)				50400

Source: Adapted from Immink and Alarcon, 1993.

Table 4.3. Demographic indicators of two Guatemalan communities based on recent (1989) community surveys.

	Cabrican and *aldeas*	Chuculjulup
Population	14,500 (92% Mam)	2,900 (97% Quiché)
Population Density	330 persons km^2	890 persons km^2
Functional literacy	73 %	60 %
Educational level		
Pre-elementary	6 %	32 %
Elementary	84 %	61.3 %
High School	9.5 %	6 %
Post-High School	0.5 %	0.7 %
Households	2870 (58 % with electric)	501 (93 % with electric)

Table 4.4. Yield characteristics of modeled crop systems in Chuculjulup and Cabrican in the highlands of western Guatemala.

System #	Modeled crops	Seed rate (kg ha^{-1})	Chuculjulup yields (kg ha^{-1})	Cabrican yields (kg ha^{-1})			
1	Maize,	30	4100	3000			
	bean,	45	310	310			
2	Maize,	30	2950	2950			
	bean,	45	120	120			
	fava,		150	150			
	squash		680	680			
3	Maize,	3045	4100	3000			
	bean,		120	120			
	fava		150	150			
4	Maize,	30	4100	3000			
	fava		200	200			
5	Maize	30	4100	3000			
6	Fava	155	790	790			
8	Potato 1st,	4100	16900	16900			
	2nd,		2500	2500			
	3rd		1550	1550			
9	Wheat	155	2050	2050			
10	Oats	125	1275	1275			
			Yields (kg tree^{-1})				
	Fruit tree variety	Tree size m^2	Year 3	Year 5	Year 7	Year 9	Year 11
12	Pear	9	0.5	5	10	18.5	27
	Peach	9	2	10.5	19	29.5	40
	Apple	9	0.5	5	10	18.5	27

Squash yields based on units harvested to better reflect the sales mechanism.
First, second and third for potato production refer to size and quality grade of harvested tubers which created a price differential.

Table 4.5. Levels of consumption of agricultural products used to parameterize the simulations in Chuculjulup and Cabrican.

	Food consumption (kg $year^{-1}$ $person^{-1}$)				
	Adult male	Adult female	Adolescent male	Adolescent female	Child
Maize	410.6	322.4	348.2	320.6	268.9
Beans	27.4	17.5	18.9	17.4	14.6
Potatoes	48.2	30.9	33.3	30.7	25.7
Fruit	9.9	6.3	6.8	6.3	5.3
Bread	32.0	20.4	22.1	20.3	17.1
Eggs	76.7	76.7	76.7	76.7	25.6
Meat	14.0	9.0	9.7	8.9	7.5
Chicken	11.5	7.3	7.9	7.3	6.1

Egg consumption in eggs per person per year.

Table 4.6. Mean household characteristics in two Guatemalan communities based on semi-structured interviews with family heads and through geographically dispersed, random surveys.

	Cabrican		Chuculjulup	
	(n=31)	(n=180)	(n=23)	(n=233)
Household size (members in residence)	7.3	6.1	5.1	5.2
Agricultural land (ha)	0.78	0.6	0.22	0.23
Non-agricultural land (ha)	0.52	0.48	0.09	0.12
Weekly food purchases (Q)	125.0 ns	87.3	113.5 ns	114.4
Household maize consumption (kg $month^{-1}$)	108	100.75	67.6	73.77
Fuelwood purchases required (% respondents)		46.9		83.7

All means significantly different at α=0.05 unless followed by ns. Means comparisons made within small (n=31, 23) samples (*sondeos*) and within large (n=180, 233) samples (household surveys) using t-test assuming unequal variances.

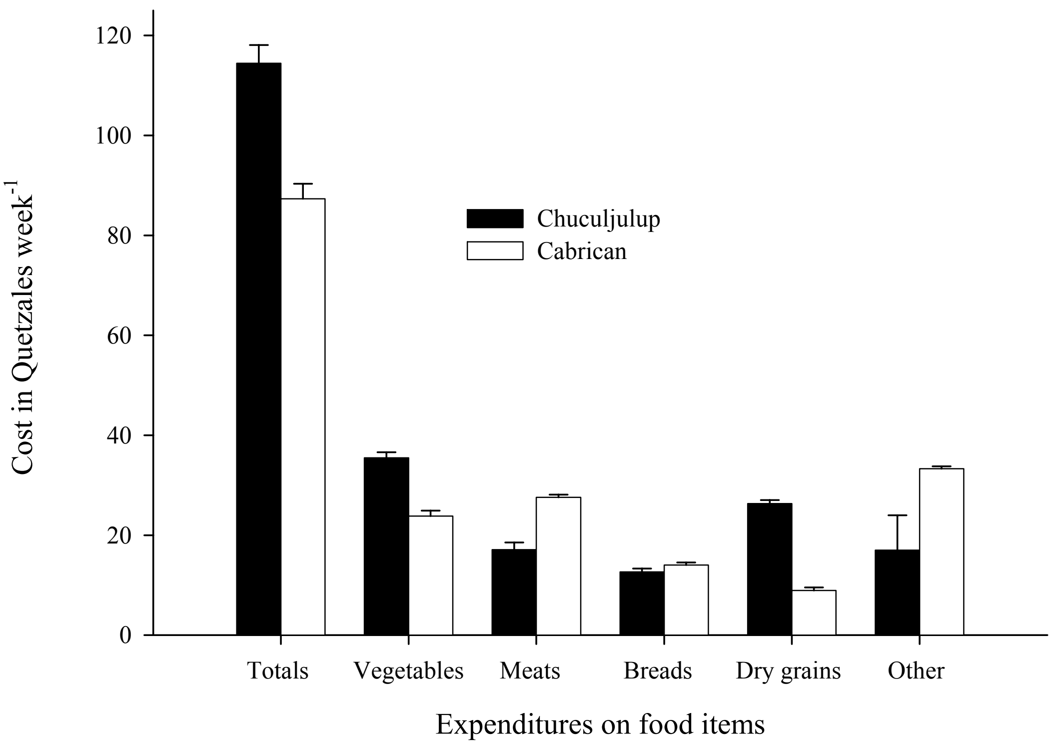


Figure 4.1. Weekly purchase expenses for several food frequently purchased by families of two communities in northwest Guatemala. (1.00 $US = 7.85 Q 2002).

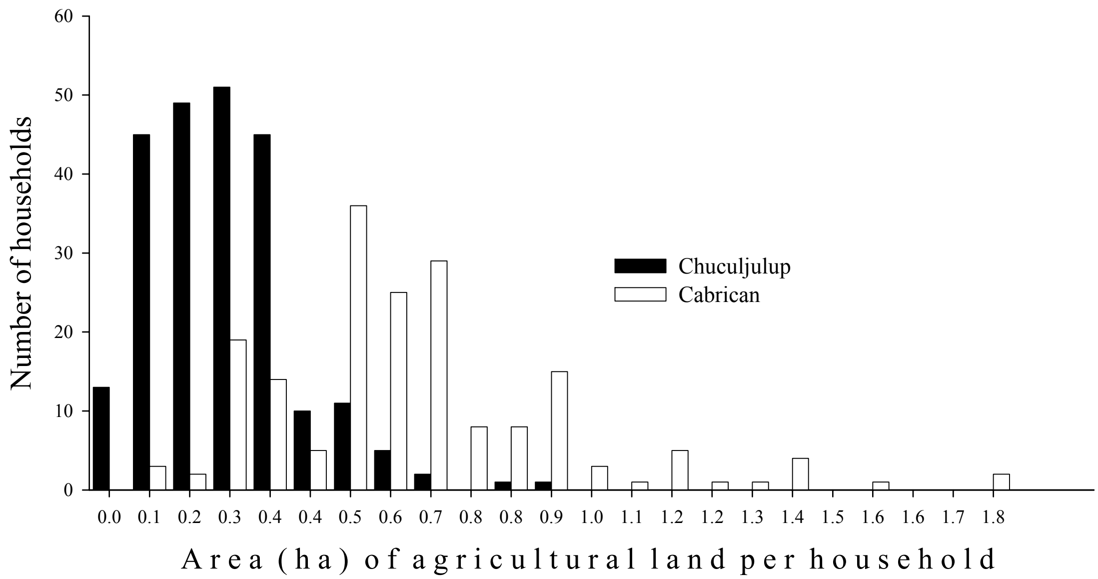
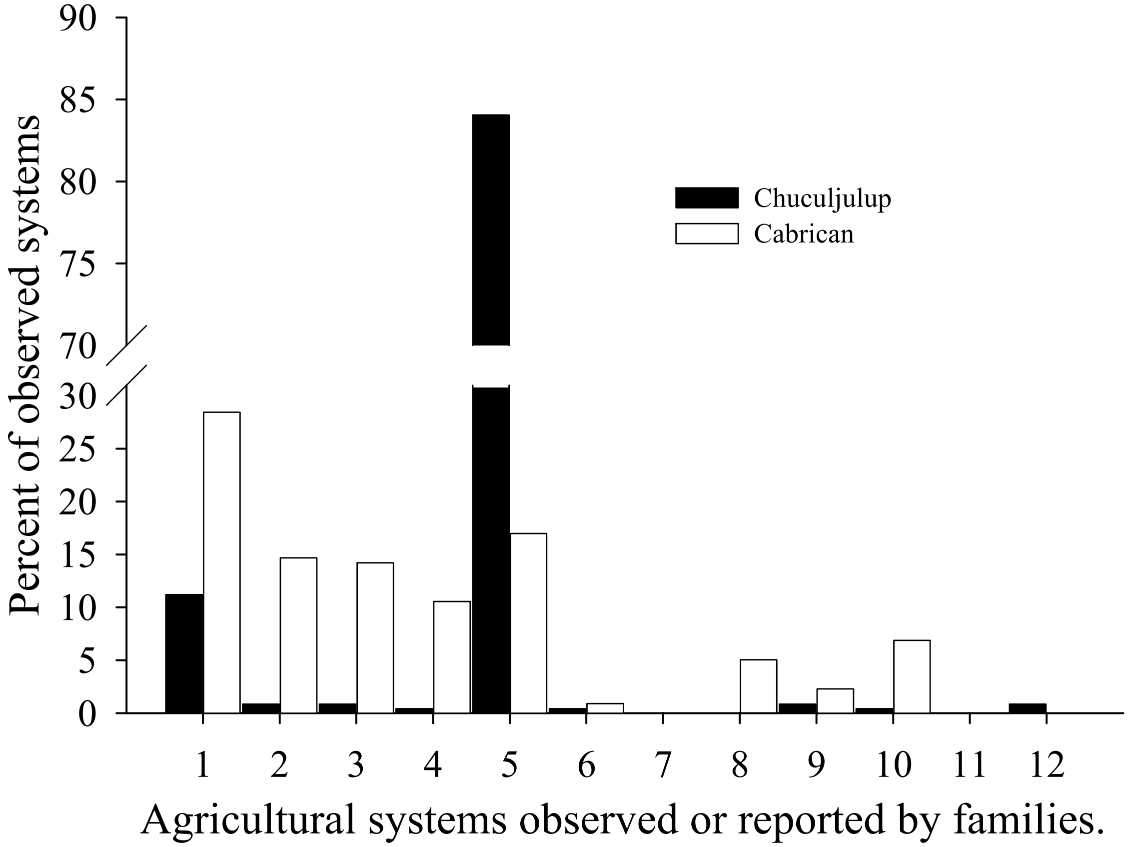


Figure 4.2. Distribution of agricultural land holdings among farmers in two highland communities of western Guatemala.



1: Maize-bean
2: Maize-bean-fava-squash
3: Maize-bean-fava
4: Maize-fava
5: Maize
6: Fava
7: Bean
8: Potato
9: Wheat / barley
10: Oat
11: Vegetables
12: Fruit orchards

Figure 4.3. Distribution of crop systems in two communities. Detailed system descriptions are found in Table 4.8.

Table 4.7. Mean weekly market prices during 2002 at Cabrican and Totonicapan markets for several locally produced agricultural products.

	Cabrican	Totonicapan
Maize (Q 46 kg^{-1})	85	72
Potato (Q 46 kg^{-1})	119	137
Fava (kg)	5.95	7.6
Piloy (kg)	7.1	7.16
Bush bean (kg)	7.72	7.5

1.00 US $ = 7.85 Q (2002). Fava price significantly different ($p<0.05$) by paired T-test assuming unequal variances.

Table 4.8. Cropping characteristics of systems observed in two highland communities of western Guatemala.

Sys. #	Principal crops	By products	Seed rate kg ha^{-1}	Mean crop yields kg ha^{-1}	Fertilizer (N-P-K) kg ha^{-1}			Labor days ha^{-1} during each quarter			
					15-15-15	20-20-0	45-0-0	1	2	3	4
1	Maize, bean	forage, pods *doblador*	30 45	5150		360	150	22.7	90.9	51.1	102.2
2	Maize, bean, fava, squash	forage, pods *doblador*	30 45	2950 120 90 15000		360	150	25	90.9	73.9	106.7
3	Maize, bean, fava	forage, pods *doblador*	30	2950 120 90		360	150	25	90.9	73.9	102.2
4	Maize, fava	forage, pods *doblador*	30	5150 360		360	150	22.7	90.9	45.5	102.2
5	Maize	*forage,* *doblador*	30	5660		360	150	22.7	113.6	22.7	90.9
6	Fava	pods	154	790	260			0	96.5	5.7	56.8
7	Bean	none			260						
8	Potato 1st, 2nd, 3rd	none	4100	16900 2570 1550	775			34	223.3	113.5	0
9	Wheat	straw, forage	155	2050				0	28.4	9.3	23.6
10	Oats	straw, forage	125	1275		125	125	27.2	0	34.1	0
11	Vegetables	none									
12	Fruit orchard	prunings, forage	n/a	4625	51			12.3	12.3	24.5	8.2

Doblador is the ear husk of maize and is used to wrap maize-based foods such as *tamales* or cheese. Potatoes reported based on size class. All values for fruit orchards are on the basis of 204 trees ha^{-1} (7.0 x 7.0 m) for 7 yr-old trees. Quarters were; F-M-A: qrt. 1, M-J-J: qrt. 2, A-S-O: qrt. 3, N-D-J: qrt. 4.

Table 4.9. On-farm maize yield self-assessments during 2001 and 2002 in Chuculjulup and Cabrican, western Guatemala.

	2001 (local var.)		2002 (improved var.)		Variety	
	Cabrican (n=6)	Chuculjulup (n=5)	Cabrican (n=7)	Chuculjulup (n=6)	2001 (n=11)	2002 (n=13)
Population (stems ha^{-1})	59,900 ns	56,300 ns	57,400 ns	48,800 ns	58,700 ns	53,900 ns
Dry Grain (kg ha^{-1})	2984	4131	4286 ns	4754 ns	3367	4498
Dry grain (g $stem^{-1)}$	51.6	74.2	87.8 ns	97.8 ns	59.2	91.8
Field dry biomass (kg ha^{-1})	16,700 ns	19,100 ns	n/a	n/a	n/a	n/a
Ear mass (kg ha^{-1})	5708	7789	6014 ns	6152 ns	6402 ns	6076 ns
Shelling percentage	66.7 ns	64.3 ns	76.6	82.1	65.8	79.1
Harvest index (kg grain kg $biomass^{-1}$)	0.24	0.27	n/a	n/a	n/a	n/a

Results from 2001 based on local land races while 2002 results based on San Marceño Mejorado distributions. Means between sites within a year or between varieties significantly different ($p < 0.05$) unless followed by ns. Means separation within years and for varieties by T-test assuming unequal variances ($p < 0.05$). Assessments for variety compares bulked local varieties in 2001 with an improved variety in 2002.

Table 4.10. Fruit cropping prevalence in two western highland communities.

	Families with >1.0 productive fruit tree	Predominance of three fruit varieties (percent of reported trees)			Families selling fruit in 2001
		Peach	Apple	Pear	
Cabrican (n=180)	83.4 %	25.7	74.1	0.21	53.0 %
Chuculjulup (n=233)	90.9 %	37.5	61.1	1.4	55.0 %

Percentage of families selling fruit based solely on those with trees. Numerous fruit varieties are contained within species classification.

Table 4.11. Percentage of smallholder farmers who practiced deciduous-fruit-tree management in agroforestry systems on their farmlands in western Guatemala highlands.

	Spraying	Pruning	Calcium application	Chemical fertilization	Fruit thinning	Organic matter application
Cabrican (n=150)	7.9 a	51.8 a	50.7 a	2.2 a	5.1 a	55.1 a
Chuculjulup (n=211)	8.3 a	13.7 b	35.6 b	2.0 a	5.4 a	12.7 b

Practice means followed by the same letter not significantly different (t-test with unequal variances, $p < 0.05$).

Table 4.12. Animal husbandry practices on small farms in two communities of the Guatemalan *altiplano*.

	Cows		Sheep		Pigs		Chickens		Turkey		Ducks		Horses	
	%	$\bar{X}$	%	$\bar{X}$	%	$\bar{X}$	%	$\bar{X}$	%	$\bar{X}$	%	$\bar{X}$	%	$\bar{X}$
Cabrican (n=180)	32	1.4a	14.4	2.5a	57.2	1.9a	78.8	9.6a	18.3	4.1a	26.1	3.8a	47.7	1.3a
Chuculjulup (n=233)	5	0.7b	12	3.1a	12	1.4b	64	6.2b	10.3	2.6b	5	3.4a	1	1.0a

The numbers are percentage of families with species and mean number of head kept by families with each species. Means separation by t-test assuming unequal variance ($p < 0.05$).

Table 4.13. Characteristics of animal production on highland farms in western Guatemala.

Animal type	Food source	Quantity	Labor days quarter^{-1}			
			F-M-A	M-J-J	A-S-O	N-D-J
Poultry	free range suppl. maize bran	20 kg yr^{-1} bird^{-1}	1.8	1.8	1.8	1.8
Turkeys	free range suppl. maize bran	20 kg yr^{-1} bird	1.8	1.8	1.8	1.8
Pigs	maize potatoes bran free range	122 kg head^{-1} 102 kg head^{-1} 400 kg head^{-1}	5.6	5.6	5.6	5.6
Cows	fresh fodder maize leaves, stover corn cobs, doblador	9000 kg yr^{-1} 3500 kg yr^{-1} 400 kg yr^{-1}	45	45	45	45
Sheep	crop residues pasture or fresh fodder	650 kg yr^{-1} 700 kg yr^{-1}	30	30	30	30

Fresh fodder is provided by cut and carry for penned animals or through grazing. These alternatives are approximately equal in labor requirements.

Table 4.14. Representative non-agricultural or off-farm livelihoods observed in Cabrican or Chuculjulup in western Guatemala.

Activity	Gender bias in labor requirements	Mean weekly earnings (Q)	Raw materials source	Earnings source
Thread dying	F / adolescent. F	100	piece work	regular buyer
Weaving (floor loom)	M	250	piece work	regular buyer
Weaving (back strap)	F / adolescent. F	200	investment	resellers
Tailoring	F	300	piece work	regular buyer/ to order
Tortilla sales	F	75	investment	local buyers
Retail sales	all	200	investment	local buyers
Firewood	M / adolescent M	120	public resource	resellers
Carpentry	M / adolescent M	300	piece work / by order	regular buyers/ to order
Pottery	F	100	land holdings	resellers
Laundry	F / adol. F	150	n/a	local buyers
Domestic	adolescent F	125	n/a	local and distant buyers
Day labor	M / adolescent M	200	n/a	local and distant buyers
Semiskilled labor	male	300	n/a	local and distant buyers

Weekly earnings based on working 5 eight hour days during the week. Quetzal (Q) at 1.00 $US = 7.85 Q (2002).

Table 4.15. Principal activities during year seven to maximize cash holdings at the end of year twelve based on differences in agricultural land holdings at Cabrican and Chuculjulup in western Guatemala.

	Chuculjulup (family size = 5)					Cabrican (family size = 6)				
Farm size (ha)	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)	Maize[2] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)
0.09	0.08	0	4.01	1.4	1027	nf	nf	nf	nf	nf
0.18	0.14	0	4.01	1.68	1840	nf	nf	nf	nf	nf
0.26	0.22	0	2.2	2.11	2849	nf	nf	nf	nf	nf
0.35	0.34	0	2.15	2.72	4867	0.33	0.01	4.62	1.89	0
0.44	0.36	0	4.01	2.81	6010	0.34	0.08	4.62	1.72	0
0.53	0.4	0	4.01	2.99	7273	0.41	0.11	4.62	2.19	53
0.62	0.4	0	4.01	2.99	6252	0.52	0.09	4.62	2.97	944
0.71	0.4	0	4.01	2.99	4448	0.54	0.12	25.96	3.39	2876
0.79	0.4	0	4.01	2.99	2633	0.55	0.16	28.14	3.73	3238
0.88	0.43	0	4.01	3.17	1843	0.71	0.12	29.5	4.66	4374

1. This selection was maize with climbing beans (*Phaseolus coccineus*).
2. This activity was composed of both maize with climbing bean and maize with climbing bean, fava, and squash.
nf: Smaller farm sizes were not feasible within the chosen constraints.

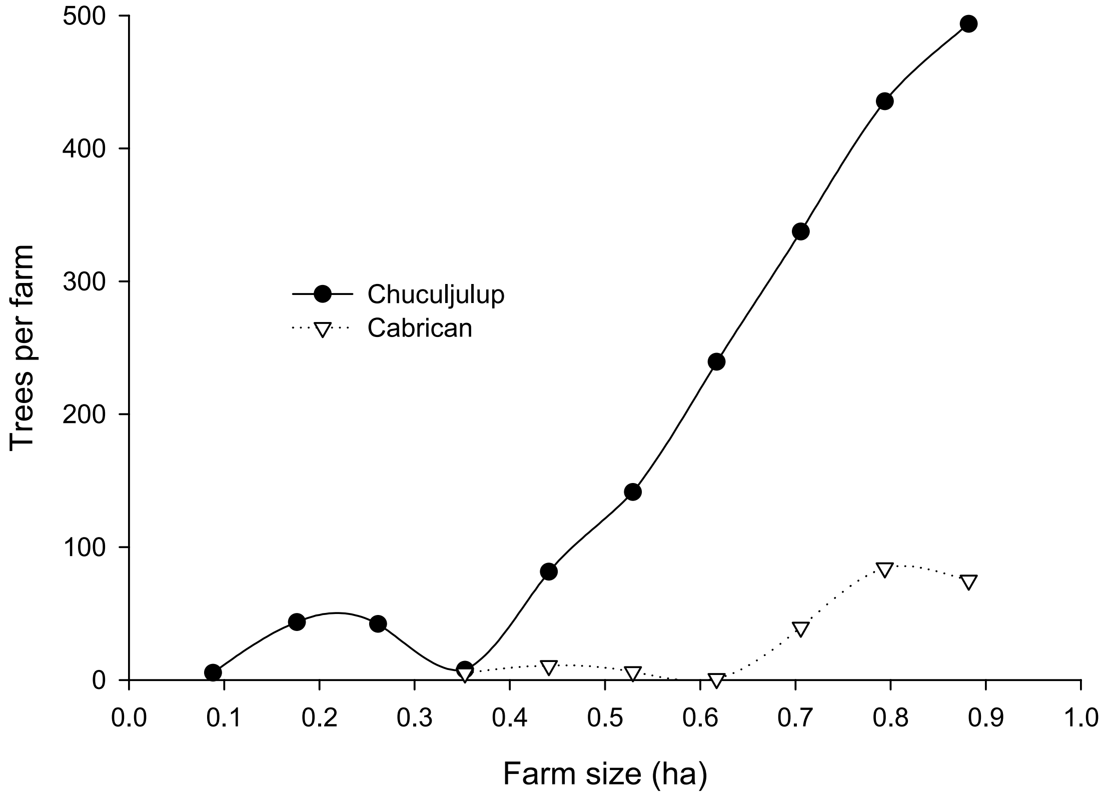


Figure 4.4. Simulated effects of agricultural land-holding size on the potential popularity of fruit trees with families of average composition in Chuculjulup and Cabrican.

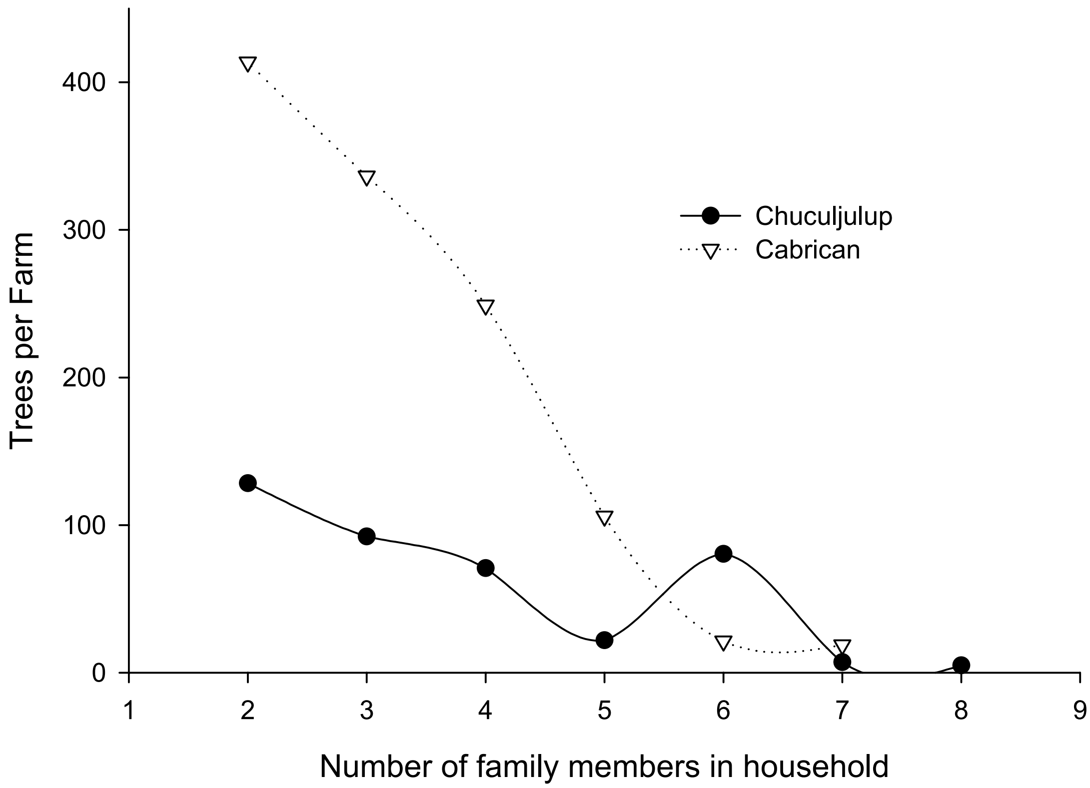


Figure 4.5. Influence of family composition for farms of average size land holdings on likely adoption and management of deciduous fruit trees in Chuculjulup and Cabrican.

Table 4.16. Principal activities during year seven to maximize cash holdings at the end of year twelve in two highland communities of western Guatemala.

	Indicator activities									
	Chuculjulup (0.23 ha)					Cabrican (0.60 ha)				
Famil y size	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash(Q)
2	0.11	0	1.88	1.56	6835	0.2	0.02	0.24	1.76	0
3	0.15	0	2.49	1.72	5715	0.25	0.04	0	2.02	0
4	0.16	0	1.2	1.82	3955	0.3	0.08	0.8	2.28	0
5	0.21	0	1.77	2.04	2880	0.41	0.09	3.83	2.62	1314
6	0.16	0	4.48	1.78	1693	0.52	0.05	4.62	2.97	1491
7	0.22	0	5.35	2.1	1216	0.54	0.03	5.35	3.57	1930
8	0.22	0	5.97	2.1	477					

Within a family size, family composition was identical between communities.
1. This selection was maize with climbing beans (*Phaseolus coccineus*).

Table 4.17. Principal activities during year seven to maximize cash holdings at the end of year twelve as a function of variations in fruit market values.

	Chuculjulup (0.23 ha, 5 family members)					Cabrican (0.60 ha, 6 family members)				
Fruit % mkt. value	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)
50	0.23	0	3.83	2.13	3801	0.46	0.14	4.44	2.86	2403.2
70	0.23	0	3.83	2.13	3714	0.46	0.14	4.44	2.86	2260.3
100	0.21	0	1.77	2.04	2880	0.46	0.12	4.44	2.86	1391.6
120	0.21	0	1.63	2.04	2989	0.46	0.13	4.44	2.86	1276.7
140	0.19	0	0	1.97	2763	0.46	0.14	4.44	2.86	1151.1
160	0.19	0	0	1.97	3082	0.46	0.14	4.44	2.86	472.77

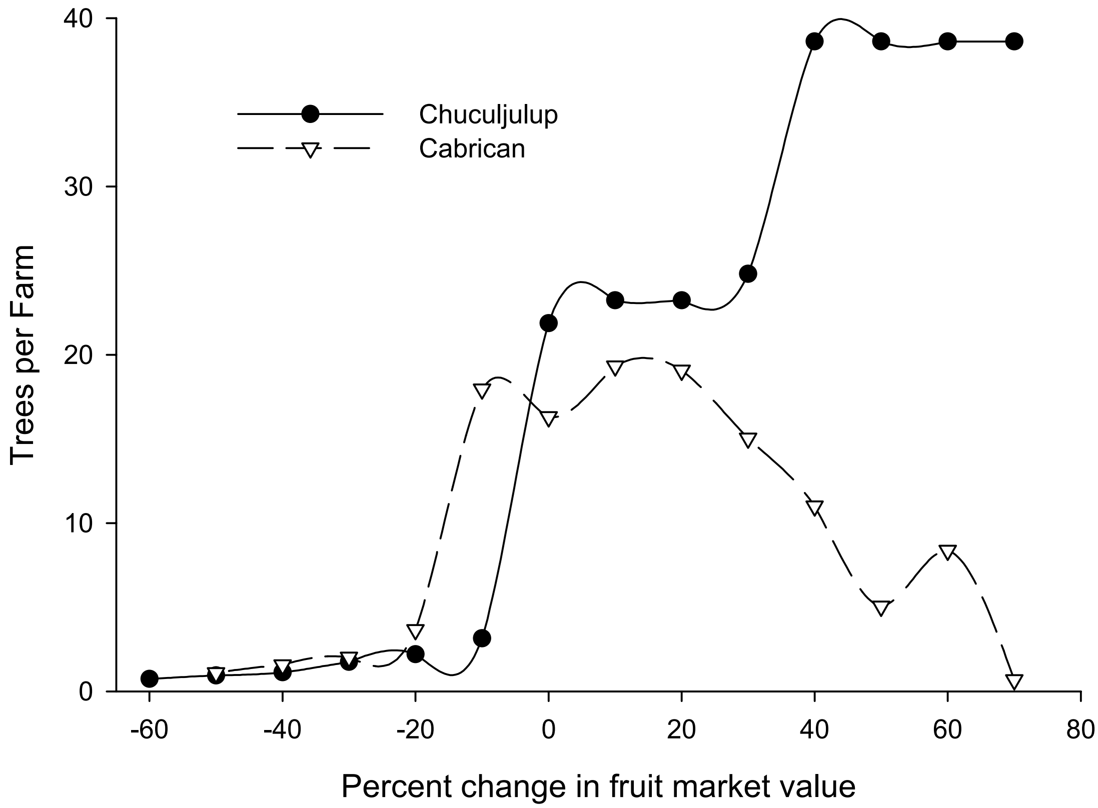


Figure 4.6. Simulated market sales and purchase prices affecting potential popularity of fruit-tree-based agroforestry by average families in Chuculjulup and Cabrican.

Table 4.18. Principal activities during year seven to maximize cash holdings at the end of year twelve as a function of variations in fruit tree yields.

	Chuculjulup (0.23 ha, 5 family members)					Cabrican (0.60 ha, 6 family members)				
Fruit yields %	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)
60	0.23	0	3.8	2.1	3514	0.46	0.14	4.4	2.9	1986
80	0.23	0	3.8	2.1	3564	0.46	0.13	4.4	2.9	1751
100	0.21	0	1.8	2	2880	0.46	0.12	4.4	2.9	1463
120	0.21	0	1.6	2	3054	0.46	0.12	4.4	2.9	1361
140	0.19	0	0	2	2892	0.46	0.12	4.4	2.9	1651
160	0.19	0	0	2	3275	0.45	0.12	4.4	2.9	1784
180	0.19	0	0	2	3659	0.45	0.12	4.4	2.9	2078

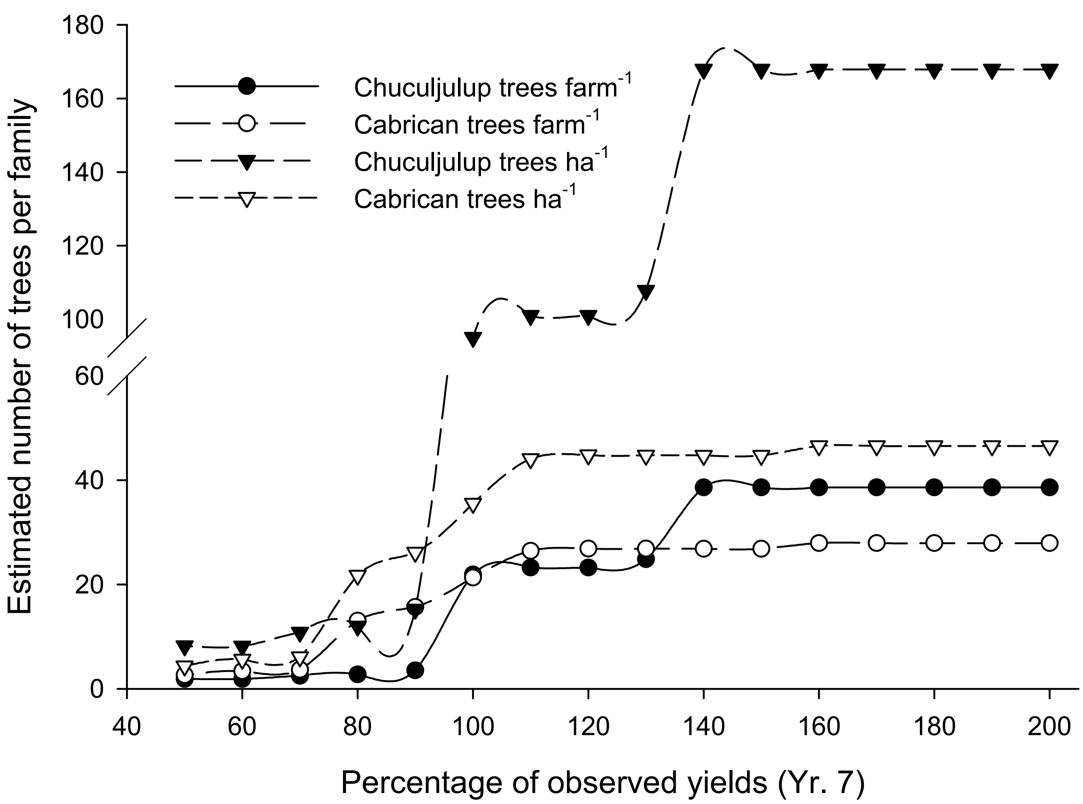


Figure 4.7. Importance of fruit yield levels on likely popularity of deciduous fruit trees as an agroforestry technology among average farm families in two highland communities.

Table 4.19. Principal activities during year seven to maximize cash holdings at the end of year twelve as a function of competition by fruit trees.

	Chuculjulup (0.23 ha, 5 family members)					Cabrican (0.60 ha, 6 family members)				
Tree area (m^2)	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)	Maize[1] (ha)	Potatoes (ha)	Poultry (head)	Cows (head)	Mean cash (Q)
4	0.2	0	0.37	1.99	2140	0.41	0.18	3.83	2.69	4076
6.25	0.21	0	1.63	2.04	2784	0.41	0.17	3.83	2.65	3991
9	0.22	0	3.52	2.12	3602	0.41	0.17	3.83	2.6	3890
12.25	0.23	0	3.81	2.13	3678	0.41	0.16	3.83	2.6	3808
16	0.23	0	3.8	2.13	3657	0.41	0.16	3.83	2.6	3656
20.25	0.23	0	3.83	2.13	3649	0.41	0.15	3.83	2.6	3483
25	0.23	0	3.82	2.13	3636	0.41	0.18	3.83	2.62	4034
30.25	0.23	0	3.8	2.13	3624	0.41	0.18	3.83	2.64	4077
36	0.23	0	3.83	2.14	3688	0.41	0.18	3.83	2.65	4091

Tree areas represent the size of the field around the tree where crop yields are reduced to a mean of 0.0 kg ha^{-1}.

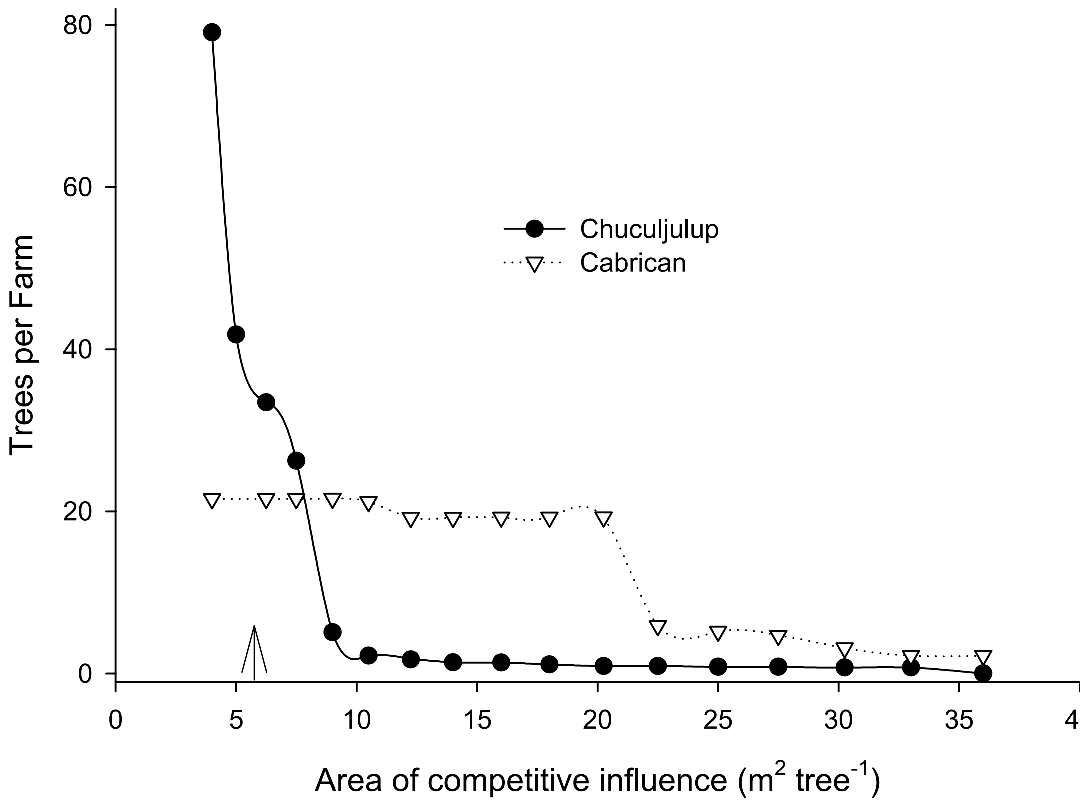


Figure 4.8. Tree-crop competition as a factor influencing the rates of tree establishment and management by families representing average conditions in two highland communities. The arrow indicates the nominal value for seven-year-old trees.

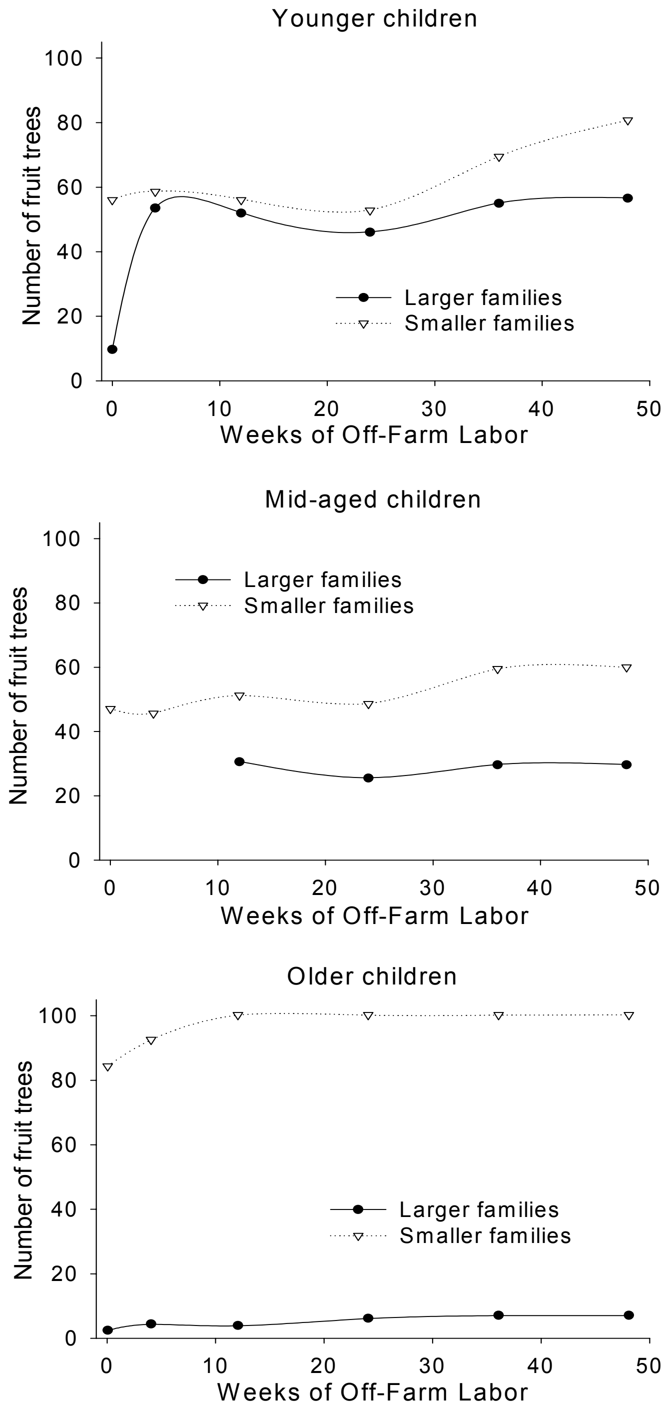


Figure 4.9. The effects of male off-farm labor availability on the optimal numbers of fruit trees managed by families of varied compositions. Small families consisted of three members while larger families contained six people.

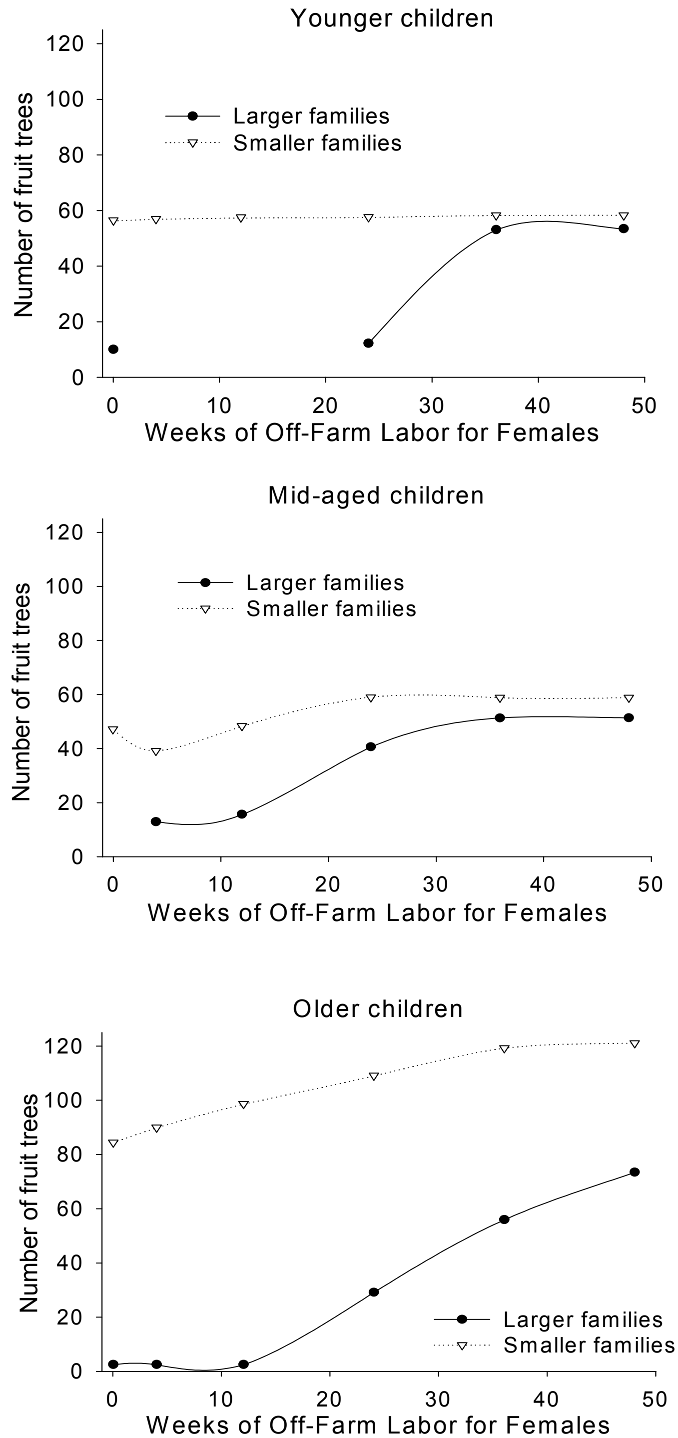


Figure 4.10. The effects of female off-farm labor availability on the optimal numbers of fruit trees managed by families of varied compositions. Small families consisted of three members while larger families contained six people.

CHAPTER 5
CONCLUSIONS

This study examined the potential for increasing small farm productivity by the inclusion of deciduous fruit trees within annual crop fields in the western highlands of Guatemala. The fruit trees were *Pyrus communis* (pear), and the crop species were *Zea mays* (maize) and *Vicia faba* (fava bean). The research revolved around two principal questions:

1. Is it advantageous to mix fruit trees with annual crops and to what extent are additional resources exploited through fruit-tree-based agroforestry?

2. How does fruit-tree-based agroforestry fit within the existing framework of small farm management in the Guatemalan highlands?

To answer these questions, investigations were carried out on biophysical interactions between the tree and crop components and socioeconomic status of the fruit-tree-based agroforestry systems.

Biophysical Interactions

The findings indicated that most of the interactions between components, measured in terms of economic yields produced, were "negative" in their effect on individual species. For example, the yield of maize and fava bean was reduced when underplanted with pear trees. The negative effect was reduced or not present when the crops were grown beneath artificial shade structures. While shade structures do not perfectly duplicate the shading characteristics of real trees, specifically with respect to light quality, this result strongly suggests that belowground competition was an important factor in the negative interactions.

When maize and fava bean were intercropped, the yield of fava bean was substantially reduced, suggesting strong competitive effects of maize. The converse was not true: under some conditions, maize yielded more when intercropped with fava. Thus interaction between either soil characteristics and/or climatic conditions and maize + fava intercrop performance was evident.

Annual crops differed substantially in their effects on fruit tree growth and yield. When maize (a C_4 grass species) was underplanted, the reproductive growth in pear was reduced. Highland maize varieties are, comparatively, as tall as the trees in this study, making shading of trees by crops an important consideration. Contrasting this observation was the facilitative effect in association with fava bean, a C_3 legume with potentially high rates of N_2 fixation. When fava was underplanted with the pear tree, fruit tree reproductive growth was enhanced resulting in significantly better performance in several measures of fruit tree response.

Taken in their totality, the component interactions observed in the study suggest that competition for PAR and for resources related to belowground processes, potentially soil water and nutrients, were important factors in system performance in the highland environment. For purposes of further study, the three components can tentatively be ranked as a) maize: most competitive, b) pear: competitive, and c) fava bean: least competitive for radiation and soil moisture. There was also evidence that additional PAR was captured at the system level in both mixed cropping (trees + annual crops) and intercropping (annual crops + annual crops).

Overall, mixed cropping with fruit trees appeared to be a case of enhanced exploitation of the available niche space, and evidence of facilitation of growth or yield was quite limited. Some indications of component facilitation were present in intercrops and pear + fava mixed cropping and it is likely that facilitation in both cases was dependent on the capture of additional PAR. The results were also consistent with the known ability of fava bean to exploit symbiotically N_2. The improved performance of systems containing favas might be due to an increased pool of plant available N within the system.

While the majority of the individual component interactions were negative for individual species, the overall response of mixed systems was strongly positive compared with the relevant individual crop alternatives. The interaction experiment showed fruit-tree-based agroforestry is advantageous when measured as returns to land area (LER) or land area duration (ATER), as economic returns, or as glucose-equivalent energy accumulated in the harvested yields. The benefits in returns to land area were also due to increased duration of cropping within fruit-tree-based agroforestry, but the advantage was still large when differences in the time that each crop occupied the land were accounted for. Thus, mixed tree-crop systems had demonstrable advantages over components grown separately on a continual basis.

Mixed cropping systems increased the energy value (as glucose equivalents) of the economic yields only slightly compared with sole cropping. Maize was the dominant source of energy in the mixed systems indicating that it is important that maize be included to maintain high productivity with the three studied components. Additionally, the differences between intercrops of maize + fava and mixed crops of pear + maize +

fava were small, suggesting that just adding a component to the system does not ensure productivity increases.

The economic value of the yields harvested from sole crops, intercrops, and mixed crops showed that value was enhanced by the introduction of high-value perennial crops into the cropping system, but without substantial increases in the glucose equivalent output of the system. The economic advantage was therefore realized by shifting the system output from a relatively high-energy but low-value crop, like maize, to pear, a low-energy, high-value substitute. The particular production needs and goals of individual producers need to be taken into consideration for optimizing the system composition.

Further economic analyses are warranted to estimate better the net benefits that the systems would provide to adopters. The study also indicated the importance of food security in permitting a shift to higher-value production mixes by small holders. Analysis of the socioeconomic status of potential adopters showed that farmers' particular circumstances, encompassing issues such as seasonal food shortages, low crop yields, or large family sizes may limit greater levels of adoption by farmers. It is possible that the lengthy time between establishment and first harvest of fruit trees negatively influences families that are have food security concerns or are less secure economically.

Complementarity Within the Socioeconomic Framework

The characterization of the two communities studied in western Guatemala revealed differences that extended much deeper than what would be suggested by preliminary demographics. One of the villages, Cabrican, exists as a community still dependent on subsistence highland agriculture to meet the needs of many of its inhabitants. This is in direct contrast to the other study-village, Chuculjulup, where substantial integration into the greater market economy has taken place. Inhabitants purchase a greater portion of their consumption needs and derive a higher fraction of their incomes from non-agricultural sources. In turn this has permitted the indigenous families in the area to remain at much higher population densities.

Fruit production is an important aspect of farming in both communities; however, the impression remains that fruit sales are of much greater importance to families in Chuculjulup than in Cabrican. Simulation modeling of farmer options for resource allocation and production alternatives indicated that principal crop yields rather than land holdings were a critical issue and that fruit-tree-based agroforestry would be very popular where subsistence needs could be satisfied. Further use of cropping systems simulations holds promise to guide future development efforts and achieve improvements in quality of life and economic status in the areas.

The study showed that fruit-tree-based agroforestry is not likely to be scale neutral in its effects. Larger, economically more stable families are more likely to be adopters compared with more marginal households. It appears unlikely that fruit-tree-based-agroforestry will supplant maize-based cropping, but when family consumption needs for maize have been met, establishment and management of fruit-trees among annual crops are very popular additions to the suite of farm activities. This highlights the need for a coordinated and holistic team approach to the small farmer’s fields with emphasis on increasing annual crop yields as a strategy for augmenting overall productivity through species diversification and fruit-tree-integration on farmlands.

Adoption-limiting Factors

Adoption of mixed cropping requires sufficient flexibility by the producer to accept changes in the percentage of the total yields coming from an individual component. This may limit adoption where an annual component is critical to food security and is in limited supply. When available land or crop yields present a constraint to farm productivity, some families probably cannot adopt the technology since doing so would reduce crop yields to a small but unacceptable degree. In spite of the biological and economic superiority of the fruit-tree-based systems over annual crop systems, the risk inherent in producing and marketing a perishable commodity in an infrastructure-limited region such as Guatemala's northwest *altiplano* reduces its overall attractiveness.

Availability of quality planting materials is another important consideration in the context of adoption of fruit-tree-based agroforestry systems. Observed low levels of management contributed to low yields and potentially limited the fruit quality. Suitable management strategies coordinated with the developmental phenology of the fruit varieties and their responses to the unique climatic conditions found in subtropical highland are also lacking. Most published information has been drawn directly from temperate sources with very limited investigation of its applicability. Farmer participants stated strong desires for additional information on fruit tree management and observations of incorrect practices in the field further reinforce the need for direct extension and training to support family-based fruit production.

Further study of the effects of improved on-farm management of fruit trees and the marketing outcome from the additional resource allocation is warranted.

Adoption-promoting Factors

In spite of the above shortcomings, fruit trees were overwhelmingly popular among farmers in both communities. More than half the families with trees were engaged at some level in the marketing of their fruit. An implicit point is that families are producing a large amount of fruit for their own consumption thereby improving their quality of life.

The fruit harvest in the region occurred mainly during the interval between the final hilling of maize and its harvest, thus complementing the dominant maize cropping cycle well. The income that can be earned from fruit sales through any of the available market channels comes at a time when families are most likely to have run short of maize from the prior year's harvest and be engaged in food purchases for daily consumption.

Immediate research needs for smallholder farmers in this area of production should focus on the development and testing of management techniques intended for limited resource production scenarios where the fruit trees will be grown in mixtures with annual crops as is currently practiced. Appropriate tree densities are likely to be substantially lower than what is acceptable for commercial orchard operations, although definitive research results to support this contention are lacking. Such strategies should furthermore not emphasize irrigation or spraying as techniques required for adequate production.

The development of more equitable support mechanisms and infrastructure could enhance farmers' ability to benefit from this form of agricultural intensification. There is little potential for the expansion of fruit exports to outside the Central American region, however, current practices fill a valuable niche and the failure to support and encourage this form of land use through refinement and extension can only have negative consequences for rural Guatemalans and the country overall.

Implications for the Field of Agroforestry

Benefits from the establishment of fruit-tree-based agroforestry systems are produced by several mechanisms. These include the redistribution and additional use of growth resources. The first occurs when the inclusion of perennial fruit trees results in a redistribution of available growth resources (light, water, nutrients) between the system components and produce a different suite of yields. Due to differences in photosynthetic efficiencies, cropping duration, and response to climatic factors, additional relative yields are realized and total productivity increased.

Furthermore, some combinations of products are of inherently greater value to the producer and provide an additional or alternative source of economic benefits. Therefore, the increased relative yields can have benefits accruing either from greater overall outputs and/or an increased value of the yield suite.

Perennial components can exploit a larger pool of resources or permit the overall system l to capture more resources due to niche differentiation than by monocultures alone. Data on soil water status and tree transpiration were collected to evaluate the extent to which additional soil water was used to achieve the observed responses. These data are e not presented here, but will appear separately in forthcoming publications.

Future Research Implications

This study found evidence that both above- and belowground effects are influential in the overall performance of the fruit-tree-based agroforestry systems in western Guatemala. Furthermore, one annual understory crop differed significatively from the other in its performance and effects when cropped among fruit trees. Additional studies are needed to identify and evaluate crops with good or superior performance beneath fruit trees. For example, cucurbits (squash), a component of the local cropping system, may be included in further trials.

The results from the on-station experiments showed higher than expected performance in pear in the presence of fava bean. This result was not well explained by the data presented in this study. While the pear responses were suggestive of altered water balances that favored fruit yield, it was not possible to reject or confirm that an increased pool of available nitrogen was responsible for these findings. Additional studies should be conducted with pear and non-vining legumes with greater attention given to N_2 fixation and tree-crop nutrient status.

The findings of this study were diminished by the original choice of clean cultivation control treatments for fruit trees. In future research, fruit-tree mixed cropping should be compared with a grass/weed sod understory or ring weeded trunks, the standard practice for the region where fruit trees are grown alone.

Unlike most trees that are grown for timber or biomass, fruit trees have historically been managed to encourage light penetration into their canopies, with concurrent greater transmission into the understory. Effective pruning and establishment regimes to optimize production with a range of annual crops are an unexplored area critical for nonindustrial producers. Fruit trees are commonly produced from at least two separate genetic individuals. One individual is selected to confer desired characteristics on the fruit and canopy, while the other independently provides features desirable in the root system. While selecting for tree height it is likely that a range of root structures has also been segregated. This aspect of fruit-tree-based agroforestry provides a unique opportunity to explore and manipulate system components to better understand and ultimately design for superior interactions. Studies evaluating tree and crop performance by comparing (root stock x annual crop) effects will provide the information fundamental to understanding belowground interactions between fruit trees and crops and allow the potential interactions to be made optimal for farmers' production goals.

The potential for linear programming as a planning tool for development, particularly when considering agroforestry technologies, remains large and merits further application. In this study, a large range of activities was considered in detail, yet some important issues such as yield responses to differential management and flexibility in the management of fruit trees were not addressed. It was quite clear that farmers were dynamically making choices about their resource allocation based on actual occurrences during the year. For example, farmers cease to weed maize plots that are poorly established, stunted, or lodged. They use the labor in other areas and accept the poor yields without further investment. A different approach to yield modeling that incorporates the additional production expected from additional resource allocation is warranted. This observation holds for the majority of activities modeled in this study. Additional research is required to characterize the effect of management on fruit production as the current study assumed higher levels of labor than actually required for trees to survive and produce fruit. Without further study, it is not possible to deny that benign neglect of established trees is the most advantageous strategy for resource-limited smallholders.

As with most of published agroforestry experiments, limitations in the amount of time that treatments could be applied and the responses measured affected the conclusions that could be drawn. In the study, interactions were observed between eight-year-old pear trees and annuals during the year that the treatments were applied and the following year. Differences were observed in the responses of both crops and fruit trees between the two years. While it is assumed that the year two responses are more indicative of the true nature of the interactions, there is no reason to expect year three observations, which were not made, would verify those of year two. Farmers are working in fields where trees range in age from one to at least forty years. The length of time before the interaction effects stabilize – or if they indeed do stabilize – is unknown; only long-term studies will provide an answer.

Numerous socioeconomic factors that influenced the performance of the mixtures were identified and discussed. Many of the factors, such as market limitations, low subsistence crop yields, regional niche opportunities for production, and farmer desires for diversified diets and food security are not unique to the Guatemalan highlands. Overall, this study provides strong support for the study and promotion of fruit-tree-based agroforestry among small holders in highland tropical and subtropical environments. In order to address the ongoing fragmentation and degradation of these environments and the concomitant reductions in quality of life among families living in these environments, additional research and extension are warranted.

APPENDIX A
SONDEO NOTES FORM

Personas en Casa _________ Tierra en Casa ______Cds.
Total Extensión de Tierra _______Cds. Tierra afuera de Casa______Cds.
Tierra en Monte ________Cds.
Casa- (Bloc) – (Madera) – (Adobe) Aldea________________Chuculjulup___________

Nombres de Familia	Edad	Gen	Educ.	Trabajo afuera	Horas semanal Ganancias

Fertilizantes/Cds ________
Maíz Consumo/men ________
Ha Usado semilla mejorada (Si) (No) -------- Tipo _____________________________

Cultivos	Extensión	Rend.	V	Cultivos	Matas	A/S	Rend.	Fecha Cos
Maíz - Piloy				Duraznos				
Hortalizas				Manzanas				
Maíz				Peras				
Maíz Piloy Haba, Ayote				Variedad.				
Papas								
Trigo		Pollos #			Vacas #		Patos	
Cabras #		Ovejas #			Pavos #		Coches #	

Compras de Maíz (qq)____________ Fechas de Sembrar _______________
Meses de comprar Maíz_________ Fechas de Cosechar_______________
Otras compras del mercado____
Alimentación de Animales____
Otro gastos de pisto____

APPENDIX B
VALIDATION SURVEY FORM

Encuesta Agrícola de Productores de CHUCULJULUP Por Ing. John Bellow

Demografía:¿ Cuantos viven en la casa y cuentan con el derecho de comer lo que tiene la familia?
Numero de miembros de la familia?___________

Sexo (M / F)	Edad	Nivel Educativo (P / S / D)	Trabajo no Agrícola ? (¿Cual es?) y (¿Cuantos jornadas semenal)

¿ Cuantas mujeres? ______________ ¿ Cuantas Personas menos de 12 años?________ ¿ Cuantas entre 12 y 18 años? ______
¿ Cuantas hombres?______________ ¿ Cuantas personas mayor de 18 años?_________

Practicas Agrícolas: ¿ Cuantas cuerdas están cultivadas de cada cultivo o asocio de cultivos (Solo los que tiene la familia)?

Cultivos *Cual indica mejor lo que tienen*	Cds	Rend. (Unidades) /cds.	Fert (Libras/cd) 15-15-15 45-0-0 orgánico	Fechas de sembrar y cosechar	**Cultivos** *Cual indica mejor lo que tienen*	Cds.	Rend. (Unidades) /cds	Fert. (Libras/cd) 15-15-15 45-0-0 orgánico	Fechas de sembrar y cosechar
Maíz - Piloy o Frijol					Papa				
Maíz - Piloy o Frijol Haba, y Ayote					Trigo				
Maíz Piloy o Frijol Haba					Avena				
Maíz y Haba					Hort.				
Maíz					árboles				
Haba									
Frijol									

¿ Ha Usado Semilla Mejorada o Comprada? Si____ No____ ¿ De cuales cultivos?__________________
¿ Usaban brosa o estericol en sus huertos Si____ No____ ¿ En que cantidades? _________________

Frutales: Cuantas matas de cada tipo de árbol cuida la familia?

¿ Cual especie?	¿ Cantidad de matas **productivas?**	¿ Cantidad de matas **No productivas?**	Rendimiento por una mata (qq) o libras	Época de Cosecha
Duraznos				
Manzanas				
Peras				
Otras				

Manejo de fruta:

¿ Vendieron frutas de cualquier tipo este año o el año pasado? Si_______ No _______
¿ Cuales Frutas vendió?___________________________ Valor de frutas vendidas___________
¿ A quien las vendieron? (Particulares) (Rescatones) (Otros) ________________________________

¿ Fumigaban a las matas? Si_______ No________ ¿Aplicaban fert. químicos? S__N__
¿ Hacían una poda de las arboles? Si_______ No________ ¿Hicieron un raleo de las frutas Si__No__

¿ Aplican cal a los troncos? Si_______ No________ ¿Aplicaban abono orgánico ? Si___No___

Agropecuaria: ¿Cual animales cuida la familia?

Animales	**Cantidad (cabezas)**	**¿Leche diario? (litros)**	¿ Que Alimentación?	Cantidad diaria de alimentación?	Valor por cabeza Q
Vacas					
Toros		XXXXX			
Ovejas					
Cabras					
Coches		XXXXX			
		¿ **Huevo diario** ?			
Pollos					
Patos					
Pavos					
Caballos		XXXXX			

Vende animales _____ Vende Leche _____ Vende Queso _____ Vende Huevo _____ Vende Lana______

Alimentación familiar: Que prepara y come por la familia

Consumo de Maíz diario _______ libras   Consumo de Frijol, Piloy, o Haba (diario) o (Semanal)_______ libras
Consumo de carne semanal _______ libras   Cuantas tortillas o tamalitos se prepara diario_________

Gastos del Mercado para comida: Incluye sal, azúcar, aceite, chili y todo:
Total para una semana __________Q
Gastos de Verduras __________Q   Gastos de pan ___________Q
Gastos de carnes __________Q   Gastos de granos secas ___________Q

Otro gastos de pisto para cosas no comestibles __________Q

¿Compraron maíz el año pasado?   Compras de Maíz (qq)   Si_____ No______

Meses de Comprar Maíz   Empieza________________________   Termina____________
¿ Cuantos quintales compraron en todo? __________qq

Uso de leña:
¿ Cuanto leña usa la familia? (Tareas por mes o semana) ______________________________
¿ La compraron or recogieron? ____________________   Costo de leña ________________Q/Tarea

¿ Tiene un vehiculo?   Si o No

Propiedad: Toda la terreno que pertenece a todos los que viven en la casa (la suma)?______Cds.
Terreno alrededor de la Casa______Cds.   Terreno lejos de la Casa______Cds.
Terreno en monte o barrancas ________Cds.   Otros Terrenos______Cds.

Nombre Familiar _________________________   ZONA___________

APPENDIX C
MICROCLIMATIC COMPARISONS IN THREE HIGHLAND SITES

During 2002, temperature, precipitation, and solar radiation data were collected in both Cabrican and Chuculjulup. Degree day accumulations were calculated using equation C1 (Ritchie and Nesmith, 1991) and a base temperature of 8.0 °C.

$$t_d = \sum_{i=1}^{n} \left(\frac{(T_{\max} - T_{\min})}{2}\right) - T_{base} \qquad \text{Eq. C1}$$

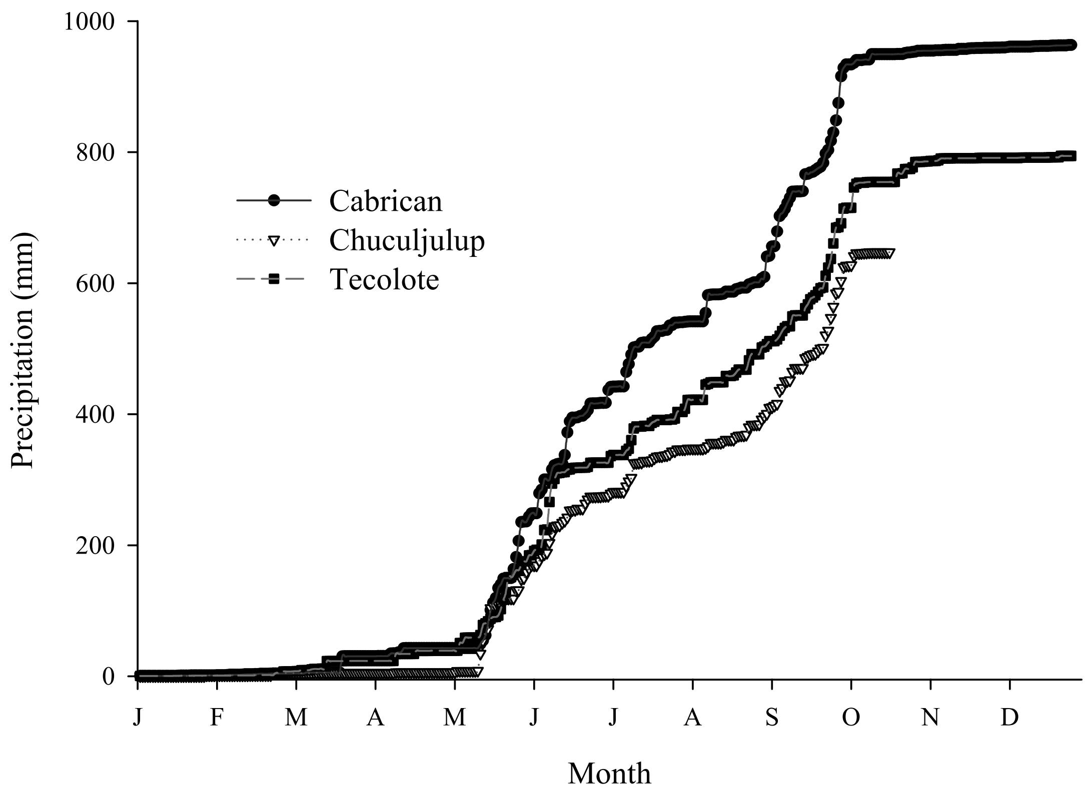


Figure C1. Cumulative precipitation (mm) as recorded in Cabrican, Chuculjulup, and at the El Tecolote station in Labor Ovalle, Quetzaltenango during 2002.

Total precipitation was greatest in Cabrican with 963 mm, and least in Chuculjulup with 647 mm through 21 Oct. (Figure C1). A total of 794 mm of precipitation were recorded in the Tecolote site.

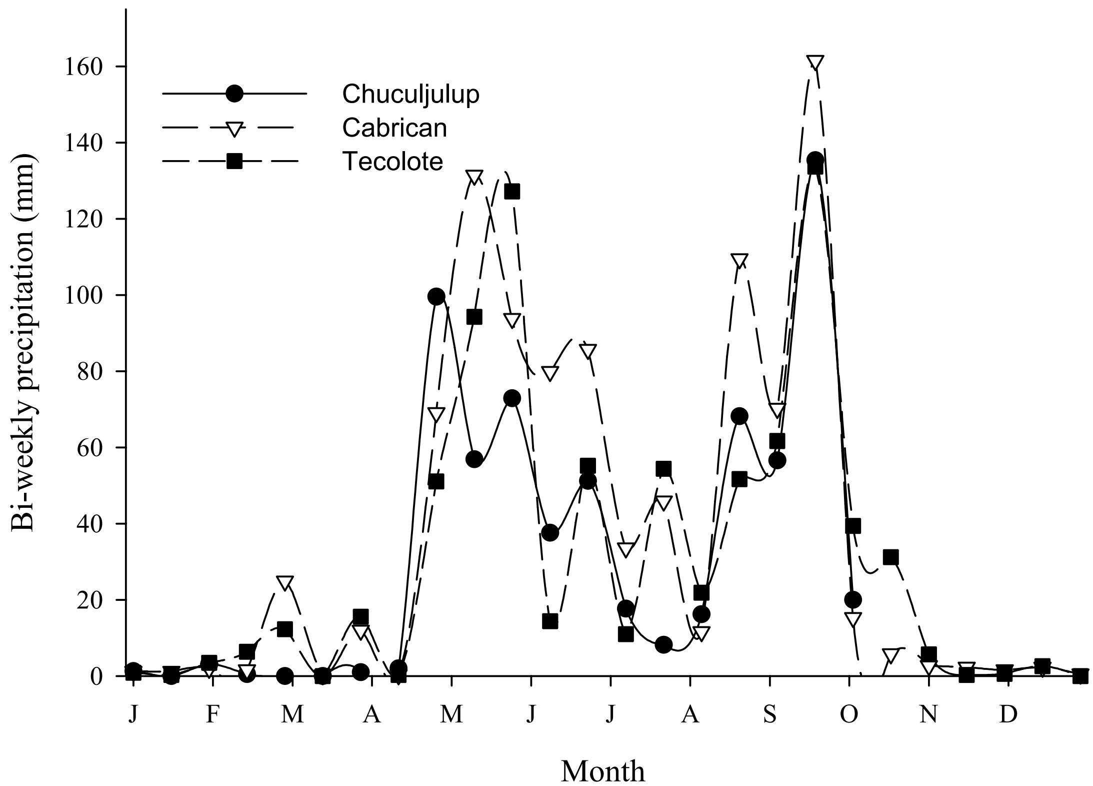


Figure C2. Precipitation totals for 2-week periods during 2002 in three highland sites.

Few major differences were observed in the timing of precipitation patterns in the three communities (Figure C2). During 2002, total precipitation during the critical planting period of Mar. and April was higher in Cabrican and Chuculjulup than in the Tecolote. It is likely that the July dry period was shorter in Cabrican. In the Tecolote, the rains lasted slightly longer at the end of the growing season.

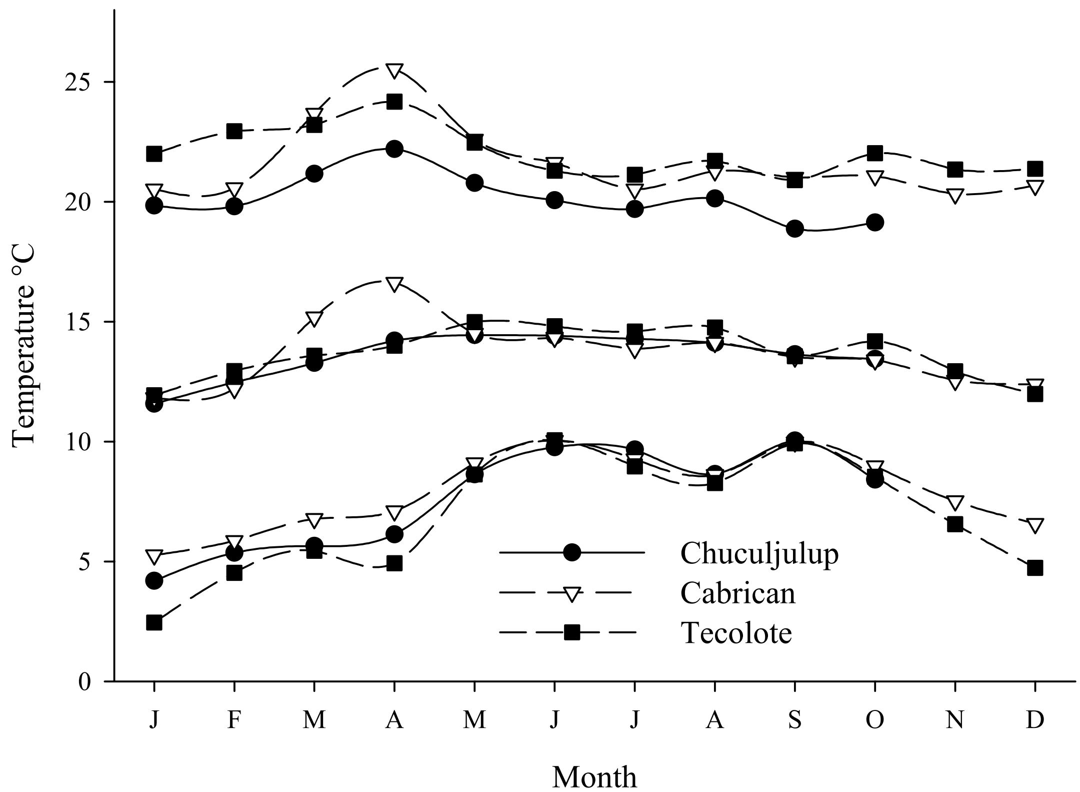


Figure C3. Monthly mean temperatures in three sites in the *altiplano* of Guatemala during 2002.

Assessment of temperature differences revealed that Chuculjulup with a mean temperature of 13.6 °C, was cooler during 2002 than either Cabrican or the Tecolote with yearly mean temperatures of 13.7 °C (Figure C3). The principal difference is in the consistently lower maximum temperature in Chuculjulup. Calculation of degree days accumulation showed a reduced accumulation in Chuculjulup during 2002 (Figure C4). Differences between the three sites at any point during the normal crop season were small. Cabrican had the greatest accumulation for the period from 1 April 2002 through 21 Oct. 2002 with 1526 °d. The Tecolote site recorded 1467 °d, while only 1319 °d were recorded in Chuculjulup.

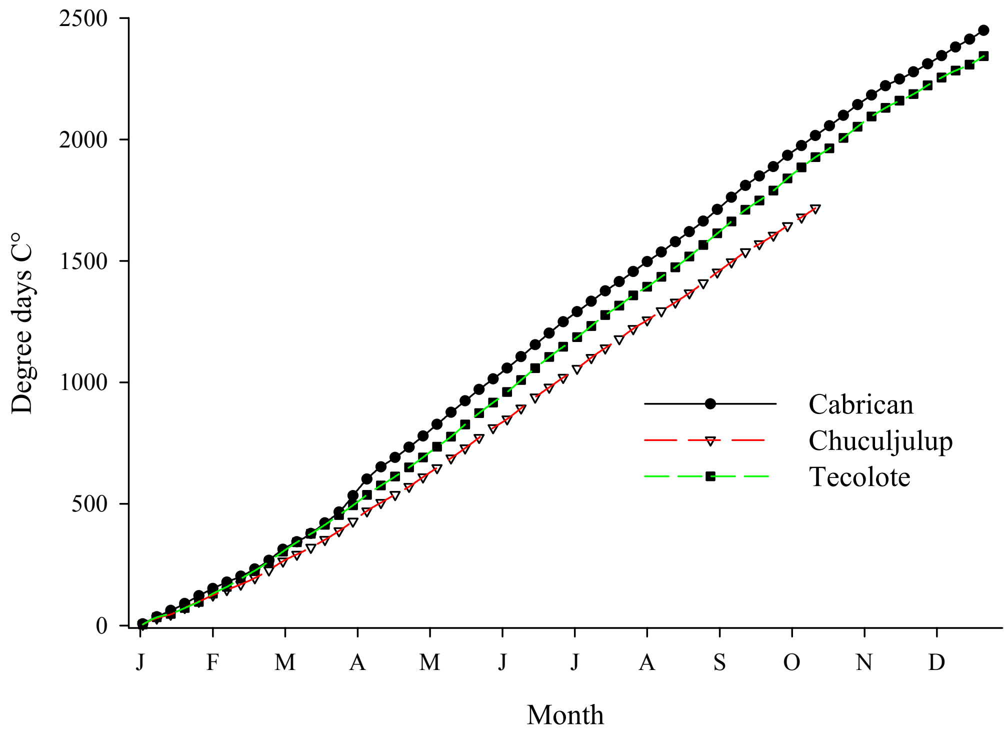


Figure C4. Degree day accumulation recorded during 2002 at three research sites in northwest Guatemala.

Evaluation of community microclimate provided at least an initial glimpse into the role of spatial climatic variability in crop yields. The results from 2002 do not provide any reasons to believe that potential biological yields in the communities differ substantially from each other or the research station due solely to edaphic conditions. Additional years of observation would be needed to suggest any systematic differences between the sites. Rather, germplasm differences, local topographic and soil conditions, and wide variations in planting dates more likely contribute to the observed yield differences. While this is in contrast to the statements of Redclift (1988), it should not be construed to indicate that dramatic differences in weather pattern over small spatial scales do not exist in the *altiplano*.

APPENDIX D
FARM ACTIVITIES DESCRIPTIONS

Annual Crop Characterization

Maize Variants

Cultivation of maize is the principal land use in both communities. Four races of maize based on grain color (white, yellow, blue/black, and red, as well as mixed ears) could be found in any of the cropping variants and frequently on the same farm though seldom in the same stand. At least four distinct varieties of climbing beans based on flower and bean color were also common. Two distinct squash varieties, *ayote* (*Cucurbita pepo*) and *chilicayote* (*Cucurbita ficifolia*) were present, frequently together. Substantial variation in farmers' planting practices were observed. These variations appear to follow primarily from individual preferences and generalized descriptions are presented with the understanding that the full range of variation was observed.

In most of the region, agriculture is based on sophisticated and well-understood strategies to regulate and manage residual soil water from one season to the next. Farmers classify their land relative to its likely moisture content prior to the beginning of the rains that begin with regularity in mid-May. In Chuculjulup, fields located in the flat part of the community were recognized as being moister than those on the hillside and farmers frequently indicated they had plots in both locations. In Cabrican, the delineations were not so fine-grained. Several *aldeas*, such as *Buena Vista* and *Chorjale*, were thought to be moister. Moister land is planted first in all locations. Farmers state that late March through early April is the preferred time to plant maize. An intermediate situation is where farmers determine that the parcel is deficient in soil moisture, but that it can be corrected by filling each planting hole with water prior to planting. These areas are planted second. The final case is fields too dry to be planted until it rains and these fields may not be planted until May.

In order to enhance soil moisture status for the following year, one to two weeks following harvest in November through January, farmers dig up and bury all plant residue in their fields and leave them with hilled beds 1.0 m wide and roughly 0.3 m tall into which the following year's crops will be sown. If the field is not to be planted in maize the following year, it will be left untended until the following rains. This explains the singular disinterest that farmers have shown in any type of cover cropping or green manure production. In the spring of 2003, we observed a clear demarcation in the soil moisture between where maize had been planted and where sole crops of fava had been grown. The fava was harvested in mid-October and had permitted a crop of weeds to establish before the entire field was worked. The weeds reduced soil moisture levels to the point where these areas were not suitable for planting in early April.

At planting, the dry dust mulch is removed from the shoulder of the bed to reveal a wetter layer below. The moist layer is cultivated and seeds planted. The dry soil is then returned in a thin layer to impede evaporation of the residual moisture. If organic matter such as forest litter, manures or bedding is applied, it is added at this time. The maize variants are planted at 0.8 to 1.2 meter between rows with 1.0 m being the most common. Planting distances within rows range from 0.5 to 1.1 m. Farmers state that closer planting distances make later management difficult and increases the amount of labor involved in planting. Maize seed is planted at a rate of 3 to 7 seeds per planting site giving stands with final densities between 25,000 to 55,000 plants ha^{-1}.

In fields where *Phaseolus coccineus* (*piloy* or runner bean) will be grown, the seed is always planted in the same hole with the maize seed. Farmers sow at a rate of two seeds per planted site which ranges from every second to fifth hill of maize. In fava variants, frequently the maize planting distance is greater (0.9 to 1.1 m) within rows and the fava is planted in the interspaces. Two seeds of fava are commonly planted between each hill of maize or where other components are present between every second or third hill. This provides stand densities of 1600 to 4000 climbing beans ha^{-1} and 4000 to 8000 favas ha^{-1}. Squashes may be present at rates of 180 plants ha^{-1}. A substantial fraction of plants may derive from volunteer plants that farmers then transplant or manage in place. This is frequently the case with *chilicayote*. The *ayotes* are more likely to be planted purposefully.

Maize-based crops are weeded two or three times during the season. The first weeding occurs with the first fertilization. The fertilizer (15-15-15 or 20-20-0) is placed to one side of the hill using the hand or a bottle cap to measure. The soil from between the rows is then scraped to one side and mounded over the fertilizer and against the young plants. This activity takes place shortly after the rains have begun (late May) for early planted fields and perhaps one month after planting for later crops. The next weeding occurs when the rows are hilled up. A large fraction of the inter-row soil is dug up to be mounded against the developing crops. This practice leaves a clean plot and trenches up to 0.2 m in depth between rows. This practice takes place in early June or July for later plantings. The second fertilization, using urea (45% N), is applied following this hilling up. Most commonly a stick or other implement is stuck into the hill to open a hole where the fertilizer is placed and the hole is then covered. The final weeding may occur in September if a large volume of weeds has grown within the field. The weeds are cut and removed to feed livestock and make entry to the field easier at harvest. Harvest in these systems begins in late October when fava is harvested if present. Climbing beans are harvested as they ripen, which generally coincides with or follows the harvest of maize. Maize harvest occurs between early November and mid-January depending on the location and planting date. Harvesting of maize may involve the cutting and piling of all ears and stalks after which ears are separated and moved to the house for husking or the ears may simply be removed from the standing stalks by men. In taller maize varieties, women and adolescents, who do a large fraction of the labor, find the second option more difficult. The final stage is the husking where husks are removed and classified to be used in the household, sold, or fed to livestock Some skill is involved as the husks of large ears are removed without tearing to be used as wrappers for cooking throughout the year. The ears are placed on roofs, patios or courtyards for 2 to 3 weeks to air dry; after which they are stored. The stalks are stored for feeding livestock, sold to neighbors, or traded for organic matter. In the case of a trade, farmers consider that the stalks for livestock are roughly as valuable as the amount of mixed manure and bedding that is needed for the area that produced the stalks.

Fava Sole Crops

Sole crops of fava are planted as soon as soil moisture conditions will allow. Farmers recognize that the large seeded variety needs a great deal of moisture relative to maize to germinate. However, here the addition of water to the planting site is common to facilitate an early planting (early March) and early harvest (August to September). Plants are frequently planted on land prepared as for maize or leveled without beds. Two seeds are planted at 0.8 to 1.0 m between rows by 0.4 to 0.6 m within rows to give stand densities of 33,000 to 65,000 plants ha^{-1}. Fava crops receive a single weeding, and at the same time that they receive 250 kg ha^{-1} of 15-15-15. As with maize, the fertilizer is placed to one side and covered with soil scraped from between the rows. Farmers may make a second cleaning when additional soil is placed against the base of the plants to prevent lodging. Three factors appear critical in the success or failure of fava crop. Within both communities fava is susceptible to several rusts (*Uromyces* spp.) and viruses transmitted by aphids. The first factor is severity of the rust and viruses based on weather conditions. The farmer's ability and willingness to spray against aphids and rusts is the second. The third may be the degree to which the plot is maintained free of weeds as cleanly weeded plots were observed to have a lower incidence of rusts in 2002. Favas are prone to shattering and harvest requires several pickings as the pods ripen.

Potato Systems

Potatoes are not as common in the two communities studied as in other areas in the *altiplano*. Land destined to be planted to potato is frequently left unprepared during the dry winter months. When sufficient rain has fallen and frost danger has diminished, the land is cultivated by hand with residues being buried and the surface left flat. Trenches are opened and potatoes planted in the bottom at rates of between 2500 and 4100 kg ha^{-1} of seed potato. Seed potato is generally not cut before using. Insecticide, organic matter, and fertilizer are often applied in the trench before covering. When used, Furadan or its equivalent is applied at 30 kg ha^{-1} to control worms. Chemical fertilizer

(15-15-15) is used at rates of 500 kg ha^{-1}. Farmers stated that they often mix the fertilizer and insecticide directly into their organic matter and apply it over the seed potatoes which are subsequently covered with soil. The next step is the cultivation, to a depth of 10-15 cm between rows that occurs shortly after emergence. The process both eliminates weeds and increases water penetration into the beds. Varieties of potato that require little fumigation are not popular with industry, and farmers must fumigate against late blight between 10 and 16 times before harvest to avoid premature death of the potatoes. Blight-resistant varieties for Guatemala are available but are unpopular for the export or industrial markets. Spraying may take place as often as three times per week and the labor and expense involved is one reason farmers give for not growing more potatoes. One week prior to harvest, the potatoes are defoliated manually and tops left in the field. The planting and harvest labor crosses gender divisions with women and men engaged in all activities at times. The harvest entails digging up the potatoes, sorting them by size into at least two commercial grades as well as potatoes for the household, bagging into 46 kg sacks, and moving them to the pickup point. The earliest plantings produce a July or August harvest while the latest are harvested in late September.

Wheat and Oat Systems

Wheat is grown by a small fraction of farmers in both communities. Farmers believe that wheat and oat are low labor-demanding crops. Wheat land is prepared just prior to planting in a similar manner as for potatoes with residues being buried or burned and a well cultivated surface left for broadcasting the seed. Wheat is seeded at a rate of 150 kg ha^{-1} in June. At the same time, fertilizer (15-15-15) is broadcast over the seed. The soil is scraped or raked lightly over the seed, which then germinates. Approximately

5 weeks after planting the stand is weeded with 2-4-D and fertilized with urea again. In December or early January, the stand is cut and bundled. The bundles are carried to an appropriate waiting point and stored until a mobile threshing machine passes. Wheat threshing is charged by the weight of threshed grain which averages 2000 kg ha^{-1}. The straw is considered as good or superior to maize stalks as dry feed for ruminants and is frequently sold or used for this purpose. Additionally, many bed mattresses in the highlands are stuffed with straw and it can be sold in the field for this purpose.

The management of oat in the highlands is similar to wheat in the steps that are required, however oat differs greatly from wheat in several key areas. The first is that oat is grown for the purpose of feeding ruminant livestock, particularly dairy cows. While oat is consumed as a breakfast cereal and beverage, families generally do not consume their own production. Difficulties getting oat threshed were mentioned by several producers as an explanation of this phenomenon. The second is that there are two cropping periods for oat in the communities. The first crop can be sown in the same manner as wheat in early May. This crop is not weeded and is harvested before maturity for use as green forage in August. Frequently it contains substantial fractions of wild mustards (*Brassica* spp) and vetch (*Vicia* spp.). A second crop can be planted in September and harvested in February. The second cropping provides nutritious forage during the dry season when forage is scarce. Oats harvested in February may yield 1100-1300 kg ha^{-1} of grain and 2000 kg ha^{-1} of straw. Oat straw is considered superior to either wheat straw or maize stover as dry feed and is highly valued for this purpose.

Fruit Culture

Common fruit crops in Cabrican and Chuculjulup were apple (*Malus* spp.), white- and yellow-fleshed peach (*Prunus* spp.), pear (*Pyrus* spp.), plum (*Prunus* spp.), and cherry (*Prunus* spp.). Additionally, avocado (*Persica* spp.), passion fruit (*Passiflora* spp.) and prickly pear (*Opuntia* spp.) were observed as managed cultivars. Both systematic planting of trees in an orchard-like arrangement and dispersed trees throughout fields and household areas were observed. Seedling trees were more prevalent than grafted trees and this problem was exacerbated through pruning practices which resulted in multiple-trunk bush-like trees where the grafted variety had been lost. Demand for quality seedlings is high within the communities and all trees that were brought to the community by the investigator were purchased informally at market prices.

In both communities, management of fruit trees is complicated by the climatic conditions that permit flowering in October and November as well as in February through April and leads to potential harvests in April through June or July through September. Peach is particularly susceptible to the frosts that may occur; early harvest of peach, although more valuable, is less likely. Apple is more frost resistant. Pear, at least, entered ecodormancy and there is not a reliable spring harvest.

Farmers' management practices ranged from "we pick the fruit and eat it when it is ripe" to farmers who engaged in all recommended practices to some extent. Little previous research could be found to permit evaluation of the impact of poor to excellent management on yields, quality, or sales in subtropical highland areas, so it was assumed that some management would be required to obtain average yields. Lime, normally without copper sulfate, is applied to the trunk and branches of the trees during the dry season (Dec. to Feb.). Farmers who engage in this practice claim that it "protects the bark from the sun" or that it helps to kill fungus or pests. Structural pruning of trees may also occur during this time when growth is at a minimum. No information was available to assess the effects of dry season pruning on subsequent growth patterns in the subtropical highlands. Fruit thinning may take place in the dry season. Thinning in this region leads to larger fruit sizes, however few farmers said that they thinned their trees and the general perception was that it would reduce yields. During May and June, organic matter in the form of leaves and residues or bedding mixed with animal manures may be applied within the drip line of the trees. This activity occurs in concert with weeding this area beneath the crowns. Where trees are associated with other crops, the area is cultivated as part of the land preparation and no additional activity taken. Organic matter applications are less common where trees are mixed with other crops. According to several growers, weekly fumigations with fungicides from May to Aug. may improve the visual appearance (and value) of apple and peach but this does not appear as critical for pear.

Harvest takes place over a 6 to 8 week period depending on fruit variety. Peach is harvested first, followed by apple, and finally pear. The largest, ripest fruits are harvested from the trees several times per week. Fruits are classified based principally on size, and may be stored for home consumption or sold. Three mechanisms for fruit sales were identified. Fruit may be sold to *rescatones* or wholesalers, who arrive in the communities with trucks and make cash purchases of 46 kg sacks or boxed fruit. Fruit may be sold by weight in the case of apple and pear or per fruit, which is more common for peach. Yellow peaches command higher prices than the white ones. This fruit is destined for regional markets or exports within Central America. Farmers mentioned El Salvador as the main destination for their fruit. Fruit may be transported to local markets which occur at least twice weekly. There the fruit is sold per fruit or per pound to the final consumer or to wholesalers when demand for fruit is high. Farmers state that competition lowers the price they receive for fruit at the market, but it is always better than what middlemen offer. The final option is door to door sales. Farmers suggest that 50 kg of fruit may be sold during a day of selling and that prices are more than the price received at the market.

Livestock Systems

Farmers in this region keep a number of types of livestock ranging from cows to poultry. Generally, communal land such as high pastures and road rights of ways are used to provide forage for ruminants. Supplemental feed and crop residues are provided to livestock particularly during the dry season. For poultry and pigs, food-scraps, rotten food, and purchased supplements are frequently provided. Poultry and pigs are most frequently permitted to range freely though pens for pigs are not uncommon. Sheep are dependent on communal pasture lands for the bulk of their forage needs. The daily care of livestock is realized primarily by women who are present in the household during the day, although men may participate to some extent. The most consistent expectation of men is that they provide cut, dry feed during the dry season and concentrates where used. Cows are put on pasture or fed cut, fresh fodder daily. Grazing entails at least 2 hours of labor daily regardless of the number of animals. If cows are not grazed, an equal amount of time must be spent in cutting and carrying fresh forage. In the communities studied, adult cows are sold mainly for slaughter and the market for purchasing is limited to immature cows. Dairy production is the principal motivation for keeping cows. Milk production begins following the birth of a calf after a nine month gestation. A newly freshened cow may produce between 8 and 12 L of milk daily which is sold to resellers at the farm gate. Milking cows require additional feed (2.5 kg day^{-1} of concentrate) to maintain their production. Forage is limited during the months of December through May, when cows are fed recently harvested maize, wheat, and oat stover. The right to cut and remove these residues often is purchased from families without livestock. Dairy cows produce enough manure mixed with bedding during 1 year to meet the organic matter application for 0.13 ha. Farmers have an expectation that sufficient manures to apply to an area of land can be traded for the maize stover that was produced within the area.

Sheep and goats require similar labor investments as cows. Both must be put on pasture daily except during the dry season when cut forage (both fresh and dry) may be more common. Consumption and manure production are less per head than dairy cattle. Neither sheep nor goats are highly valued for their meat within the communities. Goats are frequently milked, producing 1 to 2 L daily. Sheep are kept primarily for wool production (1.0 kg $head^{-1}$ $yr.^{-1}$).

Swine are more common than sheep or goats, however farmers frequently lament the low profitability of pigs. The pigs are frequently confined to pens at night and staked out on ropes during the day. Farmers estimate 0.5 hrs day^{-1} are required to tend to all the needs of one to several pigs. Farmers expect that it takes between 4 and 8 months to produce a pig for butchering. The difference is based on how much is fed daily. Pigs may be fed grain polishings or brans, concentrates, potatoes, maize, food scraps, crop residues or free range. The most profitable aspect of swine herding is the production of piglets. Farmers anticipate that an adult sow can produce its own value in offspring (mean of eight piglets) every six months. Families rarely keep a boar and several farmers stated that breeding can be an uncertain prospect as the sow's heat must be recognized and taken to stud in a timely manner in order to produce offspring. There is a fee (Q 25.00) for the service.

Farmers kept more poultry than any other animal type. Chickens are more popular than turkeys or ducks. An occasional guinea fowl or goose was also seen. Labor requirements are similar for any number of poultry at the small farm scale. Women spend 10 to 15 minutes daily feeding, watering, and collecting eggs from a small flock. One chicken may produce 15 eggs month^{-1} on a small farm and a turkey may produce 7 to10 eggs in the same time period. Farmers estimate that their families may consume all the eggs produced by two to four chickens. While difficult to quantify, it appears reasonable to expect that keeping sufficient birds to have eggs to sell will require supplemental feeds of at least 0.10 kg day^{-1} bird^{-1}. Keeping fewer birds probably permits free range and food scraps to suffice. Farmers value turkeys for their broodiness in contrast to chickens and frequently use them to hatch out chicken and duck eggs. Adult turkeys are valued at least double what adult chickens are worth.

Non-agricultural Livelihood Activities

Textile-based cottage industries ranged from the spinning and dying of threads, through the weaving of raw textiles on backstrap or floor looms, to the elaboration of finished clothing and accessories. Textile activities were conducted mainly on a piece basis, with raw materials supplied by the purchaser of the finished product. Some families functioned as a small factory, engaging sequentially in all steps, while other specialized in only a single phase of the process. Accomplished weavers might, after some extended period, produce their work independently.

Another avenue for income generation was the preparation and sale of food products such as sweets, tortillas and other maize-based products, french fries, fried chicken, fruit and fruit juices, and processed dairy products (cheeses and creams). These products tended to be sold directly within the community, however little data was available to quantify the degree of market involvement. Several families reported that they attended large festivals specifically for the purpose of vending and were not otherwise routinely engaged in the activity.

A pottery/clay industry with external markets exists in both communities with outside markets. In Chuculjulup, household production of pitchers and pots was the principal activity, while in Cabrican, bricks and roof tiles predominated. In addition, Cabrican has a widespread lime production industry with both a centralized facility and privately held wood-fired plants. The processed calcium or lime is transported in bulk to external markets. Residents of Cabrican characterized calcium lime mining as an informal source of additional income, while no one claimed it as a continual source of employment.

The local sources of timber from high forests make woodworking, both the cutting and sawing of lumber as well as the creation of furniture and wood carvings, a popular activity for some inhabitants. Furniture production was pursued as both a piece-based operation as well as by independent craftsmen. Pieceworkers generally cut and assembled items from a weekly material supply, while independent workers were more likely to build to order. Other activities include the harvest and collection of fuelwood for home-use and for sale. There was substantial anecdotal evidence that fuelwood-based activities depended on public or unclaimed resources.

Further activities include reselling of diverse products door to door, in weekly markets, or in small household based stores within the community. Agricultural or food products were the most common door to door items sold by community residents. A wide range of semi-skilled livelihoods such as masonry, carpentry, teaching, secretarial work, and cab drivers were identified during the validation survey and were obviously connected with higher wealth status within the community. Additional outlets for unskilled labor include agricultural day labor in the area as well as outside the region for males and employment as domestic laborers in larger households for unmarried females.

REFERENCES

Adams, R., 1998. Some premodernist thoughts on the Mayan population in Guatemala. Paper presented at the XXI International Congress of the Latin American Studies Association - LASA 98, September 24-26, Chicago.

Aguilar, E., 1993. Sistematización del conocimiento agrícola campesino en comunidades seleccionadas del departamento de El Quiché, a base de tecnologías campesinas. Tésis de Licenciatura, División de Ciencia y Tecnología del Centro Universitario de Occidente, Universidad de San Carlos de Guatemala, Guatemala.

Allen, J., 1990. Homestead tree planting in two rural Swazi communities. Agrofor. Sys. 11: 11-12.

Anderson, J., Bingham, G., and Hill, R., 1992. Effects of permanent cover crop competition on sour cherry tree evapotranspiration, growth and productivity. Acta Hort. 313: 135-142.

Anderson, L., and Sinclair, F., 1993. Ecological interactions in agroforestry systems. Agrofor. Abstr. 6: 57-91.

Appropriate Technology Center, 2003. Agroforestry benefits are not fully realized. Appropriate Tech. 30: 70-71.

Arachchi, L., and Liyanage, M., 2003. Soil water content under coconut palms in sole and mixed (with nitrogen-fixing trees) stands in Sri Lanka. Agrofor. Sys. 57: 1-9.

Arnold, C., and Aldrich, J., 1980. Herbicidal effect on peach seedling growth and weed control. Hortsci. 15: 293-294.

Ashour, N., Saad, A., Tayel, M., and Kabesh, M., 1997. Lentil and wheat production in peach orchards under rainfed marginal conditions of North Sinai. Egypt J. Soils. Sci. 37: 549-565.

Atkinson D., 1980. The distribution and effectiveness of the roots of tree crops. Hort. Rev. 2: 424-481.

Ayuk, E., Duguma, B, Franzel, S., Kengue, J., Mollet, M., Tiki-Manga, T., and Zenkeng, P., 1999. Uses, management and economic potential of *Irvingia gabonensis* in the humid lowland of Cameroon. For. Ecol. Manag. 113: 1-9.

Azad, K., and Sikka, B., 1991. Production and marketing of temperate fruits in Northwest region of India. Acta Hort. 271: 67-74.

Barbier, E., 1990. The farm-level economics of soil conservation: The uplands. Land Econ. 66: 199-211.

Barradas, V., and Fanjul, L., 1986. Microclimatic characterization of shaded and open-grown coffee (*Coffea arabica*) plantations in Mexico. Agric. For. Meteor. 38: 101-112.

Bellow, J., and Nair, P.K.R., 2003. Comparing common methods for assessing understory light availability in shaded-perennial agroforestry systems. Agric. For. Meteor. 114: 197-211.

Ben Salah, H., Beji, A., and Salah H., 1989. Effects of windbreak protection on faba bean production. Annales de l'Institut National de la Recherche Agronomique de Tunisie. Numero Special: 125-137.

Bénard, G., Margate, R., Daniel, C., and Eroy, M., 1996. Food intercrops under adult coconut palms. In: EEC-STD3-TS3-CT92-0132, 3rd technical report. 66 pp.

Benjamin, T., Hoover, W., Seifert, J., and Gillespie, A., 2000. Defining competition vectors in a temperate alley cropping system in the Midwestern USA: 4. The economic return of ecological knowledge. Agrofor. Sys. 48: 79-93.

Black, C., and Ong, C., 2000. Utilisation of light and water in tropical agriculture. Agric. For. Meteor. 104: 25-47.

Briggs, L., and Twomlow, S., 2002. Organic material flows within a smallholder highland farming system of South West Uganda. Agric. Ecosys. Env. 89: 191-212.

Buresh, J., Sancehz, P.A., and Calhoun, F.G., 1997. Replenishing Soil Fertility in Africa. Soil Science Society of America. Special Publication No. 51. SSSA, Madison. 51 pp.

Byerlee, D., Biggs, S., Collinson, M., Harrington, L., Martinez, J., Moscardi, E., and Winkelmann, D., 1981. On-farm research to develop technologies appropriate to farmers. I.A.A.E. occasional paper - Int. Assoc. Agric. Econ. 2: 170-177.

Caldwell, M., 1990. Water parasitism stemming from hydraulic lift: a quantitative test in the field. Israel J. Bot. 39: 395-402.

Caldwell, M., Dawson, T., and Richards, J., 1998. Hydraulic lift: consequences of water efflux from the roots of plants. Oecologia 131: 151-161.

Caldwell, M., and Richards, J., 1989. Hydraulic lift water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia 79: 1-5.

Cannel, M., Van Noordwijk, M., and Ong C., 1996. The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agrofor. Sys. 34: 27-31.

Caspari, H., Behboudian, M., and Chalmers, D., 1994. Water use, growth, and fruit yield of 'Hosui' asian pears under deficit irrigation. J. Amer. Soc. Hort Sci. 119: 383-388.

Ceccolini, L., 2002. The homegardens of Soqotra island, Yemen: an example of agroforestry approach to multiple land-use in an isolated location. Agrofor. Sys. 56: 107-115.

Chalmers, D., Burge, G., Jerie, P., and Mitchell, P., 1986. The mechanism of regulation of 'Bartlett' pear fruit and vegetative growth by irrigation withholding and regulated deficit irrigation. J. Am. Soc. Hort. Sci. 111: 904-907.

Chambers, R., 1983. Rural Development: Putting the Last First. New York: Longman.

Colchester, M., 1991. Guatemala: The clamor for land and the fate of the forests. Ecologist. 21: 177-185.

Cubero, J., 1973. Evolutionary trends in *Vicia faba*. Theoretic. Appl. Gen. 43: 59-65.

Current, D., Lutz, E., and Scherr, S., 1995. Costs, benefits, and farmer adoption of agroforestry: project experience in Central America and the Caribbean. A CATIE-IFPRI-World Bank project funded by UNDP. World Bank Environment Paper No. 14. CATIE, Turrialba, Costa Rica. 212 pp.

Currie, D., and Paquin, V., 1987. Large-scale biogeographical patterns of species richness of trees. Nature 329: 326-327.

Daniel, J., Ong, C., and Kumar, M., 1991. Growth and resource utilization of perennial pigeonpea (*Cajanus cajan* (L) Millsp) at the tree-crop interface. Agrofor. Sys. 12: 83-98.

Das, S., Sharma, S, Sharma, K., Saharan, N., Nimbole, N., and Reddy, Y., 1993. Land use options on a semi-arid Alfisol. Amer. J. Alt. Agric. 8: 34-39.

Dauzat, J., and Eroy, M., 1997. Simulating light regime and intercrop yields in coconut based farming systems. European J. Agron. 7: 63-74.

Dawson, T., 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. Oecologia 95: 565-574.

Day, W., and Legg, B., 1983. Water Relations and Irrigation Response. In: Hebblethwaite, P. (ed), The Faba Bean (*Vicia faba* L.). Butterworths, London. Pp. 217-231

De Foresta, H., and Michon, G., 1997. The Agroforest alternative to imperata grasslands: when smallholder agriculture and forestry reach sustainability. Agrofor. Sys. 36: 105-120.

Delobel, T., Evers G., and Maerere, A., 1991. Position and functions of deciduous fruit trees in the farming systems at Upper Mgeta, Uluguru Mountains, Tanzania. Acta Hort. 270: 91-102.

Dhyani, S., Chauhan, D., Kumar, D., Kushwaha, and Lepcha, S., 1996. Sericulture-based agroforestry systems for hilly areas of north-east India. Agrofor. Sys. 34: 247-258.

Dorfman, R., 1953. Mathematical or "linear," programming: a nonmathematical exposition. Amer. Econ. Rev. 5: 797-825.

Duncan, L., and Elmorshedy, M., 1996. Population changes of *Tylenchulus semipenetrans* under localized versus uniform drought in the citrus root zone. J. Nematol 28: 360-368.

Dupraz, C., Simorte, V., Dauzat, M., Bertoni, G., Bernadac, A., and Masson, P., 1999. Growth and nitrogen status of young walnuts as affected by intercropped legumes in a Mediterranean climate. Agrofor. Sys. 43: 71-80. 1999.

Early, J., 1982. The Demographic Structure and Evolution of a Peasant System: The Guatemalan Population. University Presses, Boca Raton, Florida. pp. 207.

Ellis, R., Summerfield, R., Edmeades, G., and Roberts, E., 1992. Photoperiod, temperature, and the interval from sowing to tassel initiation in diverse cultivars of maize. Crop Sci. 32: 1225-1232.

Emebiri, L., and Nwufo, M., 1994. Performance of the west African vegetable crop *Telfairia occidentalis* as a function of distance from a row of mango trees. Agrofor. Sys. 27: 183-186.

FAO (Food and Agricultural Organization), 1993. CROPWAT: A computer program for irrigation planning and management. Irrigation and Drainage. Paper No. 46. FAO, Rome, Italy, pp. 126.

Fernandes, E., and Nair, P.K.R., 1986. An evaluation of the structure and function of tropical homegardens. Agric. Sys. 21: 279-310.

Floyd, C., Harding, A., Paudel, K., Rasali, D., Subedi, K., and Subedi, P., 2003. Household adoption and the associated impact of multiple agricultural technologies in the western hills of Nepal. Agric. Sys. 76: 715-738.

Franzel, S., Jaenicke, H., and Janssen, W., 1996. Choosing the Right Trees: Setting Priorities for Multipurpose Tree Improvement. ISNAR Research Report No. 8. The Hague: International Service for National Agricultural Research.

Gallina, S., Mandujano, S., and Gonzalez-Romero, A., 1996. Conservation of mammalian biodiversity in coffee plantations of Central Veracruz, Mexico. Agroforestry Systems 33: 13-27.

Garcia de Ceca, J., Gebremedhin, K., and Jarvis, P., 1991. A decision support system for planning agroforestry systems. For. Ecol. Manag. 45: 199-206.

Glen, D., and Welker, W., 1993. Water transfer diminishes root competition between peach and tall fescue. J. Amer. Soc Hort Sci. 118: 570-574.

Glover, N., and Beer, J., 1986. Nutrient cycling in two traditional Central American agroforestry systems. Agrofor. Sys. 4: 77-87.

Gramajo, S., 1993. Autogestion comunitaria de recursos naturales, estudio de caso en Totonicapan. FLACSO programa, Guatemala City, Guatemala. 109 pp.

Green, S., and Clothier, B., 1999. The root zone dynamics of water uptake by a mature apple tree. Plant Soil 206: 61-77.

Hellin, J., Welchez, L., and Cherrett, I., 1999. The Quezungual system: an indigenous agroforestry system from western Honduras. Agrofor. Sys. 46: 229-237.

Herzog, F., 1998. Streuobst: a traditional agroforestry system as a model for agroforestry development in temperate Europe. Agrofor. Sys. 42: 61-80.

Hiebsch, C., and McCollum, R., 1987. Area-X-time equivalency ratio: A method for evaluating the productivity of intercrops. Agron. J. 79: 15-22.

Hildebrand, P., 1986. The sondeo: a team rapid survey approach. In: Hildebrand, P. (ed), Perspectives on farming research and extension. Lynne Rienner Publishing, Bolder, Colorado. 167 pp.

Hogue, E., and Neilsen, G., 1987. Orchard floor vegetation management. Hort. Rev. 9: 377-430.

Holbrook, M., and Putz, F., 1989. Influence of neighbors on tree form: effects of lateral shade and prevention of sway on the allometry of *Liquidambar styraciflua*. Amer. J. Bot. 76: 1740-1749.

Holdridge, L., 1947. Determination of world formations from simple climatic data. Sci. 105: 367-368.

Horn, H., 1971. The Adaptive Geometry of Trees, Princeton University Press, Princeton. 144 pp.

Huang, W, and Xu. Q., 1999. Overyield of *Taxodium ascendens*-intercrop systems. For. Ecol. Manag. 116: 33-38.

Immink, M., and Alarcon, J., 1991. Household food security, nutrition and crop diversification among smallholder farmers in the highlands of Guatemala. Ecol. of Food and Nutrition 25: 287-307.

Immink, M., and Alarcon, J., 1993. Household income, food availability, and commercial crop production by small-holder farmers in the western highlands of Guatemala. Econ. Dev. Cult. Change 41: 319-342.

INCAP (Instituto de Nutricion de Centro America y Panama), 1971. Valor nutritivo de los alimentos para Centro America. Guatemala, INCAP.

INE (Instituto Nacional de Estadisticas), 1994. Departmento de Totonicapan, caracteristicas generales de poblacion y habitacion. Instituto Nacional de Estadisticas, Guatemala, Guatemala. 125 pp.

International Rice Research Institute (IRRI), 1974. Multiple cropping, pp. 15-34. In: Annual Report for 1974. Los Baños, Philippines.

Jackson, N., Wallace, J., and Ong, C., 2000. Tree pruning as a means of controlling water use in an agroforestry system in Kenya. For. Ecol. Manag. 126: 133-148.

Jonsson, K., Ong, C., and Odongo, J., 1999. Influence of scattered néré and karité trees on microclimate, soil fertility, and millet yield in Burkina Faso. Expl. Agric. 35: 39-53.

Jonsson, K., Fidjeland, L., Maghembe, J., and Hogberg, P., 1988. The vertical distribution of fine roots of five tree species and maize in Morogoro, Tanzania. Agrofor. Sys. 6: 63-69.

Jose, S., Gillespie, A., Seifert, J., and Biehle, D., 2000. Defining competition vectors in a temperate alley cropping system in the Midwestern USA 2. Competition for water. Agrofor. Sys. 48: 41-59.

Kapp, G., 1998. Financial evaluation tools for smallholder forestry: a methodological comparison of two forms of cost-benefit analysis and optimization. Int. Tree Crops J. 9: 233-246.

Kappel, F., 1989. Artificial shade reduces “Bartlett” pear fruit size and influences fruit quality. Hortsci. 24: 595-596.

Kaya, B., Hildebrand, P., and Nair, P.K.R, 2000. Modeling changes in farming systems with the adoption of improved fallows in southern Mali. Agrofor. Sys. 66: 51-68.

Khemira, H., Azarenko, A., Sugar, D., and Righetti, T., 1998. Postharvest nitrogen application effect on ovule longevity of ‘Comice’ pear trees. J. Plant Nutr. 21: 405-411.

Knapp, K., and Sadorsky, P., 2000. Economics of agroforestry production in irrigated agriculture. J. Agric. Res. Econ. 25: 286-306.

Kumar, B., and Nair, P.K.R., 2004. The Enigma of Tropical Homegardens. In: Nair, P.K.R, Rao, M., and Buck, L. (eds), New Vistas in Agroforestry: A Compendium for the 1st World Congress of Agroforestry 2004. Kluwer Academic Publishers, Dordrecht, The Netherlands. 700 pp.

Kumar, J., Rana, S., Verma, H., and Parmar, D., 2001. Long-term effects of intercrops on growth, yield and fruit quality of plum (*Prunus salicina*). Indian J. Agric. Sci. 71: 687-690.

Ladizinsky, G., 1975. On the origin of the broad bean *Vicia faba* L. Israel J. Bot. 24: 80-88.

Lado, C., 1998. The transfer of agricultural technology and the development of small-scale farming in rural Africa: case studies from Ghana, Sudan, Uganda, Zambia and South Africa. Geojournal 45: 165-176.

Lassoie, J., and Buck, L., 1999. Exploring the opportunities for agroforestry in changing rural landscapes of North America. Agrofor. Sys. 44: 105-107.

Lehmann, J., Pereira da Silva Jr., J., Schroth, G., Gebauer., G., and Ferreira da Silva. L., 2000. Nitrogen use in mixed tree crop plantations with a legume cover crop. Plant Soil 225: 63-72.

Li, F., Cohen, S., Naor, A., Shaozong, K., and Erez, A., 2002. Studies of canopy structure and water use of apple trees on three rootstocks. Agric. Water Manag. 55: 1-14.

Lipecki, J., and Berbec, S., 1997. Soil management in perennial crops, orchards and hop gardens. Soil Till. Res. 43: 169-184.

Long, A, and Nair, P.K.R., 1999. Trees outside forests: Agro-, community, and urban forestry. New Forests 17: 145-174.

Long, L., Yang, S., Li, X., Zhang, F., and Christie, P., 1999. Interspecific complementarity and competitive interaction between intercropped maize and faba bean. Plant Soil 212: 105-114.

Lord, W., and Vlach, E., 1973. Responses of peach trees to herbicides, mulch, mowing, and cultivation. Weed Sci. 21: 227-229.

Lott, J., Khan, A., Black, C., and Ong, C., 2003. Water use in a *Grevillea robusta*-maize overstory agroforestry system in semi-arid Kenya. For. Ecol. Manag. 180: 45-59.

Mahat, T., 1987. Forestry farming linkages in the mountains. ICIMOD (International Centre for Integrated Mountain Development) Occasional Paper. No. 7. 47 pp.

Marmillod, A., 1987. Farmers' attitudes towards trees. In: Beer, J., Fassbender, H., and Heuveldop, J. (eds), Advances in Agroforestry Research. pp. 259-270.

Marsal, J., Mata, M., Arbone, A., Rufat, J., and Girona, J., 2002. Regulated deficit irrigation and rectification of irrigation scheduling in young pear trees: an evaluation based on vegetative and productive response. Eur. J. Agr. 17: 111-122.

Mary, F., Dupraz, C., Delannoy, E., and Liagre, F., 1999. Incorporating agroforestry practices in the management of walnut plantations in Dauphiné, France: An analysis of farmers' motivations. Agrofor. Sys. 43: 243-256.

McDonald, M., Hofny-Collins, A., Healey, J., and Goodland, T., 2003. Evaluation of trees indigenous to the montane forest of the Blue Mountains, Jamaica for reforestation and agroforestry. For. Ecol. Manag. 175: 379-401.

Mead, R., and Willey, R., 1980. The concept of a land equivalent ratio and advantages in yields from intercropping. Exper. Agric. 16: 217-228.

Mendez, V., Lok, R., and Somarriba, E., 2001. Interdisciplinary analysis of homegardens in Nicaragua: micro-zonation, plant use and socioeconomic importance. Agrofor. Sys. 51: 85-96.

Meyer, J., Zehr, E., Meagher, R., and Salvo, S., 1992. Survival and growth of peach trees and pest populations in orchard plots managed with experimental ground covers. Agric. Ecosys. Env. 41: 353-363.

Michon, G., and de Foresta, H., 1999. Agro-forests: Incorporating a Forest Vision in Agroforestry. In: Buck, L., Lassoie, J, and Fernandes, E. (eds), Agroforestry in Sustainable Agricultural Systems, pp. 381-406. Lewis Publishers, Boca Raton.

Miller, A., and Pallardy, S., 2001. Resource competition across the crop-tree interface in a maize-silver maple temperate alley cropping stand in Missouri. Agrofor. Sys. 53: 247-259.

Miller. S., Smith, G., Boldingh, H., and Johansson, A., 1998. Effects of water stress on fruit quality attributes of kiwifruit. Ann. Bot. 81: 73-81.

Mitchell, P., Chalmers, D., Jerie, P., and Burge, G., 1986. The use of initial withholding of irrigation and tree spacing to enhance the effect of regulated deficit irrigation on pear trees. J. Am. Soc. Hort. Sci. 111: 858-861.

Monteith, J., 1972. Solar radiation and productivity in tropical ecosystems. J. Appl. Ecol. 9: 747-766.

Monteith, J., 1977. Climate and the efficiency of crop production in Britain. Phil. Trans. R. Soc. London B. 281: 277-294.

Morales, H., and Perfecto, I., 2000. Traditional knowledge and pest management in the Guatemalan highlands. Agric. Human Values 17: 49-63.

Mudhara, M., Hildebrand, P., and Nair, P.K.R, 2003. Potential for adoption of *Sesbania sesban* improved fallows in Zimbabwe: A linear programming-based case study of small-scale farmers. Agrofor. Sys. 59: 307-315.

Mulk, M., Jodha, N., Banskota, M., and Partap, T., 1992. Diversity of farming systems and farmers' strategies in the mountain valley of Chitral, Pakistan. In: Jodha, N., and Banskota, M. (eds), Sustainable mountain agriculture. V. 2: farmer's strategies and innovative approaches. pp. 477-496. Intermediate Technology Publications, London.

Murray, G., 1989. The Artisans of Totonicapan: An Indigenous Development Model in Western Guatemala. A report submitted to the Inter-american Foundation. University of Florida Latin American collection. 54 pp.

Nair, P.K.R., 1998. Directions in tropical agroforestry research: past, present, and future. Agrofor. Sys. 38: 223-245.

Nair, P.K.R., 2001. Do tropical homegardens elude science, or is it the other way around? Agrofor. Sys. 53: 239-245.

Nair, P.K.R, Buresh, R. Mugendi, D., and Latt, C., 1999. Nutrient Cycling in Tropical Agroforestry Systems: Myths and Science. In: Buck L., Lassoie, J., and Fernandes E. (eds), Agroforestry in Sustainable Agricultural Systems, pp. 381-406. Lewis Publishers, Boca Raton.

Naor, A., Klein, I., Hupert, H., Grinblat, Y., Peres, M., and Kaufman, A., 1999. Water stress and crop level interactions in relation to nectarine yield, fruit size distribution, and water potentials. J. Amer. Soc. Hort. Sci.124: 189-193.

Narain, P., Singh, R., Sindhwal, R., and Joshie, P., 1998. Water balance and water use efficiency of different land uses in western Himalayan valley region. Agric. Water Manag. 37: 225-240.

Nasendi, B., Hasanudin, Nugroho, I., Mulyaningrum, Karyono, O., Tryono, Murod, A., and Sipayung, W., 1996. Analysis of industrial plantation forest model development with a mosaic system using a linear programming modeling approach: a proposed model for the Padang Lawas area, North Sumatra. Buletin Penelitian Hasil Hutan. 14: 291-307.

Nelson, K., 1994. Participation and Empowerment: A Comparative Study of IPM Technology Generation in Nicaragua. Doctoral Dissertation. School of Natural Resources and Environment, The University of Michigan, Ann Arbor.

Newman, S., 1983. Ecological and Agronomic Aspects of a Pear and Vegetable Interculture System. Open University, Milton Keynes Energy Research Group. U.S. Department of Commerce, National Technical Information Service. 188 pp.

Newton, S., and Eagles, H., 1991. Development traits affecting time to low ear moisture in maize. Plant Breeding 106: 58-67.

Njiti, C., 1988. Development of a goal programming model for land use planning with emphasis on wood for energy production in the Republic of Cameroon. Dissertation Abstracts International: Humanities-and-Social-Sciences. Southern Illinois University, 150pp.

Odhiambo, H., Ong, C., Deans, J.,Wilson, J., Khan, A., and Sprent, J., 2001. Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry system in Kenya. Plant Soil 235: 221-233.

Ong, C., 1995. The ‘dark side’ of intercropping: manipulation of soil resources In: Sinoquet, H., and Cruz, P. (eds), Ecophysiology of Tropical Intercropping, INRA Editions, Paris, France. pp 45-65.

Ong, C., Corlett, J., Singh, R., and Black, C., 1991. Above and belowground interactions in agroforestry systems. For. Ecol. Manag. 45: 45-57.

Ong, C., Odongo, J., Marshall, F., and Black, C., 1992. Water use of agroforestry systems in semi-arid India. In: Calder, I., Hall, R., and Adlard, P. (eds), Growth and Water Use of Forest Plantations. Wiley, Chichester, UK, pp. 347-358.

Penning De Vries, F., Laar, H., and Chardon, M., 1983. Bioenergetics of growth of seeds, fruits, and storage organs. In: Smith, W., and Banta, S. (eds), Potential productivity of field crops under different environments, pp. 37-59. IRRI; Los Banos; Philippines.

Perfecto, I. Rice, R., Greenberg, R., and Van der Voort, M., 1996. Shade coffee: a disappearing refuge for biodiversity. BioSci. 46: 598-608.

Price, L., and Campbell, B., 1998. Household tree holdings: A case study in Mutoko communal area, Zimbabwe. Agrofor. Sys. 39: 205-210.

Quartieria, M., Millard, P., and Tagliavini, M., 2002. Storage and remobilisation of nitrogen by pear (*Pyrus communis* L.) trees as affected by timing of N supply. Eur. J. Agron. 17: 105-110.

Raintree, J., and Wickramasinghe, A., 1992. Summary of findings. In: Raintree, J., and Taylor, D., (eds), Research on Farmers Objectives for Tree Breeding Bangkok, Thailand: Winrock International. 132 pp.

Raintree, J., 1992. Community based tree improvement: A new series of research activities beginning with the Artocarpus network. In: Raintree, J., and Taylor, D., (eds), Research on Farmers Objectives for Tree Breeding. Bangkok, Thailand. Winrock International. 132 pp.

Rao, M., and Edmunds, J., 1984. Intercropping of banana with food crops: cowpeas, maize, and sweet potato. Trop. Agric. 61: 9-11.

Rao, M., Nair, P., and Ong, C., 1998. Biophysical interactions in agroforestry systems. Agrofor. Sys. 38: 3-50.

Redclift, M., 1981. Making "Farming Systems" research serve the needs of peasant producers: A Guatemalan case. Human Organization 40: 353-355.

Ritchie, G., 1997. Evidence for red : far red signaling and photomorphogenic growth response in Douglas-fir (*Pseudotsuga menziesii*) seedlings. Tree Phys. 17: 161-168.

Ritchie, J., and Nesmith, D., 1991. Temperature and crop development. In: Hanks, R., and Ritchie, J. (eds), Modeling Plant and Soil Systems. Agronomy 31. Pp 5-29. ASA, Madison, Wisconsin.

Rockstrom, J., 1997. On-farm agrohydrological analysis of the Sahelian yield crisis: rainfall partitioning, soil nutrients and water use efficiency of pearl millet. Ph.D. Thesis. University of Stockholm.

Roder, W., Keoboulapha, B., and Manivanh, V., 1995. Teak (*Tectonis grandis*), fruit trees and other perennials used by hill farmers of northern Laos. Agrofor. Sys. 29: 47-60.

Salam, M., Noguchi, T., and Koike, M., 2000. Understanding why farmers plant trees in the homestead agroforestry in Bangladesh. Agrofor. Sys. 50: 77-93.

Sanchez, E., Righetti, T., Sugar, D., and Lombard, P., 1990. Seasonal differences, soil texture and uptake of newly absorbed nitrogen in field-grown pear trees. J. Hort. Sci. 65: 395-400.

Sanchez, E., Righetti, T., Sugar, D., and Lombard, P., 1991 Recycling of nitrogen in field-grown ‘Comice’ pears. J. Hort. Sci. 66: 479-486.

Schroth, G., Lehmann, J., Rodrigues, Barros, M., and Macêdo, J., 2001 Plant-soil interactions in multistrata agroforestry in the humid tropics. Agrofor. Sys. 53: 85-102.

Scott, W., Meade, R., Leon, R., Hyink, D., and Miller, R., 1998. Planting density and tree-size relations in coast Douglas-fir. Can. J. For. Res. 28: 74-78.

Semwal, R., Maikhuri, R., Rao, K., Singh, K., and Saxena, K., 2002. Crop productivity under differently lopped canopies of multipurpose trees in Central Himalaya, India. Agrofor. Sys. 56: 57-63.

Silim, S., and Saxena, M., 1992. Comparative performance of Some faba bean (*Vicia faba*) cultivars of contrasting plant types. 1. Yield, yield components and nitrogen fixation. J Agric. Sci. 118: 325-332.

Simons, C., and Taramo, J., 1959. Clasificación y Reconocimiento de Suelo de la Republica de Guatemala. Traducido por Tirado, P., José de Pineda Ibarra (ed), Guatemala. 1000 pp.

Smith, C., 1989. Survival strategies among petty commodity producers in Guatemala. Int. Labor Rev. 128: 791-813.

Srinivasalu, D., and Jaganatham, A., 1992. Microclimatic manipulation and performance of rainfed groundnut with crop shelterbelts. Madras Agric. J. 79: 587-589.

Storck, H., Emana, B., Adenew, B., Borowiecki, A., and Hawariat, S., 1991. Farming systems and farm management practices of smallholders in the Hararghe highlands - a baseline survey. Farming Sys. Res. Econ. Trop. 11. 195 pp.

Styger, E., Rakotoarimanana, J., Rabevohitra, R., and Fernandes, E., 1999. Indigenous fruit trees of Madagascar: potential components of agroforestry systems to improve human nutrition and restore biological diversity, Agrofor. Sys. 46: 289-310.

Sugar, D., 1992. Pear storage decay control through tree management and postharvest treatment. Proceedings of the 88th annual meeting of the Washington State Horticultural Association., Yakima, Washington, USA, 7-9 Dec., pp. 145-146.

Sumitro, A., 1983. Tree crop management. Technical appendix 5, Government of Indonesia/USAID. Composite Report of the Watershed Assessment Team, V. 3.USAID, Jakarta.

Tacio, H., 1993. Sloping Agricultural Land Technology (SALT): a sustainable agroforestry scheme for the uplands. Agrofor. Sys. 22: 145-152.

Tagliavini, M., Quartieri, M., and Millard, P., 1997. Remobilized nitrogen and root uptake of nitrate for spring leaf growth, flowers and developing fruits of pear (*Pyrus communis* L.) trees. Plant Soil. 195: 137-142.

Terán, S., and Rasmussen, C., 1995. Genetic diversity and agricultural strategy in 16th century and present-day Yucatecan milpa agriculture. Biodiversity Cons. 4: 363-381.

Tewolde, S, 1986. Farm economics in the Highlands of Ethiopia. Scot. Agric. Econ. Rev. 1: 65-71.

Trenberth, K., 1997. The definition of El Niño. Bull. Amer. Meteor. Soc. 78: 2771-2777.

Tsongo, N., 1993. The impact of the introduction of an innovation on the development of peasant farms in the mountainous zones of Kivu (Zaire). Tropicultura 11: 11-15.

Tworkoski, T., and Glenn, D., 2001. Yield, shoot and root growth, and physiological responses of mature peach trees to grass competition. HortSci. 36: 1214-1218.

Ucán Ek, E., Narváez, M. Puch, A., and Chan, C., 1982. El cultivo del maíz en el ejido de Mucel, Pixoy, Valladolid, Yucatán. In: Nuestro Maíz (pp. 243-287). México, D.F.: Dirección General de Culturas Populares.

U.S. Department of Agriculture, Agricultural Research Service. 2003. USDA National Nutrient Database for Standard Reference, Release 16. Nutrient Data Laboratory Home Page, http://www.nal.usda.gov/fnic/foodcomp.

Van Noordwijk, M., 1996. Mulch and shade model for optimum alley-cropping design depending on soil fertility. In: Ong, C., and Huxley, P. (eds), Tree Crop Interactions. CAB International Wallingford, England, 386 pp.

Van Noordwijk, M., Lawson, G., Soumare, A., Grout, J., and Hariah, K., 1996. Root distribution of trees and crops: Competition and or complementarity. In: Ong, C., and Huxley, P. (eds), Tree Crop Interactions. CAB International Wallingford England, 386 pp.

Vandemeer, J., Van Noordwijk, M., Anderson, J., Ong, C., and Perfecto, I., 1998. Global change and multispecies agroecosystems: concepts and issues. Agric. Eco. Envir. 67: 1-22.

Vasquez, J., 2000. El Manzano (*Malus pumila*) y recomendaciones para el cultivo en Guatemala. Instituto de Ciencia y Tecnologia Agricolas. Guatemala. 112 pp.

Wallace, J., and Batchelor, C., 1997. Managing water resources for crop production. Philosoph. Trans. Royal Soc. London Ser. B. 352: 937-947.

Weisema, J., and León, B, 1999. World Economic Plants: A Standard Reference. CRC Press, Boca Raton. 749 pp.

Wickramasinghe, A., 1992. Identifying tree-breeding objectives of small-scale farmers in Sri Lanka. In: Raintree, J., and Taylor, D., (eds), Research on Farmers Objectives for Tree Breeding Bangkok, Thailand: Winrock International 132 pp.

Williams, W., Cifuentes, S., del Aguila, V., and Perez, R., 1992. Rejuvenation of a peach orchard in the highlands of Guatemala through integrated management. Trop. Agric. 69: 341-346.

Williams, W., and Vasquez, J., 1990. El Cultivo de Pera. Programa de Desarrollo Agricola, MAGA-AID. 16 pp.

Wirodidjojo, S., 1989. Application linear programming model for watershed management planning. Duta Rimba. 15: 3-17, 24-29, 107-108.

Withrow-Robinson, B., Hibbs, D., Gypmantasiri, P., and Thomas, D., 1999. A preliminary classification of fruit-based agroforestry in a highland area of northern Thailand. Agrofor. Sys. 42: 195-205.

Wojtkowski, P., 1990. Bioeconomic simulation of agroforestry systems: an application to southeast Bahia, Brasil. Dissertation Abstracts International: Humanities and Social Sciences. Thesis, University of Georgia, 117 pp.

BIOGRAPHICAL SKETCH

John G. Bellow was born in 1966 in Pulaski, New York. He attended Bowdoin College in Brunswick, Maine, where he received a Bachelor of Arts in geology in 1989. He worked in international agricultural development with the U.S. Peace Corps in the Philippines as an agroforestry volunteer. Returning to the U.S., he established and operated a plant nursery and organic truck farm. In 1997, he entered the graduate program of the School of Forest Resources and Conservation at the University of Florida. In 1998, he received the Dickinson Award in Tropical Agriculture to support his work in Costa Rica during 1998 and 1999 where he participated in a course in tropical biology through The Organization for Tropical Studies (*OET*/OTS) and completed the research leading to the Master of Science in collaboration with CATIE. In 1999, he received the E.T. York Presidential Fellowship to continue his studies at the Ph.D. level. He was inducted into the Phi Kappa Phi honor society in 1999 and the agricultural honor society Gamma Delta Sigma in 2000. In 2001, he received a fellowship from the National Security Education Program for research in Guatemala on agroforestry practices among highland farmers. He worked in collaboration with *El Instituto de Ciencia y Tecnología Agricola* (ICTA) in Quetzaltenango from 2001 to 2004 to complete the research leading to the Doctor of Philosophy. His research findings have been presented both nationally and internationally. Currently he resides in Palouse, Washington, with his spouse Roxanne Hudson.