Assessment of mixed *Terminalia amazonia* plantations in tropical-humid forests in Pacific Southwestern Costa Rica

Alan Chiu and Sarah Snow

Abstract:

In Costa Rica, plantations have become a growing technique in aiding the regeneration of degraded lands. Research is limited on the types of native species that can succeed in long-term mixed plantations for restoration purposes, especially in the Southwestern area of Costa Rica. This study assesses the 12-year-old mixed plantations, which include 4 native Costa Rican species at the Firestone Center for Restoration Ecology (FCRE). There were 3 4 tree x 4 tree (with trees spaced 3 m apart) plots set up in each of the 3 types of mixed plantations (Plantation A consisted of *Terminalia amazonia* and *Astronium graveolens*, Plantations B consisted of *T. amazonia*, *A. graveolens,* and *Tabebuia rosea*, and Plantation C consisted of *T. amazonia* and *Aspidosperma spruceanum*). The average diameter, height, basal area, and canopy area, as well as form and survivorship were calculated for each plantation type. Overall, the *T. amazonia* performed significantly better than the other species with respect to diameter, height, basal area, and canopy area, possibly suggesting that the *T. amazonia* were out-competing the other species for resources. Also, the *T. amazonia* experienced a fairly high survival rate. However, Plantation C (the mixture of *T. amazonia* and *A. spruceanum*) was the poorest plantation with the lowest survival rate and the *A. spruceanum* having particularly poor survivorship and growth. This study is a preliminary assessment of the mixed plantations at the FCRE, and the establishment of permanent plots will allow future studies to develop a fuller account of the progress of the plantations towards natural regeneration into a healthy secondary forest.

Introduction:

After decades of deforestation and land degradation, there is a movement towards converting previously cleared landscapes into more economically productive and ecologically rich tree plantations. The push for planting supported by ongoing research that plantations can stimulate reforestation or damaged lands, as well as offer the incentive of alternative income to farmers. Approximately 96% to 99% of Costa Rica's original land composition was tropical forest (Leopold et al., 2001). Due to population dispersal and economic pressures encouraging cattle ranching, much of the previous tropical forest has been impacted by human activity. Within the past few decades approximately 90% of the original forests have been destroyed, and nearly 46% of the tropical forest has been cleared for cattle pasture (Leopold et al., 2001). Within moderately to extremely damaged pasturelands, the process of natural forest regeneration is hindered due to the colonization of invasive grasses and ferns (Cusack et al., 2004). Previously, land abandonment had been the primary response to damaged landscapes; however, agroforestry and plantation establishment have become a growing alternative within recent years.

There are numerous benefits to the use of plantations on previously cleared landscapes. Depending on the species planted and plantation maintenance, the economic benefits of the timber or the government issued subsidies can be incentive enough to convince small farmers to convert pasture to plantations. Also, the government of Costa Rica offers subsidies in form of the Payment for Environmental Services (PES) and the Advanced Payment of Timber (APT) (Montagnini et al., 2005). The government aid to small farmers helps reduce the high cost of creating a hardwood plantation, and farmers can benefit from having plantations by harvesting the wood for personal use or selling locally. Plantations of native tree species provide farmers with a tool to prevent soil erosion and can be used as living fences or as in agroforestry shade-tolerant crops can be planted within the plantation (Calvo et al., 2007). Although timber can be sold in the market, plantations offer more than just hardwood to the farmers who develop them.

Initially, plantations had been created with a stronger focus on economics rather than environmental rehabilitation. In the past, a greater emphasis has been placed on creating plantation monocultures, mainly consisting of exotic tree species that are known to have rapid growth rates (Leopold et al., 2001). Originally, non-native tree species were often used within hardwood plantations of the past due to the easy availability of information regarding the species' needs, growth information, and success rates, with approximately 30% of the species used for plantations being of the *Pinus* and *Eucalyptus* genera (Carnus et al., 2006). These types of species, when planted in large scale monocultures, generally require simple management since all of the trees mature at the same time, and the timber is of market quality (Mansourian et al., 2005).

Despite the benefits of monoculture plantations, research suggests that they only provide limited ecological benefits, especially in regards to secondary forest regeneration. Recently, mixed native-species plantations are becoming more common in practice. Most mixed species plantations consist of fewer than five different species and are established for either short-term cover crops or long-term plantations (Mansourian et al., 2005). Recent studies of mixed native species plantations in Costa Rica offer optimistic results, which indicate that the use of native species for mixed plantations may be of greater benefit to reforestation attempts (Montagnini, 2005; Piotto et al., 2004). Some of the benefits of mixed plantations include reduced competition due differences between nutrient and resource uptake and sunlight requirements, as well as increasing the overall biodiversity of the plantation (Guariguata et al., 1995, Piotto, 2008), while some disadvantages include the potential for interspecific competition that can negatively affect growth. However, these advantages and disadvantages depend on the interactions between the specific characteristics of the plantation species, which makes research regarding the interactions between common native species in plantations very important (Piotto, 2008).

Throughout Costa Rica and much of Central America, the native *Terminalia amazonia* trees species has commonly been used within hardwood plantations. In Costa Rica the common name for *T. amazonia* species is *amarillon*, which is thought to be the species that shows the most potential within native-species plantations (Streed et al., 2006). *T. amazonia* can be found naturally throughout Central America, ranging from Mexico to South America and the Antilles (Calvo et al., 2002). The *T. amazonia* species is a promising plantation species because it can thrive in almost all types of soils, it has an average growth of 5 m in and 5.8 cm of diameter after only three years in plantation, and the average survival rate within plantations in the northern part of Costa Rica is 85% (Jiménez et al., 2002). Previous research even suggests that *T. amazonia* is the best adapt of the native hardwood species for survival in eroded soils (Carpenter et al., 2004). This study evaluates three different mixed native-species plantations, all including *T. amazonia*.

Other native hardwood species that exist within the plantations sampled include *Astronium graveolens*, *Aspidosperma spruceanum*, and *Tabebuia rosea*. The common Costa Rican names for each species respectively are: *Ron rón*, *Manglillo*, and *Roble de Sabana*. In a comparison study of pure and mixed forest plantations, the researchers observed that the healthy structure and high quality timber of the *A. graveolens* species within mixed plantations could make up for the slow annual growth of the trees (Piotto et al., 2004). There is a limited amount of research available on the growth habits of these species especially within mixed native-species plantations.

Also, generally both forms of hardwood plantations, pure and mixed, require some type of management. In this study, the plantations have not undergone any substantial management or thinning. Normally, thinning helps to reduce competition between individuals and to ensure that the trees remain healthy and produce valuable timber by eliminating individuals that are not fit for commercial sale from competing with healthier, often more profitable trees (Sabogal et al., 2005). In mixed native-species plantations thinning could promote the growth of the hardwood individuals, which may yield in profit in a reduced time period (Piotto et al., 2004). However, there has been less research regarding the performance of plantations that are not managed for purposes of secondary forest regeneration. Since all of the plantations at the FCRE have not been managed, it is not possible to see whether moderate management, such as thinning, would have helped the planted species better grow, such as experiencing greater diameter growth (Piotto et al., 2003)

Overall, the development of mixed native-species plantations continues to be developed much still needs to be researched, especially regarding the interactions between various species within plantations (Montagnini, 2005). The objectives of this study are both local to the Firestone Center for Restoration Ecology (FCRE) as well as regional to the humid south of Costa Rica. Primarily, this study assesses the productivity of already-established mixed hardwood plantations that exist within the FCRE property. Individual tree growth was measured in diameter at breast height (dbh), tree height, canopy diameter, tree mortality, and tree structure. With the collected data, comparisons between the three different plantation types on the FCRE property were conducted; and after further study and data collection, the acquired information were compared with other mixed hardwood plantations throughout southern Costa Rica. This information provides a better understanding of the compatibility between various types of native species that have been used in plantation efforts.

Also, the plantations in this study are different because it provides evaluation of mixed native-species plantations that have not undergone any form of thinning or management, while much of the literature on tree plantations include plantations that have been carefully managed and thinned, since thinning has been shown to improve the overall growth of trees as well as the quality of timber in less time than plantations which have not been thinned (Piotto et al., 2003). This study will provide more insight into how successfully unmanaged mixed plantations grow. The study of the three mixed native-species plantations on the FCRE are expected to provide the property managers with information regarding the status of forest regeneration, which is the ultimate goal of the FCRE hardwood plantations sites.

Methods and Materials:

2.1) Study Site Description

The Firestone Center for Restoration Ecology (FCRE) property is a 60 hectare biological reserve located in Barú, in the southwestern region of Costa Rica; at 9º18'N latitude and 83º54'W longitude. Weather conditions are generally hot and humid with two distinct seasons, dry from January until May and wet from May through December. The mean annual precipitation for 2007 was 2346.7 cm. The topography of the FCRE includes areas ranging from flat terrain to steep inclines and declines.

Figure 1: Location of Firestone Center for Restoration Ecology (FCRE) within Costa Rica

Prior to the establishment of the FCRE, the property had been lowland tropical rainforest, which was cleared between the 1950's and 1960's for cattle ranching. Restoration efforts began in 1993 and in 2005 the FCRE was founded as a biological reserve and resource for ecological research and education. Currently within the FCRE land has been divided into various hardwood plantations, banana and bamboo plantations, as well as natural regenerating forest.

The FCRE hardwood plantations were approximately 12 years old at the time of this study, and were originally planted with the intention of catalyzing the natural succession of the previously cleared landscape. The hardwood plantations are not separated from each other and it is often difficult to distinguish where one plantation type borders with the next. It is assumed that the hardwood plantations in the FCRE property have not been maintained or thinned after the initial plantings. This study evaluates three different hardwood plantations on the FCRE property. All of three plantation-types that are assessed in this study include the *T. amazonia* species, which is native to the region. *T. amazonia* is commonly used for small-scale commercial plantations throughout Costa Rica because of its rapid growth rate and high rate of survival (Jiménez et al., 2002). The plantations observed include the following species: *T. amazonia, A. graveolens, A. spruceanum,* and *T. rosea* (Table 1).

Table 1: Descriptions of tree species grown in mixed plantations the Firestone Center for Restoration Ecology in the Southwestern Pacific region of Costa Rica

Species	**Common Name**	**Family**	**Native Distribution**	**Growth and Habitat**
Terminalia amazonia	Amarillón	Combretaceae	Mexico to South American and Antilles	Fast growing canopy tree, found on slopes, can grow in variety of soils, regenerates in open areas, can grow at high altitudes (1100 m)
Astronium graveolens	Ron rón	Anacardiaceae	Mexico to Bolivia and Brazil.	Canopy tree, usually in flat or moderately sloping areas, and tolerates a range of soils, grows well with partial or later shade, often found in dry forests
Aspidosperma spruceanum	Manglillo	Apocynaceae	Southwestern Costa Rica to Peru and Brazil	Sub-canopy tree, usually found in humid, well drained areas.
Tabebuia rosea	Roble de sabana	Bignoniaceae	Tropical region of Central America	Unavailable

Source: Jiménez-Madrigal et al. (2002).

2.2) Methods:

1) Plot Establishment

The three plantation types in the FCRE were identified and three plots were established within each of the three plantation types in order to assess tree growth in the various plantations. In total, nine plots were sampled from the FCRE property. Each plot was selected depending on area size and relation to other existing or potential plots. Every plot is a made up of a 4-tree by 4-tree square, made up of 16 planted hardwood trees. This format of 16-tree plots ensured uniform plot observations without depending on the initial spacing of the trees. Plots were designed by number of trees because trees on the plantation showed homogenous spacing, but with different arrangements (3 m x 3 m). This design guaranteed a uniform number of observations per plot, independent of initial tree spacing. (Piotto et al., 2003)

Plantation type "A" is composed of the *T. amazonia* and *A. graveolens* species. Plantation type "B" is the mixed species plantation of *T. amazonia*, *A. graveolens*, and *T. rosea*. Plantation type "C" is made up of *T. amazonia* and *A. spruceanum* species (Table 1). Due to the limited size of the plantation areas the study could not use staggered nor randomized plotting method.

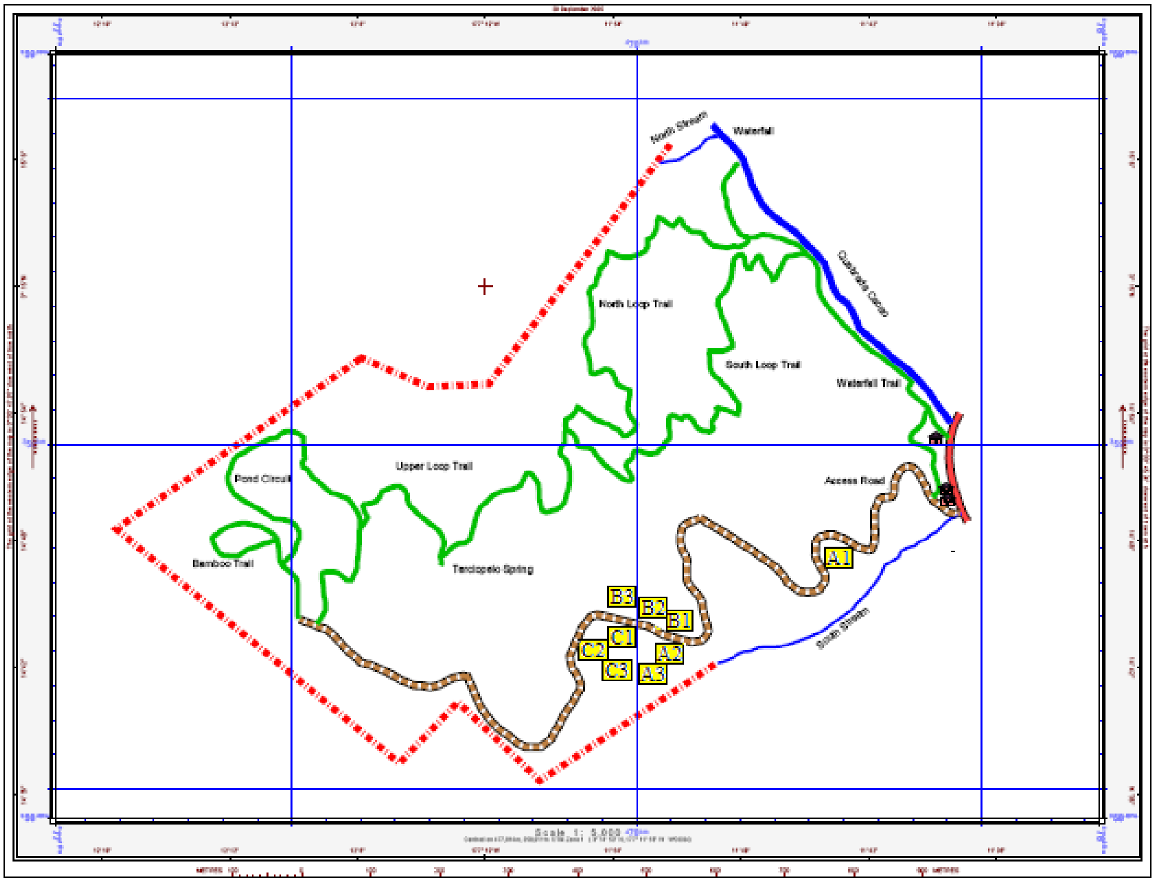

Figure 2: Location of plots of each plantation at the Firestone Center for Restoration Ecology.

2.3) Data Collection and Analysis

At each plot the diameter at breast height (dbh), tree height, crown diameter and growth structure were collected for all 16 trees and any additional trees within the plot with a dbh greater than 5 cm. A calibrated diameter measuring tape was used to measure tree dbh, 1.30 meters above the ground. Tree height was calculated by the use of a calibrated clinometer from a distance of 15 m away from the tree. Measuring the distance of horizontal length of the crown and averaging that value with the value of the perpendicular length of the crown determined the crown diameter. Tree structure was assessed by categorizing the shape of the tree (straight, slightly sinuous, or very sinuous) and observing any diseases or pests. Any bifurcation that occurred below 5 m was also recorded. For each plot, tree survival/mortality, basal area, and canopy area were calculated.

This study includes only simple statistical analyses, mainly using the t-test to assess whether the average measurements for diameter, height, and canopy area are significantly different between each plantation type. A canopy index was not calculated since the canopy area that extended outside the 9 m x 9 m plots was included in the data collection. Also, it was not possible to perform ANOVA analyses due to the inability to perform the corresponding tukey test that would allow analysis of the interactions between the different groups within the ANOVA test.

Results:

3.1) Tree growth within mixed plantations

In each of the three types of mixed plantations, the *T. amazonia* grew well in comparison to the other species. The mean dbh of the *T. amazonia* in Plantation A (M = 24.83, SE = 1.56) and in Plantation C (M = 26.31, SE = 1.45) were higher than the mean dbh for the *T. amazonia* in Plantation B (M = 17.6, SE = 1.61). T-tests further revealed that the *T. amazonia* in Plantation A had a greater average dbh than in Plantation B, $t(2) = 4.59$, $p < 0.05$ (Figure 3), while the *T. amazonia* in Plantation C were also significantly thicker than those in Plantation B, $t(3) = 5.13$, $p < .05$ (Figure 3). However, there was no statistical difference between the *T. amazonia* in Plantation A and C, $t(2) = -2.31$, ns (Table 2).

Table 2: Average diameter at breast height (DBH) and average height of *T. amazonia* and other planted species in three different plantation types at the Firestone Center for Restoration Ecology, Costa Rica.

Plantation A (*Terminalia amazonia* and *Astronium graveolens*)										
	DBH (cm)	Minimum Diameter (cm)	Maximum Diameter (cm)	Standard Error	Average Diameter Growth (cm/yr)	Height (m)	Minimum Height (m)	Maximum Height (m)	Standard Error	Average Height Growth (m/yr)
Terminalia amazonia	24.9 a	8.6	35.1	0.09	2.0	21.8 a	11.0	27.0	0.8	1.4
Astronium graveolens	9.3 b	4.1	16.2	0.36	0.8	8.9 b	4.5	15.0	0.2	0.6
Plantation B (*Terminalia amazonia*, *Astronium graveolens*, and *Tabebuia rosea*)										
	DBH (cm)	Minimum Diameter (cm)	Maximum Diameter (cm)	Standard Error	Average Diameter Growth (cm/yr)	Height (m)	Minimum Height (m)	Maximum Height (m)	Standard Error	Average Height Growth (m/yr)
Terminalia amazonia	17.6 c	6.8	31.8	1.57	1.47	18.0 c	6.0	23.0	0.7	1.2
Astronium graveolens	11.6 bc	7.4	19.8	1.73	0.96	10.5 b	5.7	14	1.7	0.7
Tabebuia rosea	6.3 b	2.0	9.2	0.84	0.53	5.6 b	2.0	9.0	1.1	0.4

Plantation C (*Terminalia amazonia* and *Aspidosperma spruceanum)*										
	DBH (cm)	Minimum Diameter (cm)	Maximum Diameter (cm)	Standard Error	Average Diameter Growth (cm/yr)	Height (m)	Minimum Height (m)	Maximum Height (m)	Standard Error	Average Height Growth (m/yr)
Terminalia amazonia	26.3 a	16.6	37.7	0.63	2.19	22.2 a	12.5	26.3	0.5	1.5
Aspidosperma spruceanum	6.2 b	1.9	10.6	2.17	0.52	9.6 b	3.3	15.0	3.2	0.6

The means are significantly different from the others when followed by different lower-case letters within the column ($p < 0.05$)

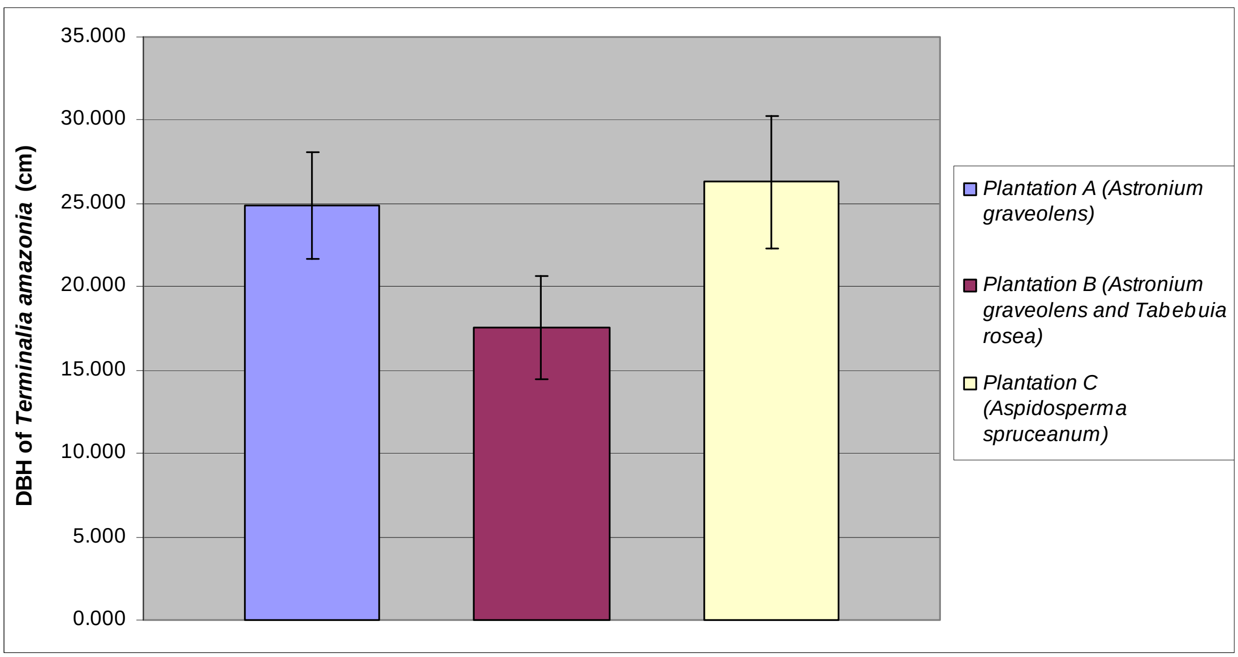

Figure 3: Average diameter at breast height (DBH) in centimeters for Plantations A, B, and C. The error bars represent standard error.

Similarly, the heights of the *T. amazonia* in each of the plantations followed the same pattern as the diameters. Therefore, the individuals in Plantation A (*M* = 21.8, *SD* = 1.44) were significantly taller than the *T. amazonia* within Plantation B (*M* = 18.0, *SD* = 1.15), $t(4) = 3.56$, $p < 0.05$; also, the height of *T. amazonia* in Plantation C (*M* = 22.2, *SD* = 0.781) was also significantly than in Plantation B, $t(3) = -5.22$, $p < 0.05$ (see Figure 4).

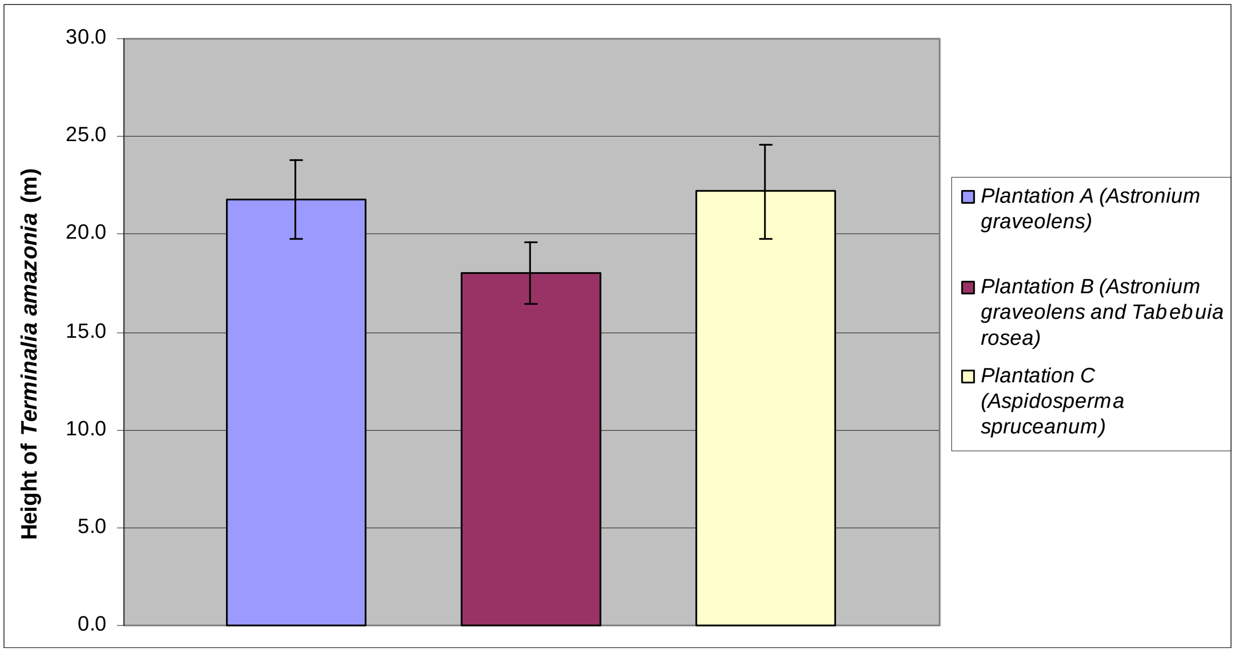

Figure 4: Average overall height in meters for Plantations A, B, and C. The error bars represent standard error.

When comparing the *T. amazonia* with the other species, *T. amazonia* had a significantly higher average diameter, t(15) = 8.70, p < 0.01, as well as significantly higher heights than the average of the other planted species, t(15) = 10.4, p < 0.01 (Table 2). Even though *T. amazonia* within Plantation B were the thinnest and shortest amongst the three plantations, the average was still significantly higher than the other planted species. Therefore, the *T. amazonia* were consistently the largest trees within each type of mixed plantation (Figure #). A t-test between the average dbh values for *A. graveolens* in Plantation A (*M* = 8.90, *SE* = 0.36) and in Plantation B (*M* = 10.2, *SE* = 1.73) showed that there was no significant difference, t(2) = 0.759, ns (Figure 5). Similarly, there was no difference between the heights of *A. graveolens* in the two plantations, t(2) = 0.759, ns (Figure 6).

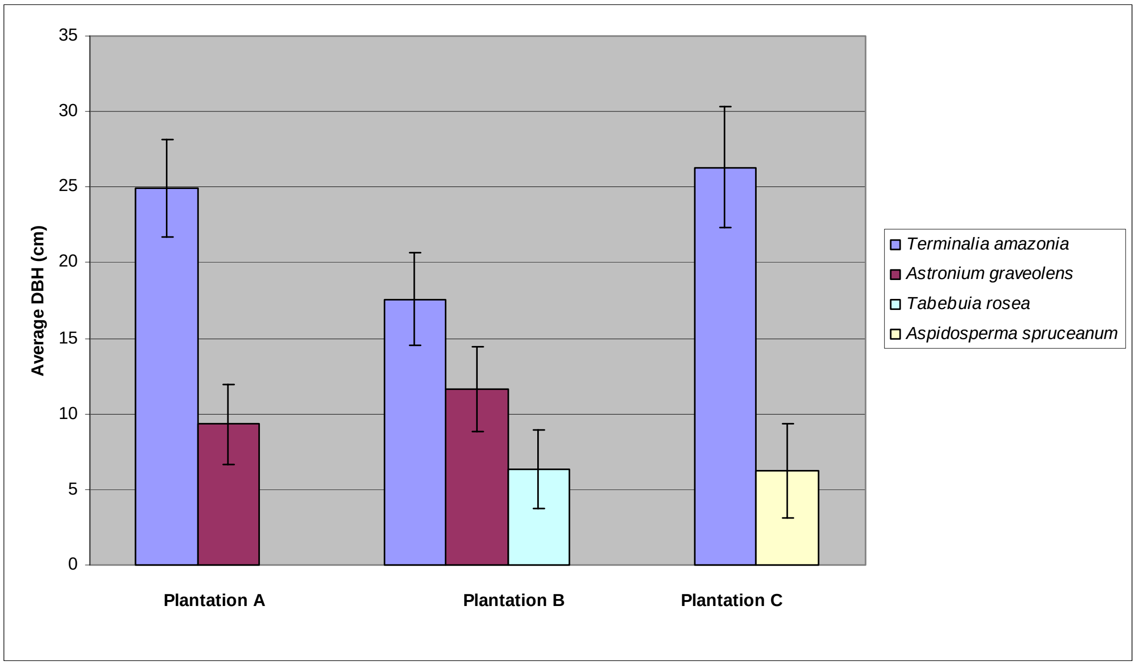

Figure 5: Average diameter at breast height (DBH) in centimeters for each planted tree species within Plantations A, B, and C

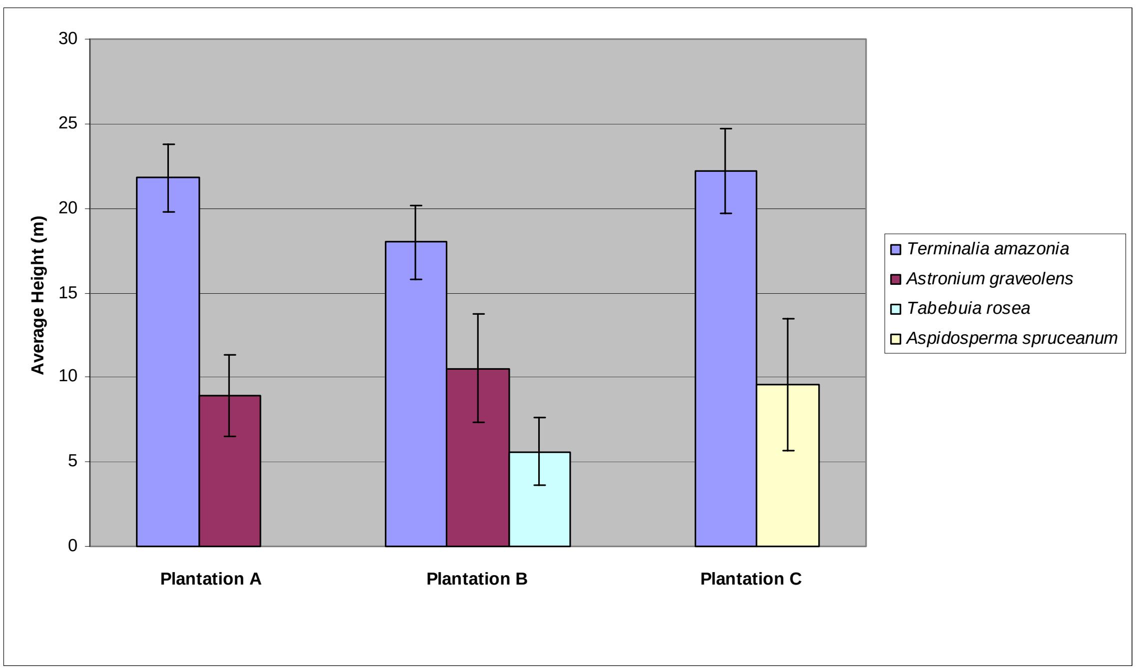

Figure 6: Average height in meters for each planted tree species within Plantations A, B, and C

Within Plantation A, the *T. amazonia* trees had a significantly greater diameter and height than *A. graveolens* (Table 2). Within Plantation B, the *T. amazonia* had significantly higher average diameter and height than both *A. graveolens* and *T. rosea* (Table 2). However, there was no significant difference between the diameters and heights of *A. graveolens* and *T. rosea* (Table 2). Also, the *T. amazonia* in Plantation C had significantly higher dbh than the *A. spruceanum*, $t(2) = 9.709$, $p < 0.05$; also, the height of the *T. amazonia* was significantly higher as well, $t(2) = 4.953$, $p < 0.05$ (Figure 5 and 6).

Overall, Plantation A had the highest overall average basal area and Plantation B had the lowest overall average basal area of the all of the 3 types of plantations; however, the overall basal areas of each were not significantly different (Figure 7). Plantation C had the highest average basal area for the *T. amazonia*, but none of the differences were significant. Both *A. spruceanum* and *T. rosea* had the smallest average basal areas (Table 3), which means that the individuals in Plantation C had both the greatest basal area average (*T. amazonia)* and the lowest basal area average (*A. spruceanum*) (Table 3). Across all the plantations, *T. amazonia* was the greatest contributor towards overall basal area of the plantations (Figure 7).

Table 3: Average basal for each planted species within Plantations A, B, and C at the Firestone Center for Restoration Ecology, Costa Rica

***Terminalia amazonia* and *Astronium graveolens* (Plantation Type A)**	
	Basal Area (m^2/ha)
Terminalia amazonia	33.8 (6.29) a
Astronium graveolens	6.6 (1.05) b
Overall	41.04 (5.33)
***Terminalia amazonia, Astronium graveolens*, and *Tabebuia rosea* (Plantation Type B)**	
	Basal Area (m^2/ha)
Terminalia amazonia	21.5 (5.92) a
Tabebuia rosea	1.5 (0.43) c
Astronium graveolens	4.9 (2.18) bc
Overall	30.9 (4.11)
***Terminalia amazonia* and *Aspidosperma spruceanum* (Plantation Type C)**	
	Basal Area (m^2/ha)
Terminalia amazonia	37.6 (4.49) a
Aspidosperma spruceanum	1.4 (0.70) c
Overall	32.7 (4.37)

The means are significantly different from the others when followed by different letters after the standard (in parenthesis) within the column ($p < 0.05$)

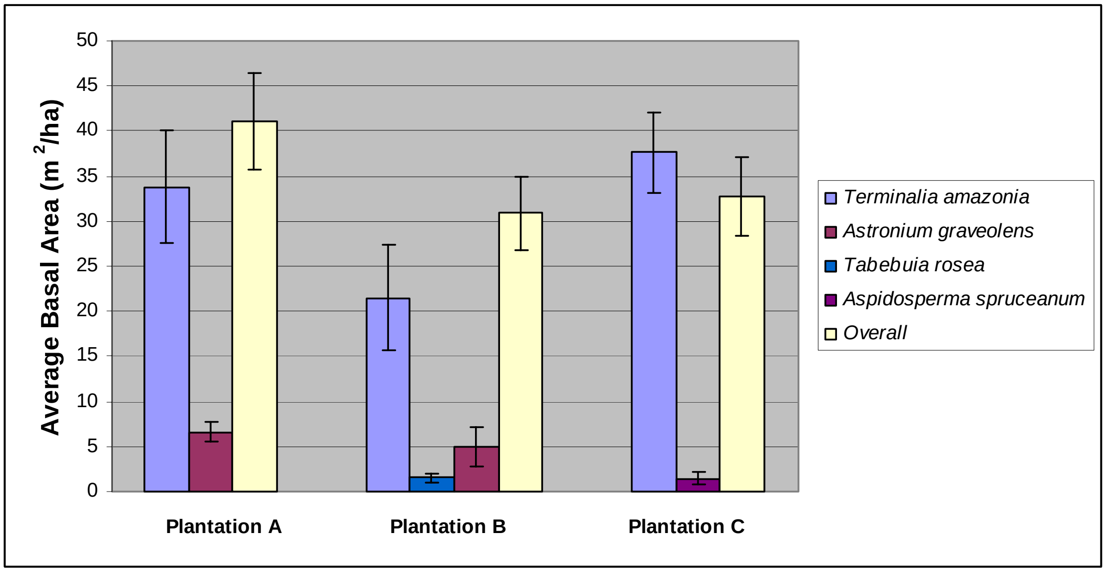

Figure 7: Average basal area in meters squared per hectare for each planted species within Plantations A, B, and C; including an overall average for each individual plantation

With respect to canopy cover, the average canopy areas of the *T. amazonia* were significantly larger than those of the other species within the plantations, but were not significantly different from each other. Also, the species with the smallest average canopy area was the *A. spruceanum*, but the canopy area of *A. spruceanum* was not significantly different than the other species (excluding *T. amazonia*) (Table 4).

Table 4: Average canopy area for each planted species within Plantations A, B, and C at the Firestone Center for Restoration Ecology, Costa Rica

Terminalia amazonia **and** ***Astronium graveolens*** **(Plantation Type A)**		
	Average Canopy Area (m^2)	**Standard Error**
Terminalia amazonia	53.0 a	6.82
Astronium graveolens	10.7 b	1.34
Overall	23.1	2.02
Terminalia amazonia, Astronium graveolens**, and** ***Tabebuia rosea*** **(Plantation Type B)**		
	Average Canopy Area (m^2)	**Standard Error**
Terminalia amazonia	54.6 a	8.87
Tabebuia rosea	9.2 b	1.77
Astronium graveolens	12.7 b	3.56
Overall	28.7	3.16
Terminalia amazonia **and** ***Aspidosperma spruceanum*** **(Plantation Type C)**		
	Average Canopy Area (m^2)	**Standard Error**

Terminalia amazonia	43.4 a	5.69
Aspidosperma spruceanum	7.4 b	1.39
Overall	31.5	5.07

The means are significantly different from the others when followed by different letters after the standard (in parenthesis) within the column ($p < 0.05$)

The overall survivorship of the trees in Plantation A were the highest (83%), while Plantation C had the poorest overall survival rate (52%). For the *T. amazonia*, the survival rate in Plantation A was the highest (80%), but was lower in Plantation B (75%), and even more so in Plantation C (67%), which resulted in a 74% survival rate across all of the mixed plantations (Table 5). The *A. graveolens* had a higher survival rate than the *T. amazonia* at 85%, and the *T. rosea* had the highest rate of survival of all of the species (92%), but there were also a total of only 12 individuals planted within the plantations, as opposed to the 68 *T. amazonia* that were planted (Table 5). Conversely, the *A. spruceanum* had the lowest survival rate at only 40%. As a result, Plantation C had the lowest overall survivorship out of all of the plantation types (52%), while Plantation A and B had survival rates that were approximately 30% higher (83% and 81%, respectively) (Table 5).

Table 5: Species mortality rates and survival rates for each planted species in Plantations A, B, and C at the Firestone Center for Restoration Ecology, Costa Rica

***Terminalia amazonia* and *Astronium graveolens* (Plantation Type A)**					
	# of Trees Planted	**# of Living Trees**	**# of Deaths**	**Mortality Rate**	**Survival Rate**
Terminalia amazonia	20	16	4	0.20	0.80
*Astronium graveolens**	27	23	4	0.15	0.85
Overall	47	39	8	0.17	0.83
***Terminalia amazonia, Astronium graveolens*, and *Tabebuia rosea* (Plantation Type B)**					
	# of Trees Planted	**# of Living Trees**	**# of Deaths**	**Mortality Rate**	**Survival Rate**
Terminalia amazonia	24	18	6	0.25	0.75
Tabebuia rosea	12	11	1	0.08	0.92
Astronium graveolens	12	10	2	0.17	0.83
Overall	48	39	9	0.19	0.81
***Terminalia amazonia* and *Aspidosperma spruceanum* (Plantation Type C)**					
	# of Trees Planted	**# of Living Trees**	**# of Deaths**	**Mortality Rate**	**Survival Rate**
Terminalia amazonia	24	16	8	0.33	0.67

Aspidosperma spruceanum	24	9	15	0.60	0.40
Overall	48	25	23	0.48	0.52
	# of Trees Planted	**# of Living Trees**	**# of Deaths**	**Mortality Rate**	**Survival Rate**
Overall for *Terminalia amazonia*	68	40	18	0.26	0.74
Overall for *Astronium graveolens*	39	33	6	0.15	0.85
Overall for *Tabebuia rosea*	12	11	1	0.08	0.92
Overall for *Aspidosperma spruceanum*	24	9	15	0.60	0.40

Across all of the plantations, *T. amazonia* consistently observed the best form out all of the other species. However, the *T. amazonia* in Plantation B did have the most sinuosity (17%) in comparison to the *T. amazonia* in the other plantations, while the *T. amazonia* in plantation C showed the highest percentage of forked trees (Table 6). Also, all of the *A. spruceanum* individuals in Plantation C were straight, but there were only a total of 9 individuals within the mixed plantation. The *T. rosea* had the highest percentage of "very sinuous" individuals (82%), but *A. graveolens* and *T. rosea* showed comparable sinuosity and bifurcation within Plantation B (Table 6). Similarly, the *A. graveolens* and *T. rosea* within Plantation B had the highest amount of bifurcation (Table 6). In addition to form, cankers (*Nectria* sp.) were found within the *T. amazonia* population, but not present in the other species. For example, 21% of the *T. amazonia* within Plantation B were diseased with the canker, and 6% of the *T. amazonia* in Plantation A were infected.

Table 6: Overall form of planted tree species and number of diseased individuals within Plantations A, B, and C.

Plantation A (*Terminalia amazonia* and *Astronium graveolens*)					
	Straight	**Slightly Sinuous**	**Very Sinuous**	**Forked**	**Diseased (cankers)**
Terminalia amazonia	100% (16)	0% (0)	0% (0)	13% (2)	6% (1)
Astronium graveolens	4% (1)	39% (9)	57% (13)	35% (8)	0% (0)
Plantation B (*Terminalia amazonia*, *Astronium graveolens*, and *Tabebuia rosea*)					
	Straight	**Slightly Sinuous**	**Very Sinuous**	**Forked**	**Diseased (cankers)**
Terminalia amazonia	83% (15)	17% (3)	0% (0)	6% (1)	21% (4)
Astronium graveolens	10% (1)	20% (2)	70% (7)	50% (5)	0% (0)
Tabebuia rosea	18% (2)	0% (0)	82% (9)	45% (5)	0% (0)
Plantation C (*Terminalia amazonia* and *Aspidosperma megalocarpum*)					
	Straight	**Slightly Sinuous**	**Very Sinuous**	**Forked**	**Diseased (cankers)**

Terminalia amazonia	94% (15)	6% (1)	0% (0)	19% (3)	0% (0)
Aspidosperma spruceanum	100% (9)	0% (0)	0% (0)	0% (0)	0% (0)

The number in parentheses to the right of the percentage signifies the number of total individuals.

Discussion:

The performance of the plantations at the FCRE is difficult to assess, mainly due to the unique mixture of species in the plantations. The *T. amazonia* showed the best growth of all of the species across all of the mixed plantations. This corresponds with previous studies that have shown *T. amazonia* have performed well in mixed plantations (Carpenter et al., 2004; Redondo-Brenes and Montagnini, 2006). The average basal area averages of the *T. amazonia* (Table 3) were actually higher than other those in other mixed plantations of similar age in Costa Rica (Redondo-Brenes and Montagnini, 2006; Redondo-Brenes, 2007). However, the drastic difference between the growth of the *T. amazonia* and the other species within the plantations suggests that the *T. amazonia* have been out-competing the other species for nutrients and other resources. Also, the fact that the average canopy area, basal area, dbh, and height of the *T. amazonia* are all significantly higher than those of the other species (Table 2) further suggests the rapid growth of the *T. amazonia* is inhibiting the growth of the other species, possibly due to the large canopies of the *T. amazonia*.

However, it is important to remember that *A. graveolens* is considered a slow-growing species (Jimenéz and Poveda, 1997), but the average dbh for the *A. graveolens* at these plantations were much lower than the values obtained in another study. For example, *A. graveolens* on a mixed, 6-year-old plantation had an average dbh of 8.01 cm (Piotto, 2004), which is higher than the 6.3 cm average dbh of the *A. graveolens* in the 12-year-old plantations at the FCRE. Also, another study observed *T. rosea* to have an average dbh of 9.34 in an open pasture setting (Piotto, 2007), which is also higher than the average dbh from this study (Table 2).

Despite the slow growth of the *A. graveolens* and *T. rosea*, the survivorship of these two species was high (Table 2), which corresponds with findings in other studies (Piotto, 2004; Piotto, 2007). This suggests that despite their inability to reach the canopy, they are still able to survive under the canopy formed by mainly *T. amazonia*. And overall, the survivorship of Plantation A and Plantation B are high. Conversely, the *A. spruceanum* both had very low growth and high mortality, suggesting that the species does not grow well with *T. amazonia*.

Similarly, the low survival rate of the *T. amazonia* in Plantation C also suggests that the presence of *A. spruceanum* negatively *T. amazonia*. Furthermore, another interesting finding was that the *T. amazonia* and the *A. spruceanum* in Plantation C had the highest and lowest average basal area, respectively. A possible explanation is that poor growth of the *A. spruceanum* reduced any competition that could have been occurring between the two, allowing the *T. amazonia* to freely grow. Such interspecies competition occurs when species do not cooperate in mixed plantation settings (Piotto, 2008). Unfortunately, very research has been conducted on the performance of *A. spruceanum* (as well as *T. rosea* to a lesser extent), which makes it difficult to explain this potential negative interaction.

In Plantation A and Plantation B, a few of the *Terminalia amazonia* individuals suffer from infectious cankers (*Nectria* sp.) on their trunks (Table 6). These cankers caused by a disease known as *Nectria* may have been established after animals or human activity scratched the tree stem. Further research and assessment should be done to discover the exact cause and effect of the cankers on the individual trees as well as the plantation overall, to prevent future spread of the disease.

Figure 8: a) left: Image of a *T. amazonia* infected with a bacterial canker (*Nectria* sp.).
b) right: Image of a *T. amazonia* after the bacterial canker had spread along the tree.

Although not mentioned previously and formally documented, the presence of nitrogen-fixing tree species within some of the hardwood plantations may be of interest for evaluation.

Studies suggest that mixed plantations of hardwood trees with nitrogen-fixing species prove useful for encouraging natural regeneration in areas of damaged soils (Piotto, 2008). The investigation of such nitrogen-fixing species within the plantations, whether intentionally planted or regenerating, is useful to determine the productivity of the hardwood plantations. Informal observations showed that various species of *Inga* were present in the understory of the plantations. *Ingas*, which are a type legume, have been shown to aid in the regeneration process due to its ability to replenish nitrogen in degraded soils (Carpenter et al., 2004) and further studies have shown that plantations containing *T. amazonia* perform particularly well in the presence of legumes, including *Inga edulis*, since it is believed that *T. amazonia* may be limited by nitrogen availability (Nichols and Carpenter, 2006).

Even though this study assessed the crown cover of the plantation plots, it is recommended that future canopy analysis be conducted with more accurate methods and instruments. One process for more precise canopy measurement is evaluation of light availability through the use of a handheld spherical densiometer, as employed by Cusack & Montagnini (2004). This approach reduces the human variability and biases that occur when measuring the tree crowns with a measuring tape. The most accurate assessment of light availability or crown cover can enable future research of the correlation between crown cover and understory growth within these mixed species plantations.

It has been observed that plantations promote the regeneration of understory species by shading out grasses, increasing nutrient richness of topsoil, allowing the growth of more sensitive tree species, and creating a microclimate that attracts seed dispersers (Cusack & Montagnini, 2004). Therefore, future studies can evaluate understory growth within the plantations at the FCRE, especially since previous studies have shown that *T. amazonia* promotes high amounts of understory growth (Cusak and Montagnini, 2004). Understory assessment should include the number of individuals within different class heights, as well as the number of different species. By evaluating understory growth in the hardwood plantations at the FCRE property, the researchers can judge the productivity of the plantations as catalysts for regeneration on site.

Future observations of wildlife, specifically bird species, within the hardwood plantations should also be conducted to assess seed-dispersal process as well as the potential use of plantations as wildlife habitat. Wildlife in plantations assumes an important role in seed dispersal and influences the growth of understory plant species. In most cases, more than 40%, understory species depend on bird species to disperse seeds; therefore birds are considered the most significant agents for seed dispersal (Butler, 2008). Therefore, collecting data of the seed dispersers in the plantations provides another means to assess how successfully the plantations are regenerating into secondary forests.

A survey of soil quality at each of the sites would be useful for assessing plantation output. Previous studies have shown that *Terminalia amazonia* can survive in eroded soils, and can also grow in soils that lack phosphorous (Carpenter, 2004). Future soil samples could shed light on whether factors like nutrient deficiencies due to competition are the main causes for the difficulties with the non-*Terminalia amazonia* species in the plantations.

Lastly, this research should be used as preliminary data for a long-term assessment of the hardwood plantations at the FCRE. Future researchers should continue collecting dbh, height, and canopy data and keep a running database of accumulated information. With the data collected in the future growth, height and mortality models can be created for more in-depth analysis. Overall, it is imperative that more research and literature are established about mixed hardwood plantations in the Southwestern area of Costa Rica. Further studies of various plantations in the south of Costa Rica will be helpful for those who intend on catalyzing regeneration of tropical rain forest on previously damaged land.

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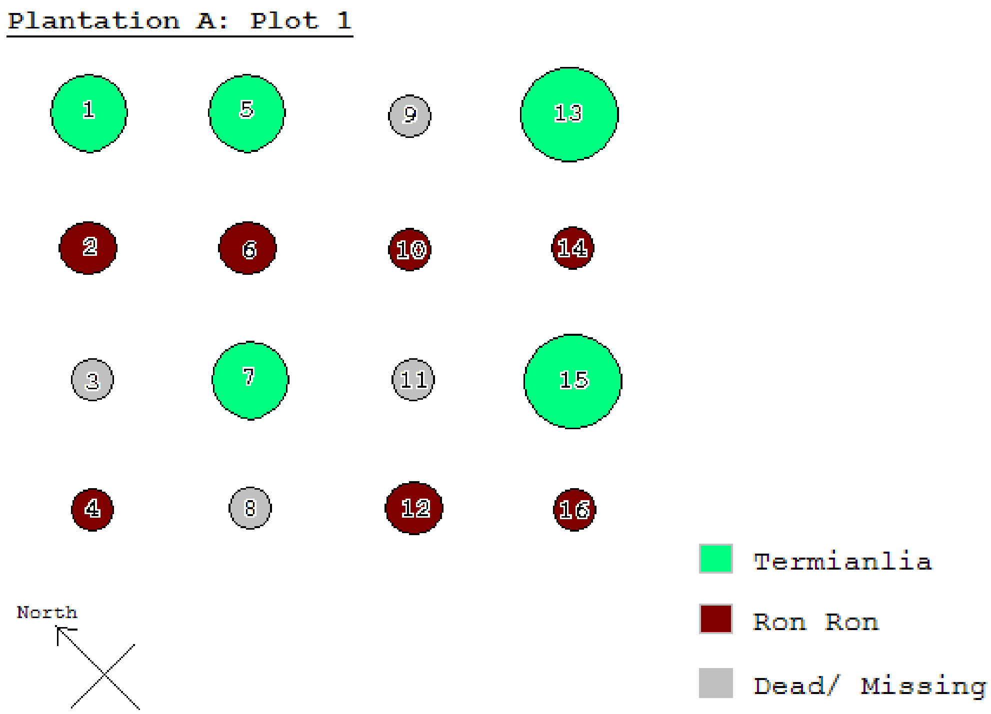
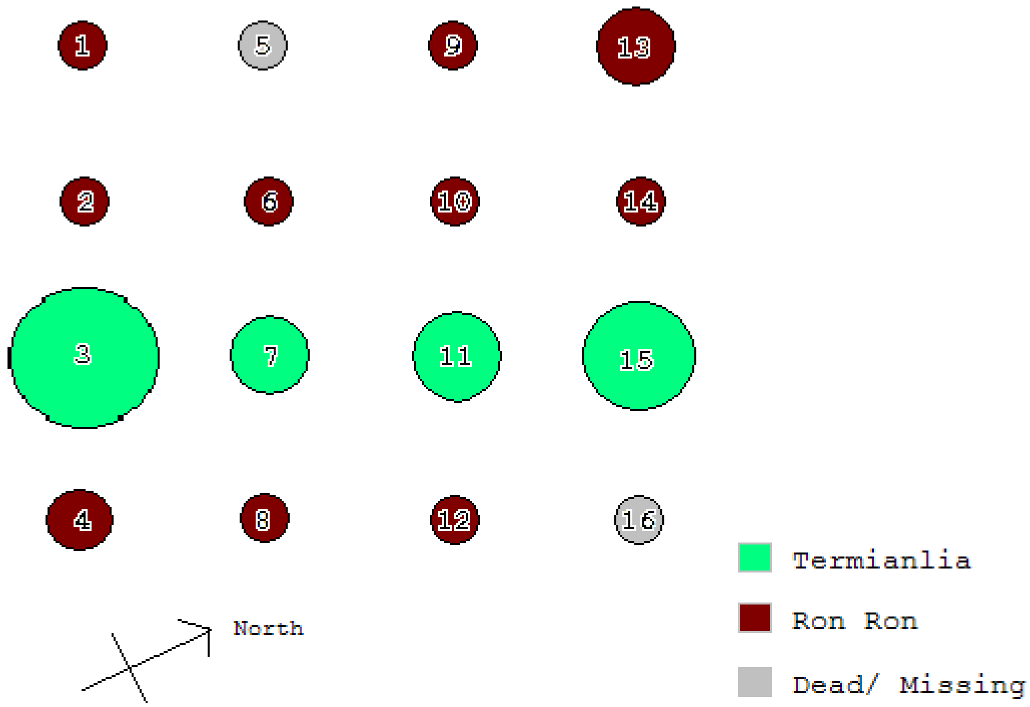
Appendix

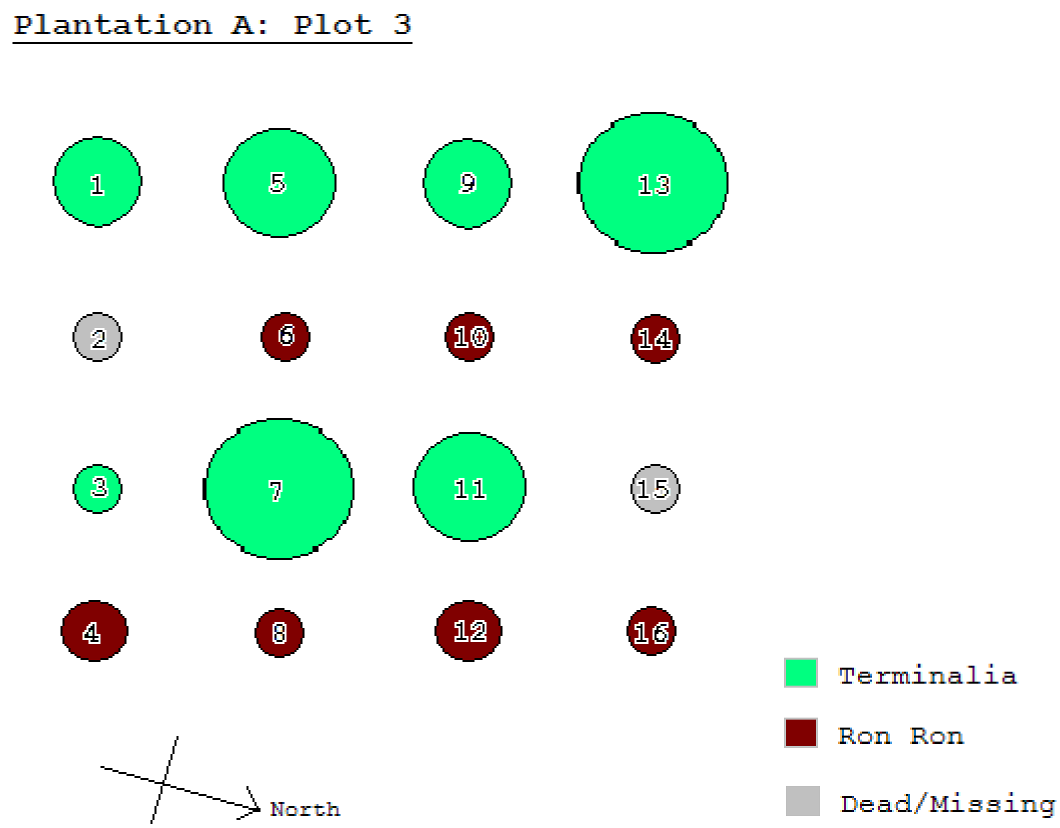


Site:	Plantation A Plot 1		
tree #	species	dbh (cm)	height (m)
1	Terminalia	23.4	24.5
2	Ron Rón	10.5	9.3
3	Terminalia	-----	-----
4	Ron Rón	09.0	9.5
5	Terminalia	24.1	21.8
6	Ron Rón	13.2	15.0
7	Terminalia	22.1	19.5
8	Ron Rón	-----	-----
9	Terminalia	-----	-----
10	Ron Rón	09.5	8.3
11	Terminalia	-----	-----
12	Ron Rón	10.5	9.8
13	Terminalia	25.5	19.0
14	Ron Rón	08.9	5.5
15	Terminalia	28.8	22.0
16	Ron Rón	08.6	7.5
17	?	07.3	11.5

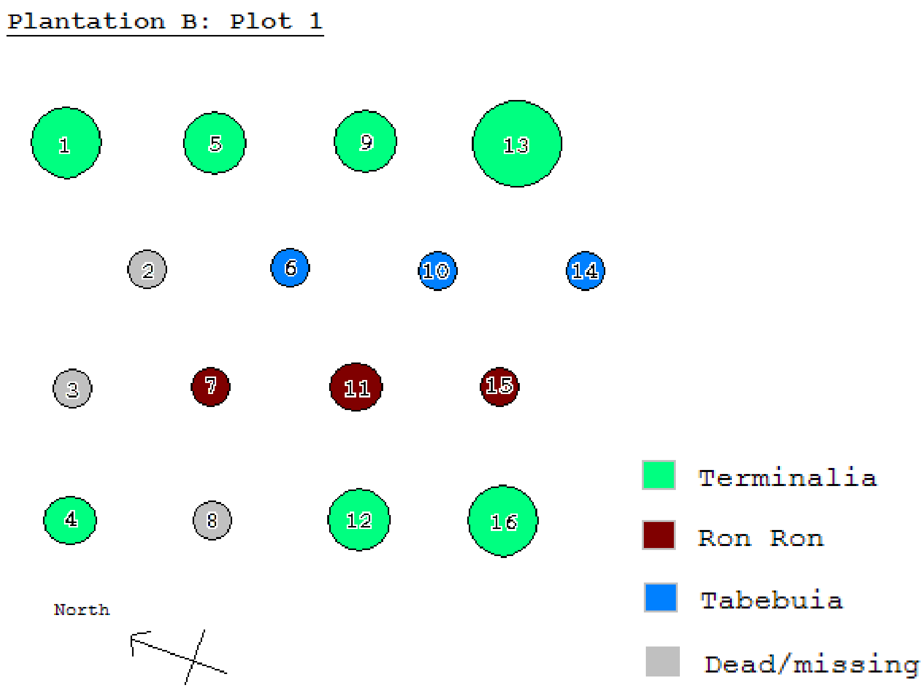
Plantation A: Plot 2



Site:	Plantation A Plot 2		
tree #	species	dbh	height
1	Ron Rón	05.9	7.9
2	Ron Rón	07.0	8.5
3	Terminalia	35.1	26.2
4	Ron Rón	14.2	5.8
5	Ron Rón	-----	-----
6	Ron Rón	08.6	9.5
7	Terminalia	17.1	18.5
8	Ron Rón	07.0	5.0
9	Ron Rón	08.6	11.3
10	Ron Rón	08.0	11.3
11	Terminalia	21.5	21.5
12	Ron Rón	08.6	4.5
13	Ron Rón	16.2	12.5
14	Ron Rón	04.1	10.8
15	Terminalia	25.1	27.5
16	Ron Rón	-----	-----

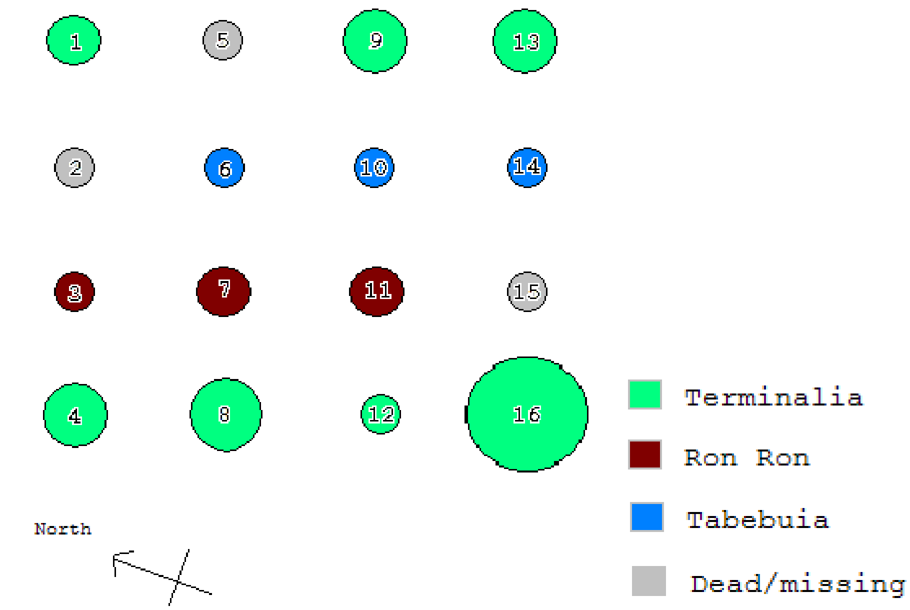


Site:	Plantation A Plot 3		
tree #	species	dbh	height
1	Terminalia	24.7	22.0
2	Ron Rón	-----	-----
3	Terminalia	08.6	11.0
4	Ron Rón	10.7	9.5
5	Terminalia	28.7	22.2
6	Ron Rón	07.4	8.0
7	Terminalia	32.8	24.0
8	Ron Rón	08.9	8.5
9	Terminalia	23.3	22.2
10	Ron Rón	08.0	8.0
11	Terminalia	26.4	22.5
12	Ron Rón	12.0	9.5
13	Terminalia	30.6	20.0
14	Ron Rón	07.8	8.5
15	Terminalia	-----	-----
16	Guazuma	05.6	8.5



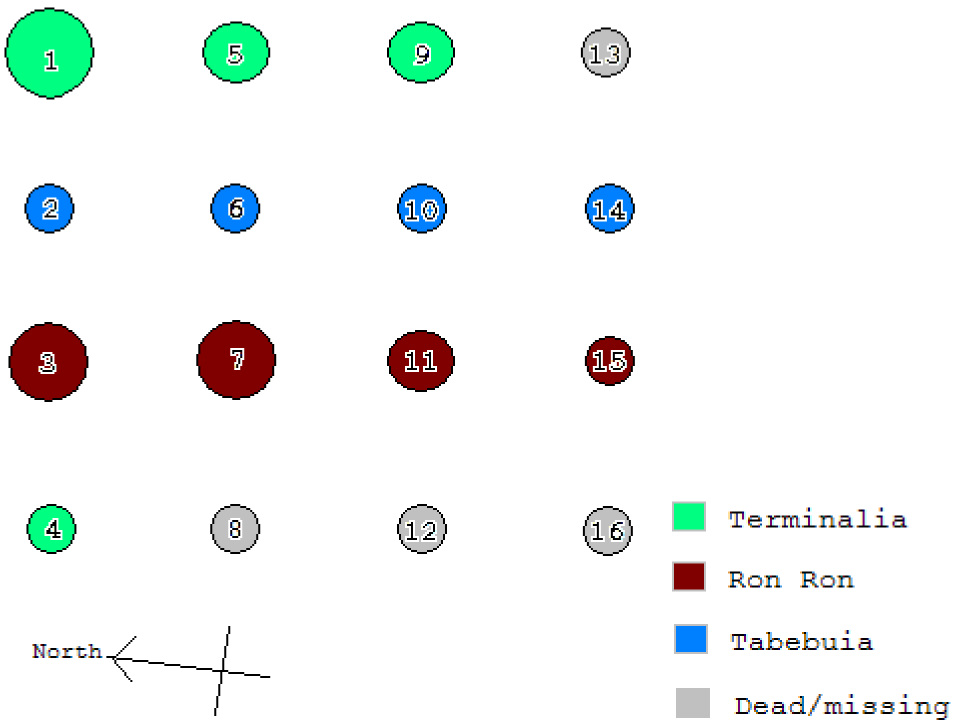
Site:	Plantation B Plot 1		
tree #	**species**	**dbh**	**height**
1	Terminalia	24.7	20.5
2	Tabebuia	07.7	8.2
3	Ron Rón	-----	-----
4	Terminalia	14.5	17.7
5	Terminalia	15.3	18.0
6	Tabebuia	05.8	6.7
7	Ron Rón	07.6	5.7
8	Terminalia	-----	-----
9	Terminalia	18.3	18.8
10	Tabebuia	05.1	5.8
11	Ron Rón	11.1	8.0
12	Terminalia	17.3	17.1
13	Terminalia	29.5	19.5
14	Tabebuia	08.9	8.9
15	Ron Rón	09.1	6.8
16	Terminalia	23.0	23.0
17	?	05.0	8.5
18	?	10.0	9.0
19	?	07.5	4.5

Plantation B: Plot 1



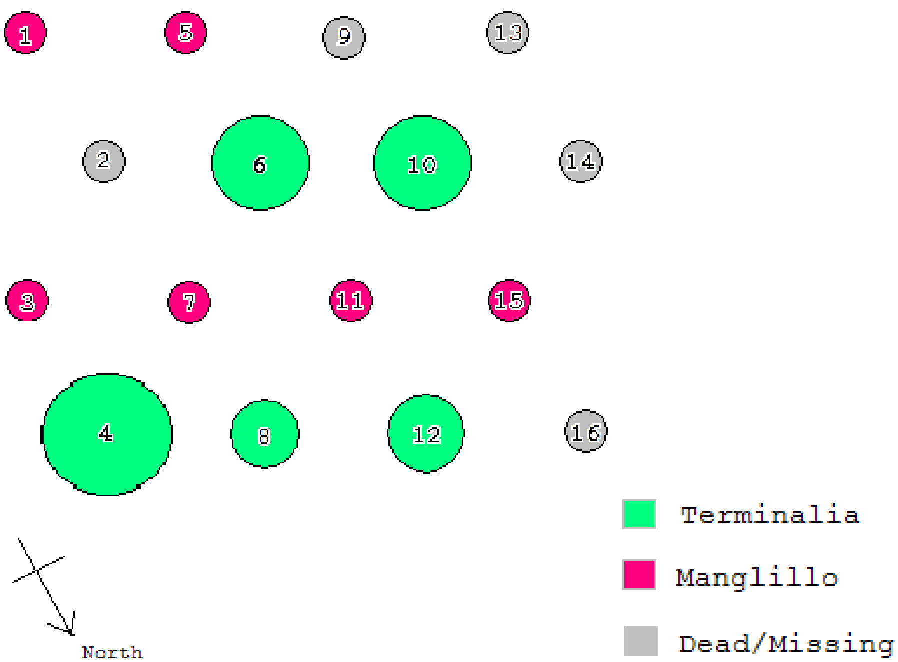
Site:	**Plantation B Plot 2**		
tree #	**species**	**dbh**	**height**
1	Terminalia	10.6	15.0
2	Tabebuia	-----	-----
3	Ron Rón	07.8	8.8
4	Terminalia	15.9	20.0
5	Terminalia	-----	-----
6	Tabebuia	05.7	4.5
7	Ron Rón	10.2	12.0
8	Terminalia	21.6	22.0
9	Terminalia	18.3	19.5
10	Tabebuia	05.7	4.5
11	Ron Rón	11.4	13.5
12	Terminalia	06.8	6.0
13	Terminalia	17.6	19.5
14	Tabebuia	02.0	2.0
15	Ron Rón	-----	-----
16	Terminalia	31.8	23.0
17	Inga	05.0	8.0

Plantation B: Plot 3



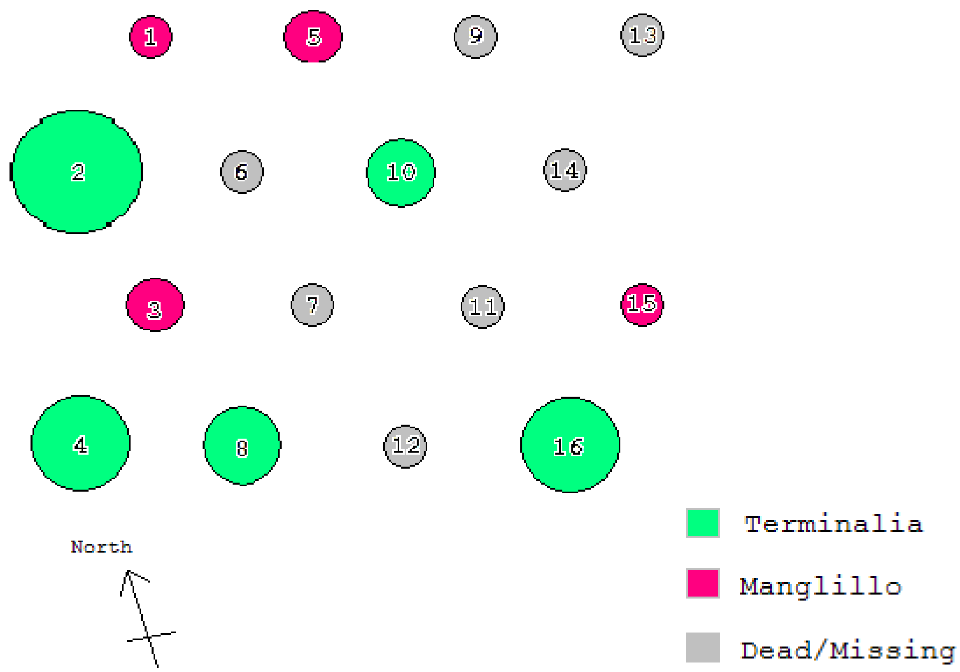
Site:	Plantation B Plot 3		
tree #	**species**	**dbh**	**height**
1	Terminalia	24.8	21.0
2	Tabebuia	06.9	5.5
3	Ron Rón	19.8	14.0
4	Terminalia	08.8	12.5
5	Terminalia	13.3	17.0
6	Tabebuia	06.3	4.0
7	Ron Rón	17.7	14.0
8	Terminalia	-----	-----
9	Terminalia	12.8	17.0
10	Tabebuia	05.9	5.0
11	Ron Rón	14.0	13.5
12	Terminalia	-----	-----
13	Terminalia	-----	-----
14	Tabebuia	09.2	6.5
15	Ron Rón	07.4	8.5
16	Terminalia	-----	-----

Plantation C: Plot 1



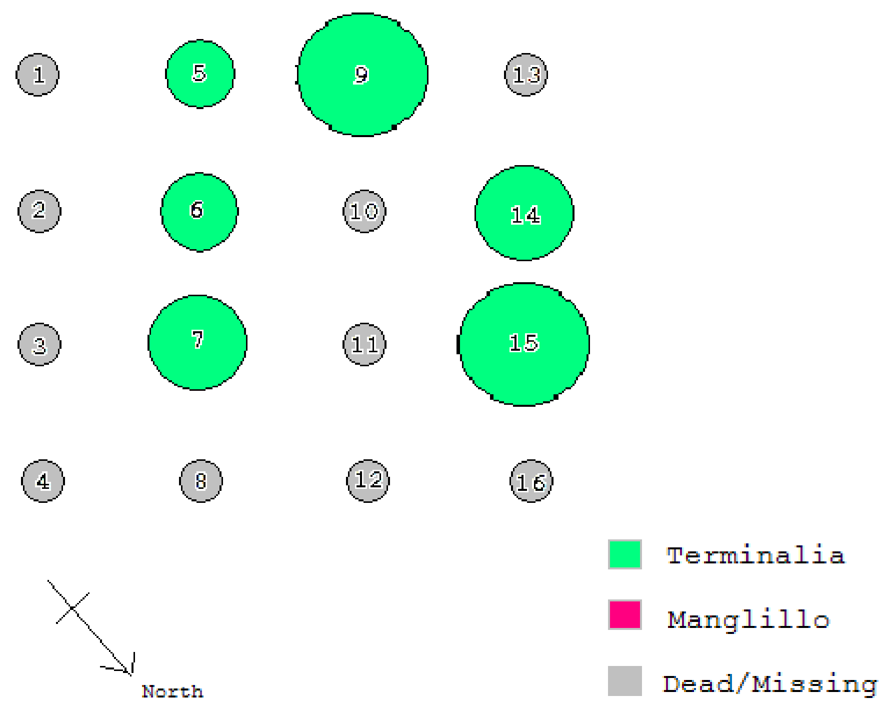
Site:	Plantation C Plot 1		
tree #	species	dbh	Height
1	Manglillo	01.9	11.5
2	Terminalia	-----	-----
3	Manglillo	09.9	15.0
4	Terminalia	31.2	23.5
5	Manglillo	06.7	7.0
6	Terminalia	30.0	21.5
7	Manglillo	03.3	5.0
8	Terminalia	17.9	23.5
9	Manglillo	-----	-----
10	Terminalia	26.9	22.0
11	Manglillo	05.8	9.5
12	Terminalia	22.7	22.5
13	Manglillo	-----	-----
14	Terminalia	-----	-----
15	Manglillo	07.1	11.0
16	Terminalia	-----	-----

Plantation C: Plot 2



Site:	Plantation C Plot 2		
tree #	species	Dbh	height
1	Manglillo	07.8	10.2
2	Terminalia	31.4	23.5
3	Manglillo	10.6	14.0
4	Terminalia	28.3	25.0
5	Manglillo	-----	-----
6	Terminalia	-----	-----
7	Manglillo	-----	-----
8	Terminalia	24.6	25.8
9	Manglillo	-----	-----
10	Terminalia	16.6	16.8
11	Manglillo	-----	-----
12	Terminalia	-----	-----
13	Manglillo	-----	-----
14	Terminalia	-----	-----
15	Manglillo	02.9	3.3
16	Terminalia	27.3	22.2

Plantation C: Plot 3



Site:	**Plantation C Plot 3**		
tree #	**species**	**dbh**	**height**
1	Manglillo	-----	-----
2	Manglillo	-----	-----
3	Manglillo	-----	-----
4	Terminalia	-----	-----
5	Terminalia	18.6	12.5
6	Terminalia	22.8	21.0
7	Terminalia	25.7	24.0
8	Manglillo	-----	-----
9	Terminalia	37.7	22.5
10	Manglillo	-----	-----
11	Manglillo	-----	-----
12	Terminalia	-----	-----
13	Manglillo	-----	-----
14	Terminalia	26.9	26.3
15	Terminalia	33.7	21.3
16	Manglillo	-----	-----