FIRST-YEAR GROWTH AND SOIL RESPONSES OF AN AGROFORESTRY SYSTEM UTILIZING FIVE NATIVE TREE SPECIES AND *MANIHOT ESCULENTA* IN THE EASTERN AMAZON OF BRAZIL

By

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(Under the Direction of Daniel Markewitz and Lawrence Morris)

ABSTRACT

Native populations in the Brazilian Amazon produce manioc as a staple crop for sustenance and sale through slash-and-burn agriculture. Farmers are reducing fallows from 15-25 to 5-7 years, which is not enough time to accumulate the nutrients necessary to sustain the cropping phase of the cycle.

In Pará, Brazil, a one hectare 7-year-old secondary forest was cleared using a mulching tractor. Four experimental treatments (N=4) were established in four blocks utilizing manioc and native tree species in a mixed culture with and without P and K fertilizer with and without N-fixers. Fertilization increased growth of tree species and biomass production of manioc. In the presence of *I. edulis,* there were trends of increased growth and survival among all tree species, except *P. multijuga*, as well as increased biomass of manioc. Fertilization increased biomass of competition, although, the presence of *I. edulis* reduced competing biomass in the fertilized treatment.

INDEX WORDS: Agroforestry system, Eastern Amazon, Native tree species, cassava, N-fixing trees, *Inga edulis*, *Manihot esculenta*

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INTRODUCTION

Throughout the Amazon of Brazil and in the Bragantina region of the northern State of Pará, native populations produce manioc (*Manihot esculenta*) as a staple crop for sustenance and sale through slash-and-burn agriculture. Typically, secondary forest is felled, burned and manioc is cultivated for 2 years before being re-abandoned to secondary forest succession (Brienza Jr., 1999). Population and market pressures have forced farmers to reduce the fallow phase of the rotation from 15-25 years to 5-7 years which is not enough time to accumulate the nutrients necessary to sustain the cropping phase of the cycle (Metzger, 2002).

Trees of native forest succession have little commercial value, yet one way to sustain manioc production and generate additional income is to plant tree species that can improve soil conditions and/or have market value to provide income that farmers can use to buy fertilizers. N-fixing trees have been planted in agroforestry systems (AFS) to improve soil fertility and to improve fallow growth (Brienza Jr., 1999).

Productivity of forest species native to the Eastern Amazon has been sparingly studied and literature concerning productivity of forest species in mixed-species and multi-purpose AFS is rarer still. The species combination and crop grown that generate the maximum short-term profit might be considered most desirable to some whereas others might be willing to wait longer for greater revenues generated by lumber species such as *Cedro* (*Cedrela odorata*), *Ceiba* (*Ceiba pentandra*) or *Favá* (*Parkia multijuga*). The objective of this study was to evaluate the initial growth and soil responses when native trees and manioc are grown in the presence of the N-fixing *Inga edulis*. This study also investigated the effects of phosphorus and potassium fertilizers on the growth of native trees and on the biomass response of competing vegetation and manioc. Competing vegetation was unfortunately not controlled so the effects of either the *I.* edulis or fertilizer were not solely directed to the trees or manioc. However, farmers generally perform competition control and could therefore expect the results of this study to indicate minimum responses of trees and manioc to these treatments.

CHAPTER I

LITERATURE REVIEW

Subsistence farming by small landholders covers as much as 30% of cultivated land in the world (Attiwill, 1994) and deforestation caused by small landholders is significant in certain regions of the world. Despite its prevalence, negative connotations such as primitive, haphazard, wasteful and inefficient (Schmidt, 2003) stigmatize this practice. It is blamed for massive deforestation (Fox et al. 2000), yet in many areas other activities have greater impacts. For example, in the Brazilian Amazon cattle ranches alone account for 80% of land originally deforested (Fearnside, 2001). Deforestation from small-holding land-clearing appears to be of minor importance in the Americas (Schmidt, 2003), particularly in the Brazilian Amazon where 83% of agricultural establishments occupy less than 100 ha each and only 11% of the agricultural land. In contrast, 2% of establishments are greater than 1,000 ha but comprise 63% of agricultural land (Simmons et al., 2002). The most common form of subsistence agriculture in Brazil is "slash-and-burn", with over 500,000 families farming this way as of 1996 (Serrão et al., 1996).

Land-use history, settlement density and community infrastructure are not homogenous in the Brazilian Amazon. All of these factors can influence the applicability of management techniques suitable to any particular region. The Eastern Amazon of Pará, Brazil, in particular, has been heavily occupied for over 100 years yet subsistence farmers still occupy over 80% of the agricultural land of the region (Kato et al., 2005).

As available lands have become limited around urban centers and rural-to-urban migration increases, sustaining the productivity of these lands has become a critical issue. In this article I review the settlement, agricultural history and current ideas for improving subsistence farming in this area.

The Bragantina Region of Brazil

The Bragantina is distinct when compared to other places in the Brazilian Amazon due to its settlement history. Belém, the capital of Pará, has been settled since 17th Century and expansion of settlements into the native forests of the region began soon afterwards and many towns in the Bragantina have been settled permanently or intermittently for nearly 400 years, making it one of the oldest agricultural frontiers in the Amazon (Vielhauer and Sá, 1999). A railroad was built to connect Belém with the port city of Bragança in the latter half of the 19th century which prompted a wave of immigration where settlers began opening plots out of the native forest along its path (Metzger, 2002). Today the Bragantina has paved roads connecting many cities and towns in the region (Fig. 1.1) as well as electricity and other aspects of modern development. The current landscape of the Bragantina is the most densely populated rural area in the Amazon (Metzger, 2002) leaving very little, if any, land available for new agricultural settlements. Land tenure among the inhabitants of the Bragantina is also strongly defined, when compared to other regions of the Brazilian Amazon, and emigration within the region is very limited.

The Bragantina is located between 0°45'S and 1°39'S latitude and 46°16'W and 48°15'W longitude and covers 23,000 km^2, about 2% of the state of Pará, and is of the

Am climate according to the Köppen (1936) climate classification system. At the turn of the 20th Century there were nearly one million hectares of rain forest in the Bragantina but due to a century of continuous population growth and expansion of agriculture throughout the region, over 95% of the original vegetation has been removed (Costa, 2000a) with roughly 55% of the land now in secondary forests (Perreira and Vieira, 2001). Of the remaining 5% not removed, most is riparian habitat and has been selectively logged or otherwise modified (Costa, 2000a).

The Bragantina was originally opened to immigration to supply food to Belém and was settled by laborers from failed rubber plantations and Brazil-nut plantations, or *castanhais* (Costa, 2000a). Colonists also arrived from the semi-arid Northeast to claim new lands and gain a subsistence living when periodic droughts in that region caused crops to fail (Metzger, 2002). In the late 1960s, the government began offering incentives and other subsidies to agribusinesses and large landowners to make the region more productive (Costa, 2000b). Throughout Pará, and to a lesser extent in the Bragantina, absentee landowners from other regions of the country developed large properties that focused on cattle ranching and soy bean farming.

In Pará, smallholding farms (<100 ha) represent 89% of agricultural establishments. They occupy only 40% of the cultivated area and produce 60% of the agricultural value of the region (Kato et al., 2005). In 1985 agro-industries generated 3,124 jobs in Pará while small-holding establishments generated 43,527 jobs; meanwhile small farms received no subsidies from the government and only 40% of the larger properties that received benefits from 20 years of federally subsidized incentives generated profits (Costa, 2000b). Low-input and small-holding farmers have demonstrated that their establishments can efficiently compete with high-input, large-holding properties. Increased productivity of small-holding farms should also increase the sustainability of small-scale farming and raise the productivity of the region.

With the influx of immigrants and large ranches (*fazendas*), land-use patterns have changed in the North of Brazil and created a different landscape. When the government began offering incentives for people to colonize Pará, nearly all of the land was native forest or forest lightly disturbed by activities like lumber extraction, rubber-tapping, or Brazil nut extraction, with little cropped land (Costa, 2000a). Only 8% of Northeast Pará was planted in annual row crops as of 2000 while 10% was in permanent crops, 17% pasture and 19% fallow (Costa, 2000a).

Permanent crops like cacão, dendê (oil palm), coffee, banana, coconut and oranges increased by over 69,000 ha (1,500%) from 1978-1990 while annual crops fell by the same amount (Costa, 2000b). These changes in land-use reflect the inherent instabilities in market prices and profitability of annual crops like corn, rice and beans, (Costa, 2000b) since smallholding farmers cannot compete with cheaper commodities arriving from states in the South and Southeast of Brazil (Pinedo-Vasquez et al., 2001). Growing trees as permanent crops can help protect the farmer from fluctuations in the market and can be used as an investment. Pinedo-Vasquez et al. (2001) interviewed smallholding farmers in the state of Amapá, north of Pará, and found that families actively managed and/or planted seedlings of valuable lumber species for future generations.

Fallow Vegetation and Agriculture of the Eastern Amazon

Agriculture in Eastern Pará is mainly based on small-holding farms that practice shifting cultivation, or swidden agriculture (Brienza Jr., 1999; Vielhauer and Sá, 1999; Kato et al., 2005). The most commonly used swidden system in the Bragantina is "slash and burn" where the fallow vegetation is felled ("slashed") and burned to provide nutrient inputs and raise the pH at the soil surface (Perreira and Vieira, 2001). This system requires the disturbance of the previous vegetation and related ecosystem processes, and the subsequent restoration of biological processes and components through the use of fallow vegetation (Palm et al. 1996). Fields are cropped for one to three years (Metzger, 2002) before they are abandoned due to declining crop yields and weed invasion (Vieira, 1996) and then the fallow period begins again. Slash and burn agriculture, which is common throughout the tropics, relies on the biological processes of succession to replenish nutrients lost during cropping and is inherently a sustainable system if given the proper temporal distribution (Sanchez, 1976).

If there is a net loss of nutrients from one crop-fallow cycle to the next due to impaired recovery of nutrients by forest succession after abandonment there will be decreased productive capacity of the agroecosystem (Jordan et al., 1983). This danger is greater on weathered soils such as the Oxisols and Ultisols abundant in the Amazon due to their low nutrient-retention. Direct comparisons of soil types are dificult since Brazilian soil surveys use different nomenclature than U.S. Soil Taxonomy, even so, Richter and Babbar (1991) estimate that 70% of soils in the Brazilian Amazon are Oxisols (40%) or Ultisols (30%). Upland *terra firme* soils of the Bragantina are dominated by Oxisols and Ultisols. Soils of the municipality of Igarapé Açu in the

Bragantina are described as Typic Kandiudults (Rego et al., 1993). Soils in the region are developed from Tertiary and Quaternary fresh water sediments from the Guyanese and Brazilian Shields (RADAMBRASIL, 1973) which have been transported from their source of origin but have since developed deep clay horizons once deposited. Igarapé Açu has a generally flat topography dissected by rivers and stream channels (*igarapé*). The limiting nutrient for crop production in Igarapé Açu is P (Sá et al., 1998) with 3.6 mg kg^{-1} soil of extractable P in the upper 10 cm and a mean of 2.1 mg-P kg^{-1} soil to a depth of 50 cm (Gehring et al., 1999) although N is considered a co-limiting nutrient in Eastern Pará by Davidson et al. (2004).

Lands allowed to regenerate as forest fallows (*capoeira*) are a critical component of shifting agriculture because of the dynamic interaction between soil nutrient availability and organic matter accumulation (Brienza Jr., 1999; Martius et al., 2001) that these forests provide (Tiessen et al., 2001). "Nutrient pumping" by tree roots from deeper soil layers to the surface (Fisher, 1995; Gauguin et al., 2002) helps capture nutrients leached to depth and augments nutrient cycling through organic material inputs (Greenland et al., 1992). The accumulation and eventual recycling of nutrients to the surface by trees during the fallow period is essential to maintaining soil fertility in shifting agriculture systems.

Shortening of the cultivation-fallow cycle has a direct impact on sustaining soil fertility in shifting agriculture systems. When farmers decrease the time in fallow in relation to cropping, there is invariably a decline in crop yields (Sanchez; 1976; Vieira, 1996; Vielhauer and Sá, 1999) which is correlated to a depletion of soil nutrient reserves (Metzger, 2002) as well as soil organic matter (SOM) (Denich et al., 2004). In the

Bragantina, socioeconomic pressures have forced farmers to shorten the fallow while maintaining or extending the cropping phase (Kettler, 1997; Vielhauer and Sá, 1999; Costa, 2000a; Gehring et al., 1999) which jeopardizes the sustainability and productivity of swidden agriculture while vitally important fallow land becomes a limiting resource to farmers.

In the Bragantina region of Pará, Brazil, and throughout Tropical America, the role of N-fixing tree species has been shown to increase fallow biomass growth and nutrient accumulation. Utilizing four N-fixing species resulted in an increase of 20-150% in above-ground biomass compared to naturally regenerating fallow with no effect on manioc tuber biomass due to competition or nutrient mineralization when trees were planted during the last part of the cropping cycle (Brienza Jr., 1999). N-fixing trees used in the region include *Inga edulis*, *I. thibaudiana*, *I. macrophylla*, *I. heterophylla*, *Sclerolobium paniculatum*, *Clitoria racemosa, Cassia siamea*, *C. reticulata*, *Gliricidia sepium*, and also non-native N-fixers such as *Acacia mangium* and *A. angustissima* (Brienza Jr., 1999).

Nutrient Cycling in Slash and Burn Agriculture

Ash left on the surface after forest burning has beneficial effects during the cropping phase such as raising surface pH and providing mineralized nutrients. However, these properties are short-lived, lasting only 2-3 years in tropical climates. Nutrients that have been incorporated into the biomass during the growth of the fallow forest are placed on the soil surface (Palm et. al, 1996) yet only the biomass that is turned into ash will be available to crops within the two years of cropping as any wood that becomes carbonized charcoal is highly stable and resistant to decay (Glaser et al., 2002). Palm et al. (1996) also note that decomposition of organic matter and soil organic material should also be considered as nutrient inputs. Burning of a seven year-old fallow in Igarapé Açu, Brazil produced ash with nutrient content of 2.2 kg N, 1.4 kg P and 12 kg K ha^{-1}. Nutrient balances, however, show that as much as 47% of P and 96% of N accumulated in fallow biomass can be volatilized or oxidized during burning (Hölscher, 1997).

Mature tropical forest ecosystems store and cycle large quantities of N. After disturbance, including fire, N can be replenished through fixation of atmospheric inputs. Other elements like P and cations that have much lower levels of atmospheric inputs may accumulate very slowly. Due to these low external inputs and also the potential for strong P fixation by some soils (Vitousek, 1984), some mature tropical forests have been shown to have very efficient nutrient cycling systems through biomass and soil organic material (Jordan and Herrera, 1981). Most of the cycling properties characteristic of some mature tropical forests are destroyed or altered by converting forests to cropping fields.

During the cropping phase nutrients can be lost from the system through crop harvest (due to plant uptake and subsequent export), erosion from the surface, or leaching through the soil. During slash-and-burn, the intricate cycling and conservation mechanisms of mature tropical forests are disrupted (Palm et al., 1996). After 1-3 years, cropped fields will become too infertile to support crops (Sanchez, 1976) and will be abandoned so that fallow vegetation may establish again. Soil, biomass and nutrient content data of agroforestry projects in Igarapé Açu are presented in Tables 1.1 to 1.3.

The length of the fallow period directly affects how many nutrients will be released to the soil surface when the site is prepared again for the next cropping cycle. Forest fallows in the Bragantina show increases of over 50% in total biomass between five and ten years with woody species causing continual reduction in grass and herb biomass (Denich et al., 2004). Similar increases in above-ground biomass were observed when improved fallows were planted with N-fixing trees as compared to spontaneous fallow growth (Brienza Jr., 1999). Greater above-ground biomass of forest species in Costa Rica was correlated to greater nutrient uptake from the soil and storage in the biomass, regardless of species (Montagnini, 2000).

Forest fallows in slash and burn agriculture have traditionally been left to grow for up to 25 years before returning to cropping. Secondary forests in the Bragantina can store enough minerals in above-ground biomass after 12 years to support three years of crops without damaging the sustainability of the system, according to modeling reported by Vielhauer and Sá (1999). Farmers in the Eastern Amazon commonly crop fields for two years with seven years of fallow, a 3.5 fallow-cropping ratio, which may not be enough to sustain soil fertility (Metzger, 2002).

Slash and Mulch

Slash and mulch is an alternative to slash and burn where the standing vegetation is cut and left on the site as an organic layer over the mineral soil. Since the vegetation is not burned none of the nutrients are lost to oxidation or volatilization nor can they be lost as eroded ash, although some would be lost if mulch eroded off the site. However, nutrients can be lost in this system through leaching when the crop roots are not sufficiently developed to absorb nutrients mineralized from the decomposing mulch layer (Van Noordwijk et al., 1991). Nutrient losses from leaching to a depth of 40 cm (minus atmospheric inputs) can reach rates of 14 kg N, 0 kg P, 2.4 kg K, 68 kg Ca and 12 kg Mg ha^{-1} yr^{-1} in an AFS in Sulawesi, Indonesia (Dechert et al., 2005).

Slash and mulch studies in the Eastern Amazon have utilized a mulching tractor (Denich et al., 2004) which chops up to 20 Mg of fresh biomass per hour. Leaving the mulched vegetation on the surface maintains moisture in the soil which allows farmers to extend the cropping season, to plant crops off-season, and modify crop rotation (Denich et al., 2004). These modifications to planting and harvesting regimes allow farmers to take advantage of seasonal differences in market prices of crops. Farm income and labor productivity from slash-and-mulch systems can be up to two times greater than from traditional slash-and-burn systems (Denich et al., 2004). Coupling of slash-and-mulch technologies with improved fallow practices using fast-growing leguminous tree species can be a method to restore or augment soil fertility, crop and tree productivity and augment on-farm revenue sources. Slash and mulch systems can reduce crop yields in the first year compared to slash-and-burn due to nutrient immobilization and increased competition due to root sprouts (Kato et al., 1999), although long-term benefits, such as a more closed nutrient cycling system compared to slash-and-burn, should not be overlooked.

Agroforestry Systems

Trees restore nutrient stocks to the soil surface and/or crop by exploiting larger and deeper soil volumes to recover nutrients that would otherwise leach beyond the crop rooting zone and pump them in to above-ground biomass (Palm, 1995). Trees used in agroforestry can also augment nutrient stocks by capturing atmospheric inputs (Jordan, 1985). Agroforestry systems (AFS) are diverse in structure, desired benefits, inputs, outputs, sustainability and profitability. Sanchez (1995) proposes that there are two forms of interaction occurring in AFS; complementary and competitive. "Complementarity" occurs if multiple species interact in such a way as to benefit each other by making nutrients available to the other passively, by creating beneficial microclimates, by utilizing resources at different stages of development or at a different time of year. Competition, on the other hand, reduces the overall productivity of the species mixture due to resource limitation. Simultaneous AFS are designed so that tree and other crop components are grown at the same time and in proximity to each other so that interactions occur. Sanchez (1995) cites hedgerow intercrop (HI) systems, contour hedges, parklands, boundary plantings, homegardens and several silvopastoral systems as types of simultaneous AFS. Sequential AFS are designed to capture light, water or mineralized nutrients at different times to maximize productivity. Important examples of sequential AFS include shifting cultivation, improved fallows, and multistrata systems. Relay cropping allows simultaneous systems to become sequential by discontinuing the cropping phase.

Research using N-fixers within the cropping phase of a site has generally focused on alley cropping or hedgerow intercropping. In these AFS approaches single rows of trees are planted at broad spacing amidst rows of food crops or along the edges of the field. Pruned leaf litter from the trees, particularly of the N-fixer(s), can be used for supplemental fertilization and weed control. *I. edulis* can act as an important source of N and P to AFS in Central Amazônia (Tapia-Coral et al., 2005); however pruned leaves might meet only 50% of the P demand of the crop (Mafongoya et al., 1998; Sanchez, 1995). Twelve Mg of leaf litter ha^{-1} yr^{-1} can be obtained from leguminous species, giving an additional input of 190 kg N ha^{-1} yr^{-1} (Franco and de Faria, 1997) yet litter additions of HI systems cannot fully compensate for nutrients exported by crops without external inputs of fertilizer or other mulches (Palm, 1995). Improved fallow systems hold greater promise for AFS than HI or other simultaneous systems due to the reduction in competition for resources and greater potential for complementarity (Sanchez, 1995).

Many species of the Family Leguminosae fix atmospheric N_2 to NH_4^+ through a symbiotic relationship with bacteria that live in infected nodules of plant roots. Plants can then take up NH_4^+ or NH_4^+ can nitrify to NO_3^-, which can also be absorbed by roots. Losses of N after fixation can occur through leaching of NH_4^+ or, especially, NO_3^- beyond the rooting depth, denitrification of NO_3^- to gaseous forms or made unavailable to plants through immobilization by soil organisms. Estimates of atmospheric N-fixation by trees vary widely between analytical technique used, species tested and site-specific environmental conditions. N-fixation estimates ranged from 0.1 to 110 kg ha^{-1} year^{-1} using acetylene reduction assay (ARA) techniques with *Acacia extensa* and *Leucaena leucocephala* and from 40 to 580 kg ha^{-1} year^{-1} using total nitrogen difference (TND) with *Sesbania sesban* and *L. leucocephala* (Danso et al., 1992).

Although results are mixed due to a variety of competitive interactions, some studies show large increases in crop yield due to N input from legumes (Sanginga et al. 1986), although it is not clear if the response was due to mineralized N from litter or from the roots. Increases of 8 – 45% in maize yield were obtained when applying *G. sepium* and/or *Stylosanthes hamata* mulch to a maize crop planted after two years of fallow growth (Kaya and Nair, 2001). It appears that the ability of N-fixing trees to positively affect crop yield is best done through improved fallow where increased nutrient content is made available to the subsequent cropping cycle (Sanchez, 1995).

Mixed-species Agroforestry Systems

Mixed-species AFS can provide benefits to farmers through diversified products such as construction materials, fiber, fruit, firewood (Smith et al., 2000), charcoal (Glaser et al., 2002), pollination services (Metzger, 2002) and indirectly through water management, erosion control (de Clerck and Negrero-Castillo, 2000) and biodiversity management (Fearnside, 1999). Older fallows offer greater value due to a greater diversity of products (Denich et al., 2004) where as many as 40% of the species are used for firewood and charcoal (Rios et al., 2001). These products, services and potential income are available to the farmer while the site is in fallow (Navarro et al., 2004) and can protect the farmer from wide fluctuations in market prices of crops (Sanchez, 1995). Despite extensive home consumption in the Bragantina, products derived from un-managed fallows provide little to negligible income (Denich et al., 2004), which suggests that these objectives can be augmented by improved selection of species used in fallow.

Fallows improved with N-fixers produce greater biomass than fallow vegetation alone in the Eastern Amazon (Brienza Jr., 1999); however, no evaluation was made for the potential of utilizing species of differing growth habits, such as pioneers and climax species. Fast-growing pioneers, such as *Schizolobium amazonicum*, could be expected to yield timber quickly whereas *I. edulis* grows more slowly but yields fruits, green manures and fodder while *Cedrela odorata* grows slowly but has high lumber value. To complement the fertility-recovery potential of fallow vegetation, the ability to obtain harvests of food crops augmented by tree crops should be considered for AFS.

To effectively maintain soil fertility for crops in this region where new, arable lands are a limited resource for the growing population, low-input farmers must be able to increase the quantity and/or quality of organic material and therefore nutrients generated by the fallow vegetation to be released to the crop when the fallow vegetation is cleared. The majority of research into the use of improved fallow comes from Africa (Sanchez, 1995) and some studies report positive crop responses to 2-year *S. sesban* fallows (Kwesiga and Coe, 1994; Mafongoya and Dzowela, 1999). An improved fallow system in Pará, Brazil utilizing *I. edulis*, *A. mangium*, *A. angustissima* and *C. racemosa* increased biomass production by up to 200% compared to natural fallow and also generated leaf litter 77% richer in N concentration than natural fallow (Brienza Jr., 1999).

Improved fallow growth enhances the small-holding farmer's productivity and other ecological services improved fallows provide. Fallow re-growth provides goods that benefit the farmer monetarily like food, firewood, fiber and building materials and services that have less tangible ones that benefit society as a whole, such as carbon sequestration, erosion control and water management (Sanchez, 1995) as well as charcoal, which can be sold for cash in the market or used to enhance soil fertility (Glaser et al., 2002). Few examples exist of policies designed to compensate farmers for ecological services but it is a possibility that is becoming ever more tangible. If farmers extend the length of the fallow they will recover more nutrients in the biomass to benefit the next crop while using the goods provided by the fallow as a source of income and/or sustenance, but without policies to assist them or that recognize the ecological services provided by fallows, it will be difficult to advance wide-scale adoption of lengthened fallows.

Trees compete with crops for water, nutrients and light in AFS and can have a negative effect, but if high-value lumber trees are chosen to complement the crops, the value of the marketable wood alone could compensate for the loss of income from the crop (Beer et al., 1998). *Cordia alliodora* planted at a density of 100 stems ha^{-1} in various locations throughout Tropical America will produce 1-13 m^3 ha^{-1} yr^{-1} of merchantable volume worth $US 150 yr^{-1} and sale of *C.* alliodora timber would buffer the loss of 17 – 33% of the coffee crop at high and moderate coffee prices and 100% of a failed coffee crop at low coffee prices (Beer et al., 1998). Farmers who choose to use AFS must be financially stable enough to withstand lower crop returns for many years until the end of the tree rotation to earn the compensation that trees can provide. The use of several tree species with different rotation lengths would enable farmers using AFS to not rely on a single wind-fall income and have the flexibility to sell their trees when the market value is favorable. Beer et al. (1998) point out that sustained increases in timber species, such as *C. odorata*, are likely while sustained increases in coffee prices are not.

Thirty-six native tree species are currently bought by local mills in the Amazonian state of Amapá (Table 1.4), the northern neighbor of Pará, whereas only six were bought during the "boom period" that ended in the late 1970s (Pinedo-Vasquez et al., 2001). Valuable species such as *C. odorata*, *C. pentandra*, *Calophyllum brasiliensis*, *Calycophyllum spruceanum* and *Virola surnamensis* were found in fallows at densities approximately 75% of those in mature forests but with 50% of the merchantable timber volume indicating that smallholding farmers can include valuable tree species in their land management plans without altering their land-use practices. The market for moderate and fast-growing trees is expanding and AFS developed on small-holdings should cultivate a variety of native, tropical species to take advantage of an expanding national market for lumber and wood products. The market for non-timber forest products is expanding in Brazil with products like açai (*Euterpe oleracea*) dendê oil and biodiesel (*Elaeis guineensis*) and castanha-do-Pará (*Bertholletia excelsa*) commonly available throughout the country.

Biomass production of enriched fallow vegetation in Igarapé Açu, Brazil was 1.3 Mg ha^{-1} yr^{-1}, about 60%, greater than a non-enriched control and had 56% greater N concentration in Igarapé Açu, Brazil (Brienza Jr., 1999). Tree biomass was inversely related to competing biomass, which indicates suppression of competing vegetation (Kettler, 1997; Brienza Jr., 1999) which should increase over time as the canopy of the trees closes further. Competing vegetation in an AFS in Kenya was supressed by 400% between a control and a 8 x 8 m planting. Competing vegetation was reduced another 400% when tree spacing was reduced from 8 x 8 m to 2 x 2 m (Jama et al., 1991). Brienza Jr. (1999) also reported reductions in competition of approximately 200% by increasing density of tree planting from 2 x 2 m to 1x 1 m.

Mulch Decomposition and Nutrient Mineralization

Soil organic matter and other organic materials at various stages of decomposition on the soil surface are major storage reservoirs for N, S, P, Ca, K and Mg (Jordan, 1985). Soils of the Eastern Amazon are limited by plant-available P and inorganic P mineralized from decomposing litter and dead roots can contribute to long-term productivity (McGrath et al., 2000). Decomposition of organic matter also helps to reduce Al toxicity because the products of decomposition bind Al and reduce Al saturation (Rao et al., 1997).

Decomposition and humification of the mulch layer are important parts of the nutrient cycle in AFS and are microbially driven processes controlled by temperature, soil moisture, pH and available nutrients (Zech et al., 1997). Much of the nutrient stock of many tropical forest types is bound in living biomass, therefore quantity and quality of mulch can control rates of nutrient mineralization and availability (Mafongoya et al., 1998; Palm, 1995). Slow release of N and P from SOM and other organic inputs indicate that mulch and litter application will have a longer lasting effect on soil fertility than inorganic fertilizers (Mafongoya et al., 1998). Utilizing litter that decomposes slowly may be advantageous when rehabilitation of degraded soils is the goal (Nichols et al., 2001) because more organic material accumulates on the surface when coupled with slower decomposition rates.

As much as 8.4 t ha^{-1} of aboveground biomass and 5.8 t ha^{-1} of belowground biomass would have to be added to an AFS each year to maintain SOM at levels equal to those of humid forests (Palm et al., 1996). Leguminous litterfall is generally high in N concentration but of variable quality, which affects the rate of decomposition and transformation of N (Seneviratne, 2000; Oglesby and Fownes, 1992; Mafongoya et al., 1998). High quality litter, such as *S. sesbans*, decomposes rapidly and has low levels of polyphenols (2.6%) and lignin (14.5%) whereas litter from *I. edulis* contains 4.7% polyphenols, 18.3% lignin and was the slowest decomposing of seven species tested

(Oglesby and Fownes, 1992). Seneviratne et al. (2000) reports that generic legume leaves (3.8%) have marginally higher polyphenol concentrations than non-legumes (3.6%).

Phosphorus dynamics

Results of nutrient limitation for plant growth in the Eastern Amazon are somewhat conflicting. Although P is a more limiting nutrient than N for secondary forest growth in the Eastern Amazon, results are sometimes only evident after large doses or after multiple applications (Gehring et al., 1999). Fallow vegetation biomass increased by 540, 329, and 193%, respectively, between one year and 28 months using complete, minus-N and minus-P fertilization regimes. Gehring et al. (1999) conclude that P is the dominant limiting nutrient while N is a secondary limiting nutrient. From a site further south in the state of Pará, Brazil woody secondary forest growth responded more consistently to N and N + P fertilization than to P-only fertilization, although grass and vine growth responded more to P-only than to N or N + P fertilization (Davidson et al., 2004).

Acid soils with high iron (Fe) and aluminum (Al) sesquioxides, such as many of those found in the Eastern Amazon, quickly and permanently immobilize P through adsorption to clay colloids. McGrath et al. (2000) found that the upper 20 cm of soil contained 80-97% of total P in primary, secondary or AFS in the Amazon region, although the plant-available pool was relatively small and potentially limiting to an AFS. Inorganic P added as fertilizer to tree crops can be expected to have a long-lasting and pronounced effect (Schroth et al., 2001a) if applied at high rates. Saturation of the P adsorption capacity of the soil may be important if these effects are to be seen quickly.

Leguminous mulches are used to add P to crops, but the 8-12 kg ha^{-1} of P contained in a realistic application of 4 t ha^{-1} is only about half of the P required by maize (Sanchez, 1995). Tapia-Coral et al. (2005) report that the litter layer in a variety of AFS in central Amazônia contained 0.2-0.5 kg ha^{-1} of P in the wet season and as much as 1.01 kg ha^{-1} of P in the dry season and though the litter mass was less than in a neighboring secondary forest, the litter quality was higher and decomposed more rapidly. Fertilizing with P increased the total amount of P extracted from decomposing mulch but not the P released from mulched residue indicating that P mineralization may be controlled by its ratio to polyphenols, lignins, cellulose and carbon contents (Baggie et al., 2004).

New Directions for Research in Agroforestry Systems

Two of the principle avenues of agroforestry research follow the concepts of hedgerow intercropping (HI), where trees and crops are grown simultaneously, and improved fallow (IF) where fallow forests grow, accumulate nutrients and are then felled to grow crops. Integrating HI and IF systems is a logical extension of these technologies and could improve the efficiency of low-input farms. Planting trees within the cropping field towards the end of the last crop could give trees the head start on competition and allow the trees to take advantage of management techniques such as weeding that would ostensibly be done for the crop alone, thereby improving the survival, growth and productivity of planted trees and potentially shortening the fallow phase of the cycle.

Tree species obviously play an integral role in AFS but rarely receive attention beyond their ability to alter the chemical or physical aspects of soil and their ability to improve micro-climate conditions such as temperature and moisture. Focus on these aspects alone undervalues the contribution that trees can provide farmers throughout and at the end of the crop-fallow cycle. Management of forest fallows can be performed while crops are in the field and throughout the fallow to ensure that farmers maximize the benefits provided to them by forest fallows.

Trees can also provide financial resources to the farmer at various stages throughout the cycle and more research should be dedicated to mechanisms for increasing productivity of trees used in AFS as well as crop productivity. Research into increasing productivity of lumber species could be used to highlight the investment value of trees to low-capital farmers. Research into the environmental services provided by AFS could cause government agencies and NGOs to provide incentives and stability for farmers and/or communities to invest in AFS technologies.

Use of fertilizers, particularly P, should be addressed in regions that have P-limiting soils. The nutrient conservation mechanisms of soils that support tropical forests (Jordan, 1985) should make P fertilization more efficient than N fertilization and could stimulate crop growth and tree growth simultaneously. Synchronization of crop/tree fertilization should be studied so as to maximize survival, growth and productivity of crop, trees and fallow as well as increasing the efficiency and profitability of tropical AFS.

Conclusions

Increasing the productivity of AFS in the Bragantina through the use of improved fallows could contribute to increased agricultural sustainability in a region that greatly depends on fallow forests as a resource. Improving productivity of fallow forests could also raise agricultural productivity by increasing nutrient cycling and storage in above-ground biomass which will be placed on the soil surface when the forest is felled. Fallow forests also provide goods and services that can be utilized during the fallow that can provide income and sustenance to the farmer. The incorporation of high-value lumber species within the fallow cycle can act as a "savings account" and could increase the value of the forest fallow by allowing farmers to lengthen fallows, which increases nutrient cycling as well as products and services of the fallow. Additionally, the value of products provided by fallow forests may allow for the purchase of fertilizers which can further improve the agronomic potential of the cropping phase of the swidden agriculture cycle.

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Table 1.1. Soil data from Igarapé Açu, Pará, Brazil. Source: Gehring et al. 1999.

Depth	Coarse Sand	Fine Sand	Silt	Clay	pH (H_2O)	N_{tot} (%)	P[1]	K[1]	Ca + Mg[2]	Al[2]
- cm -	------ % weight ------						- mg kg^{-1} -		meq 100 g^{-1}	
0–10	45	35	11	10	5.5	0.1	3.6	30.8	2.2	0.04
10–20	40	34	10	15	5.1	0.07	2.1	17.4	0.8	0.33
20–30	34	33	12	21	4.9	0.06	1.4	12.7	0.6	0.46
30–50	33	31	11	24	4.9	0.05	1.2	10.5	0.5	0.56

[1]extracted with Mehlich double-acid solution; [2]extracted with KCl

Table 1.2. Aboveground biomass (dry matter) of fallow vegetation of different ages in the northeast of Pará, Brazil.

Component (Mg ha^{-1})	1 year	4- to 5-year	7-year	10-year
Wood	1–3	9–25	29–61	58–68
Leaves	<1–2	3–5	4–6	6–9
Litter, standing dead	3–6	6–8	8–11	12–17
Herbs, grasses	<1–4	<1–1	<1	<1–1
Total	8–12	19–38	42–77	78–94

Sources: Denich, 1989; Nunez, 1995

Table 1.3. Biomass and nutrient stocks of 4 and 10-year-old fallow vegetation [Mean (SE)]. Source: Kato et al., 1999.

Compartment	Biomass		N		P		K		Ca		Mg	
	-----t ha^{-1} -----		----------kg ha^{-1} ----------									
	4 years	10 years	4 years	10 years	4 years	10 years	4 years	10 years	4 years	10 years	4 years	10 years
Leaves[a]	5 (0.4)	8 (0.8)	57 (16)	94 (22)	3 (0.1)	4 (0.8)	26 (5.0)	74 (6.8)	48 (8.3)	54 (11)	14 (2.6)	20 (3.7)
Wood	15 (2.5)	44 (7.6)	52 (6.8)	181 (29)	4 (0.5)	3 (0.8)	41 (6.1)	106 (21)	57 (11)	312 (71)	18 (3.2)	56 (8.3)
Litter[b]	4 (0.2)	7 (0.3)	34 (3.4)	57 (8.0)	2 (0.4)	1 (0.2)	5 (0.4)	7 (0.6)	45 (0.8)	64 (8.2)	10 (1.4)	11 (1)
Total	24	59	143	332	9	9	72	186	150	430	42	87

[a]Including herbs and grasses; [b]Including standing dead

Table 1.4. Timber Species Managed by 12 households in their forests, fallows, house gardens and fields. Data for seedlings, juveniles and adults are calculated mean densities (Individuals ha^{-1}). Table and data adapted from Pinedo-Vasquez et al., 2001.

Species	Seedlings	Juveniles	Adults	Growth	Density
Aniba amazonica	125	84	18	slow	hard
Apeiba tibourbou	76	39	12	fast	soft
Belluccia glossularioide	1077	410	24	fast	hard
Callycophyllum spruceanum	2110	624	78	fast	hard
Calophyllum brasilensis §	50	18	11	slow	hard
Campsiandra laurifolia	149	76	6	fast	hard
Carapa guianensis §	33	21	24	slow	hard
*Cedrela odorata § **	15	6	8	slow	hard
*Ceiba pentandra § **	16	9	11	slow	soft
Clinostemon mahuba	171	95	23	fast	soft
Couratari guianensis	63	38	6	slow	hard
Ficus sp.	36	24	19	fast	soft
Guara sessiflora	143	105	20	fast	hard
Gustavia augusta	317	112	13	fast	soft
Hernandia guianensis	210	102	11	fast	hard
Hura crepitans	33	18	13	fast	soft
Licania heteromorpha	256	114	42	slow	hard
Maquira coreacea §	192	110	15	slow	soft
Mora paraensis	600	270	33	fast	soft
Mouriri glandifolia	25	13	6	fast	hard
Pentachletra macrolloba	1096	704	76	fast	hard
Platymiscium huberi	148	92	31	fast	hard
Pseudolmedia maxima	134	82	15	fast	soft
Pterocarpus amazonico	100	45	11	fast	hard
Quararibea guianensis	42	29	12	slow	soft
Saccoglottis guianensis	59	27	11	slow	hard
Sapium guianensis	127	88	11	fast	soft
Siparuma guianensis	268	110	9	slow	hard
Sterculia speciosa	135	93	13	fast	hard
Swartzia acuminata	33	24	17	fast	hard
Swartzia racemosa	233	121	32	fast	hard
Symphonia globulifera	25	17	8	fast	hard
Tabebuia sp.	128	77	7	slow	hard
Virola surinamensis §	217	115	29	slow	soft
Xylopia sp.	58	20	26	fast	hard

§Over-exploited species; *Species used in this study

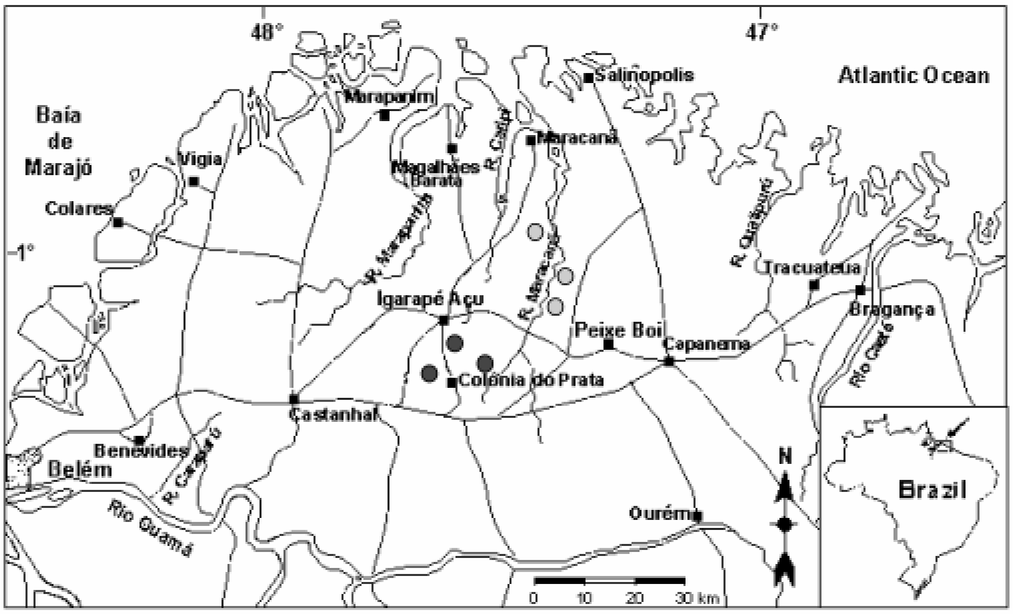

Figure 1.1. The Bragantina region of Pará, Brazil. Source: Metzger, 2002.

CHAPTER II

FIRST-YEAR GROWTH RESPONSE OF FIVE NATIVE TREE SPECIES AND MANIOC (*MANIHOT ESCULENTA*) GROWN IN MIXED-CULTURE IN THE EASTERN BRAZILIAN AMAZON[1]

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Abstract

In the Eastern Amazon of Brazil native populations produce manioc (cassava), often through slash-and-burn agriculture, as a staple crop for sustenance and sale. Typically, secondary forest is felled and burned and then crops, including manioc, are cultivated for 2 years before being re-abandoned to secondary forest succession. Population and market pressures have forced farmers to reduce the fallow phase of the rotation from 15-25 years to 5-7 years. The shortened fallow does not provide enough time for vegetation to accumulate the nutrients necessary to sustain the cropping phase of the cycle.

To facilitate nutrient accumulation, a variety of improved fallow schemes have been investigated, including the use of native nitrogen-fixing trees. Trees of native forest succession have little commercial value yet can help sustain manioc production through rapid biomass accumulation and a deep rooting habit. N-fixation may also help to accelerate N accumulation. Both N-fixing and non-N fixing trees have been planted in agroforestry systems to improve fallow growth and soil fertility. Trees should also be considered for potential to increase on-farm revenue through sale of forest products. This revenue could be used to purchase P and K fertilizers to augment crop production. The objective of this study was to evaluate the growth potential of native N-fixing and non N-fixing trees in combination with manioc.

In the Bragantina region of Brazil, 1 hectare of 7-year-old secondary forest was cleared through use of a mulching tractor. Four experimental treatments were established in four blocks utilizing native tree species (2 N-fixing; 3 non N-fixing) in a mixed culture with or without N-fixers and with or without P and K fertilizers. Manioc was planted in

all plots (n=16) at 1 x 1 m spacing. Growth response varied widely within treatments due to unforeseen edaphic variance across the site (i.e., high water table) which limited the statistical significance of the observed responses despite clear patterns in the data. For instance, use of P and K fertilizer increased tree growth of four of the five species planted and increased biomass production of manioc stems and tubers. Trends of increased growth and survival were observed among all tree species, except P. *multijuga*, in the presence of the N-fixing *I. edulis* as well as for increased biomass of manioc. Fertilization increased the biomass of competing vegetation, although the presence of *I. edulis* caused a reduction in competing biomass in the fertilized treatment. After one year, fertilization with P and K dramatically improved tree and manioc growth but improved growth of competing vegetation which requires control.

Introduction

In the Bragantina region of the northern Brazilian state of Pará, *mandioca* (manioc or cassava) is a staple crop produced for sustenance and sale. Land-use in the Bragantina region is dominated by swidden-fallow agriculture where forest vegetation is slashed and burned to prepare the land for cultivation. The ash of the burned vegetation serves as fertilizer for the subsequent crops, which are usually cultivated for up to two years before declining fertility and increasing weed competition forces farmers to abandon the plot to secondary forest succession. Sustainability of this system depends largely upon the length of time in fallow vegetation before being cleared for the cropping phase of the cycle again. Enough nutrients must be accumulated in the fallow vegetation to fertilize the soil after clearing and thus sustain crop growth.

The nutrient cycle of swidden-fallow agriculture is dominated by the role of fallow vegetation. Nutrients are depleted from the system when the forest is burned through volatilization, oxidation, ash dispersion, erosion and leaching (Hölscher, 1997), and also during the cropping phase through nutrient export (Palm et al., 1996). The fallow forest takes up nutrients from the mineral soil through shallow and deep root uptake (Montagnini, 1999, Gauguin et al., 2002) and acts as a storehouse of nutrients to be released to the surface when felled. Farmers in this region are reducing the length of time in fallow vegetation (Gehring et al., 1999), thereby reducing the ratio of fallow period to cropping period; potentially to levels too low to sustain the system (Metzger 2002).

The swidden-fallow cycle employs a cropping phase that lasts 1-3 years followed by fallow vegetation that has traditionally occupied 15-25 years. Farmers in the

Bragantina region have reduced the fallow phase of the cycle to 3-7 years (Gehring et al., 1999) while continuing to maintain two years of cropped fields. As nutrient stocks are depleted, crop productivity declines and farmers must turn to new lands to sustain their livelihoods or move to urban centers for employment. Secondary forest management offers the potential to increase the value of secondary forests and farmers' holdings while sustaining soil fertility. Brown and Lugo (1990) indicate that secondary forest cover has expanded greatly in Tropical America. Improved management techniques of secondary forests for greater productivity could reduce pressure on native forests and could improve overall forest sustainability.

Trees of early natural forest succession have little commercial timber value (Pinedo-Vasquez et al., 2001) yet early successional forests are often the only forest resource for low-capital rural populations (Smith et al., 2000). Although timber values may be low, they can provide many products such as medicines, fruit, firewood and building materials (Perreira and Vieira, 2001) as well as increasing the efficiency and productivity of smallholders' farms (Pinedo-Vasquez et al., 2001). Secondary forests also provide ecological services such as maintenance of hydrological processes (de Clerck and Negreros-Castillo, 2000) and biodiversity (Fearnside, 1999; Sagoff, 2006) that have great value when viewed across the landscape.

The use of N-fixing trees and other fast-growing species to augment fallow growth can stimulate greater nutrient acquisition which gives farmers the option to shorten the fallow or to utilize products from the fallow forest without jeopardizing the nutrient stock available for the cropping phase. Enrichment plantings of fallow forests using N-fixing legumes, such as *Inga edulis*, generated greater biomass than control fallows in the Bragantina (Brienza Jr., 1999). N-fixing trees can also be used during the cropping phase as a source of green manure for manioc and then left to stimulate secondary forest succession. However, Sanchez (1995) cautions that trees incorporated into the cropping phase can have a negative effect on the crop through competition and could be against the farmers' interests.

The objective of this research is to quantify the first-year growth and survival of five forest tree species and the biomass production of manioc, when grown in combination. Phosphorus is a limiting nutrient in the soils of the Bragantina (Gehring et al., 1999) but in other parts of the State of Pará, N and P were co-limiting nutrients (Davidson et al. 2004). This research also seeks to determine the effect of P and K fertilization on the growth and survival of the five tree species and manioc. This research also seeks to quantify the effects of an N-fixing species (*I. edulis*) on non-N-fixing trees and on manioc production.

Materials and Methods

Site Description

The research site is located at the experimental farm of the Universidade Federal Rural da Amazônia (UFRA) in the Municipality of Igarapé Açu (1°07'41"S 47°47'15" W), approximately 110km East of Belém, capital of Pará, Brazil. This region, known as the Bragantina, is one of the oldest continually inhabited agricultural areas in the Amazon (Denich, 1991) and the landscape is now completely dominated by human activities; urban areas, row-crop farms, forest plantations, cattle ranches and secondary forests.

Soils in the municipality of Igarapé Açu are predominantly Typic Kandiudults (Rego et al. 1993) with a bulk density (BD) of 1.2 g cm^{-3} from 0-5 cm and 1.4 g cm^{-3} from 5-10 cm. Igarapé Açu has an average annual temperature of 26°C and annual rainfall of 2500 mm (IBGE, 1996; cited in: Kato et al., 2005). Its driest months are August -November and its wettest months are January – May (Fig. 2.1).

Species Descriptions

The following species are present in the Amazon and are native to forests of the Bragantina region.

Parkia multijuga Benth. (Mimosoideae)

P. multijuga is a strong light-demander and also a commercially valuable species (de Carvalho et al., 2004), however it may not demonstrate good growth form for commercialized timber production (Tonini et al., 2006). *P. multijuga* plays a substantial role as a secondary tree in Peruvian agroforest systems (Peck and Bishop, 1992). Although *P. multijuga* is a mimosoideae, Moreira et al. (1992) did not note nodulation on plants in the Central Amazon, and nodulation was not noted on this species at this site either.

Schizolobium amazonicum Hub. ex Ducke. (Caesalpinioideae)

S. amazonicum is a short-lived, early successional pioneer species (Peña-Claros, 2003) and a legume, although it is not known to nodulate (Moreira et al., 1992). It has beneficial commercial timber properties, rapid growth and is considered a promising species for agroforest systems (AFS) in the Amazon region (Tonini et al., 2006). It is not a species of high lumber value, due to its soft, weak wood though it does have enough market value for farmers in the Bragantina region to grow it for timber (Yamada and Gholz, 2002).

Ceiba pentandra (L.) Gaertn. (Bombacaceae)

C. pentandra is commonly used in paper-pulp production (Vázquez-Yanés, 1998) and is also known as a high-value lumber species (Pinedo-Vasquez et al., 2001). It was harvested heavily during the "boom years" of Amazonian logging and effectively eliminated from forests near lumber mills by the early 1980s. It is a fast-growing heliophyte, although it is a late secondary forest species (Lorenzi, 2002).

Cedrela odorata Linn. (Meliaceae)

C. odorata is a strong light demander and considered a somewhat fast-growing species (Pennington et al., 1981), although it has also been described as a slow-growing species (Pinedo-Vasquez et al., 2001). *C. odorata* has one of the highest commercial timber values in Brazil (Lorenzi, 2002) as well as being among the most important timber species for shading coffee in Central America (Beer et al., 1997 cited in: Navarro et al., 2004) and is used in AFS from Mexico to Central America (Hellin et al., 1999) to Brazil (Jong, 1996; Yamada and Gholz, 2002). One limitation of *C. odorata* as a lumber species is its susceptibility to the shoot-boring insect *Hypsipyla grandella* (Navarro et al., 2004) causing the trunk to fork at a low height (Rodgers et al., 1995).

Inga edulis Mart. (Mimosoideae)

The Genus *Inga* is widely represented in AFS in the Americas with over 50 species being used by low-input farmers for fuelwood, fruit and fertilizer due to the high N content of its litter (Fisher, 1995). Of these 50 species, *I. edulis* is the most commonly used because it is acid-soil tolerant and has high rates of N-fixation (Tilki and Fisher, 1998). It is considered a pioneer species associated with large gaps (Park et al., 2005) and a heliophyte (Lorenzi, 2002). It has high survival and good production in both monoculture and multi-species plantings (Kettler, 1997). It is a nodulating N-fixer (Moreira et al., 1992; Fisher, 1995).

Manihot esculenta Crantz (Euphorbiaceae)

M. esculenta, alternately known as cassava, manioc or *mandioca*, is a staple crop throughout the tropics of the world, although it is native to South America. Bitter manioc produces a carbohydrate-rich tuber that is toxic due to high levels of hydrocyanic acid (HCN) and becomes edible only after a labor-intensive detoxification process (El-Sharkawy, 1993). Bitter manioc grows well in very acid, nutrient poor soils, such as many found in the Amazon Basin, and can produce a reasonable crop without external inputs on soils that would fail to produce acceptable grain yields although manioc crops begin to decline with consecutive cropping largely due to K deficiency (Howeler, 2002); K fertilization may be necessary to sustain manioc production in consecutive cropping systems.

Establishment

In March of 2005, a one-hectare study site was selected by the directors of Projeto Tipitamba/SHIFT in conjunction with the Empresa Brasileira de Agropecuária (Embrapa). The site is nearly uniform in lack of slope with a slight (unnoticed at planting) depression in the south-central area of the site. After selection, the site was cleared and mulched using a TRITUCAP mulching tractor (Denich et. al, 2004). The mulching tractor evenly distributed the above-ground biomass of the seven year old secondary forest over the soil surface. Experimental treatments were applied to the prepared site in June, 2005. Four experimental blocks that run north-south across the site were established. Each block was divided into four plots (n=16) that measured 24 x 24m. A factorial combination of fertilization treatment and N-fixing species additions was assigned to these blocks in a split-plot design. The two main plot fertilizer treatments consisted of no fertilization (PK-) and broadcast application of 46 kg P ha^{-1} as P_20_5 (100kg of 46% Super-Simple Phosphate) and 30 kg K ha^{-1} applied as KCl (50 kg of 60% KCl) (PK+). Subplot treatments consisted of planting the native species *S. amazonicum, C. odorata* and *C. pentandra* together (I-), or in combination with the N-fixing species *I. edulis* as well as *P. multijuga* (I+).

Within each plot, a 2.0 m buffer area was established along both the North and South edges (between plots) and a 1.5 m buffer along the East and West edges (between blocks). Each plot contained six rows of trees with 13 trees per row for a total of 78 trees per 0.06 ha plot (1354 trees ha^{-1}). Within each row, 1.8 m spacing was utilized while four meters were used between rows of trees.

Seedlings were produced at the local commercial nursery AIMEX in Benevides, Pará, Brazil and varied in age between three and five months at the time of planting. The seedling soil medium was a mixture of local soil with organic potting soil contained in black planting bags that were approximately 25 cm deep and 10 cm across. Seedlings were delivered to the site (approximately 75 km distance) in the back of a medium-sized flat-bed truck with a tarp over them. Seedlings were left in their bags and in the shade until planting two days later. Seedlings were planted in holes dug with a post-hole digger and were filled in to cover the top of the planting medium flush with the soil surface.

Seedlings were not removed from their bags until directly before planting. A crew of four local Brazilians was employed to establish the plantation.

In July of 2005, bitter manioc was planted at 1 x 1 m spacing in all treatments, for a planting density of 10,000 stems ha^{-1}. Rows of manioc were planted so that 0.5 m spacing was observed on both sides of each row of trees and the nearest row of manioc; which may have allowed manioc to benefit from or cause competition with trees. Manioc cuttings measuring approximately 10 cm were taken from mature plants to be used as planting stock. All planting of manioc was performed by a local crew. Traditionally in the Bragantina, fallow vegetation is slashed at the beginning of the dry season and burned after it has dried sufficiently while planting of manioc coincides with the onset of the rains in December or January. Planting was not completed until July for this project; however, the use of the mulching tractor produces a thick mulch layer that maintains soil moisture at levels acceptable to manioc growth, as opposed to burning the slash (Denich et al., 2004). Mulching does not raise the surface pH or provide large amounts of mineralized nutrients initially like ash from burned vegetation.

Growth Assessment

To determine initial size of the nursery-grown seedlings, 10% of the trees planted were randomly selected before planting for measurement of ground-line diameter (GLD) and height. Then, in March of 2006, survival, GLD, height and diameter at breast height (DBH), when applicable, were recorded for all species. GLD and DBH were measured using electronic calipers that measured to 0.1 mm. Height was measured using a 3 m pole. Heights were read to 0.1 cm, except when trees were taller than two meters in which case trees were read to 1 cm. Since nearly all *I. edulis* developed multiple stems above the ground, only the most vigorous and/or longest reaching branch was selected for height and DBH measurements. In July, 2006, all trees were re-measured for survival, GLD, height and diameter at DBH, when applicable, using the same methodology as described above.

Biomass of Manioc and Competition

At the time of planting in June of 2005 there was no appreciable above-ground biomass of weed competition or manioc as the site had recently been mulched and planted. In June of 2006 manioc and above-ground weed competition biomass were collected. Each plot was divided into four quadrants and each quadrant was divided into twenty potential sampling sectors. A 1 m^2 sampling frame constructed from PVC tubing was placed within a randomly selected sector within each quadrant. All live vegetation within the vertical plane above the PVC tubing was collected using scissors or hand clippers. This procedure was used to collect all competing vegetation that was neither a) manioc leaves or stems nor b) tree species utilized in the design of this project.

Growth Assessment of Comparable Plantations

In June of 2006 three 15m-radius plots of *S. amazonicum* were measured for height and DBH within one plantation in Paragominas, Pará, Brazil (S 2’55’’35.7 W 47’24’’01.3). All trees within a 15m radius of a tree at the center of the selected plot were measured. A Haglöf (Sweden) Vertex III Hypsometer was used to estimate heights and a forester’s tape was used to measure DBH. This 1000 ha commercial plantation was established in 1993. It is not known what site preparation techniques were used; however, the site manager reported using a variety of inorganic fertilizers as well as mulched organic material (e.g., manure or chicken litter) at planting (D. Markewitz, pers. comm.). The trees were originally planted at 3.5 x 3.5 m spacing but received a 50% thinning prior to the current measurement and thus were in a 3.5 x 7.0 m matrix. The exact year of thinning is unknown but stump sprouts were generally between 5 and 10 m tall. Basal Area within the 15m-radius plot was measured using a 10 factor forester's Basal Area prism.

Statistical Analysis

Analysis of variance (ANOVA) was used to analyze the project as a two-way factorial randomized complete block design. Fertilizer treatment with and without P and K additions were the main plot treatments (N=4) and treatments with or without the presence of *I. edulis* were the sub-plot treatments. Statistical significance was conferred at the P=0.10 level.

Results

Survival

The all-species mean survival at one year was significantly higher (P=0.001) in un-fertilized (PK-) plots than in fertilized (PK+) plots (Table 2.1). However, the presence of N-fixing *I. edulis* did not have a significant effect on survival (P=0.4), nor was the interaction between fertilization and the presence of *I. edulis* significant (P= 0.2). A trend of increased survival was observed in the unfertilized (PK-) main-plot treatment in the presence of *I. edulis* compared to fertilized treatment (PK+). Survival for manioc was not measured, but from field observations there was significant mortality in the low lying area of the site where there was frequently water impounded on the surface both at the time of planting and again in March and June/July of 2006.

Growth Responses of Planted Trees

Fertilization had a positive, significant ($P<0.01$) effect on the growth of several tree species; however, the presence of *I. edulis* did not have a significant effect (figures 2.2 and 2.3). There was large variance in tree growth both among and within plots. Individual trees were observed to be suppressed by weed competition, poor root development in waterlogged conditions and/or insect attack. Within the fertilized treatment, for example, tree heights of *S. amazonicum* ranged from <1 to >11 m after one year and those of *C. pentandra* ranged from <1 to >6 m. This pattern occurred for *C. odorata* as well, but was less pronounced, where some seedlings did not grow after planting and were alive but without leaves whereas others were over 2 m tall with luxuriant green leaves. *I. edulis* did not appear to follow this pattern as variability was very low in both fertilized and unfertilized treatments. *I. edulis* grew in manioc-shaded areas but grew only a central stem without lateral branches. It is important to note that no *Hypsipila grandella* damage was noted on any *C. odorata* at the site.

Manioc Response

There were no significant differences among treatments ($P=0.9$) for dry-weight production of manioc leaves with a mean of 218 g ha^{-1}. Also, there were no significant differences in dry-weight of stem or of tuber biomass at the P=0.10 level for either main-plot fertilizer or sub-plot treatments. Although not statistically significant, obvious trends were observed of increased biomass with fertilization and in the presence of *I. edulis* for manioc stems and manioc tubers (Fig. 2.4). The significance of these trends is undermined by high variability, which might be overcome with more sampling within plots or by growth of manioc plants through the second year.

Competing Vegetation Biomass

The PK+ treatment produced significantly greater (P=0.03) competition dry-weight biomass than the PK- treatment. The presence of I. edulis (sup-plot treatment) was not significant (P=0.10). In the PK- treatment, the I- sup-plot treatment had more weedy competition biomass than did the I+ sub-plot treatment; however, there was not a significant difference in the PK+ treatment (P=0.5), although a trend of increased competition biomass was observed (Fig. 2.5).

Discussion

Survival

Survival of all species was greater in non-fertilized treatments than in fertilized treatments (Table 2.1). Clearly, a variety of factors worked together to cause this response. The most obvious factor was the dramatic increase in competing vegetation that responded to fertilization with a 25% increase in biomass (Fig. 2.5). This additional biomass likely increased competition for both water and nutrients. The rapid height growth of the competing vegetation also increased shading for the crop trees, a few of which were shade intolerant. Allelopathic effects from some of this competing vegetation are also possible (Hoffman and Carroll, 1995). It is also possible that fertilization directly stressed the trees. Fertilization with K may cause stress to immature root systems of seedlings which can lead to stunted initial growth or even death during the dry season due to reduced drought tolerance as was observed in a study of *Pseudotsuga menziesii* in Oregon, USA (Jacobs et al., 2004). In that study, fertilization with NPK caused significantly more drought stress when compared to non-fertilized seedlings.

Secondly, planting season for crops and trees in the Eastern Amazon region generally coincides with the onset of the rainy season in January. In this study, planting did not take place until late June due to logistical complications; which is during the transition from the wet to dry season. It is remarkable that the survival rate in the un-fertilized treatment was >85% considering the difficulties associated with such a late planting, including the stresses of transport from nursery to site, planting, and the short amount of time for roots to establish in the soil before the onset of dry conditions. It is possible that the mulch layer left from the mulched secondary forest, which averaged 53.6 Mg ha^{-1} (Joslin et al., in preparation) was able to maintain enough soil moisture to sustain the immature root systems throughout the dry season.

Although no insect damage inventories or capture studies were done, several species were observed to have suffered attack. Insect attacks were typically girdled twigs or defoliation. The most commonly observed insect attacks occurred on *S. amazonicum* and *C. pentandra*. Insect attack was greater in open areas without vigorous tree and/or competition growth. Interestingly, no *C. odorata* were observed to have suffered *Hypsypila spp*. damage.

When the site was mulched the site appeared flat with no obvious areas of concern. However, when returning to the site in March and again in June of 2006, it was apparent that there was a large, approximately 35 m radius depression in the middle of the site that was extremely poorly drained and periodically had water at the surface. This depression spanned both fertilized and non-fertilized treatments and survival was very low in both, especially for *C. odorata*, *P. multijuga*, *S. amazonicum* and *M. esculenta.* Within this depression there was standing water throughout the rainy season that either killed or stunted the growth of almost all trees within this area.

C. odorata had exceptionally low survival in the fertilized treatment, <10%, in this study. Davidson et al. (1998) also showed very low survival of *C. odorata* with fertilization in Perú. It appears that *C. odorata* does not respond well to fertilization at planting and should only be fertilized well after the seedlings are established, perhaps after one year. In fact, Davidson et al. (1998) also showed that among the 15 species of native species planted, grouped into early and late successional groups, survival was less in fertilized vs. unfertilized treatments.

Tree Species Growth Response

S. amazonicum showed the greatest response to fertilization with 417% greater growth when fertilized. *I. edulis,* had the next greatest response, with a difference in height of 67% between fertilized and unfertilized treatments with *C. pentandra* following with a 40% difference. Height responses of the five species compares favorably to results reported elsewhere from the tropical Americas (Table 2.2). The low planting density used here probably resulted in greater competing vegetation and somewhat reduced growth when compared to Brienza Jr. (1999) for *I. edulis*. Farmers could expect very vigorous growth of *I. edulis, C. pentandra* and *S. amazonicum* after 3-5 years (Table 2.2), since early growth values are similar to those reported here. Both *C. odorata* and *P. multijuga* performed better than the least performing values reported in Table 2.2, however, *C. odorata* did not perform as well as values reported by Browder and Podlowski (2000) or Menalled et al. (1998). Farmers in the Bragantina should not expect rapid growth from *C. odorata* when planted in a mixed-species agroforest system but should not arbitrarily avoid this species as they will need to balance slower growth rate with regional lumber values. *P. multijuga,* on the other hand, might be expected to grow 6 m in height in five years, as reported by Tonini et al. (2006).

Trends were observed in *I. edulis, S. amazonicum* and *P multijuga* for an increase in growth rate during the three months between measurements in March and July. This is probably due to a response to the seasonal variation in rainfall. There was a strong four-month dry season after planting in which it is likely that very little growth took place while the nine-month and one-year measurements took place during the rainy season (Figure 2.1). It is unlikely litter fall from either manioc or the planted tree species had any effect since it was still the first growing season and no species had deposited litter on the surface.

The positive growth response of the tree species to the PK+ treatment and not to I+ treatments indicates that *I. edulis* was not able to influence the growth of neighboring trees. One year might not be enough time for the N-fixing trees to influence N availability either through their roots or through litterfall. It is also possible that N is not a limiting nutrient at this site, which would confirm the conclusions Gehring et al. (1999). The strong growth response of *S. amazonicum* and *I. edulis* and moderate growth response of *C. pentandra* and *C. odorata* as well to the PK+ treatment indicate that P is limiting tree. The positive biomass response of manioc tubers may have been due to K fertilization (Howeler and Cadavid, 1983), and not P fertilization.

Although growth responses in sup-plot treatments with *I. edulis* were not statistically significant due to high variability, they do indicate trends of greater growth in the presence of *I. edulis*. *C. odorata* did not respond positively to the presence of *I. edulis* with fertilization, suffering high mortality and suppressed growth. As noted previously, *C. odorata* is a light-demanding heliophyte and appears to have suffered from the increased growth of *I. edulis* with fertilization. However, all five tree species showed increased rates of growth between April and July only in the PK+ I+ treatment potentially indicating accelerated growth due to increased mineralization of fertilizer and N.

As mentioned above, insect damage played a role in the development of both *S. amazonicum* and *C. pentandra*, and both had damage from insects, especially in the non-fertilized plots. *C. odorata* showed no visible damage from *Hypsypila spp.* herbivory which is consistent with results from Menalled et al. (1998) who saw no damage in the first year but 20% mortality in the second year of monocrop plantation.

Manioc Response

Manioc tuber dry weight biomass was on the lower end of the reported values for manioc in other studies (see Table 2.3). El-Sharkawy (1993) reports that, in Brazil manioc tubers are 25 - 30% dry-weight biomass. It is not clear if the presence of trees had an impact on biomass production of manioc as no treatments without trees were done, but there was a trend of increased manioc tubers and stems in the presence of *I. edulis*. Brienza Jr. (1999) reports no loss of manioc tubers with the inclusion of N-fixing trees at any planting density; 1 x 1, 1 x 2 and 2 x 2m.

Competing vegetation (planted trees and "weeds") could be the main factor causing lower yields of manioc when compared to Kato et al. (2005), whose research plots were in the same Experimental Farm as this study. Although the lowest mean yield reported here is much lower than the average reported by El-Sharkawy (1993) for the Northeast of Brazil and Kato et al. (2005) from Igarapé Açu, many of the varieties used were improved hybrids grown in monocrop field trials with standard vegetation control.

Although tests with ANOVA do not show a difference between the treatments, the data show a strong increasing trend (Fig. 2.4) for biomass of manioc stems and tubers in both the fertilized and unfertilized treatments in the presence of the N-fixing *I. edulis*. The statistical strength of treatments is undermined by high variability with maximum variability for manioc tubers and stems in the PK+ I- treatment where only one of four plots yielded any biomass. Howeler (2002), however, did not report significant differences for manioc tubers between control and NPK fertilization in Colombia until harvest in the third consecutive year of cropping.

Growth of manioc plants was obviously affected by the fertilizer treatments. In the fertilized treatment the manioc plants grew tall, often up to 3+ m in height, whereas manioc plants in the unfertilized treatments were less than 2 m. This difference in height was not accompanied by a difference in greater leaf production (Fig. 2.4) because manioc only carries leaves at its canopy level, few low-lying leaves were noted.

Competing Vegetation Biomass

Fertilization with P and K increased the biomass of weedy competition compared to the unfertilized treatment; however, there was no trend for the effects of the presence of *I. edulis* in the sub-plot treatments. One interesting response was that when not fertilized, *I. edulis* might suppress competing vegetation. There was more competing biomass in the I- sub-plot treatment than I+ without fertilization. *I. edulis* growth, GLD (Fig. 2.2) and height (Fig. 2.3), was greater with fertilization, competition biomass was not reduced in the presence of *I. edulis* with fertilizer. Since *I. edulis* has many lateral branches, especially as it grows taller, it might have been able to shade out and retard competing vegetation in the PK+ treatment. None of *S. amazonicum*, *C. pentandra* or *C. odorata* has dense lateral branching like *I. edulis* and therefore probably had a negligible effect through shading on weedy vegetation after just one year.

In this study, weeding was to be performed by hand according to Projeto Tipitamba standards, but was not performed at any time other than at Year 1 data collection. Weed competition biomass was intense and was probably a major factor in mortality, especially for shade-intolerant species such as *S. amazonicum*. Most of the competition biomass came from stump sprouts and shoot runners of the cut vegetation that was mulched when the site was prepared. The mulch had little effect on competing woody vegetation since sprouts were able to establish under the mulch layer, contrary to earlier results of Rippin et al. (1994). However, where the mulch layer completely covered the soil there was very little grassy competition.

Intense weed competition, especially in the fertilized treatments, undoubtedly had a negative impact on growth and survival of planted tree species as well as manioc. Jama et al. (1991) suggest row-spacing of two meters for maximum weed reduction, up to 98%, in agroforestry systems. Light reduction was found to be the principal cause of weed reduction by Jama et al. (1991) in Kenya although at such close spacing the manioc might respond negatively to the trees as well, although Brienza Jr. (1999) did not report reduced manioc yields when relay cropped with trees, even at 1 x 1 m spacing. Species with slowly decomposing biomass, such as *I. edulis*, have been noted to achieve greater weed control when compared to other legumes (Salazar et al., 1993). Competition suppression due to *I. edulis* could probably be expected to increase over time as trees age and deposit more biomass on the surface.

Selection and management of appropriate tree species can reduce labor input and weeding costs considerably through reduced competition, and in this research it appears that *I. edulis* may have exerted some control on competition when not fertilized. In the fertilized treatment it appears that the addition of P and K was more than enough to free competing vegetation from nutrient limitations and the trees were unable to out-compete the vegetation for light, water and/or nutrients.

Conclusions

I. edulis should be considered as a viable option for low-input farmers interested in utilizing AFS due to its excellent survival when not fertilized and moderate survival when fertilized. The ability of *I. edulis* to tolerate acid soils makes it a good choice for use in this region. Nodulation was noted on several individuals planted at this site in both fertilized and unfertilized treatments. Additionally, the use of *I. edulis* as an N-fixer in AFS when not using P and K fertilizer should be considered due to consistent trends of increased tree growth and survival, manioc biomass, mulch layer mass and macronutrient content loss, as well as weed suppression.

The significantly greater growth demonstrated by trees, manioc and competition coupled with elevated mortality of trees and manioc in the fertilized treatment indicate that synchronization of management techniques is needed. Competing vegetation was greater with fertilization and may have reduced tree survival. It appears that planting trees near the beginning of the dry season did not have a negative impact on survival because the survival in the non-fertilized treatment was acceptable. Fertilization with P and K may have triggered a negative survival response due to root shock at planting due to fertilizer salt stress. It may be advisable to fertilize only after tree seedling roots have developed in the native soil and/or after the onset of the rainy season to avoid moisture stress and for trees and manioc to compete effectively against other vegetation.

Fertilization caused significant increases in both manioc tuber yield and tree growth so it may be an attractive allocation of resources. However, *I. edulis* may not be advisable when planted with slower-growing heliophytes, especially when fertilized, due to strong light and resource competition that will likely result in unacceptably low performance for trees like *C. odorata*.

The responses of tree growth to fertilization by wood density may have been correlated. Tree species with soft wood, *S. amazonicum* and *I. edulis*, showed the greatest growth response and suffered the least survival reduction with fertilization while species with dense wood, *C. odorata* and *P. multijuga*, showed no growth response and the greatest reduction in survival with fertilization. The negative survival response of *C. odorata* and *P. multijuga* may have been due to increased competition biomass when fertilized. Early successional tree species may be limited by P availability whereas later successional and/or primary forest species may be limited by N availability.

Since no vegetation control was performed, the manioc tuber yields and tree growth reported here should represent the lowest expected values for a farmer in this region. If the farmer performed any form of competition control they could reasonably expect higher yields due to reduced competition.

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Table 2.1. Percent survival (mean ± 1 SE) of five species of trees native to the Amazon grown under different treatments twelve months after planting in June 2005 in Igarapé Açu, Pará, Brazil. There were 16 plots with four plots per treatment (N=4) with 78 total trees per plot; 26 per species in I- plots and 40 *I. edulis*, 8 *P. multijuga* and 10 each of other three species in I+ plots.

Species	Treatment[1]			
	PK- I-	PK- I+	PK+ I-	PK+ I+
	% ± 1 SE			
Inga edulis		98.8 ± 0.7		51.3 ± 6.1
Parkia multijuga		87.9 ± 5.1		14.3 ± 5.5
Cedrela odorata	79.8 ± 3.6	80.0 ± 4.1	6.9 ± 3.4	5.3 ± 6.3
Schizolobium amazonicum	63.6 ± 4.4	65.8 ± 5.9	51.5 ± 3.4	43.6 ± 10.3
Ceiba pentandra	97.1 ± 1.4	100 ± 0.0	37.4 ± 6.7	25.0 ± 10.4
All species mean	80.1 ± 3.6	91.3 ± 1.6	32.0 ± 4.4	37.2 ± 4.0

[1]Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK-) and planting with 5 native species including *I. edulis* (I+) or of 3 native species without *I. edulis* (I-).

Table 2.2. Mean height, diameter at breast height (DBH), survival and age of 5 species of native trees from various locations.

Location	Source	Species	Age Months	Height	DBH	Survival %
				---- cm ----		
Yurimaguas, Perú	Alegre et al., 2005	*I. edulis*	12	250	4.4	
		I. edulis	24	440	5.2	
		I. edulis	36	670	6.7	
La Selva, Costa Rica	Tilki and Fisher, 1998	*I. edulis*	36	630	10.5	97
Igarapé Açu, Brazil	Brienza Jr., 1999	*I. edulis*	12	470	3.5	97
Veracruz, Mexico	Ricker et al., 2005	*C. odorata*	16	59.4		46
Rondônia, Brazil	Browder and Podlowski, 2000	*C. odorata*	18	318	9.3	89
La Selva, Costa Rica	Menalled et al., 1998	*C. odorata*	18	340	4	
			30	673	6.6	
			42	935	8	
Mt. Mee, Australia	Erskine et al., 2005	*C. odorata*	60	730	14.6	96
Mato Grosso, Brazil	Rondon, 2002	*S. amazonicum*	60	1600	15.1	
Roraima, Brazil	Tonini et al., 2006	*S. amazonicum*	72	1860	17.6	72
Barcarena, Pará, Brazil	Banco da Amazônia, 1998	*S. amazonicum*	80	1316	13.8	
Paragominas, Pará, Brazil	This Study	*S. amazonicum*	156	2533	28.6	
Acre, Brazil	d'Oliveira, 2000	*C.pentandra*	12	163		90
		C.pentandra	60	309	2.2	50
Amazonas, Brazil	Camargo et al., 2002	*P. multijuga*	12	50		
Roraima, Brazil	Tonini et al., 2006	*P. multijuga*	60	610	12.3	86

Table 2.3. Manioc yields from various locations. Location, source of data, soil type and fresh or dry weight as well as low, high and mean reported yields, if given.

Location	Source	Soil Type	Unit[1]	Low yield	High yield	Mean yield
				------- Mg ha^{-1} -------		
Phillipines	Escalda and Ratilla, 1998	Eutropept	Fresh	6	26	
Benin	Carsky and Toukourou, 2005	Ferrali-Haplic Acrisol	Fresh	16	21	
Igarapé Açu, Brazil	Kato et al., 2005	Typic Kandiudult	Fresh	11.3	33.8	
Brazil	El-Sharkawy, 1993	Various	Fresh			9
Colombia	Howeler and Cadavid, 1983	Various	Fresh	0.4	55	
Cameroon	Numbem, 1998	Variuos	Dry			1
Cameroon	Hauser et al., 2000	Typic Kandiudult	Dry	1.8	4.8	
Igarapé Açu, Brazil	This study	Typic Kandiudult	Dry	0.2	3	1.5

[1]Denotes Fresh Weight or Dry Weight at measurement

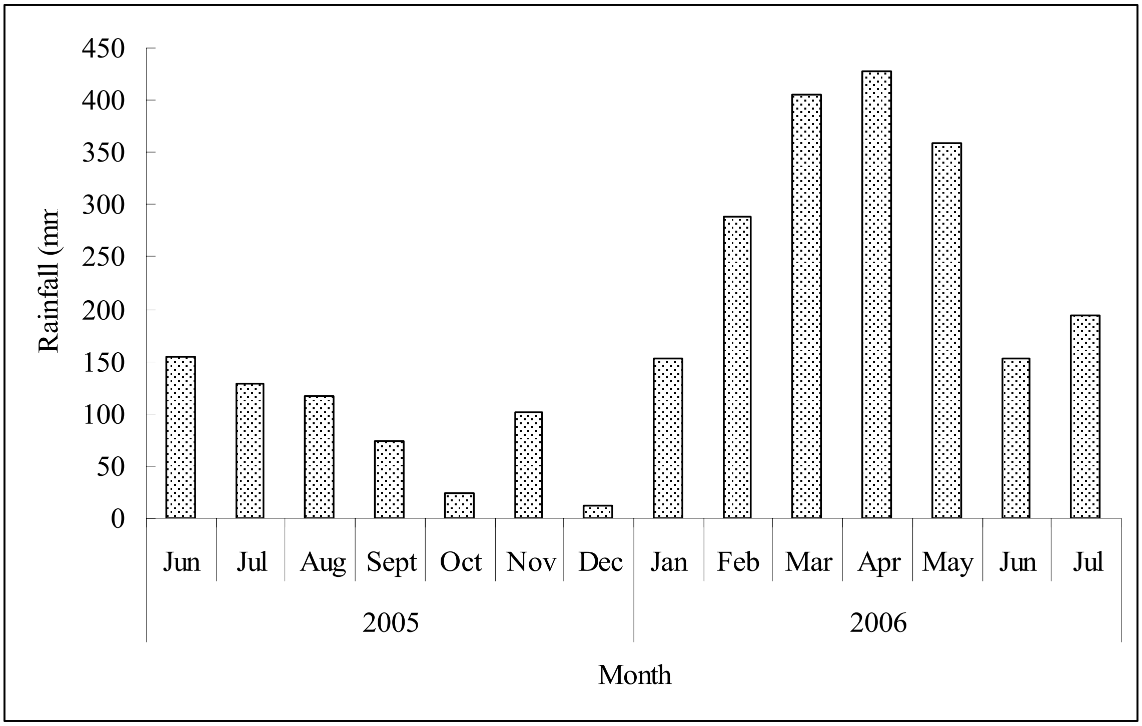

Figure 2.1. – Rainfall by month in Igarapé Açu, Pará, Brazil from June 2005 until July 2006. Total rainfall was 2242 mm, 210 mm less than mean annual rainfall of 2450 mm; the distribution pattern was normal for this area except for the month of November, which was about 80 mm more than the monthly mean.

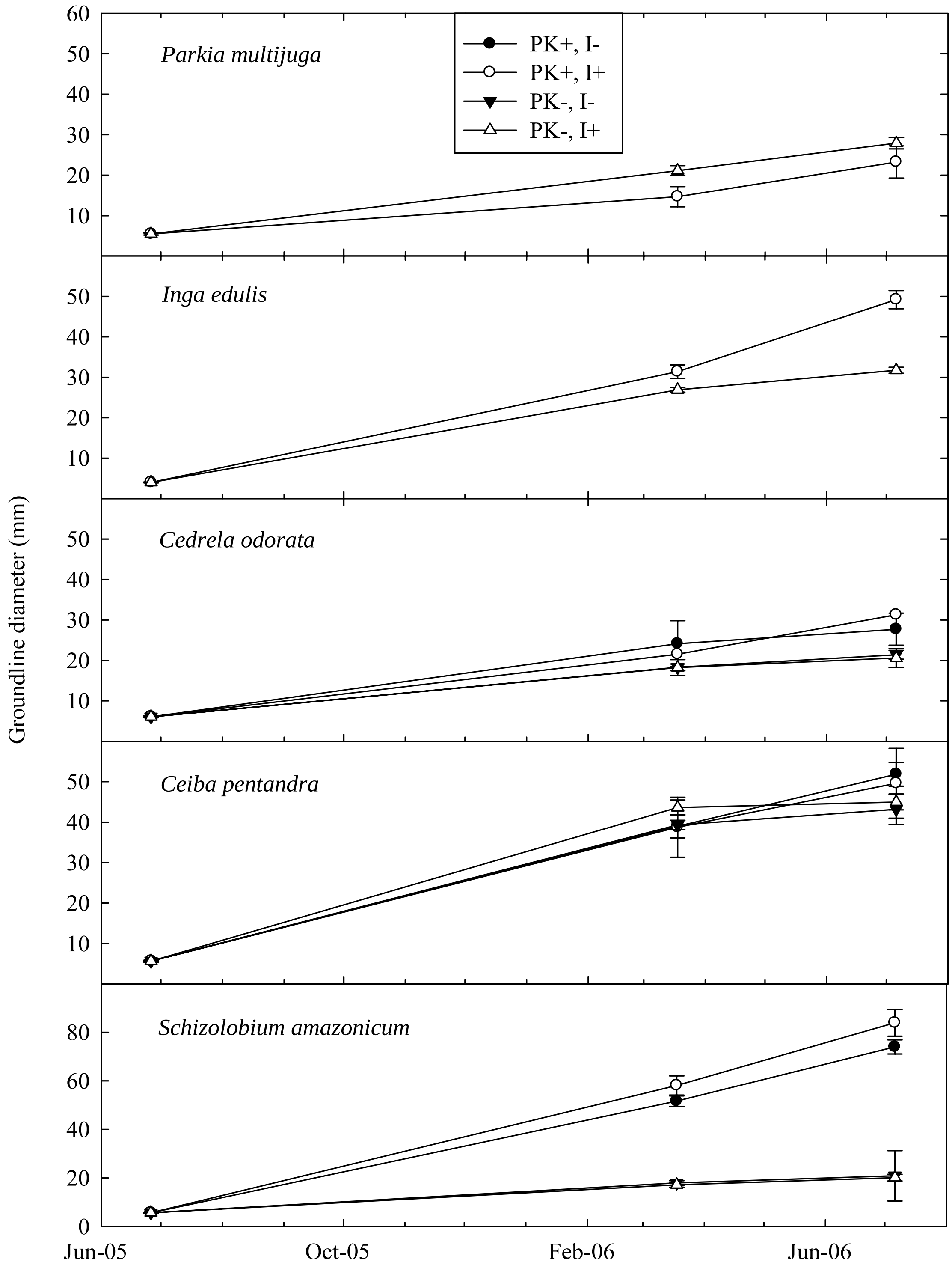

Figure 2.2. Ground line diameter of 5 native tree species 1 year after planting in June 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without fertilizer (PK-) planted with manioc and with 5 native tree species including *I. edulis* (I+) or of 3 native species without *I. edulis* (I-). Error bars represent 1 SE.

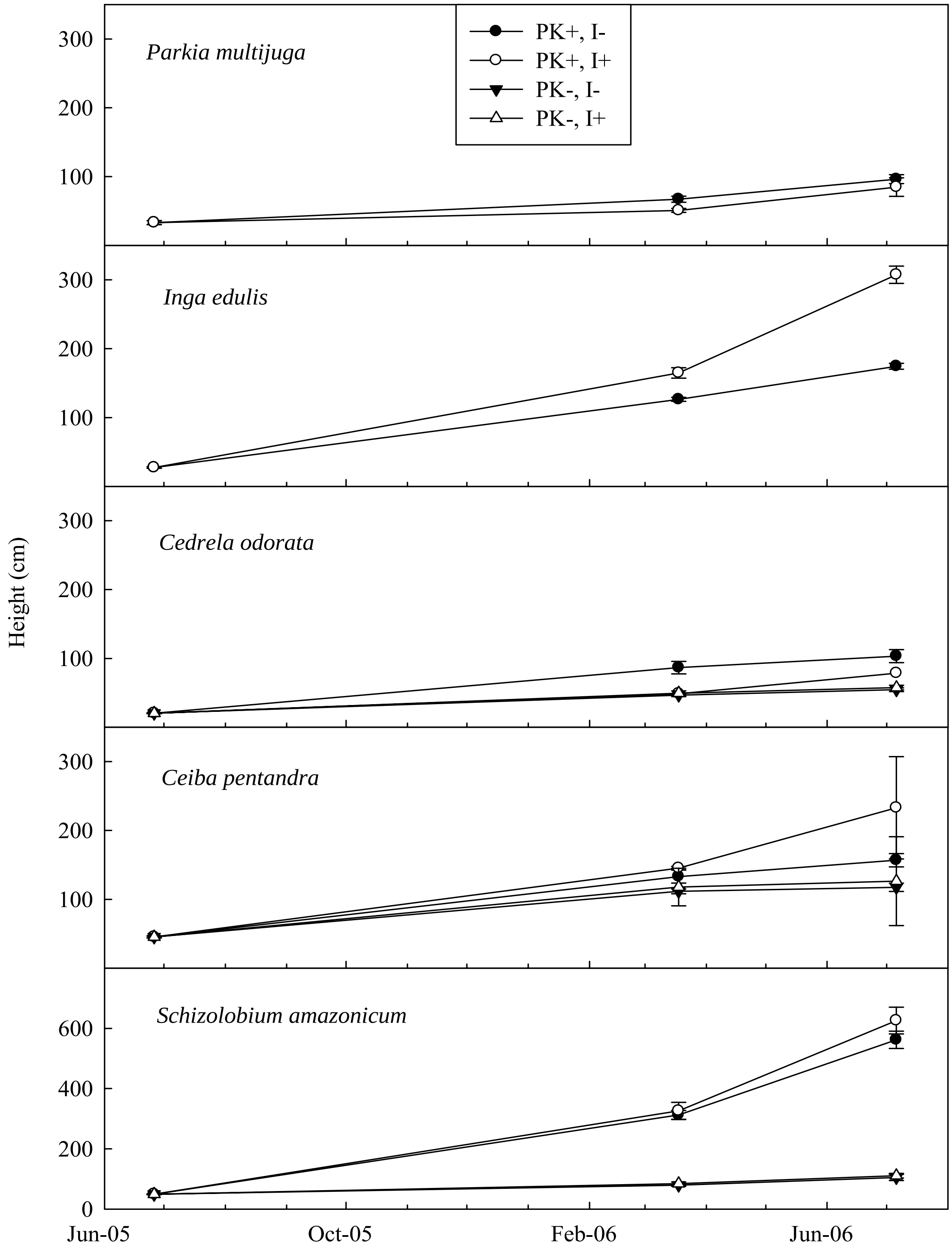

Figure 2.3. Height of 5 native species 1 year after planting in June 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of fertilization with P and K (PK+) or without fertilizer (PK-) planted with manioc and with 5 native tree species including *I. edulis* (I+) or of 3 native species without *I. edulis* (I-). Error bars represent 1 SE.

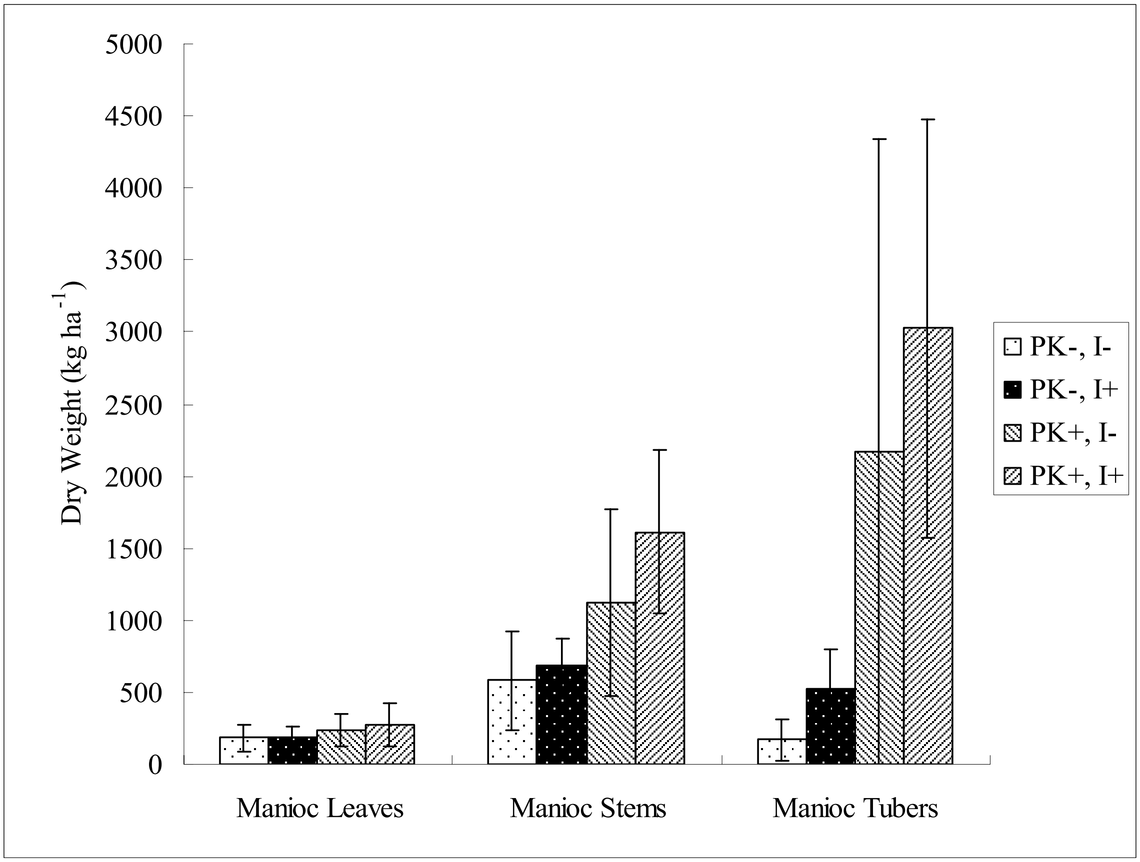

Figure 2.4. Manioc dry weight response (mean ± SE) to treatments one year after planting in July 2005 in Igarapé Açu, Pará, Brazil. Four plots per treatment (N=4) with a planting density of 1 x 1m or 10,000 stems ha^{-1}. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK-) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I-).

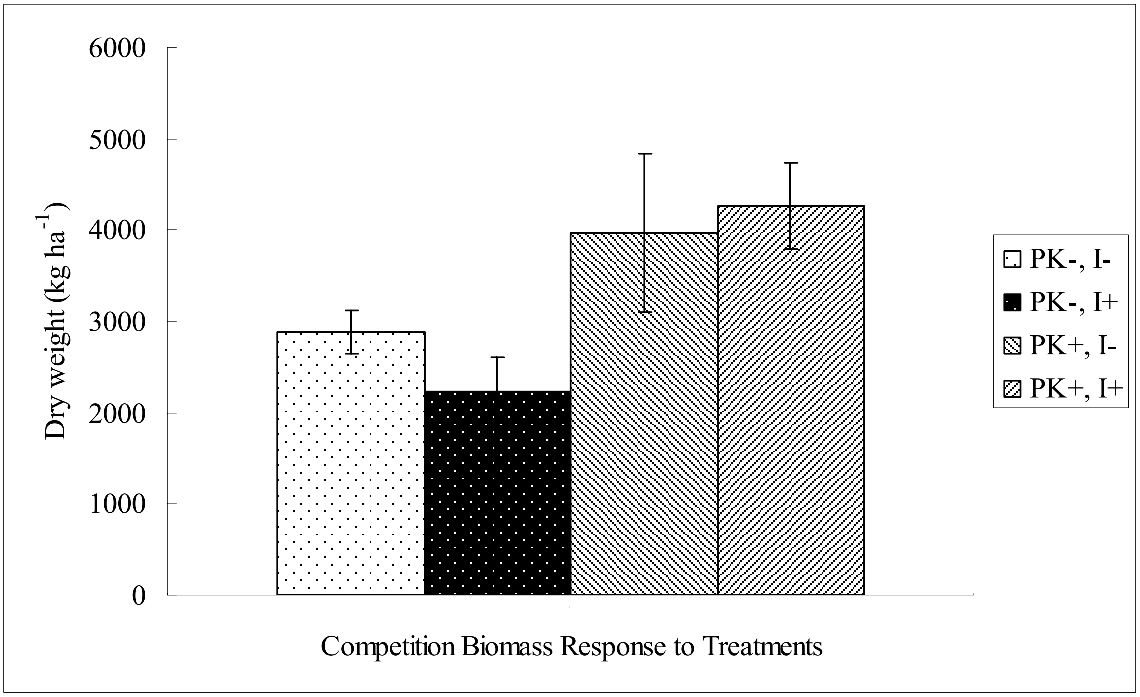

Figure 2.5. Dry weight of competing vegetation response to treatments one year after planting in June 2005 in Igarapé Açu, Pará, Brazil. Four plots per treatment (N=4). Error bars indicate 1 SE. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK-) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I-).

CHAPTER III

SOIL RESPONSES ONE YEAR AFTER INSTALLATION OF AN AGROFORESTRY SYSTEM IN THE EASTERN AMAZON OF BRAZIL[1]

[1]Aaron H. Joslin, Daniel Markewitz, Lawrence A. Morris, Oswaldo R. Kato, Ricardo O. Figuereido and Francisco de A. Oliveira. To be submitted to: *Agroforestry Systems*

Abstract

Agriculture in the Eastern Amazon of Brazil is dominated by swidden, or slash-and-burn, practices where native vegetation is felled, dried and then burned. Ash from the burned vegetation supplies nutrients to the crop and typically increases the pH of surface soils. Nitrogen and other nutrient losses during burning can be large and demand by food crops such that fields are often abandoned after only 1-2 years, due in part to nutrient depletion. The use of slash-and-mulch technology prevents loss of nutrients from smoke and run-off during burning and creates a more closed nutrient-cycling system. Furthermore, increasingly short fallow cycles between cropping phases is limiting biomass and nutrient accumulation for subsequent cropping cycles. Enrichment plantings with N-fixing trees have been suggested as a way to increase fallow biomass and cycle nutrients more rapidly than occurs with spontaneous fallow vegetation.

A multi-species agroforestry system (AFS) was installed after a one hectare site was cleared with a mulching tractor at the Experimental Farm of Universidade Federal Rural da Amazônia (UFRA) in Igarapé Açu, Pará, Brazil in June of 2006. The study evaluated the effect of fertilization with P and K the utilization of 5 native tree species including the N-fixer *Inga edulis* or of 3 native tree species without *I. edulis* on soil conditions, mulch decomposition and nutrient uptake by *Manihot esculenta* and native vegetation.

Neither fertilization nor the presence of *I. edulis* produced consistent effects on the soil nutrient concentrations or on mulch, competing vegetation, or manioc nutrient concentrations. Trends of increased nutrient content in manioc stems and tubers with fertilization and in the presence of *I. edulis* and in competing vegetation with fertilization.

Additionally, mulched material showed a decrease in nutrient content for Ca and Mg while a trend was observed for decreased N content after one year although P and K content increased in the mulch layer.

Introduction

Mineral soil that is low in available nutrients, particularly N, P and Ca, restricts the productivity of low-input agriculture in the highly weathered upland soils of Northeast Pará, Brazil. Native forests, however, can maintain high levels of productivity due to efficient cycling mechanisms (Jordan, 1985) which ensure that most of the actively cycled nutrients remain in the living biomass or in the litter layer. Conversion of these forests to agricultural systems disrupts these cycling mechanisms. Incorporation of trees in agroforestry systems (AFS) can restore nutrient cycling in agricultural landscapes.

When a forest is cut and mulched, decomposition allows for N immobilized in the biomass of living vegetation to mineralize and become available for plant uptake. Upland soils in Pará, Brazil contain between 2.2 and 4.1 g N kg^{-1} soil (Markewitz et al., 2004; Smith et al., 1998) in the upper 20 cm where 70% of soil-N is stored (McGrath et al., 2000). Annual net N mineralization rates are high at 328 kg N ha^{-1} yr^{-1} in the Eastern Amazon, and net nitrification of 436 kg N ha^{-1} yr^{-1} in a native forest in Pará, Brazil although N mineralization and nitrification rates were lower in plantation forests, including plantations of N-fixers (Smith et al., 1998).

Nitrogen (N)-fixing trees have been used in AFS to provide a variety of services to increase or maintain productivity through their effects on N and other nutrient cycles. Estimates of atmospheric N fixation by trees range widely from 0.1-110 kg ha^{-1} $year^{-1}$ using acetylene reduction assay (ARA) techniques or 40-580 kg ha^{-1} $year^{-1}$ using total nitrogen difference (TND) (Danso et al., 1992). Although root exudates and fine-root turnover can augment soil N throughout the life of the tree, quantifying how much N contributed by N-fixing trees to agroecosystems remains problematic. Whichever mechanisms are at work, enrichment planting with N-fixing trees can increase biomass production of fallow vegetation compared to spontaneously regenerated fallow in the Bragantina (Brienza Jr., 1999).

Pruned foliage from N-fixing trees is used by farmers as "green mulch" and can annually contribute 254 kg N, 23 kg P, 173 kg K, 108 kg Ca and 37 kg Mg per hectare from 8.7 tons ha^{-1} of leaf matter applied to the surface (Szott et al., 1991). These are high rates of input such that Sanchez (1995) suggests that only 4 tons ha^{-1} of litter is likely feasible. Foliar concentration of N in *I. edulis* can range up to 2.5%, which is greater than the 1.5% common in fallow vegetation. *I. edulis* produced 4.1 tons ha^{-1} of litter in Igarapé Açu (Brienza Jr., 1999), which was the highest among five leguminous species tested at various planting densities. It appears as though the natural litter-fall rate of plantations of *I. edulis* would satisfy the rate of pruned litter application as recommended by Sanchez (1995). Even though *I. edulis* litter has high leaf lignin and polyphenolic content, making it resistant to decomposition (Zech et al., 1997), its high productivity and slow nutrient release makes it a good choice for AFS projects.

Swidden farming is usually initiated by slashing vegetation and then burning it, this process is commonly called slash-and-burn farming. Burning reduces the nutrient capital of the system and uncontrolled fires are an additional problem. Slash-and-mulch technology has developed as a response to eliminate losses from fire by chopping vegetation and laying it on the surface with a mulching tractor. When using a mulching tractor to bring down a young forest, all of the components are added to the surface and the high carbon content of the woody material initially immobilizes nutrients. A 7 year-old secondary forest in Igarapé Açu could be expected to contain 370-590 kg N, 12.6-

21.3 kg P and 130-227 kg K per hectare when mulched with 69-79% of biomass from wood, 8-10% from leaves, 14-19% from litter and less than 2% from grasses (Denich et al., 2004). Only 8-12% of the mulched biomass would be derived from materials conducive to mineralization and high C:N ratios may initially immobilize nutrients, causing a negative impact on crop and tree yields.

High C:N ratios of felled vegetation can initially immobilize nutrients and fertilization may be necessary if slash-and-mulch systems are to attain economically acceptable yields (Denich et al., 2004). Additions of N, P and K fertilizers can stimulate increases in foliar nutrient concentrations of fallow vegetation and accelerate nutrient cycling (Gehring et al., 1999). Fertilization with N can increase N concentrations in decomposing material (Zimmerman et al., 1995), thereby lowering the C:N ratio which allows for greater rates of decomposition and mineralization of N. N-fixation by nodulating legumes is variable and responsive to soil nutrient status and chemical characteristics. High levels of mineral N, or fertilization with N, inhibit nodulation and N-fixation by up to 50% (Danso et al., 1992) as do soils with low pH (Tilki and Fischer, 1998). High nitrate levels can also inhibit N_2 fixation and accelerate nitrate leaching, causing acidification of deeper soils (Schroth et al., 2001), limiting N-fixation at depth. Nitrate and ethylene stimulate germination of weedy competition, principally grasses, which can cause serious crop and economic losses (Gallagher et al., 1999), but N may not be the major limiting nutrient for plant production in all upland soils of the Eastern Amazon (Davidson et al., 2004; Gehring et al., 1999).

Inorganic P fertilization may not increase decomposition and in one study, adding mulch immobilized P during initial stages of decomposition (Baggie et al., 2004).

Above-ground biomass, regardless of species, transfers nutrients from the below-ground to the above-ground components of the ecosystem (Montagnini, 2000). In a region where agriculture depends so heavily on fallow vegetation for maintenance of soil fertility, the use of trees with rapid growth characteristics is ideal because more nutrients can be put back on the surface for food crops to utilize.

Manioc (cassava) is a staple crop in Brazil that is typically grown in shifting cultivation systems. Existing vegetation is then cut, burned and then manioc can be planted until the field is abandoned to secondary forest succession. The objectives of this study were to investigate the dynamics of N and other nutrient with fertilization with P and K and in the presence of N-fixing tree species, *I. edulis*. This study investigated whether P and K fertilization and *I. edulis* would increase nutrient concentration of soil; and whether P and K fertilization and *I. edulis* would increase nutrient concentration and/or content of the mulch material and phytomass. Phytomass analysis was performed on manioc leaves, stems and tubers as well as on composite samples of competing vegetation.

Materials and Methods

Site Description

The research site was located at the experimental farm of the Universidade Federal Rural da Amazônia (UFRA) in the Municipality of Igarapé Açu (1°07’41”S 47°47’15” W), approximately 110km East of Belém, the capital of Pará, Brazil. This region, known as the Bragantina, is one of the oldest continually inhabited agricultural areas in the Amazon and the landscape is now completely dominated by human activities;

urban areas, row-crop farming, forest plantations, cattle ranches and secondary forests. The project site was cleared with a TRITUCAP mulching tractor (Denich et. al, 2004) from a seven year-old secondary forest that had previously been cultivated. The mulched forest material was evenly distributed across the site by the tractor.

Igarapé Açu has an average annual temperature of 26°C and annual rainfall of 2500 mm (IBGE, 1996 cited in: Kato et al., 2005). Its driest months are August through November and its wettest months are January to May. Rainfall distribution by months is presented in Figure 3.1.

Typic Kandiudults are the most common soil family of the municipality of Igarapé Açu. A more general analysis of soil characteristics under primary forest, fallow and agriculture are provided by Rego et al. (1993). These soils are acidic with a low cation exchange capacity, high Al saturation and low available P contents.

Experimental Treatments

In March of 2005, a one-hectare study site was selected by the directors of Projeto Tipitamba/SHIFT in conjunction with the Empresa Brasileira de Pesquisa Agropecuária (Embrapa). The site is nearly uniform in lack of slope with a slight depression (unnoticed at planting) in the south-central area of the site. The mulching tractor evenly distributed the above-ground biomass of the seven-year-old secondary forest over the soil surface. Experimental treatments were applied to the prepared site in June, 2005. Four experimental blocks that run across the site from north to south were established. Each block was divided into four plots (n=16) that measured 24 x 24 m. A factorial combination of fertilization treatment and nitrogen (N)-fixing species additions were assigned to these blocks in a split-plot design. Main plot fertilizer treatments consisted of no fertilization (PK-) and P and K fertilization (PK+). Fertilized plots received a broadcast application of 46 kg ha^{-1} of phosphorus (P) as P_20_5 (100 kg of 46% Super-Simple Phosphate) and 30 kg ha^{-1} of potassium (K) applied as KCl (50 kg of 60% KCl). Subplot treatments consisted of planting the native species *S. amazonicum, C. odorata* and *C. pentandra* together (I-), or in combination with the N-fixing species *I. edulis* and *P. multijuga* (I+). Trees were planted at a spacing of 1.825 x 4 m with a 2 m buffer between plots within blocks and a 1 m buffer between blocks. Manioc was planted with 1 x 1 m spacing for a density of 10,000 stems ha^{-1} with a distance of 0.5 m on either side of each row of trees.

Soil sampling

In June 2005, prior to fertilization, soil cores were taken from each of the four quadrants within each plot; soil cores were divided into 0-10 and 10-20 cm depth increments. The four cores from each depth were then mixed together to make a composite sample by depth within each plot. All plots of the same block were then mixed together to form a composite sample. Composite samples were analyzed for total N, extractable P, K, Ca, and Mg as well as pH at the UFRA soil chemistry laboratory while, organic material, sand, silt and clay were analyzed at the Soil Analysis Laboratory of Embrapa Amazônia Oriental in Belém. Soil bulk density characteristics by block are presented in Table 3.1 and organic material and particle size distribution of soils are presented in Table 3.2.

Buried-bag study

To assess the rates of soil N mineralization on per plot basis, in June/July2006, one year after establishment a buried-bag incubation study was conducted. Soil cores were sampled from a distance of 50 cm from the base of randomly selected trees. Following the methods of Eno (1960), paired soil cores were taken from a depth of 0-8 cm and placed inside of a 10 x 20 cm (4 x 8 inch) 4 mil polyethylene bags. One sample from the pair was placed in a cooler with synthetic ice ("Blue Ice"™) until they could be stored in a refrigerator at the Soil Chemistry Lab at UFRA and extracted with 2M KCl the following day while the other was placed back in the ground to incubate for 2 weeks and then extracted with 2M KCl. Samples weighing 2.5 g were mixed with 25 ml of 2M KCl, shaken for 30 minutes and extracted through Whatman™ 42 filter paper. Samples were stored in a refrigerator until analysis at the Phillips Laboratory at the University of Georgia (UGA), Athens. Samples were analyzed using Flow Injection Analysis (OI Analytical, College Station, TX) for NH_4-N and NO_3-N.

Resin capsule study

In June of 2006, an open-top cylinder N mineralization experiment was conducted using UniBest PST-1 resin capsules (Bozeman, MT) placed at the bottom of 8 x 2 cm PVC plastic tubing. A plastic tube was inserted into the soil, removed and the resin capsule was placed inside the bottom of the tube and replaced into the soil. Tubes were inserted at a distance of 50 cm from the stem of three randomly selected trees in each plot. No distinction was made between *I. edulis* and other species because the intent of this study was to evaluate soil-N at the plot rather than tree level. The resin capsules were removed from the soil after three months *in situ*.

Transect soil-N sampling

In addition to this plot level mineralization sampling, soil cores were also taken from a distance of 10, 25 and 50 cm from each of two paired trees. Handling of samples is the same as described above. As such, each pair of trees consisted of one *I. edulis* and the neighboring tree of any other non N-fixing planted species. Each transect, on from each tree, approached each other. Transect soil samples were collected as a one time sample collection in June 2006 without a companion two week *in situ* incubation sample for the 10 and 25 cm distance.

Mulch sampling

To quantify the nutrient contents of the mulch, in June 2005, each plot was divided into four quadrants along the vertical and horizontal axes. A 25 x 25 cm frame was placed randomly within each quadrant and all mulched biomass was collected down to the mineral soil surface. Mulch material was air-dried in a greenhouse for 48 hours and then in a forced-air oven at 60C for 48 hours and then weighed. Mulch material was analyzed at the UFRA soil chemistry laboratory N, P, K, Ca and Mg. In June 2006, the same procedures were followed to estimate changes in mulch content.

Phytomass sampling

In June 2006, all manioc leaves, stems, tubers and competing vegetation inside of 1 x 1 m sampling plot were collected within each of four quadrants inside of each plot (n=4). Leaf and weedy vegetation samples were dried in paper bags for 24 hours at 65°C in a forced-air oven. Manioc stems were cut diagonally and dried in paper bags for 48 hours at 65°C in a forced-air oven. Manioc tubers were cut into small pieces and dried in paper bags for 96 hours at 65°C in a forced-air oven after air-drying for three days.

Analytical procedures

Soil and phytomass N was analyzed using Total Kjeldahl Nitrogen procedures. Soil macronutrients were extracted using Mehlich 1 double-acid procedures for P and K; while Ca and Mg were extracted using a 1 M KCl solution. Phytomass macronutrients were digested with a 3:1 nitric acid + perchloric acid digest. Phosphorus was read using spectrophotometic procedures; K was read by flame photometry; and Ca and Mg were read by atomic absorption spectrophotometry (AAS).

Statistical Analysis

The study evaluated a factorial combination of two levels of fertilizer treatment (main plots) and two levels of N-fixing species (sub-plot) in a split-plot design with four complete blocks. Analysis of variance (ANOVA) was used to analyze the project as a two-way factorial randomized complete block design. Fertilizer treatment with and without P and K additions were the main plot treatments (N=4) and treatments with or without the presence of *I. edulis* were the sub-plot treatments. Statistical significance is conferred at the P=0.10 level.

Results

Soil Nutrients

Soil nutrient concentrations and pH at establishment and after one year are presented in tables 3.3 and 3.4, respectively. At establishment, N concentrations were 0.3 mg kg^{-1} soil greater at depth than at the surface while after one year N concentrations were 0.2 mg kg^{-1} soil greater at the surface than at depth. Mean N concentrations in the surface horizon at establishment were lower than values reported from other studies conducted in the Amazon region of Brazil (Table 3.5) and were probably the result of the mulch layer initially immobilizing N, as the site was mulched several weeks prior to sampling. After one year quadrant sampling demonstrated no significant differences in total soil N concentrations.

Concentrations of P in the 0-10 cm depth varied from 3.6 to 5.2 mg kg^{-1} across the blocks prior to planting and from 1.2 to 2.5 mg kg-1 in the 10 – 20 cm depth. These values changed little on average by the end of year one, although they were slightly higher, increasing by 2.3 mg kg^{-1} soil in 0–10 and by 0.46 mg kg-1 soil in 10 – 20 cm depths. At the end of year one there was no significant differences (P=0.10) in extractable P with treatment.

Soil exchangeable K varied little across the blocks at time 0 and among the plots after one year. The mean exchangeable K values were 0.09 mg kg^{-1} soil at a depth of 0-10 cm and 0.07 at a depth of 10-20 cm. Responses of Ca, Mg and pH were similar to those above in that variation across blocks or plots was limited and there were no significant differences (P=0.10) in the 0-10 or 10-20 cm depths after one year between treatments.

Soil-N Studies

The differences in N concentration of soils between installation and one year could not be analyzed statistically because composite samples prior to installation were taken by block while samples taken after one year were taken by treatment and were not made into composite samples. There was a mean increase of 0.4 mg kg^{-1} soil in the 0-10 cm depth and decrease of 0.3 mg kg^{-1} soil at 10-20 cm depth.

NO_3^- was significantly lower in the PK+ than in the PK- main-plot treatment (P=0.05) at installation, but not after two weeks, in the 50 cm buried bag study (Table 3.6). There were no significant differences (P=0.10) between I+ and I- treatments for NH_4-N, NO_3-N or the sum of both at T=0 or after two weeks in the 50 cm buried-bag study.

Ammonia (NH_4^+) concentration was significantly lower (P=0.025) in the I+ than in I- sub-plot treatment when sampled with resin capsules after a 2-week *in-situ* incubation (Table 3.7). There were no significant differences (P=0.2) in NH_4^+ concentrations after 3 months. Nitrate (NO_3^-)/nitrite (NO_2^-) concentrations were not significantly different in either the main-plot fertilizer (P=0.17) or sub-plot N-fixer treatment (P=0.5) when sampled with resin capsules after a 2-week *in-situ* incubation. After 3 months there was significantly less (P=0.003) NO_3-N in PK+ compared to PK- main-plot treatment. The sum value of NH_4-N and NO_3-N was significantly lower in I+ treatments than in I- treatments when sampled with resin capsules after 2-week (P=0.04) and 3-month (P=0.01) *in-situ* incubations.

Sum soil-N from the transect study range from 8.6 µg g^{-1} soil to 11.7 µg g^{-1} soil, which are within the high end of the range of Amazonian soils reported by Smith et al.

(1998). Sum N was significantly greater (p=0.05) at a distance of 25 cm than at 50 cm in the transect study when sampled next to *I. edulis* than when next to a non-N-fixer, although Sum N was not different (P=0.10) from 10 cm to 50 cm or from 10 - 25 cm (Table 3.8). NH_4-N was significantly greater at 25 cm than 50 cm (P=0.05) from *I. edulis* trees compared to all other trees. There were no differences (P=0.10) for NO_3-N in the transect study. There was a trend of increased NH_4^+ in I+ compared to I- in unfertilized plots yet decreased NH_4^+ in I+ compared to I- in fertilized plots.

Soil O horizon – Mulch

Mulch layer mass at establishment and after one year are presented in Figure 3.2. There was a 70% mass loss from the mulch layer in the PK+ I+ treatment, which was significantly different (P=0.07) than the 36% mass loss in the PK+ I- treatment. There was a 45% mass loss in the mulch layer in the unfertilized treatment (PK-). There was a trend of increased mass loss with fertilization and in the presence of *I. edulis*.

Mulch layer nutrient concentration and content values are presented in Table 3.10 and Fig. 3.3, respectively. At establishment of the site, content of N in the mulch layer was significantly greater in the PK- I- than in PK- I+ and greater in the PK+ I+ than in PK+ I- treatments (P=0.01). Additionally, K (P=0.05), Ca (p=0.03) and Mg (P=0.03) content were significantly greater in the PK- than in PK- I+ treatment as well as in the PK+ I+ than in PK+ I- treatment. There were no significant differences for the nutrient contents measured in the mulch layer at the P=0.10 level after one year. Only Ca produced a positive response to fertilization in the presence of *I. edulis* (P=0.06) for content change from installation to Year 1. Despite large mean changes in P and K content, there were no other significant changes among the other nutrients due to extremely high variability.

Phytomass Nutrient Concentrations

Nutrient concentrations for manioc and competing vegetation are presented in Table 3.9. There were no significant differences for any nutrients measured for manioc leaves, stems or tubers in either main-plot or sub-plot treatments. Fertilization resulted in greater concentration of Ca (P=0.05), yet lower Mg concentration (P=0.10) in competing vegetation. A modest trend of increased N in manioc leaves and tubers in the presence of *I .edulis* in fertilized and unfertilized plots was detected.

Nutrient concentrations for the mulch layer at establishment and after one year are presented in Table 3.10. There were no significant differences (P=0.10) for nutrients analyzed at establishment. After one year there was significantly greater P concentration in the PK+I+ treatment than PK+I- (P=0.06). There were no other significant differences (P=0.10) for other nutrients in either main-plot or sub-plot treatments. A modest trend of increased N in the mulch layer in the absence of *I. edulis* was detected.

Phytomass Nutrient Content

Nutrient content results for macronutrients for manioc are presented in Figure 3.4. There were no significant differences (P=0.10) in manioc leaves for nutrient content for any of the measured nutrients in either the main-plot fertilization treatment or in the sub-plot N-fixer treatment. Nitrogen content was significantly greater (P=0.08) in I+ than in I- sub-plot treatment for manioc stems. Manioc stem K content was significantly greater

(P=0.09) in the main-plot PK+ than PK- treatment. Calcium (P=0.09) and Mg (P=0.04) content were significantly greater in the sub-plot I+ treatment for manioc tubers. Magnesium content was also significantly greater (P=0.08) in the main-plot PK+ treatment for manioc tubers. No other nutrients were significantly different at the P=0.10 level for either the main-plot or sub-plot treatments.

Nutrient content results for macronutrients in competing vegetation are presented in Figure 3.5. K and Ca (kg ha^{-1}) were greater (P=0.05) as was Mg (P=0.09) in the main-plot fertilization treatment for competing vegetation. There were no significant differences (P=0.10) for competing vegetation in the sub-plot *I. edulis* treatment.

Mulch nutrient content values are presented in Figure 3.3. At establishment of the site, content of N in the mulch layer was significantly greater in the PK- I- than in PK- I+ and greater in the PK+ I+ than in PK+ I- treatments (P=0.01). Additionally, content of K (P=0.05), Ca (P=0.03) and Mg (P=0.03) were significantly greater in the PK- I- than in PK- I+ treatment as well as in the PK+ I+ than in PK+ I- treatment. There were no significant differences (P=0.10) for the nutrient contents measured in the mulch layer after one year. Only Ca produced a positive response to fertilization in the presence of *I. edulis* (P=0.06) for content change from installation to Year 1; there were no other significant changes among other nutrients or treatments.

Discussion

During establishment of the experimental plots, four blocks were established in strips from north to south. With blocking we tried to account for a slight (<1%) gradient across the site. After mulching the vegetation on the site and numerous visits, it was clear that there was a poorly drained depression near the center of the 1-ha site which crossed a number of the blocks and contributed to high variability within the treatments. This high variability was reflected in the growth responses of trees, manioc and competing vegetation (Joslin et al., in preparation) as well as soil, phytomass and mulch layer responses reported below. This high variability limited the statistical differences of the observed responses despite some relatively clear responses.

Nitrogen

Soil N

Though not significant in all cases, there were some differences in soils among treatments. The results of this study show trends of greater nitrification next to *I. edulis* trees. Greater nitrification also was observed following fertilization with P and K by both buried-bag and open-top cylinder resin studies. The transect buried-bag study captured an instantaneous view of plant-available, mineral N and revealed that NH_4-N as well as the sum of NH_4-N and NO_3-N were greater when sampled next to the N-fixing *I. edulis* than next to non-N-fixers. A similar response of soil-N to the presence of N-fixers was reported from Costa Rica (Montagnini and Sancho, 1994).

NH_4^+ and NO_3^- values from the transect study reported here show relatively low rates of N mineralization and nitrification with P and K fertilization but relatively high rates without. These data indicate that *I. edulis* trees contributed to an elevation of N in the soil environment in the absence of fertilization, or that fertilization released the trees, competing vegetation and manioc from P and/or K limitation allowing for greater uptake of N from the soil. However, neither the 50 cm buried bag nor 50 cm resin capsule experiments confirmed this finding. In fact, the resin-capsule N-responses indicated immobilization of N rather than mineralization. The difference in responses could reflect the spacing of sampling employed. The transect buried bags employed two sampling points, 10 and 25 cm, inside of the distance of 50 cm used for resin capsules. Due to lack of development, one year-old root systems of trees might have only been able to affect soil mineralization closer to the trees. Competing vegetation and manioc were likely to have reduced soil N availability through uptake while weed suppression by trees at closer distances likely eliminated some competition.

The effectiveness of N sampling using resin capsules in open-top cylinders was limited because interactions between root and soil, such as N-fixation in *I. edulis* roots, were not measured. Soil inside of the cylinder did not contain any live roots. Also, several of the tubes from the 3-month study had become elevated above the surface of the soil, probably due to decomposition of organic material in the surface horizon, thus preventing roots from growing over the encased soil volume above the resin capsule. Soil-sampling with resin capsules without enclosures, however, leads to nutrient capture from an unknown soil volume and makes determining nutrient content on a per-area basis problematic (L. Pangle, pers. comm., 2006).

Rates of nitrification ranged from 0.014 $\mu g\ g^{-1}\ day^{-1}$ in the PK- main-plot treatment to 0.09 $\mu g\ g^{-1}\ day^{-1}$ in the PK+ main-plot treatment. The PK+ I- treatment immobilized NO_3^- at a rate of 0.19 $\mu g\ g^{-1}\ day^{-1}$. Nitrification can be inhibited by soils with low pH (Attiwill and Adams, 1993) and by agroecosystems with high C:N ratios (Gallagher et al., 1999). Although the C:N ratio in the mulch layer, assuming that C is 50% of mulch biomass, decreased from 88:1 to 59:1 during this study, it still remained well above the ratio at which N is immobilized (Seneviratne, 2000) and probably contributed to low rates of nitrification in the soil.

Rates of N ammonification ranged from 0.35 μg g^{-1} soil day^{-1} in unfertilized treatment to 0.14 μg g^{-1} soil day^{-1} in unfertilized treatment in this study, which compares favorably with those reported from western Pará, Brazil (Smith et al., 1998). Those investigators found N mineralization rates to be highest in July and August, the end of the rainy season; since our N mineralization studies were also taken at the end of the rainy season, we probably sampled at a time of highest N mineralization for this site.

Rates of N mineralization ranged from 0.36 μg g^{-1} soil day^{-1} without fertilization to N immobilization of 0.06 μg g^{-1} soil day^{-1} with fertilization. Gross nitrification was as much as 64% that of mineralization (Silver et al., 2005), whereas we found maximum nitrification rates to be only 39% of mineralization. Although the high C:N ratios mentioned above might indicate that there would be no net mineralization of N, the mulch layer on the soil surface may not have been able to immobilize N from soil up to 8 cm depth.

Danso et al. (1992) report biological N-fixation by different species of trees used in AFS ranging from 43-102 to 448-548 kg N ha^{-1} yr^{-1}, none of which were from the Inga genus. It is reasonable, however, to assume that during the first year of growth N-fixation by *I. edulis* in this project would be below or in the lower end of this range due to low planting density (~680 stems $ha\text{-}^{1}$) and incomplete root development.

Soil O-horizon - Mulch N

A 10 year-old secondary forest in Igarapé Açu yielded 24 t ha^{-1} of mulched biomass with 332 kg ha^{-1} of N (Kato et al., 1999), which is nearly identical to the initial N content reported in this study (Fig. 3.4). Before application of treatments, N content was significantly higher in the I- sub-plot treatment of the PK- treatment and higher in I+ sub-plot treatment of the PK+ treatment. After one year, N content in all treatments decreased and developed a consistent trend of decreased N concentration and content in the presence of *I. edulis* with and without fertilizer. Fertilization also produced a trend of decreased N content, or greater mineralization of N out of the mulch layer. Trends of N loss are entirely consistent with mass loss by treatment of the mulch layer. There were no consistent trends among treatments for N content decreases from establishment to Year 1.

If the carbon (C) to biomass ratio is 0.5, then the mean C to N ratio (C:N) of the mulch layer at establishment was 88:1 while after 12 months it had decreased to 59:1. There were no significant differences between treatments for the C:N ratio (P=0.10). In both cases the mulch layer had a C:N ratio that was too high for net mineralization, but rather immobilized N from the mulch layer as well as from the soil surface.

Manioc N

A trend was observed of increasing N concentration in manioc leaves, stems and tubers (Table 3.9) in both the main-plot fertilizer treatment and with the presence of *I. edulis* in the sub-plot treatment. Manioc leaf N content showed modest trends of increased N concentration with the presence of *I. edulis*; however, both manioc stems and tubers showed very clear trends of increased N content with fertilization and with the presence of *I. edulis* despite the lack of trends in N concentration (Fig. 3.4). In Colombia, foliar N concentrations were identical between fertilized and unfertilized treatments; however, stems and tubers both had increased N concentrations with NPK fertilization (Howeler, 2002). Foliar N concentrations reported here are 24 and 27% lower than reported by Howeler (2002) in unfertilized and fertilized treatments, respectively. Manioc stem and tuber concentrations reported here are 22, 34, 19, and 41% lower between unfertilized and fertilized treatments, respectively, than reported in Howeler (2002). Working in Benin, Africa, Carsky and Toukourou (2005) did not report consistent increases for N content in stems or tubers (Table 3.11) between unfertilized control and 60-16-138 N-P-K fertilization; however, they did report significant increases in N content for whole-plant uptake with fertilization. They also reported continual decreases of N content in fields harvested in three consecutive years in both fertilized and unfertilized treatments.

Manioc stem N concentrations in the PK+ I+ treatment were identical but other treatments resulted in stem concentrations 44 – 65% lower than those reported by Carsky and Toukourou (2005). Tuber N concentrations ranged from 15% greater to 72% lower than reported by those investigators. Manioc stem content of N ranged from 59% less to 180% greater while tuber content of N ranged from over 1000% less to 30% greater than those reported by Carsky and Toukourou (2005). Even though mean differences among treatments were large, high variability resulted in few statistically significant differences.

Long-term fertilizer studies in Colombia indicate that K is removed in large quantities by manioc tuber harvest and limits tuber production in successive harvests (Howeler, 2002). Fertilization with K may have freed manioc from K limitation and allowed manioc tubers to exploit N resources to a greater degree than without fertilization. However, there is conflicting evidence for increased N uptake by manioc with fertilization (Howeler, 2002; Carsky and Toukourou, 2005). Data presented here indicates that fertilization with P and K may, in fact, increase N uptake by manioc tubers.

Competing vegetation N

Competing vegetation showed trends of increasing N concentration in sub-plot treatments in the presence of *I. edulis;* however, N concentration in competing vegetation tended to be lower in fertilized treatments. Even though there was a trend of reduced biomass of competing vegetation (Joslin et al., in preparation), there was a trend of increased N content in the presence *I. edulis*. This indicates that even though *I. edulis* may have suppressed the growth of weedy plants through light and water competition, competing vegetation may have benefited nutritionally from the N-fixing properties of *I. edulis*.

Mean N concentrations from the most common species of secondary vegetation in Paragominas, Pará, Brazil are slightly higher than the mean N concentrations for competing vegetation reported here (Davidson et al., 2004). From a study in Kenya, Baijukya et al. (2005) report 12 kg ha^{-1} of N accumulation in only 0.9 Mg ha^{-1} of weedy fallow biomass, both of which were 20–25% of the values reported here, although N concentrations were similar between the projects. Weeding in the cropping field could be expected to supply between 40-65 kg ha^{-1} year^{-1} of N if the residue is applied back to the field.

Cations

Soil Sampling

Cation concentrations reported for the Amazon region are extremely variable and concentrations reported here are within the range reported (Table 3.4), but follow no discernible pattern. Fertilization with P and K did not create consistent patterns in soil concentrations of any nutrients at the P=0.10 level. The only significant response (P=0.03) to fertilization in the main-plot treatment was a decrease in Mg.

Soil O-horizon – Mulch layer

Gains in P content in the mulch layer were probably due to decomposition of the organic matter itself (Kato et al., 2000) which had not leached from the mulch into the soil or from redistribution of dissolved fertilizer through surface-ponded water. Baggie et al. (2004) observed that fertilizing mulch with P increased P extracted but not release of P from mulch residue. However, Kato et al. (2000) report decreases of up to 50% in the mulch layer of Mehlich-1 available P over 18 months without fertilizer. It could be expected that P and K would increase in concentration or content in the mulch layer in fertilized treatment, as reported here (Fig. 3.3, Table 3.11), but would be expected to decrease in concentration and/or content without fertilization.

Sá et al. (1998) reported net losses from the mulch layer on the soil surface in an AFS in Igarapé Açu, Brazil of 285 kg N, 75 kg K, 125 kg Ca, and 16 kg Mg ha^{-1}; however P content increased by 11 kg ha^{-1} after 18 months. Increases in cation content were not consistent for treatments in this study, however, although we also observed decreases in Ca and Mg content. Increases in P content of the mulch layer were greater than those observed by Kato et al (2000) and varied in this study from 50 - 97 % of the amount applied while K content increased by 12 - 62% of K applied as fertilizer.

High rates of decomposition and mineralization of accompanying nutrient stocks are reported in the months directly following the dry season in the sate of Amazonas, Brazil (Martius et al., 2004). Decomposition of the mulch layer in this project was also an important factor but it remains unclear if mineralization of nutrients from the decomposing mulch layer was tied to decomposition, fertilization, *I. edulis* or to a combination of all three factors.

Manioc

Concentrations of P, K, Ca and Mg in manioc tubers fell within the lower end of the range reported in Howeler (2002). No consistent patterns emerged for P or K in manioc leaves, although Ca and Mg displayed a trend of greater concentration in the presence of *I. edulis*. There were no clear patterns for manioc stem concentrations with fertilization or in the presence of *I. edulis*. There was a modest trend of lower P concentration for manioc tubers in the presence of *I. edulis* but no trends for K emerged. A trend of higher Ca concentration with fertilization emerged in manioc tubers although there was no trend for Mg with fertilization but a modest trend for higher Mg concentration in the presence of *I. edulis*.

Due to extreme variation for nutrient content in the PK+ I- treatment there were no significant differences for any nutrients in manioc tubers and high levels of variance also occurred in manioc stems. Despite the lack of statistical significance there were very clear and very consistent trends of increased nutrient content in all nutrients analyzed with fertilization and with the presence of *I. edulis*.

Competition

Phosphorus limits growth for agriculture in the Eastern Amazon (Gehring et al., 1999) yet P fertilization produced only a trend of increased P content in competing vegetation in the presence of *I. edulis*. Davidson et al. (2004) report an increase of 23% in foliar P concentrations with N and P fertilization while there was a decrease of about 10% in foliar P concentrations in this study. The other cations sampled all responded to fertilization with P and K indicating that fertilization increases the rate at which nutrient content is removed by weedy vegetation and could cause reduction in nutrient availability to trees and crops.

Conclusions

Neither fertilization with P and K nor the presence of *I. edulis* resulted in consistent changes in soil N or other nutrient concentrations, however, both fertilization and the presence of *I. edulis* generated trends in both mulch and phytomass responses. Therefore, this study cannot confirm that the presence of the N-fixing *I. edulis* increased or decreased the availability of soil-N.

Decomposition (mass loss) of the mulch layer was stimulated fertilization and by the presence of *I. edulis*; however, mineralization of nutrients from the mulch layer was not consistent. Losses of N from the mulch layer were modest after one year while losses of Ca and Mg were more pronounced. P and K, however, showed large accumulations in the mulch layer which indicates that thick mulch layers may help reduce P losses to fixation with clay soils and reduce K losses to leaching by cycling P and K through organic materials. It is possible that the mulch layer retained P and K fertilizer when applied on top of the mulch layer rather than to the soil surface. Maintenance of organic or inorganic fertilizers cycling through organic materials, soil biota and phytomass could help augment long-term nutrient cycling in AFS.

All forms of phytomass clearly showed trends of increased nutrient content, and therefore uptake, with fertilization and with the presence of *I. edulis* which will increase the rate of nutrient cycling. Changes in crop and fallow management will be required to maximize the utility of increased nutrient cycling. A larger quantity of nutrients will be exported with harvest of manioc roots yet more nutrients might be made available to the manioc during the growing cycle if competing vegetation is cut and left to decompose in the field. The presence of tree species within the field should reduce nutrient losses from leaching due to deep root uptake that the shallow-rooted manioc and competition cannot access. Large increases of N content in manioc stems with fertilization indicate that they could be utilized as a mulch material for crops with high N requirements or could be mixed with mulch material to reduce the C:N ratio and increase rates of decomposition.

Fertilizer in combination with N-fixers, such as *I. edulis*, appears to increase the rate at which soil nutrients cycle through vegetative biomass. Improved fallow biomass could be expected to accumulate nutrient stocks suitable for cropping more rapidly with fertilization than in natural fallow. On-farm management decisions, however, will determine whether to utilize increased nutrient cycling to reduce the length of fallow and increase cropping intensity or to allow for longer fallows with the objective of utilizing trees as a high-income windfall crop.

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Table 3.1. Bulk density of soil at two depths in Igarapé Açu, Pará, Brazil. Samples were collected in June 2005.

Depth	[1]PK - I-	PK- I+	PK+ I-	PK+ I+
cm	-------------------------------	g cm^{-3}	-----------------------------------	
0-10	1.22 ± 0.02	1.18 ± 0.02	1.19 ± 0.03	1.20 ± 0.03
10-20	1.24 ± 0.02	1.26 ± 0.01	1.23 ± 0.02	1.25 ± 0.04

[1]Treatments consist of a factorial combination of fertilization (PK+) or without (PK-) and the presence of *Inga edulis* with 4 other native tree species (I+) or of 3 species without *I. edulis* (I-).

Table 3.2. Soil organic material and particle size distribution at two depths at establishment of research study in Igarapé Açu, Pará, Brazil in June, 2005. Analyses completed at the Embrapa Amazônia Oriental Soil Analysis Laboratory, Belém, Pará, Brazil.

Depth	Block	Organic Material	Coarse Sand	Fine Sand	Silt	Total Clay
cm		----------------------------	------------	$g\ kg^{-1}$	------------	----------------------------
0-10	A	17.1	365	335	186	114
	B	18.2	390	320	196	94
	C	19.2	420	310	190	80
	D	20.5	410	310	146	134
10-20	A	10.3	330	340	156	174
	B	11.9	325	335	186	154
	C	9.5	350	330	180	140
	D	12.7	390	275	161	174

Table 3.3. Soil pH and nutrient concentrations by block at establishment of research site in June, 2005.

Depth (cm)	Block	pH (KCl)	pH (H_2O)	N[1]	P[2]	K[2]	Ca[3]	Mg[3]	Al[2]
				g kg^{-1}	mg kg^{-1}	-------- cmol$_c$ kg^{-1} --------			
0-10	A	4.2	5.1	1.05	3.59	0.14	0.54	0.22	0.92
	B	4.2	5.6	1.09	4.17	0.17	0.47	0.15	0.17
	C	4.6	5.9	1.05	5.15	0.19	0.24	0.20	0.36
	D	4.5	5.4	1.23	4.63	0.14	0.31	0.16	0.48
10-20	A	4.1	5.1	1.40	1.16	0.12	1.87	0.38	0.48
	B	4.3	5.2	1.42	1.35	0.12	2.03	0.41	0.14
	C	4.2	5.1	1.26	1.74	0.18	3.48	0.49	0.43
	D	4.3	5.3	1.65	2.48	0.14	4.10	0.57	0.44

[1]Total Kjeldahl Nitrogen, [2]Double-acid extracatable, [3]KCl-extractable

Table 3.4. Soil pH and nutrient concentrations one year after establishment of research site in Igarapé Açu, Pará, Brazil in June, 2005. Treatments consist of a factorial combination of fertilization (PK+) and un-fertilized (PK-) plots with 5 native species of trees including *I. edulis* (I+) or of 3 native species without *I. edulis* (I-).

Treatment	Depth (cm)	pH (KCl)	N[1]	P[2]	K[2]	Ca[3]	Mg[3]	Al[2]
			g kg^{-1}	mg kg^{-1}	------------------------ $cmol_c$ kg^{-1} ----------------------			
PK- I-	0-10	4.3 ± 0.2	1.8 ± 0.8	4.6 ± 0.3	0.08 ± 0.01	2.2 ± 1.0	0.3 ± 0.1	0.4 ± 0.1
PK- I+		4.4 ± 0.2	1.5 ± 0.2	5.9 ± 2.5	0.09 ± 0.02	2.1 ± 0.4	0.3 ± 0.1	0.4 ± 0.1
PK+ I-		4.3 ± 0.2	1.4 ± 0.4	5.9 ± 3.2	0.09 ± 0.03	2.6 ± 1.2	0.3 ± 0.2	0.3 ± 0.0
PK+ I+		4.3 ± 0.3	1.4 ± 0.2	5.7 ± 3.9	0.09 ± 0.06	1.7 ± 0.7	0.3 ± 0.1	0.3 ± 0.1
PK- I-	10-20	4.1 ± 0.2	1.3 ± 0.6	1.9 ± 0.8	0.06 ± 0.01	0.4 ± 0.3	0.1 ± 0.1	0.9 ± 0.7
PK- I+		4.2 ± 0.3	1.1 ± 0.1	2.2 ± 0.8	0.06 ± 0.01	0.5 ± 0.1	0.1 ± 0.0	0.5 ± 0.1
PK+ I-		4.1 ± 0.1	1.1 ± 0.2	1.4 ± 0.8	0.07 ± 0.04	0.5 ± 0.3	0.1 ± 0.1	0.5 ± 0.0
PK+ I+		4.4 ± 0.5	1.0 ± 0.0	3.1 ± 1.2	0.07 ± 0.01	0.2 ± 0.0	0.04 ± 0.0	0.5 ± 0.1

[1]Total Kjeldahl Nitrogen, [2]Double-acid extracatable, [3]KCl-extractable

Table 3.5. Mean N and cation concentrations of soils at carious sites in the Amazon Region of Brazil.

Source	Location	Depth	N[1]	P[2]	K	Ca	Mg	Fertilizer
		cm	g kg^{-1}	mg kg^{-1}	----	$cmol_c$ kg^{-1}	----	
McGrath et al., 2000	Acre, Brazil	0-10	2.4	1.7	0.2	7.3	1.1	No
		10-20	1.7	0.5	0.1	3.4	0.5	
Schroth et al., 2001	Amazonas, Brazil	0-10	2.11	72	0.17	2.05	1.02	High[a]
			1.97	27	0.10	0.95	0.21	Low[b]
Smith et al., 1998	Pará, Brazil	0-20	3.6	3.8				No
Kato et al., 1999	Pará, Brazil	0-10[c]	5.3	0.3				No
		0-10[d]	7.5	0.2				
Markewitz et al., 2004	Pará, Brazil	0-10	2.19	0.19				No
		10-20	1.33	0.18				
This study	Pará, Brazil	0-10	1.10	4.38	0.16	0.39	0.18	No
		10-20	1.43	1.68	0.14	2.87	0.46	

[1]Total Kjeldahl N, [2]double-acid extractable

[a]application of 31-21-39 and [b]0-6-12 NPK fertilizer, [c]4 yr-old and [d]10 yr-old secondary forest

Table 3.6. Ammonification and nitrification (mean ± SE) after 2 week in-situ incubation 12 months after installation of project in Igarapé Açu, Pará, Brazil.

N Form	[1]PK- I-	PK- I+	PK+ I-	PK+ I+
	----------------------------	μg g^{-1} soil	----------------------------	
NH_4-N	4.9 ± 1.2	4.9 ± 0.9	1.8 ± 0.5	1.9 ± 0.5
NO_3-N	0.2 ± 0.9	-0.2 ± 1.4	-2.6 ± 1.0	1.2 ± 0.9
Sum	5.1 ± 1.8	4.8 ± 1.7	-0.8 ± 1.0	3.1 ± 0.9

[1]Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

Table 3.7. N captured by resin capsules (mean ± SE) in open-top cylinders after two incubation periods in the 0-8 cm depth during the rainy season of 2006 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

N Form	Incubation	PK- I-	PK- I+	PK+ I-	PK+ I+
		----------------------------	$\mu g\ g^{-1}$ soil	---------------------------	
NH_4-N	3 months[1]	0.43 ± 0.11	0.55 ± 0.18	0.15 ± 0.06	0.24 ± 0.07
	2 weeks[2]	0.45 ± 0.17	0.33 ± 0.05	0.15 ± 0.01	0.18 ± 0.03
NO_3-N	3 months	1.43 ± 0.30	1.46 ± 0.53	0.19 ± 0.02	0.28 ± 0.08
	2 weeks	0.14 ± 0.03	0.13 ± 0.03	0.09 ± 0.02	0.07 ± 0.00

[1] Resin capsules incubated in soil *in situ* from March 29 - June 28, 2006 and [2] from June 29 - July 12, 2006.

Table 3.8. Extractable NH_4-N and NO_3-N (mean ± SE) of soil at three distances away from planted trees in an agroforestry system in Igarapé Açu, Pará, Brazil in 2006. Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

Distance	PK- I-	PK- I+	PK+ I-	PK+ I+	PK- I-	PK- I+	PK+ I-	PK+ I+
	NH_4-N				NO_3-N			
	µg g^{-1} soil							
10 cm	8.2 ±1.1	9.7 ± 1.1	8.7 ± 0.8	8.1 ± 1.3	2.8 ±1.4	1.4 ± 0.2	1.1 ± 0.1	1.4 ± 0.3
25 cm	10.4 ±1.6	6.3 ± 0.4	8.2 ± 1.7	7.2 ± 1.6	1.3 ±0.2	1.5 ± 0.4	1.2 ± 0.2	1.4 ± 0.3
50 cm	9.6 ± 2.0	7.7 ± 1.1	8.7 ± 1.8	8.3 ± 1.4	1.6 ± 0.2	1.6 ± 0.4	2.6 ± 1.2	1.1 ± 0.1

Table 3.9. Nutrient concentrations (mean ± SE) of manioc and competing vegetation one year after establishment in 2005 in Igarapé Açu, Pará , Brazil. Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

Sample Type	Treatment	N[1]	P[2]	K[2]	Ca[2]	Mg[2]
		------------------------------	------------------------------	g kg^{-1}	------------------------------	------------------------------
ManiocLeaves	PK- I-	25.7 ± 2.4	3.1 ± 0.2	8.8 ± 0.3	8.1 ± 0.4	3.3 ± 0.2
	PK- I+	27.1 ± 2.7	3.6 ± 1.2	6.3 ± 0.4	9.7 ± 0.3	3.0 ± 0.2
	PK+ I-	22.0 ± 1.9	3.2 ± 0.5	7.5 ± 0.6	11.0 ± 1.1	3.4 ± 0.5
	PK+ I+	28.7 ± 3.0	1.7 ± 0.8	7.2 ± 1.1	11.4 ± 1.8	3.6 ± 0.3
Manioc Stems	PK- I-	10.2 ± 1.2	3.1 ± 0.8	5.34 ± 0.5	6.4 ± 0.7	1.5 ± 0.2
	PK- I+	7.8 ± 2.1	3.0 ± 0.6	5.7 ± 0.8	5.6 ± 0.7	1.7 ± 0.1
	PK+ I-	7.0 ± 1.0	3.9 ± 0.6	6.8 ± 0.4	5.9 ± 0.8	1.7 ± 0.2
	PK+ I+	14.4 ± 4.2	2.5 ± 0.7	5.7 ± 0.2	5.9 ± 0.7	1.5 ± 0.03
Manioc Tubers	PK- I-	3.1 ± 1.4	2.3 ± 1.4	3.8 ± 1.7	1.2 ± 0.6	0.4 ± 0.2
	PK- I+	3.7 ± 1.0	2.3 ± 0.9	7.3 ± 2.0	1.7 ± 0.5	0.9 ± 0.3
	PK+ I-	4.2 ± 1.0	2.8 ± 0.7	6.0 ± 1.5	2.2 ± 0.5	0.7 ± 0.2
	PK+ I+	6.2 ± 1.5	2.3 ± 0.7	4.9 ± 0.8	3.1 ± 0.8	1.1 ± 0.1
Competition	PK- I-	12.4 ± 1.4	2.7 ± 0.7	5.4 ± 0.6	7.3 ± 0.4	2.1 ± 1.7
	PK- I+	11.9 ± 3.5	2.1 ± 0.5	3.7 ± 1.1	5.2 ± 1.8	1.7 ± 0.5
	PK+ I-	12.8 ± 0.6	2.6 ± 0.2	5.7 ± 0.3	8.5 ± 0.2	2.1 ± 0.2
	PK+ I+	8.4 ± 2.8	1.8 ± 0.4	4.5 ± 1.0	5.8 ± 1.8	1.5 ± 0.5

[1]Total Kjeldahl Nitrogen, [2]Nitric acid + perchloric acid digest extractable

Table 3.10. Nutrient concentration (mean ± SE) of mulch layer at establishment in 2005 and after 12 months in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

Year	[1]Treatment	N[1]	P[2]	K[2]	Ca[2]	Mg[2]
		$g\ kg^{-1}$				
2005	PK- I-	5.9 ± 1.0	0.26 ±0.01	0.3 ± 0.04	6.8 ± 0.5	0.9 ± 0.1
	PK- I+	5.2 ± 0.3	0.25 ±0.01	0.2 ± 0.04	5.8 ± 0.8	0.7 ± 0.04
	PK+ I-	5.3 ± 0.2	0.26 ±0.02	0.2 ± 0.02	5.8 ± 0.5	0.8 ± 0.05
	PK+ I+	5.9 ± 0.9	0.26 ±0.03	0.2 ± 0.05	5.9 ± 1.1	0.8 ± 0.1
2006	PK- I-	8.7 ± 1.3	3.2 ± 0.5	2.2 ± 0.7	5.5 ± 0.7	0.7 ± 0.2
	PK- I+	6.9 ± 0.7	2.4 ± 0.6	1.7 ± 0.5	4.9 ± 0.5	0.7 ± 0.2
	PK+ I-	11.9 ± 1.2	2.9 ± 0.6	1.1 ± 0.1	6.5 ± 0.7	0.6 ± 0.1
	PK+ I+	9.9 ± 2.2	3.6 ± 0.5	1.8 ± 0.4	5.5 ± 1.1	0.7 ± 0.1

[1]Total Kjeldahl Nitrogen, [2]Nitric acid + perchloric acid digest extractable

Table 3.11. Summary of manioc nutrient content under various treatments in various locations in the Tropics.

Treatment	Component	Spacing	N	P	K	Ca	Mg	Dry Mass
		-- m --	---------------------- kg ha^{-1} ---------------------------					
[1]Unfertilized	Leaves	1 x 1	39.1	3.6	16.2	14.5	2.4	1022
	Stems		33.8	6.4	23.4	26.4	11	1810
	Roots		18.1	2.2	15.4	4.6	1.6	1542
	Leaves	0.5 x 0.5	93.2	8.3	38.8	21.9	8.6	2245
	Stems		19.3	4.1	18.8	15.7	5.8	1028
[2]Fertilized	Tops		69.1	7.4	33.6	37.4	16.2	
	Roots		30.3	7.5	54.9	5.4	6.5	
	Fallen Leaves		23.7	1.5	4	24.7	4	
[2]Unfertilized	Tops		99.9	11.1	74.3	55	15.3	
	Roots		67.3	16.8	102.1	15.5	8.4	
	Fallen Leaves		30.5	2	7.1	31.9	4.7	
[3]Unfertilied	Whole plant		176.6	26.9	108.1			
[3]Fertilized			203.4	31.9	111.7			

[1]Putthacharoen et al., 1998; [2]Howeler, 2002; [3]Carsky and Toukourou, 2005

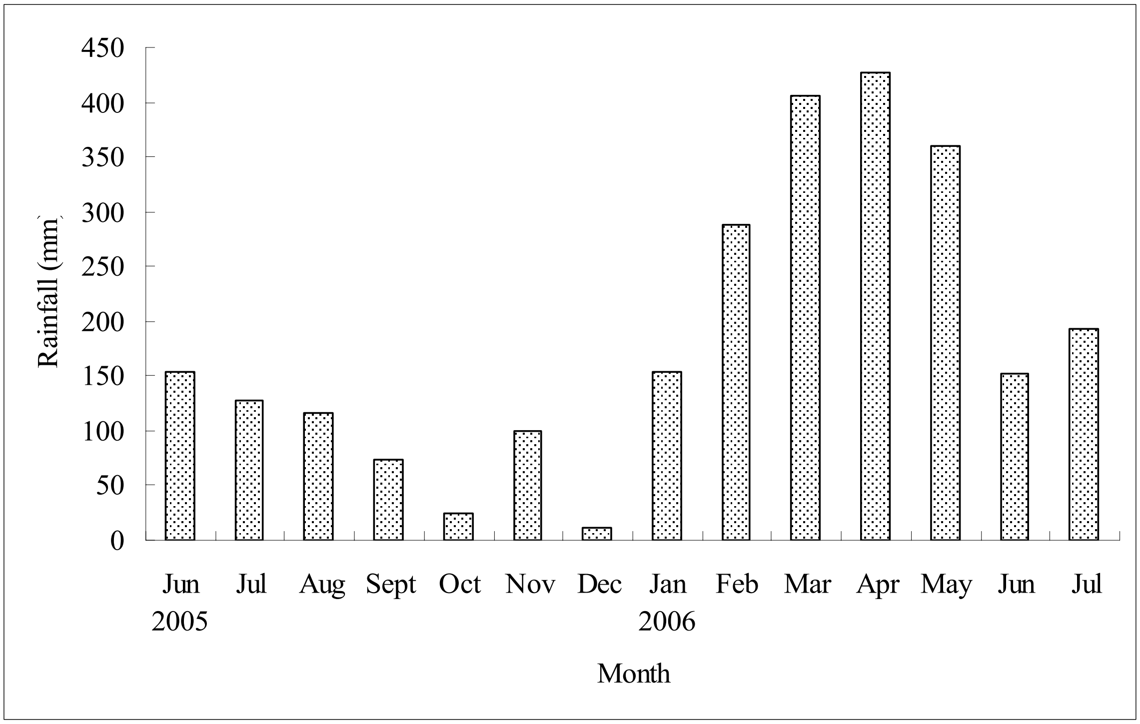
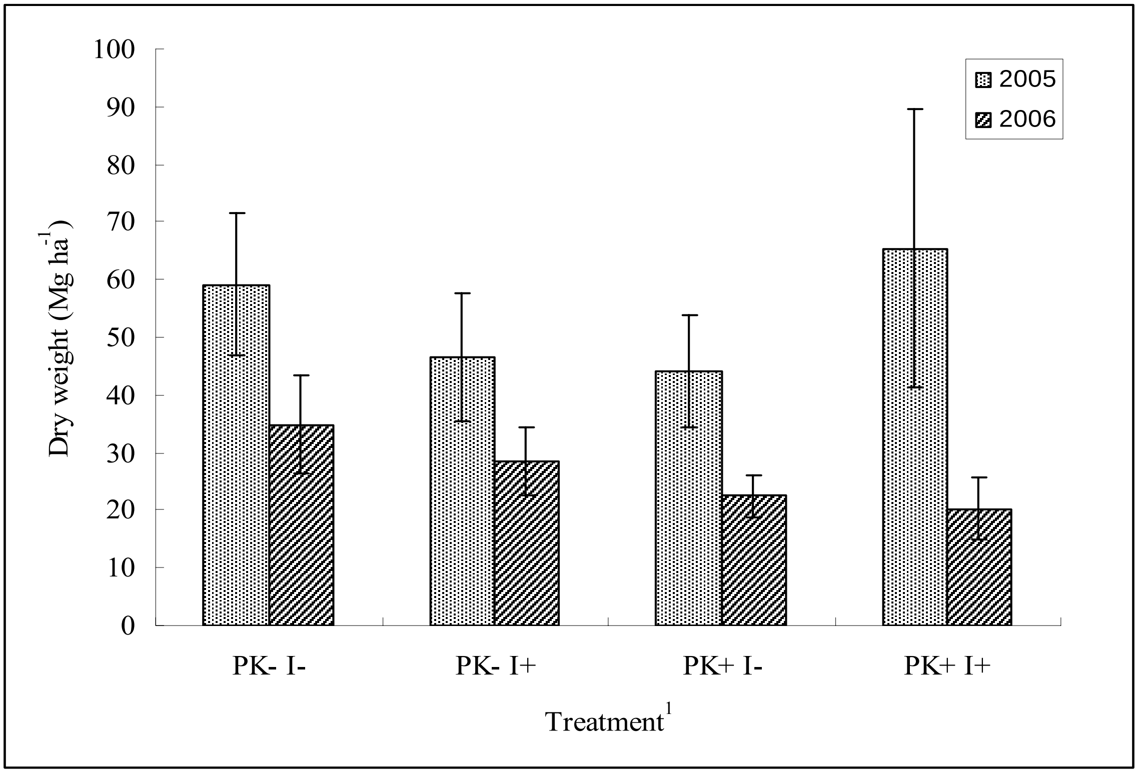


Figure 3.1. Rainfall distribution in Igarapé Açu, Pará, Brazil from June 2005 until July 2006. A total of 2242 mm of rain fell in the 12 months from July 1, 2005–June 30, 2006.



[1]Treatments consist of a factorial combination of fertilization with P and K (PK+) or without fertilization (PK-) and 5 native tree species including *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I-).

Figure 3.2. Mass of mulch layer by treatment at establishment in June 2005 and after one year in Igarapé Açu, Pará, Brazil. Mean mass and error bars indicate 1 SE.

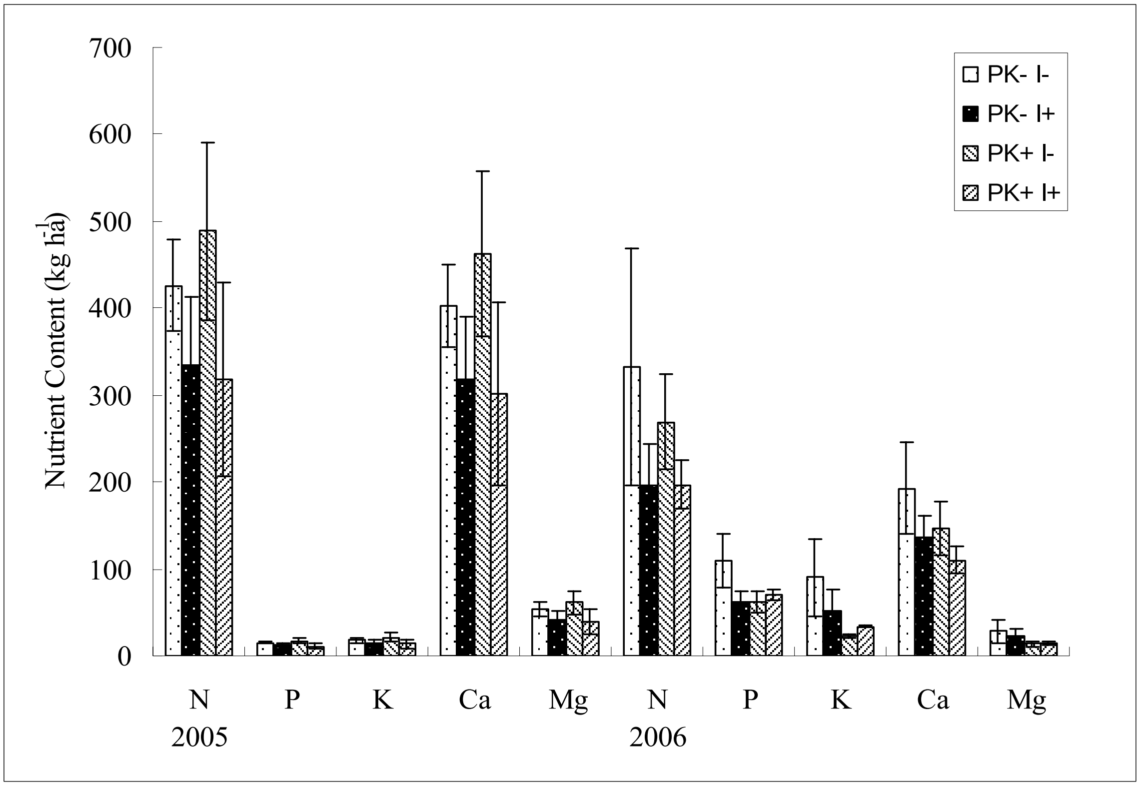


Figure 3.3. Nutrient content of mulch layer at establishment in 2005 and after 12 months in Igarapé Açu, Pará, Brazil. Mean values are presented and error bars represent one SE. Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

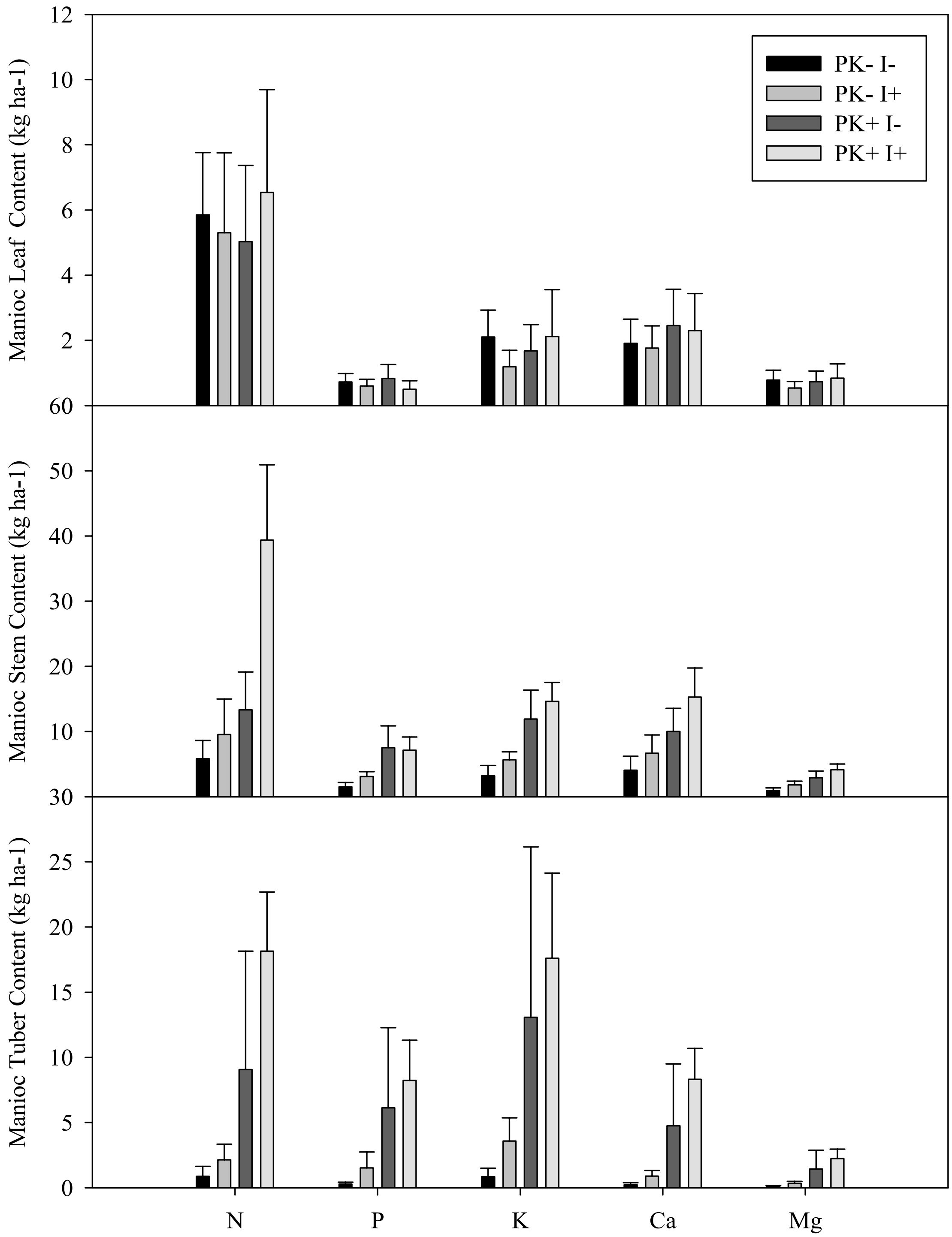


Figure 3.4. Manioc nutrient content one year after establishment in July 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

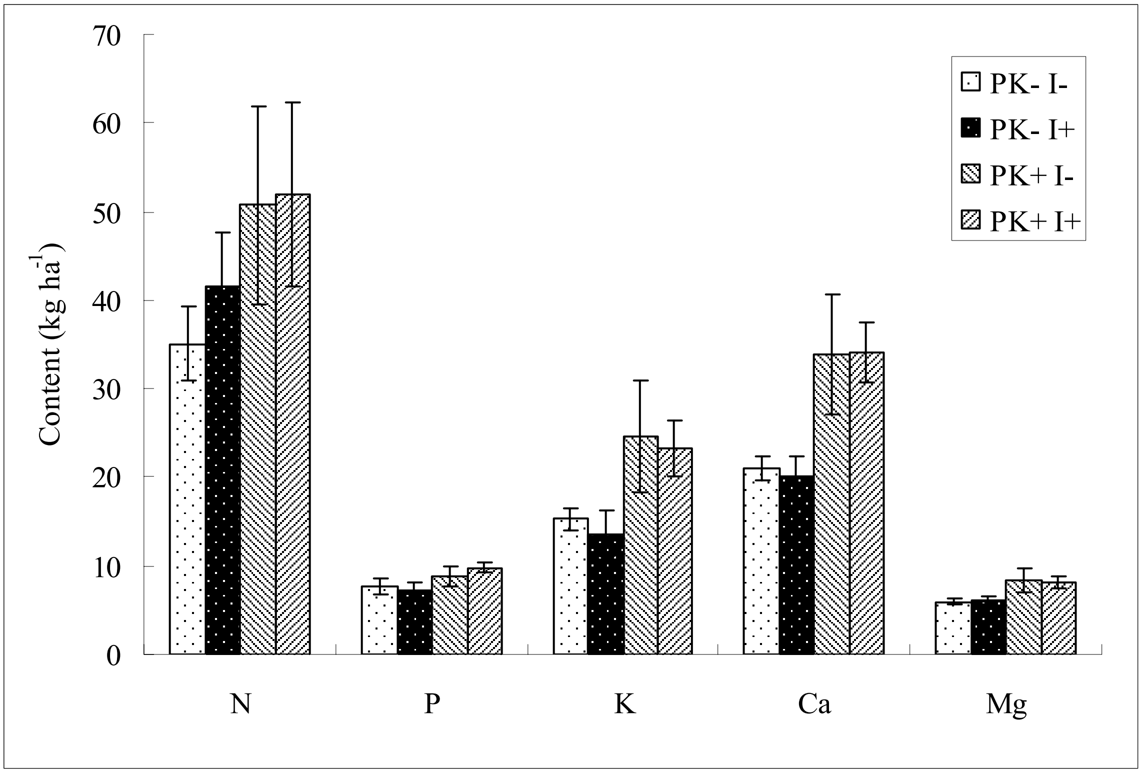


Figure 3.5. Nutrient content (mean ± SE) of competing vegetation 12 Months after establishment in July 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilized (PK+) and un-fertilized (PK-) plots planted with 5 native species of trees including *I. edulis* (I+) or 3 native tree species without *I. edulis* (I-).

CONCLUSIONS

The objectives of this study were two-fold; 1) to determine the effects of P and K fertilization on the survival, growth and biomass production of native tree species and manioc when grown with N-fixing tree species, in this case *I. edulis*, and 2) soil-N and soil macronutrient as well as mulch and manioc uptake responses to those treatments.

Results reported here indicate that all species suffered lower survival when fertilized with relatively high levels of P and K fertilizer, possibly due to increased competing vegetation and manioc. Three of the five species tested, *S. amazonicum*, *I. edulis* and *C. pentandra*, showed positive growth responses to P and K fertilization while *C. odorata* showed no response and *P. multijuga* showed a non-significant negative response. Tree species also generated positive trends for survival in the presence of *I. edulis* when not fertilized but negative trends when fertilized. It appears that *I. edulis* was a more efficient competitor for resources compared to the other species when fertilized but may have had a positive effect on the survival of other tree species when not fertilized, possibly through suppressing competing vegetation, however; there were not consistent responses among species for growth in the presence of *I. edulis*. Competing vegetation was suppressed by *I. edulis* without fertilization but was not affected by *I. edulis* with P and K fertilizer. Manioc biomass production and nutrient content responded positively to P and K fertilization and positive trends were observed in manioc content responses to the presence of *I. edulis*.

There may have been a correlated response in tree growth by wood density to fertilization. Tree species with soft wood, *S. amazonicum* and *I. edulis*, showed the greatest growth response and suffered the least survival reduction with fertilization while species with dense wood, *C. odorata* and *P. multijuga*, showed no growth response and the greatest reduction in survival with fertilization. The negative survival response of *C. odorata* and *P. multijuga* may have been due to increased competition biomass when fertilized.

Soil responses to treatments were not as consistent as those reported for growth and biomass responses. Soil-N responses showed ammonification, nitrification and immobilization in buried bag *in situ* incubation and resin capsule experiments. Soil-N values from the transect soil sampling were within the lower end of the range of values reported from other parts of the Amazon basin. Neither fertilization nor the presence *of I. edulis* increased concentrations of soil N. Responses to the presence or absence of fertilization or *I. edulis* in other soil macronutrients were not consistent.

Mulch layer mass loss at Year 1 produced a clear trend of increased decomposition with fertilization and with *I. edulis*. The greatest mass loss, least remaining mass and greatest percent mass loss took place with fertilization and *I. edulis* and there was the greatest remaining mass of the mulch layer without fertilization or *I. edulis*. It is clear that both fertilization and *I. edulis* stimulated the decomposition of mulched organic material on the soil surface. However, there were no consistent trends for macronutrient concentrations in the mulch layer after one year. Mulch layer N, Ca and Mg content changes closely resembled mass loss patterns observed in the mass loss or decomposition of the mulch layer. Application of P and K fertilizer on the mulch layer surface may prevent P and K losses and will likely stimulate decomposition as will the presence of N-fixers, in particular, *I. edulis*.

Consistent trends were detected of increased N and macronutrient content of manioc leaves stems and tubers with fertilization and with *I. edulis*, but these were due to biomass increases and not to increases in nutrient concentrations. N and macronutrient content in competing vegetation was reduced in the presence of *I. edulis* without fertilization but did not respond to *I. edulis* with fertilization. Macronutrient losses from the mulch layer may have corresponded to macronutrient increases in manioc tubers and stems.

Edaphic variation within the site was a critical factor affecting the variability of response to treatment in this project. The use of blocking was not able to completely control for the shallow but large depression in the site, which contributed to ponding of water on the surface throughout the rainy season. Mortality of trees and manioc was high within the depression, which was probably also responsible for soil macronutrient variability and macronutrient content variability of manioc.

Large growth responses to fertilizer of tree species and manioc indicate that fertilization with P and K would be desirable. However, decreased survival of tree species with fertilization at planting and high variability of manioc indicate that fertilizer should be applied after trees have become established and that competition control is necessary. The negative response of competing vegetation and trends of increased survival of tree species, as well as trends of increased biomass production of manioc, in the presence of *I. edulis* without P and K fertilizer further support the utilization of a management strategy that allows for the establishment of tree species and manioc prior to fertilization, as well as supporting the use of *I. edulis* as an N-fixer in AFS.

It appears likely that when fertilized, competing vegetation, and possibly *I. edulis*, was able to suppress the survival of all tree species and was also able to suppress the growth of valuable timber species such as *C. pentandra* and *C. odorata*. It is therefore advisable to cut competing vegetation and prune *I. edulis* branches and foliage to reduce competition for resources but also to provide additional mulch and mineralized nutrients for tree species and manioc. Since no weed control measures were performed during the duration of this study, the relatively small growth and biomass responses should be viewed as a minimum response to treatments. Farmers who perform any amount of weed control or pruning should expect greater responses from trees and manioc to treatments than those reported here.

The use of *I. edulis* as an N-fixer in AFS when not using P and K fertilizer should be considered due to consistent trends of increased tree growth and survival, manioc biomass, mulch layer mass and macronutrient content loss as well as weed suppression. Survival of unfertilized *I. edulis* was also excellent. The presence of *I. edulis* was associated with trends of increased nutrient uptake in manioc, therefore appropriate management strategies will be needed to mitigate these losses. Macronutrient content loss from the mulch layer in the presence of *I. edulis* indicates that there is potential for increased macronutrient loss to leaching. Research into the pathways of macronutrient movement from mulched material is therefore needed to determine uptake and leaching potential of macronutrients with fertilization and in the presence of N-fixers.