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Timber-based agrisilvicultural systems to facilitate reforestation in Panama - A silvicultural and economic evaluation

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Dedicado a la comunidad de Tortí –
sus habitantes y su paisaje –
que siempre los llevaré en mi corazón

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Contents

1 Introduction

One of the greatest challenges of the 21st century is assuring food security while at the same time combatting accelerating deforestation in the tropics - a main driver of greenhouse gas emissions and irreversible losses of biodiversity. In the past decade, a gross area of 13 Mio ha of forest was worldwide lost each year, with more than half of this area located in Central and South America (FAO 2010b). The conversion of tropical rain forest to agricultural land, due to a growing population, with rising demand for meat and energy crops, coupled with unsustainable land use practices has been identified as one of the main sources of deforestation (Ewers 2006, Wassenaar et al. 2007, McAlpine et al. 2009, FAO 2010b, Goers et al. 2012). However, once forest is converted to agricultural land, crop and livestock yield usually declines rapidly, due to the loss of soil fertility. This forces the landowner to either intensify inputs, or to abandon the degraded land and clear more forest (Ashton et al. 2001, Fischer et al. 2011). The consequences of this trend are dramatic. The degradation of forests[1] leads to a considerable loss of ecological services, such as the regulation of climate and water flow, hosting of biodiversity, carbon sequestration and storage, erosion control and maintenance of soil fertility (Reid 2005, Sands 2005, Chazdon 2008). However, most apparent is the loss of numerous goods produced in and by the forest - timber and firewood as well as non-timber forest commodities, such as rattan or honey (Vantomme 2011). The lack of these goods most severely affects the rural population, as they lose the fundamental basis of their livelihoods. On top of that, there are also far-reaching consequences for global markets, as for instance, rising wood prices (Montagnini and Jordan 2005, ITTO 2011).

It is widely acknowledged that the restoration of these degraded and unproductive lands is necessary in order to recover their ecological, as well as their economic value, and improve the livelihood of the local people (Lamb et al. 2005, Knoke et al. 2008). However, the natural recovery after human disturbance of forest ecosystems usually takes more than 40 years (Jones and Schmitz 2009). Humid tropical forests are often characterized by low resilience, particularly where repeated fires or cattle grazing were part of the land use history (Holl 2007, Palomeque 2012). Factors which hinder natural succession include the absence of a seed source (Günter et al. 2007), competition with aggressive and often exotic, grasses (Kuusipalo et al. 1995, Griscom et al. 2009), microclimate and soil limitations (Moran et al. 2000, Goers et al. 2012) and fires (Aide and Cavelier 1994, Zimmermann 2002). Even though some studies have shown that natural succession under certain conditions can lead to the recovery of basal area, aboveground biomass, and species richness of the original forest within four decades (Benayas et al. 2009, Letcher and Chazdon 2009), it remains unlikely that these forests will show the same abundance of valuable hardwoods. Thus they will not likely be able to reach the economic value of old-growth forests and at the same time meet global demands for timber and other forest resources (Aide et al. 2000, Günter et al. 2008, Akindele and Onyekwelu 2011).

An alternative to passive restoration in the form of natural succession is the active planting of fast-growing tropical hardwoods. Tropical timber plantations present an economically attractive alternative to natural succession (Cubbage 2010), and might also be a practical option for the farm portfolio (Knoke et al. 2009a, Knoke et al. 2012). Due to the ongoing degradation of natural forests, commercial forest plantations are assumed to play a vital role in meeting future demand for tropical timber (Sedjo 2001, Paquette and Messier 2009). Compared to natural and secondary forests, timber plantations in the tropics usually have higher yields of high-value wood, and thus produce higher incomes within shorter rotation lengths (Evans and Turnbull 2004, Cubbage et al. 2007, Knoke and Huth 2011). In addition to its economic value, reforestation with

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[1] Degraded forests are defined as forests where changes have negatively altered the structure or function of the site (FAO 2010b).

commercial hard woods[2] can help to recover a range of ecosystem services within a comparably short time: Forest plantations have been shown to contribute considerably in terms of carbon sequestration (Silver et al. 2000, Paul et al. 2009), increased soil organic carbon (Paul et al. 2002) conservation of biodiversity (Bremer and Farley 2010, Butler et al. 2008, Weber et al. 2008), water quality and quantity (van Dijk and Keenan 2007, Jobbágy et al. 2012) and the availability of soil nutrients (Montagnini and Sancho 1990). They have thus been found to play an important role in the ecological restoration of tropical ecosystems (Lamb et al. 2005, Parrotta 1992).

The greatest obstacle to the implementation of timber plantations for most farmers is, however, the long term investment of land, labor and other farm resources in trees (Garen et al. 2009, Vieira et al. 2009). In tropical tree plantations, the first income from thinning can be obtained after approximately 10 years at the earliest (Onyekwelu et al. 2011). Tropical farmers can usually not afford to wait this long for their efforts to yield profit. Also for many investors, reforestation cannot compete with other forms of investments that provide earlier payback.

The aim of the present study was to develop methods to generate earlier returns from tropical timber plantations and, hence, turn reforestation into a more attractive land use option for both small- and large-scale land owners. One possible way to overcome this problem might be the use of "agroforestry", which is

> *"a collective name for land-use systems and practices where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence"* (Lundgren and Raintree 1982).

Agroforestry is a rather young research area, which only emerged in the scientific community in the 1970s, even though it has been practiced for hundreds of years throughout the world (Nair 1993). The renewed scientific interest in these traditional systems is based on the need to strike a balance between conservation and the people's demand for food, energy and materials (Batish 2008). Traditional agroforestry practices[3] include a vast range of different designs which combine woody perennials with crops or animals, such as the so-called "homegardens", "living fences", and shade trees in pastures or for coffee production. In recent decades, a lot of work has been carried out in order to describe and classify traditional systems (e.g. Nair 1985, Sinclair 1999). The second focus has been on the investigation of potentially positive impacts of trees on the nutrient cycle, soil quality, microclimate and productivity of agricultural systems (see literature reviews in Rao et al. 1997, Brenes 2005, Jose and Gordon 2008, Batish 2008). Scant attention has, however, been dedicated to the possible advantage of integrating crops into forest plantation management.

Such concepts for the sequential plantings of short term crops that are phased out as forest matures are known under the name "Taungya". This term was given to this agroforestry practice by Dietrich Brandis, a German botanist who worked for the British Empire in Colonial Burma (now Myanmar) in the 1860s. Brandis encouraged the Karen tribesmen to sow Teak (*Tectona grandis*) trees between their cotton and upland rice fields. After the trees had shaded out the understory crops, the established plantations came under the Forest Department's management, which offered rewards to the peasants for successfully established teak plantations (Lamprecht 1986, Jordan 1992). Even though Brandis' expression is now frequently used for the classification of such sequential intercropping systems, there are indications that similar systems have existed for hundreds of years in other parts of Asia (Menzies 1988, Hsiung et al. 1995). The modern concept of Taungya has been adapted and modified for application throughout the tropics, (Watanabe et

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[2] Fast-growing forest plantations for the purpose of bioenergy production with rotation lengths of less than 5 years are not regarded as reforestation in this context.

[3] An agroforestry practice denotes a distinctive arrangement of components (trees, crops and/or animals) in space and time, while an agroforestry system is a specific local example of a practice (Nair 1993, p. 32)

al. 1988, Weaver 1989, Wilkinson and Elevitch 2000, Agyeman et al. 2003, Hossain et al. 2006), with most scientific trials having been established and monitored in Asia (Messerer 2011). In Central America, however, where the present study was conducted, experience with such systems is rare (to be reviewed in chapter 2.1). The main focus of research in this region has been on other agroforestry systems, such as shade tree systems with coffee and cacao (Brenes 2005). The planting of crops between tree seedlings during the initial phase of forest establishment might, however, have substantial advantages compared to pure forest plantations, due to potential complementary effects of crops on young seedlings, for example, improved microclimate, shading of competing grasses, reduction of soil transpiration and improvement of soil fertility (Vieira et al. 2009). Revenues from crops might furthermore offset costs for the management of tree seedlings (Platen 1995) and thus also improve the financial feasibility of forest plantations.

The present study aims to evaluate the suitability of such sequential intercropping systems for the production of high-quality timber in tropical hardwood plantations. The interdisciplinary assessment will be carried out from both a silvicultural and an economic perspective. The overall aim is to identify suitable tree-crop combinations by their biophysical and economic performance. The community of Tortí, situated in the East of the Republic of Panama, has been chosen as the study site for the present case study, as this region shows typical characteristics of a tropical rural area – a high and accelerating deforestation rate, low income of local farmers, high dependency of their income on agriculture and forest land and continued dominance of slash-and-burn practices (Fischer and Vasseur 2000, Moreno 2001, Tschakert et al. 2007, see also site description in chapter 3.1). Land that becomes unproductive for agriculture in this area is increasingly being bought by foreign investors for large-scale reforestation, mostly with exotic tree species (ANAM 2010). The ecological benefit of such monocultures of exotic tree species is however, debated (Bremer and Farley 2010, Griscom and Ashton 2011). Many scientists recommend the use of native tree species, not only because they might be more appropriate for restoration of biodiversity and other environmental services (Oelmann et al. 2010), but also for silvicultural reasons, as they are already adapted to their native habitats (Onyekwelu et al. 2011). They might furthermore fulfill traditional services to local landholders (Garen et al. 2009) while requiring less financial investment in external seed sources or foreign technologies (Lamb et al. 2005, Plath et al. 2011b). As with the majority of reforestation projects, research on the integration of annual crops in tropical hardwood plantations has mainly focused on only a small number of tree species – most of which are not native to Central America (e.g. Kapp and Beer 1995, Ceccon 2005). This is surprising, considering that Panama's flora is one of the richest and most diverse in the world (Myers et al. 2000), including approximately 2,308 tree species (Carrasquilla 2006). The present study will therefore also consider native tree species in hopes of contributing to a better understanding of their growth performance and management in forest plantations.

Successful integration of crops during the establishment phase of forest plantations has the potential not only to increase financial viability of forest plantations, but also to make a substantial contribution towards improving food security in rural areas (FAO et al. 2012).

The following chapter will review timber-based agroforestry systems, and summarize methodological approaches to the study of intercropping systems. Chapter 2.3 will then present the detailed hypotheses that were developed based on these findings. The introductory sections will be followed by a description of resources, materials and methods used in this study. The results obtained will be summarized and discussed in chapter 5. Conclusions and recommendations for practical on-site implementation of the findings can be found in chapter 6.

2 State of knowledge

2.1 Review of timber-based agrisilvicultural practices

2.1.1 Identification and classification of timber-based agrisilvicultural practices

Agrisilvicultural practices[4] are defined as the combination of trees with agricultural crops (Nair 1993). Before determining the spatial design and the possible tree-crop combinations for this case study, an extensive review of literature on past experiences with agrisilvicultural practices for the purpose of timber production was carried out. The emphasis of this review was on the integration of crops in forest plantations during the establishment phase, which was defined as the first two years after tree planting, due to the time limitations of this study. For this reason, silvopastoral systems - where animals are grazed within forest plantations - were not considered, even though they might offer attractive opportunities in later stages of forest plantations (see e.g. Knoke et al. 2009a, Cubbage et al. 2012a).

Many authors have attempted to classify agroforestry practices by the nature and arrangement of their components (Nair 1985, Somarriba 1992, Sinclair 1999). According to these definitions, three main agrisilvicultural practices linked to timber production - Taungya, alley cropping, and the use of shade trees for woody crops (Table 2.1) - will be shortly described in the following paragraphs, and evaluated with respect to their appropriateness in achieving the objective of this thesis.

"**Taungya,**" which was briefly described in the introduction, is certainly the agroforestry practice that has the strongest connection to forest plantations. The definition of "Taungya" differs considerably depending on region and historical background: While Lamprecht (1986) defines Taungya as a conversion system of tropical forests to an even-aged forest, Watanabe et al. (1988) states that it is a primary reforestation method. Due to its connection to shifting cultivation[5], Taungya can be considered as a "forerunner of agroforestry" (Nair 1993, p.75). However, both authors agree that the system serves to support the production of high quality wood products. In contrast, some Chinese systems concentrate on the production of firewood (Saint-Pierre 1991), and other systems are reported to concentrate on the production of fodder by leguminous trees (Watanabe et al. 1988). Under the name Taungya, descriptions of systems in which trees line fish pods even exist (Effendi 1990), which today are more commonly known as "Aquaforestry". These examples show the multitude of possible interpretations of the Taungya practice.

Nair (1993, p. 33) gives a general definition of this practice: Taungya is a "combined stand of woody and agricultural species during early stages of establishment of plantations". Nair (1993) also states that a further characteristic of Taungya is that the

> *"land belongs to the forestry departments or their large-scale lessees, who allow the subsistence farmers to raise their crops. The farmers are required to tend the forestry seedlings and, in return, retain a part or all of the agricultural product. This agreement would last for two or three years, during which time the forestry species would grow and expand its canopy."* (Nair 1993, p. 75, see also Sinclair 1999)

Today, the term "Taungya" and the traditional idea of creating incentives for indigenous farmers to give up shifting cultivation in favor of a more settled agricultural system seems outdated and does not meet the objectives of this study. A more modern concept of Taungya, aimed at the reforestation of abandoned land by its owner, might rather be associated with other,

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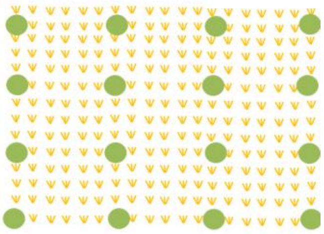
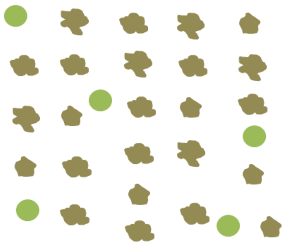
[4] Synonyms: silvoarable practices (e.g. Eichhorn et al. 2006, agrosilvicultural practices (e.g. Sinclair 1999)

[5] Taungya is derived from the words "Taung" for hill and "ya" for cultivation, which is the traditional term for shifting cultivation in Myanmar (Jordan 1992).

agrisilvicultural systems, such as **alley cropping**. Modern agroforestry technologies which combine the production of high-value wood products with modern, mechanized agriculture are known in both Europe (Eichhorn et al. 2006, Makkonen-Spiecker 2007, Brix et al. 2009) and North America (Jose et al. 2000, Cubbage et al. 2012b). However, in the tropics, the term alley cropping is mostly used in the sense of “hedgerow intercropping,” with the woody component mostly consisting of “fast-growing leguminous trees that are coppiced vigorously,” (Nair 1993, p. 33) such as *Gliricidia sepium* and *Leucaena leucocephala* (Kang 1993, Rao et al. 1997). The cut branches are then used as mulch on the fields or for fodder. These and other leguminous fodder tree species do however also appear in Taungya literature as described above. Alley cropping furthermore, does not address the aspect of an early temporary cultivation of herbaceous crops between forest plantation rows, where the emphasis is on the production of the woody component. Similar practices that are not discussed in detail, but are also designed for the protection of agricultural fields from wind erosion using leguminous fodder trees, are “living fences” and border or “contour plantings” (León and Harvey 2006).

Table 2.1: Characteristics of agrisilvicultural practices for the purpose of timber production. See text for details.

	Agrisilvicultural practices for timber production		
Characterstics	Traditional Taungya System	Alley cropping with valuable timber species	Shade trees for woody crops
Scematic figure ● = Tree ѵ = annual crop ♣ = perennial shade-tolerant woody crop			
Synonyms (see text for sources)	Sequential intercropping, plantation intercropping	Intercropping, Hedgerow intercropping, plantation intercropping	Plantation intercropping
Primary production aim	Tropical hardwoods	Hardwoods, firewood, fodder, used as windbreak for improved crop production	Production of shaded coffee/cacao or other shaded crops, hardwoods
Associated crops	Annual	Annual/perennial	perennial
Time frame of intercropping	Short term association of trees and crops Until canopy closure (2-5 years)	Long term association of trees and crops during whole rotation period of trees	Long term association of trees and crops during whole rotation period of trees
Planting density of trees	Common density 3 x 3 m ~ 1111 trees/ha (Jordan 1992)	Between tree rows: 3 – 50 m (Kang 1993)	~ 150 trees/ha (Cordero and Boshier 2003)
Tree planting design	Regular	Regular	Regular to scattered

Another agrisilvicultural system that is aimed toward production of hardwood timber, but also offers early returns, is the long-term association of **timber trees with perennial shade tolerant crops**, such as coffee and cacao. Shaded coffee and cacao are certainly the most intensively studied agrisivilcultural systems in Central America (Brenes 2005). However, in these systems, the advantage of an offset of establishment costs for timber plantation is usually not achieved, as cacao itself takes approximately four years until the first revenues can be expected. Furthermore, timber tree density is usually very low (Table 2.1). This method was therefore not considered appropriate for this study. Establishment costs can only be buffered by income from additional shade components such as bananas (*Musa spp.*) that are usually only grown until they are shaded out by timber trees (Beer et al. 1997, Oke and Odebiyi 2007, Lieberei and Reisdorff 2012).

Even though substantial differences between these practices have been demonstrated, some characteristics overlap (Table 2.1). Accordingly, a chronology of different systems might be possible, such as the Taungya system followed by a shaded crops system. Moreover, by using a systematic thinning regime, the Taungya System can also be converted to an alley cropping system. These examples show that a clear distinction of these systems is only possible at a small spatial and temporal scale.

Regarding the research question formulated above, the general concept of the Taungya practice seems to fit best to the idea of an initial integration of crops in forest plantations. However, due to the rather outrun and loose definition of Taungya, and in some aspects, its similarity to other agrisilvicultural practices, modern concepts often avoid the use of this term and the established classifications of Nair (1985), Sinclair (1999), and others. In recent literature, the term “intercropping” - which originates from the agricultural practice of combining two or more crops (Willey 1985, Federer 1993, Vandermeer 1989) - is increasingly used to describe the simultaneous planting of trees with annual crops, as for instance by Wilkinson and Elevitch (2000), Haggar et al. (2003), Ceccon (2005), Martin and van Noordwijk (2011), Paul and Weber (2013). Alternatively, scientists tend to mix definitions as for example Combe (1981) speaks of “Taungya” with perennial crops and Montambault and Alavalapati (2005) combine alley cropping, hedgerow intercropping, Taungya and shaded perennial crops under the term “Plantation Intercropping”. This development shows that traditional classifications do not adequately describe new agroforestry technologies that are being designed by both farmers and scientists to meet the increasing demand for productive agroforestry systems that also address both subsistence and industrial needs. In this study, the term “timber-based agrisilvicultural practices” (TBAPs) is used and defined as

- an association of trees with annual crops, during the initial phase of forest plantation establishment to offset management costs.
- For this purpose trees and crops are planted in a regular grid, with an initial tree density commonly used in forest plantation management, and the
- primary aim is hardwood production.

The basic idea of such TBAPs originates – as described earlier – from the Taungya practice. Therefore, the historical development of this agroforestry practice will be reviewed first, while the later description of experiences with TBAPs will also consider modern equivalents.

2.1.2 Historical development and geographical distribution of the Taungya practice and its modifications

In this chapter, the historical development of the traditional Taungya System and its modifications will be presented. These trends are crucial for understanding possible past shortcomings of this practice that might prevent implementation of these systems despite their potential advantages. As a part of this project, a comprehensive literature review on the Taungya System and its modifications was carried out by Messerer (2011) in the form of a Bachelor Thesis under the author's supervision. This work reviewed 123 studies from 1926 to 2011 which investigated Taungya practices. Forty percent of these publications dealt with Taungya practices in Asia, 31% with their application in Africa, and only 19% were carried out in Central America[6] (Messerer 2011, p. 11). This demonstrates that the focus of research has been on **Asia,** due to the origin of Taungya in Myanmar as described in chapter one. Historically, it is widely distributed from Indonesia to China (Jordan 1992, Messerer 2011, p. 5, Norgrove 2003).

The first introduction of the System to **Africa** is thought to have been at the beginning of the 20th century (Lamprecht 1986, p. 147, Witcomb and Dorward 2009), where state authorities tried to introduce the Taungya-system in degraded forest reserves (Lamprecht 1986, Hellermann 2007). Through this system, a significant area of forest plantations was established, such as 35.000 ha in Ghana (Agyeman et al. 2003). However, this attempt to introduce the system into African agricultural practice, and hence to stimulate restoration of degraded forests, widely failed because of a lack of both incentives for farmers and of know-how due to insufficient supervision by forest authorities, inadequate financing mechanisms and corruption (Kiriinya 1994b, Agyeman et al. 2003, Hellermann 2007). In Ghana, farmers had no rights to the revenues from tree plantings and no decision-making role. As a result, farmers tended to abuse the system, neglecting tree crops or even illegally clearing other, still untouched areas of the forest reserve (Agyeman et al. 2003). These experiences show that land ownership is an essential factor for successful implementation of agroforestry systems. Nevertheless, governmental support can certainly play an important role in the transition phase of agriculture to agroforestry through incentives such as subsidized loans or the donation of tree seedlings (Current et al. 1995b, Danso 2007). However, the transition will only be successful in the long run if the decision for a change in land use practice has been made by the farmer himself, which will mainly be determined by cost-effectiveness and financial or productive incentives of the new land use system (Alavalapati et al. 2004, Knoke et al. 2008). For this reason, in addition to silvicultural considerations, an economic evaluation was an essential part of this study.

As stated earlier, little is known about the viability of Taungya systems in **tropical America**. This might in part be attributed to the rather late introduction of the system on this continent. In contrast to the African development, in Central America the implementation was proposed by scientists rather than state authorities. The first studies - recorded in the 1960s - investigated the feasibility of the system overall, as well as potential tree species (Aguirre 1963, Schlönvoigt and Beer 2001). In Belize, the system was considered to be a possible method to recover valuable stands of big-leaf mahogany plantations (Mayhew and Newton 1998) – an idea that spread to many other Caribbean countries (Weaver 1989). In Central America, the majority of studies on possible Taungya practices have been carried out at the Centro Agronomico Tropical de Investigación y Enseñanza (CATIE) in Costa Rica (e.g. Schlönvoigt 1993a, Current 1995, Kapp and Beer 1995, Somarriba et al. 2001c). In Panama agroforestry trials - including different Taungya Systems using exotic tree species - were established in the 1980s by the National Institute for Natural Resources (INRENARE), with support from the Food and Agricultural Organization of the United Nations (FAO) and the United Nations Development Programme (UNDP). Other small-scale projects using this practice have been reported from the Panama Canal area (Hauff 1998), however, a systematic scientific investigation of possible tree-crop combinations in Taungya systems is lacking.

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[6] In 10% of the publications the location was unknown or not related to a specific country or site.

Since its first description in the 1860s (Lamprecht 1986), the Taungya system has not only undergone a variety of modifications, but has also aroused increasing scientific interest. This development is illustrated by Figure 2.1, which shows the number of publications on the Taungya system by year, based on the literature review by Messerer (2011).

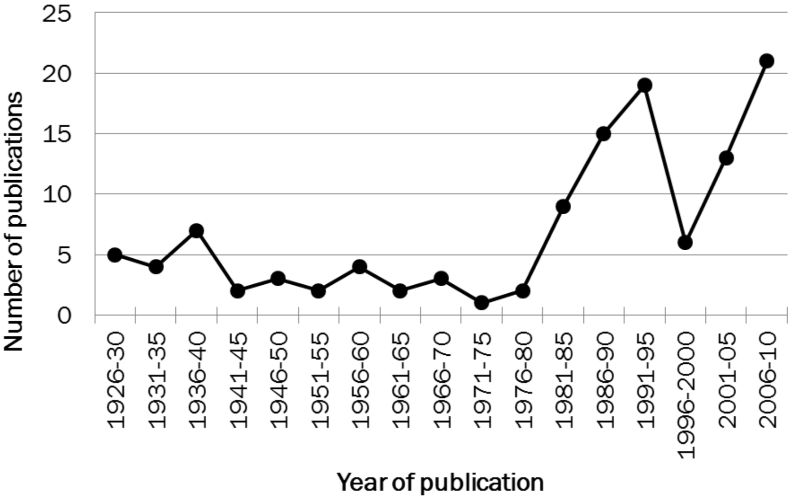

Figure 2.1: Number of publications on Taungya Systems by year of release (1926-2010), data taken from Messerer (2011).

2.1.3 Experiences with economic performance of timber-based agrisilvicultural systems

The driving interest in integrating crops in tree plantations is the economic value of generating earlier returns. Economic viability of Taungya systems or modifications of such systems has therefore been a major field of research since its first mention. However, systematic economic comparison between pure forest plantations and initial intercropping of trees has rarely been carried out. Messerer (2011) found 20 studies in the time frame 1926 to 2011 that addressed economic issues of the Taungya system. However, the majority of these studies only stated general observations or advantages of the system that were mentioned by farmers, while very few studies actually quantified cost effectiveness. General observations showed that "these systems reduce tree maintenance costs relative to planting trees alone" Vieira et al. (2009) and more importantly, that farmers can both meet their subsistence needs and generate extra income (Witcomb and Dorward 2009, Kalame et al. 2011). Land hunger can be relieved (Vanderhout 1984) and additional employment generated (Somarriba 1981, Witcomb and Dorward 2009).

Somarriba (1981) reviewed Taungya systems throughout the world, and reported positive net cash flows in the majority of projects during the first years. Aguirre (1963) found that 60% of establishment costs of a tree plantation in Costa Rica were offset by planting annual crops. In contrast, Haggar et al. (2003) found that Taungya in Costa Rica has only limited potential to finance reforestation costs for farmers, as intercropping of the native tree species *Terminalia amazonia, Vochysia guatemalensis, Dipteryx panamensis* and *Cordia alliodora* was cost effective in combination with plantain, but not with cassava, heart-of-palm or pineapple.

Higher Internal Rates of Return[7](IRR) in Taungya systems compared to pure plantations were for instance, reported for *T. grandis* (Agyeman et al. 2003, Kalame et al. 2011), *Gmelina arborea* (Ball 1977) and for native tree species in Tanzania (Chamshama et al. 1992) (IRRs ranged between 5 and 18%). In the INRENARE Project in Panama, growing *Eucalyptus camaldulensis* and

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[7] See chapter 3.5.6 for explanation

Pinus caribaea[8] was financially more attractive in terms of IRR when planted in combination with corn, compared to pure woodlots (Gómez 1995). In contrast, planting *Acacia mangium* was slightly more financially viable when planted in pure woodlots (Gómez 1995), but this tree species showed the highest IRR in both systems - 25% . However, none of the tree-maize combinations could compete with pure maize production. Yet, an overall assessment of agroforestry practices in Central America and the Caribbean showed that in the majority of projects, Taungya could compete with pure agricultural production with a medium benefit-cost ratio of 2.5 (ranging from 0.75 - 5.84) (Current et al. 1995b, p. 12). Some studies have also shown that the diversification of products in the Taungya system leads to a lower sensitivity towards price changes and other possible risks (Gómez 1995, Blay et al. 2008, Martin and van Noordwijk 2011).

Overall, the majority of publications revealed positive economic effects of integrating agricultural crops in forest plantations. However, comparative economic assessments of Taungya systems, pure forest plantations and other land uses remain scarce.

2.1.4 Experiences with growth performance in timber-based agrisilvicultural systems

Only a very few studies in the tropics have focused on the systematic comparison of initial tree and crop growth between pure plantations and TBAPs. As the original Taungya system was designed for planting *T. grandis*, which is the most commonly planted hard-wood species in Asia, a great deal of practices studied in past research projects focused on this species (Messerer 2011). The effect of crops on tree growth performance of *T. grandis* has been described as rather negative (Coster and Hardjowasono 1935, Aguirre 1963). In contrast to these findings, the effect of introducing crops or shrubs in plantations of *Terminalia ivorensis* improved tree growth in both Cameroon (Norgrove and Hauser 2002) and Costa Rica (Combe 1981). Tree growth has also been reported to be superior in Taungya systems compared to pure forest plantations for *Grevillea robusta* and *Pinus merkusii* in Kenya (Kiriinya 1994a). In Tanzania, a variety of native trees species showed higher survival rates when intercropped with maize and beans (Chamshama et al. 1992). In Kenya, Imo (2009) showed that tree biomass of *Cupressus lusitanica* and *Pinus patula* was not significantly reduced by the maize intercrop. He additionally investigated tree growth in a pure plantation on a weedy site, which was significantly lower than in plots of the same species in combination with maize, thus showing that competition from crops had significantly less of an effect on tree growth than competition from weeds.

In Central America and the Caribbean, the valuable timber species *Swietenia macrophylla* and *Cedrela odorata* have both shown a satisfying growth rate in Taungya systems (Weaver 1989, Mayhew and Newton 1998). In Costa Rica, Kapp and Beer (1995) and Somarriba et al. (2001c) investigated the intercropping of *Acacia mangium* and *Cordia alliodora* seedlings with a sequence of maize, ginger and the perennial shrub species *Eugenia stipitata*[9]. Both tree species performed significantly better than in pure plantations. Haggar et al. (2003) also found that a range of tree species native to Costa Rica grew better in combination with cassava, plantain, pineapple and heart of palm. In contrast, Schlönvoigt and Beer (2001) found no effect of maize on *C. alliodora*, and found that cassava negatively influenced tree growth. This was also true for *Eucalyptus deglupta*. However, *E. deglupta* showed a positive reaction to intercropping with other crops, such as maize (Schlönvoigt and Beer 2001), beans (Ceccon 2008), rice (Ceccon 2008) and sugar cane (Pinto et al. 2005).

While many tree species seem to positively react to intercropping, most annual agricultural crops show an overall decline in yields (Combe 1981, Agbede et al. 1987, Khybri et al. 1992, Schlönvoigt and Beer 2001, Pinto et al. 2005, Ceccon 2008). A range of studies has shown that

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[8] Rotation length of *E. camaldulensis*: 5 years, *Pinus cariabea* 20 years, tree spacing 1100 trees per ha

[9] Observation length was 5 years

the yield of agricultural crops strongly depends on tree spacing (Vanderhout 1984, Schlönvoigt 1993a, Friday and Fownes 2002, Pinto et al. 2005, Prasad et al. 2010a, Ding and Su 2010). These studies show that crops seem to influence tree seedling growth and vice versa. The investigation of these tree-crop interactions is of major importance in agroforestry research in order to identify effects and control them. The following chapter will provide an overview of possible effects that might influence growth performance of both components in timber-based agrisilvicultural systems as well as methodological approaches to study these effects.

2.2 Review of plant interactions in timber-based agrisilvicultural systems

2.2.1 Identification of possible tree-crop interactions in timber-based agrisilvicultural systems

The interaction between plants in the agroforestry context is defined as the effect of one component of a system on the performance of another component and/or the overall system (Nair 1993, p. 243). Rao et al. (1997) states that the "exploitation of interactions between woody and non-woody components is the key to success of all agroforestry systems". Past research on plant interactions in agroforestry systems has however, mainly focused on the effects of trees on the agricultural component (Nair 1993, Ong 1996, Rao et al. 1997). Accordingly, Kohli et al. (2008) describes under the headline of "Ecological Interactions in Agroforestry" exclusively positive and negative impacts of trees on crops. This seems, however contradictory to the term "interaction", which is generally defined as a two-way effect, as opposed to a one-way causal effect (WIKIPEDIA 2013b, see also Vandermeer 1989). This one-sided investigation of tree-crop interactions might not be adequate for modern timber-based agroforestry systems, as the effects of the components on one another can change over time: While tree seedlings are usually smaller than most intercrops during the first months, they overgrow crops within the first years, and eventually reach a size where any intercropping of light-demanding crops is no longer possible. An additional difference to other agroforestry systems is that the positive long-term effects of trees on crops might be irrelevant during the short and early intercropping phase of a Taungya system. Possible effects of crops on tree seedlings might be of silvicultural interest though, as observed in the studies presented above. Therefore, known interactions in agroforestry systems will be reviewed in the following section, and discussed regarding their potential importance in TBAPs. Table 2.2 shows the major potential tree-crop interactions influencing plant productivity[10] in tropical agroforestry systems according to Rao et al. (1997).

These "interactions" are often partitioned into complementary, supplementary or competitive effects of one component on the other (Filius 1982, Watanabe 1992, Nair 1993, Ong et al. 1996). **Complementarity**[11] exists if the presence and growth of one crop increases productivity of another crop. Such a mutual benefit can be achieved by introducing woody (e.g. *Leucena leucocephala, Gliricidia sepium, Acacia mangium* etc.) or annual (e.g. cowpea, *Phaseolus spp.*, *Cajanus Cajan*) legumes, due to their ability to fix nitrogen, thus increasing soil fertility for the other component. Other soil-related effects mentioned in Table 2.2, can be also expected in Taungya systems over the course of tree growth, but will most likely not affect crop cultivation

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[10] In the context of interaction some authors include ecological and social aspects as e.g. carbon sequestration or alleviation of poverty as "complemantary effects" (s. Ong 1996, Kohli et al. 2008). However tree-crop interactions are interpreted in this thesis from a productive perspective in the sense of intercropping research (see Vandermeer 1989). Other ecological and socioeconomic advantages have been described in chapter 2.1.

[11] Complementary effects are also known as the „facilitative production principle" or simply facilitation in intercropping (Vandermeer 1989, p. 12) or plant community research (Kikvidze and Armas 2010). Facilitation in this sense is defined as a positive "one-way plant interaction" (Kikvidze and Armas 2010). Other effects often mentioned in this context are mutualism and commensalism (Kikvidze and Armas 2010), which will not be considered in detail in this study.

during the first years. However, crops could also provide some of these positive effects, as they could potentially help to overcome degraded soil conditions by providing a temporary soil cover between trees and accumulating organic litter that protects the soil from splash impacts of rainfall, reduces runoff, and maximizes water and nutrient recourse use (e.g. Young 1997, Montagnini 2008).

Table 2.2: Major tree-soil-crop interaction processes in tropical agroforestry systems according to Rao et al. (1997) (modified and extended).

Nature of interaction	Process
Soil fertility: chemical	▪ Increase in active pools of soil organic matter through litterfall, root turnover and incorporation of plant parts ▪ Increased soil N supply through nitrogen fixation, deep soil N capture, reduced leaching ▪ Transformation of less available inorganic P forms into plant-avilable forms ▪ Relocation of Cations (Ca, Mg, K) in soil profile ▪ Organic acids binding aluminum ▪ Localized aluminium detoxification
Soil fertility: physical	▪ Improved soil aggregation, porosity and pore connectivity through incorporation of organic matter and root penetration ▪ Reduced soil bulk density ▪ Break up of compacted soil layer
Soil fertility: biological	▪ Build up of soil macrofauna and microbial populations ▪ Reduced/increased soil insect pests and pathogens
Competition	▪ Sharing of growth resources: light, water and nutrients
Microclimate	▪ Shading: reduced soil and air temperature, reduced evaporation ▪ Protection from wind ▪ Rainfall interception and re-distribution
Conservation	▪ Reduced soil erosion ▪ Reduced leaching
Weeds	▪ Reduced weed populations ▪ Shifts in weed species ▪ Decreased viability of perennial weed rhizomes ▪ Decay of annual weed seed bank ▪ Potential invasive behavior of introduced species
Pests and diseases	▪ Reduced/increased pest populations ▪ Reduced/increased pest-parasite/predator populations
Allelopathy	▪ Release of growth affecting chemicals into soil environment

Another complementary effect might be the modification of the microclimate and the resulting reduction of evapotranspiration: Trees have been shown to positively affect production of perennial crops such as coffee and cacao[12], as tree crowns moderate the intensity of sunlight and wind and maintain a higher level of humidity, hence protecting crops from sudden extreme weather conditions (Beer et al. 1997, Huxley 1999, Somarriba et al. 2001a, Staver et al. 2001). This effect could be reciprocal, and crops could potentially have a “nurse-effect” (Vandermeer 1989) for young tree seedlings, protecting them against extreme solar radiation, which limits reforestation success on open fields (see chapter 1).

From a management point of view, the weeding of crops in Taungya systems benefits both crops and trees, by reducing competition for nutrients and water. Once cut weeds are used as mulch, they can provide nutrients and reduce erosion and evaporation of the soil (Jama et al. 1991, Watanabe 1992).

The basic idea of Taungya is that effects of crops on trees and vice versa are actually **supplementary** (i.e. not influencing the production of the other component) as crop plants use the space, light and soil resources between tree seedlings that would otherwise not be exploited

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[12] Other examples: Cardamom, ginger, black pepper

(Watanabe 1992). However, as farmers generally aim at maximizing the per area use of their land, it is unlikely that mixing trees with crops can be done without creating some level of tree-crop interface, within which productivity of one or the other is affected.

This potential **competition** in Taungya systems is, ecologically speaking, temporarily asymmetric. Asymmetric or one-sided competition occurs for example, if larger individuals have a disproportionate effect on smaller individuals, thus leading to a great variation in growth rates (Thomas and Weiner 1989, Stoll et al. 1994). In a Taungya system, competition will only be symmetric during a very short period, when both components have the same height or have similar additional characteristics influencing their use of resources. Competition of trees and crops can occur for water, nutrients and solar energy. However, in most humid tropical, fertilized agro-ecosystems, competition for water, soil nutrients or pests is not likely to be a limiting factor for plant growth. In these cases, the amount of photosynthetically active radiation[13] determines plant growth (Monteith 1978, Rao et al. 1997). Shading by trees is generally reported to have a negative effect on crop productivity[14] (Ong et al. 1996, Rao et al. 1997, Friday and Fownes 2002, Ding and Su 2010). As this effect depends on soil type, climate, crop/tree species and management practices (Huxley 1999), shading has also been reported to have no effect (Jose et al. 2000), or even positive effects on annual crops under a given set of environmental conditions (Lin et al. 1998). The degree to which production of particular crops is reduced by shading strongly depends on their carbon fixation pathways, meaning whether they are C3 or C4 plants. In contrast to crops, tree growth and especially timber quality of trees might be improved by shading. Watanabe (1992) cites an experiment of intercropping *T. grandis* with *Leucacaena leucocephala*. Side shading by this fast growing legume resulted in good growth form in *T. grandis*. In natural tropical forests, competition for light is a key determinant of community dynamics (Hubbell et al. 1999). When growing in competition, tropical tree species have been observed to increase height growth in an attempt to secure access to light, which has also been observed in mixed tree plantations (Coomes and Allen 2007, Potvin and Dutilleul 2009). It is furthermore known that competition with neighbor trees of another species might either increase (“overyielding”) or decrease (“underyielding”) the production of biomass in a particular species in mixture as compared to monoculture, because of differing competitiveness (McGilchrist and Trenbath 1971, Montagnini and Jordan 2005, p. 32, Oelmann et al. 2010).

Competition is often partitioned into that for above- and belowground resources (Nair 1993). In a Taungya system, competition for belowground resources might affect tree growth rather than crop production during the first years following tree establishment, as crops often have a high demand for nutrients and are planted in a high density, competing with shallow young tree roots. This effect might reverse with time, as roots of trees grow and, depending on the soil conditions and root architecture, might be able to use nutrients and water from deeper soil, thus consuming resources before they become available to crops (Schroth 1998, Kohli et al. 2008). Selecting tree species by their root architecture can reduce this effect (Noordwijk and Purnomosidhi 1995, Noordwijk et al. 1996), even though it seems more likely that tree species in Taungya systems are selected with regard for their market value and other criteria related to forest management. In contrast to the negative effects of tree roots on crops it is also argued that nutrients which would otherwise be located out of reach of crop roots are made available to crops through the litter fall of trees (Montagnini and Sancho 1990, Kumar 2008). Overall, several authors have found that shading (aboveground competition) is more important in intercropping systems than belowground competition (Verinumbe and Okali 1985, Nair 1993, Rao et al. 1997).

Another negative influence of one plant species on the other which is not directly related to competition in the ecological sense is allelopathy. This refers to plant-plant biochemical

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[13] This photosynthetic active radiation (PAR) is most frequently used for assessing quality and quantity of light reaching crops in agroforestry systems (Park et al. 2002, Friday and Fownes 2002, Bellow and Nair 2003)

[14] Agroforestry practices deliberately creating shade, as e.g. shaded coffee or cocoa are excluded.

interactions (Watanabe 1992). One plant might release chemicals into the environment through decomposition of its fallen parts or litter, through root exudates or, in the case of aromatic plants, through volatilization, all of which can be detrimental to the other plant[15] (Rao et al. 1997, Batish et al. 2008). Some tropical tree species are known to release such substances that affect seed germination rate, root growth or dry matter production, as for instance, *Eucalytpus spp., Leucaena leucocephala* and *Gliricidia sepium* (Vázquez-Yanes and Orozco-Segovia 1992, Batish et al. 2008, Macías et al. 2010). The most frequently used tree species in Taungya systems – *T. grandis* – has been shown to release toxic substances from its bark and leaves with negative effects on crop growth – (Manimegalai and Prakash 2008, Macías et al. 2010, Lacret et al. 2011). However, in practice, allelopathic effects are generally difficult to distinguish from other effects (Batish 2008). In addition, when mixing two species, one component might host pest or parasites that harm the other species (Schroth et al. 2000).

In order to quantify, evaluate and optimize these tree-crop interactions in agroforestry systems, a wide range of concepts and models have been set up (see review of Kho 2008). Some authors approach the topic from a production-based perspective which originates from the agronomic perspective of intercropping science (Vandermeer 1989). In this context, the overall interaction effect on crop/tree production is the difference between the positive and negative effects (Sanchez 1995, Ong 1996). Other authors approach the topic from a more quantitative and physiological perspective, using resource capture modeling (Ong et al. 1996, Lawson et al. 1995) and the concept of resource balance (Kho 2000). Newer studies often use computer-based modeling approaches to study interactions of possible tree-crop combinations as for example, WaNuLCAS (van Noordwijk and Lusiana 1999). Martin and van Noordwijk (2009) used these approaches to model tradeoffs in timber-based agroforestry systems and showed that "higher tree densities will lead to a loss of crop yield that is approximately proportional to the gain in wood volume". Positive interaction effects were not detected. However, fertilizer used for crops showed the best effect on tree growth, which demonstrates that in practice, management of the different components might have the most crucial role in optimizing the growth of components rather than ecological competition or facilitation effects. Rao et al. (1997) argues that "little or no progress in translating this knowledge [about biophysical interaction between plants] into management options has been made". Rao et al. (1997) therefore states, that more effort has to be put into investigating the "agronomic significance of biophysical interactions". In this study, the silvicultural significance of tree-crop interactions was the focus. Effects of trees on crops were however, also considered in order to carry out an economic evaluation of the overall systems. Hence, the objective was not to identify and separate possible interaction effects but rather to evaluate and optimize the outcome, in terms of tree growth and crop production.

2.2.2 Methodological approaches to measuring tree-crop interactions in systematic research designs

The previous chapter has revealed that possible interaction effects in Taungya systems strongly depend on the selection of tree and crop species and their planting design. The use of standard agricultural and forestry research designs, as for example complete randomized blocks developed for controlled conditions might however, not be appropriate in order to study the various experimental factors of an agroforestry trial and their spatial and temporal variability, (Rao and Coe 1991, Somarriba et al. 2001a). In forestry or agriculture, such randomized block designs are used to test one or two experimental factors (such as spacing and thinning regimes, or fertilizer and varieties). Each treatment variant is then replicated at least twice (Cochran and Cox 1992, Pretzsch 2009). These designs are relatively easy to establish and to manage; however, they

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[15] Some allelopathic effects of trees on weeds are used for weed management in agroforestry systems. This effect is not discussed here but see (Kohli et al. 2008, Batish et al. 2008)

occupy a large area. Agroforestry experiments usually take up even more space, as trees are combined with crops at comparably wide planting distances, while the actually measured area of the tree-crop interface is only a fracture of the whole monitored area (Huxley 1985b, Rao et al. 1991). Hence, an agroforestry experiment using a block design with adequate replications, a range of tree-crop combinations, and different planting densities would occupy a large area. In order to ensure intensive monitoring and management of such a trial, considerable human and financial resources would be necessary (Schlönvoigt 1993b), which are usually very limited in research projects. Hence, a number of scientists have worked on developing systematic research designs for intercropping research that allow for the survey of different plant combinations at varying densities on a limited area (see review of Connolly et al. 2001b). The most commonly used designs that include a systematic change in plant spacing are the Nelder fan design (Nelder 1962) and the parallel row design (Bleasdale 1967), which have been further refined and modified (Lin and Morse 1975, Mead and Stern 1980, Mead and Riley 1981, Huxley 1985a). These designs are based on an approximately rectangular planting grid in which the area per plant and/or rectangularity[16] of the space available to a plant changes in some consistent fashion (Nelder 1962). These systematic designs originated from agricultural intercropping research (e.g. Franco and Harper 1988, Willey and Rao 1981) but have also been applied in both forestry (Freeman 1964, Imada et al. 1997, Steenackers et al. 1993, Vanclay 2006, Stape and Binkley 2010) and agroforestry (Jama and Getahun 1991, Schlönvoigt and Beer 2001, Kohli and Saini 2003) research. The advantages of these designs are that they occupy a comparably small area, while having a proportionally larger effective experimental area. Extreme situations can easily be incorporated to obtain a better appreciation of plant responses to density stress or other factors, and are thus useful for demonstration trials (Huxley 1985a, Schlönvoigt 1993a, Gibson et al. 1999). However, they are more difficult to establish, and gradients need to be established on environmentally uniform plots, which should be adequately replicated as mortality of plants can easily compromise the analysis (Huxley 1985a, Vanclay 2006). Schlönvoigt (1993a) argues that these strict systematic designs usually do not allow an economic analysis of tree-crop combinations.

For this study, a simplified systematic design, which will be described in chapter 3.2.2 was therefore applied to evaluate different tree densities, while still allowing for conventional crop cultivation between trees (see 3.2.2).

2.3 Research objectives and hypotheses

The aim of this study was to develop methods to provide earlier returns out of timber plantations to make reforestation more attractive as a land-use concept for large- and small-scale landholders. The interdisciplinary research approach used is intended to develop timber-based agrisilvicultural systems that combine high-value hardwood species with staple food crops during the establishment phase of the timber plantation. As delineated earlier, previous studies investigating TBAPs have mainly focused on very few, mostly exotic tree species. The objective of this study is therefore to test four different crop rotations in combination with one exotic and five native valuable tree species. The effect of the presence of agriculture on the tree seedling performance and vice versa shall be analyzed. The study design shall furthermore allow for evaluating the effect of different tree densities on crop production. The most profitable tree- crop combination shall be identified also taking into account their ecological and social suitability. Possible advantageous effects of product diversification shall be investigated.

Finally, based on ecological and economic data the suitability of the agroforestry approach as a sustainable land use concept and as a silvicultural option to improve traditional large and small-scale plantation forestry shall be evaluated.

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[16] Rectangularity is defined as the ratio of inter- and intra- row distances (Nelder 1962)

Based on the knowledge previously described in this chapter, the following working hypotheses were developed:

- *H1:* *Intercropping tree seedlings with crops does not negatively influence growth, survival and quality of timber species.*
- *H2:* *The presence of commercially valuable timber species negatively influences crop production.*
- *H3:* *Tree spacing is positively correlated with crop yield and biomass production.*
- *H4 a)* *The initial intercropping of trees with crops generates positive Net Cash-Flows in the first years after tree establishment.*

  H4 b) *When the whole rotation period is considered, the agrisilvicultural concept is more profitable than monocultures of either trees or crops or cattle farming.*

3 Materials and Methods

3.1 Study Site

The study was realized outside the town of Tortí at the border of the Provinces Panama and Darién in the Republic of Panama (8°54'21'' N, 78°20' 01'' W).

Figure 3.1: Location of the study site (red circle) in the Republic of Panama (Online source of map: http://www.geographicguide.com/pictures/maps/panama-map.jpg)

The trial was established on land lent to the project by the Forest Finance Group, which is specialized in forest investments and has been carrying out reforestation with native and exotic tree species in Panama since 1995[17]. For a sound evaluation of the feasibility and potential for adoption of the agrisilvicultural concept a detailed analysis of the natural and socioeconomic site factors is necessary.

3.1.1 Natural site characteristics

The study site is located at an elevation of 119 m above sea level in the natural vegetation zone classified as 'Humid Tropical Forest' (Holdridge 1967, ANAM 2011). The mean annual temperature is 26.4% and the mean annual precipitation is 1910 mm (ETESA 2011a). There is a dry season between January and March with less than 30 mm of monthly rainfall (ETESA 2011a, see Figure 3.2).

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[17] For more information see www.forestfinance.de

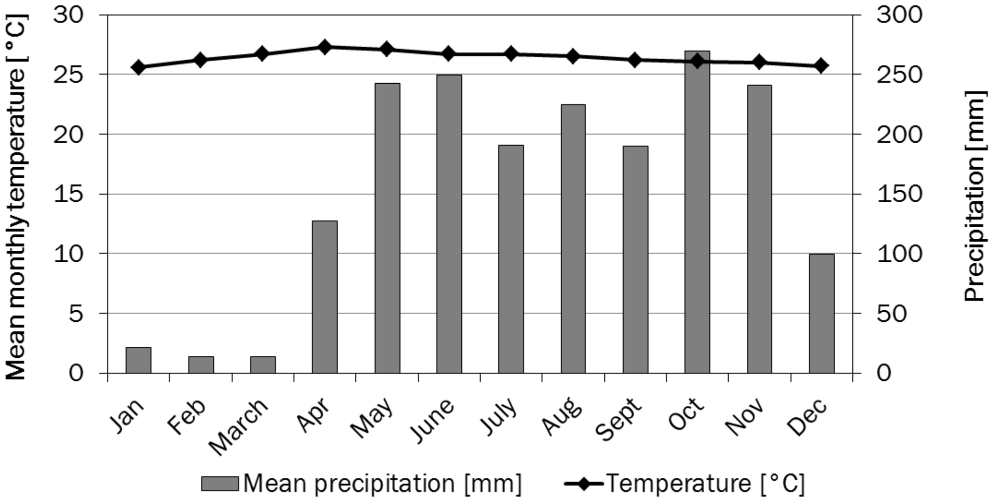

Figure 3.2: Mean monthly temperature and precipitation in Tortí (location of weather station: 8°54'57'' N, 78°12'33'' W, recording since 1977). Data was provided by ETESA (2011a).

The year of trial establishment (2009) was characterized by weather anomalies due to the 'El Niño' phenomenon[18]. This let to very low rainfalls during rainy season in 2009 and a long dry period until end of May 2010 (Figure 3.3). Furthermore it was observed that monthly rainfall occurred within short and unusual intensive intervals between long dry periods (ETESA 2011b). Following the El Niño phenomenon Panama suffered under the impact of 'La Niña' – another weather phenomenon which led to extremely high precipitation from November 2010 to January 2011, resulting in severe inundations along the Caribbean coast, in the Province of Darien and Chiriquí (La Prensa 2010, ETESA 2011b).

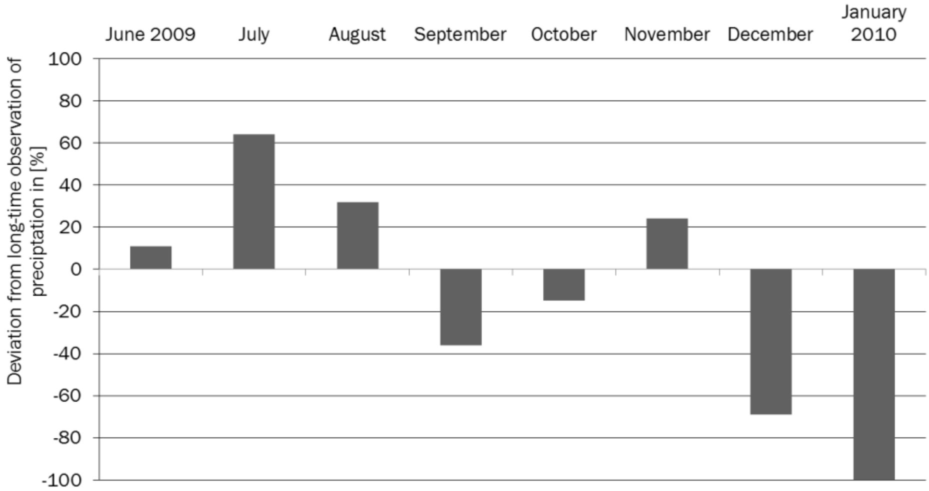

Figure 3.3: Deviation in [%] from long-term mean of monthly rainfall during the El Niño phenomenon in 2009 according to ETESA (2011b)

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[18] "El Niño/La Niña–Southern Oscillation, is a band of anomalously warm ocean water temperatures that occasionally develops off the western coast of South America and can cause climatic changes across the Pacific Ocean. The 'Southern Oscillation' refers to variations in the temperature of the surface of the tropical eastern Pacific Ocean (warming and cooling known as *El Niño* and *La Niña*, respectively) and in air surface pressure in the tropical western Pacific. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific" (WIKIPEDIA 2013a).

The soils of the study site developed from sedimentary rock, including Tertiary lime stone, arenite and lutite (ANAM 2011) and were classified as Vertisols[19], due to their high clay content of more than 30 % (see Table 3.1) and the typical feature of "Gilgai". This is the name for the formation of mounds and depressions due to the shrinking and swelling of the soils (Mermut et al. 1996). In order to have detailed information on soil conditions, extensive sampling of soil was carried out which will be described in chapter 3.4.4 and 4.1.

Table 3.1: Soil texture of two soil samples (see Figure 3.4) taken previous to trial establishment. For location of soil profiles see Figure 3.5. Data was provided by BARCA S.A.[20]

Soil horizon	Soil texture [%]			Soil texture class
	Sand	Silt	Clay	
Soil profile 1 (close to plot 20)				
Ap	16	27	58	Clay
AB	7	23	70	Clay
Bw1	7	15	78	Clay
Bw2	2	20	78	Clay
Soil profile 2 (plot 10)				
A	17	20	63	Clay
Bw1	5	18	78	Clay
Bw2	1	16	83	Clay

Figure 3.4: Pictures of soil profile 1 (left) and 2 (right) (cf Table 3.1). Pictures were provided by H. Thiele.

The inclinitation of the study site is less than 5%. Previous to the experiment, the site was used for several years as cattle pasture.

3.1.2 Socioeconomic site characteristics and land use

Socioeconomic situation in the Republic of Panama

Despite its small population of 3.4 Mio people in May 2010 (INEC 2010) the Republic of Panama is considered as a rising economy. In recent years Panama's economy has experienced a boom, with growth in real gross domestic product (GDP) averaging 8% from 2005-2011 (Index Mundi

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[19] According to both, US Soil Taxonomy and WRB-Classification

[20] Soil sampling and classification was carried out by H. Thiele.

2013b). Since the handover of the Panama Canal by the USA to Panama in 1999[21] Panama has made a rapid development in the service sector including trading, banking, commerce, tourism among others along with a rising number of large construction projects. 63.4% of the population are between 15 and 64 years old, which indicates a high percentage of economically active population (INEC 2010). The unemployment rate decreased between 2000 and 2011 from 13.0% to 4.5% (Index Mundi 2013b).

The given numbers reveal the economic potential of the Central American country. But, despite Panama´s status as an upper-middle income nation – as measured by per capita GDP of US$ 14,300 in 2011 (Index Mundi 2013a) – it remains a country of stark contrasts. The income of the 20% of Panamas population with the highest income accounts for 60% of the national gross income. Hence, Panama has the second worst income distribution in Latin America (CIA 2013). This disparity is especially evident between the urban and rural areas. 73% of the Panamanian population lives in urban areas (INEC 2010). While only 3.2% of these suffer from extreme poverty[22], 22.2% of rural and 84.8 % of indigenous population, mainly living in the eastern part of the country and along the Caribbean Coast, is not able to satisfy basic needs (ANAM 2011). The disparity between the capital Panama City, where 50.3% of the Panamanian population lives (INEC 2010) and rural areas is particularly evident in the education. While 2% of the population in the city is illiterate, 15.9% of the people living in the district of Darién do not know how to read and write. Among indigenous people[23] 27.3% are illiterates. Overall, 8% of the Panamanian population has no access to drinking water and electricity (INEC 2010).

Agricultural Sector

Of the 27% of the population living in rural areas 72% work in the agricultural sector (FAO 2010b), which had a share of 3.8 % on the GDP in 2012 (CIA 2013). While the importance of agriculture for Panama's economy has decreased due to the rising banking and construction sector, in rural areas many families still depend on agricultural production to meet their subsistence needs. This situation is especially evident in the Eastern Part of Panama, where the present study has been carried out. Only 39.7% of people older than 15 years were employed, while the rest work on their own bill - mostly carrying out subsistence farming (INEC 2010).

Land tenure

The distribution of land is typical for Latin American countries: 80% of the farmers own only 10% of the agricultural land (INEC 2010). However, compared to other Latin American countries most of this land is titled: 97% of farms hold a land title (INEC 2010), which demonstrates that Panama is a suitable study site to investigate innovative agroforestry systems that imply a politically secured long-term use of land. However, legal land titles in Panama are mostly based on possessor rights: The article 30 of the Panamanian Agrarian Code says that the use of the land needs to meet the social function, which means that two-thirds of the land must be under cultivation or planted in hardwood trees, and if under pasture, the stocking has to be higher than 2 animals per ha. These requirements must be met within a two year time period or it is subject to state appropriation (Simmons et al. 2002). This means, that a continuous land use is required to receive a land title based on possessor rights. Hence, this law might have fostered deforestation during the last decades in the study region, where the systematic cultivation of land has only started during the last decades.

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[21] Before this date, the United States had a monopoly over the Panama Canal for 85 years.

[22] In this context defined as a person consuming less than US$ 639 per year, which corresponds to the expenses necessary to meet the minimum caloric requirements and an additional tranche necessary to cover basic needs such as housing, transport, education, health and clothing (ANAM 2011)

[23] This data is restricted to the Comarca Kuna Yala, Comarca Emberá and Comarca Ngöbe Buglé

Past and present land use at the study site

While the main driver of deforestation in western Panama was the introduction of cattle by the Spanish settlers since the 1520s (Castillero Calvo 2010, p. 94), the eastern part of the country stayed rather untouched due to the resistance of the Kuna people against the Spanish conquerors (Castillero Calvo 2010, p. 116). Until the early 20th century population in the Province of Darién was below 9,000, which rose however up to 48,378 in 2010 (Castillero Calvo 2010, p. 94, INEC 2010). This increase in population is due to an ongoing migration of farmers from degraded unproductive land in the west to the east. Interviews among farmers in Tortí, carried out in the course of this research project by Schuchmann (2011)[24] showed that 76% of respondents migrated to Tortí from western regions, with the majority coming from the densely populated Province Los Santos. Decreasing yields and the lack of new agricultural land forces farmers to seek new land in the eastern parts of the country. As the interviews show, the settlement of the study region has only started during the last 30-40 years and hence, Tortí has only been registered as a township in 2000 (Moreno 2001).

Arriving settlers brought their traditional land use practices, which mainly consist of cattle farming and cultivation of annual crops like rice, maize, beans and cassava (Heckadon and Espinosa 1985), which are, along with plantains, still the most frequently planted crops around Tortí (Schuchmann 2011). Other cultivated crops include yams, sugarcane, pigeon pea, coffee, tomato, watermelon and capsicum (Schuchmann 2011). 58% of respondents exclusively produced for household consumption, the rest sold parts of their production but none of the households exceptionally produced for selling. The mean monthly income of farmers in Tortí was $ 385, while 25% of respondents said that they had no income and 64% had a household income of less than $ 300 per month. 60% of farmers interviewed answered that agriculture was their only income (Schuchmann 2011). This shows that the majority of farmers are subsistence farmers who depend on agriculture for their livelihood. This dependency is reinforced by globally rising food costs which severely affect Panama, as the country highly depends on food imports (FAOSTAT 2009)[25].

The average farm size in Tortí, based on the interviews was comparably high with 85 ha ranging from 2.5 to 496 ha, with 72% of farmers having farms smaller than 90 ha. The average land size in the Darién region is 44 ha and 18 ha in the Province of Los Santos (INEC 2010), where most migrants came from. This reflects the motivation of farmers from the densely populated western provinces to cultivate area in the East and receive land titles through new possessor rights. In this tradition of cultivating former forest, slash and burn practices are still dominating agricultural traditions (Fischer and Vasseur 2000, Schuchmann 2011), as commonly observed in tropical forest frontiers (Palm 2005). Farmers around Tortí also repeatedly burn their fields between the cultivation of annual crops or pasture. The main reasons for this practice are the easier and faster results in soil preparation, the short-term availability of nutrients through higher pH of soil and the control of soil pests (Cochran and Bonnell 2005, Palm 2005). However, this practice exhibits a number of risks as the spreading of fire, the destruction of soil fauna and soil organic matter, along with nutrient leaching and erosion. Agroforestry and forest plantations might, however offer opportunities to overcome these practices towards a more sustainable land use (Fischer and Vasseur 2000).

Today, the main land use of Tortí is cattle farming. The region can be considered as a transition zone between the cultivated landscape of the western parts of Panama and the District of Darien, where conversion of forest to agriculture is still ongoing (Table 3.2).

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[24] Based on interviews with 25 households, actively carrying out agriculture in the township of Tortí

[25] (Exports-Imports)/Consumption (calories) in Panama is below -25 (FAO 2013c)

Table 3.2: Proportion of Agricultural area [%] dedicated to different land uses in the township of Tortí, the district of Darién and the whole Republic of Panama according to INEC (2011)

Land use	Township Tortí	District of Darien	Country Average
Annual crops	5.0	3.4	9.4
Permanent crops	3.2	2.6	7.0
Pasture (total)	64.2	44.2	57.0
Traditional pasture[1]	35.4	21.7	26.4
Improved pasture[2]	17.1	17.8	21.1
Natural pasture[3]	11.6	4.7	9.5
Forest and regenerating forest[4]	16.7	32.9	13.6
Abandoned or fallow	8.1	14.8	10.6
Other uses	2.8	2.1	2.4

[1] Sowing of traditionally used exotic pasture grasses (e.g *Hyparrhenia rufa, Panmicum maximum*)

[2] Sowing of improved, newly introduced exotic pasture grasses (especially *Brachiaria spp.*)

[3] without sowing of pasture grasses or use of cut grasses and protein banks (other forage plants)

[4] Forest does in this context only refer to forested area on agricultural lands, while natural forest area is not included.

The land use with the highest consumption of land is cattle farming. Love and Spaner (2005) state that pastures replaced 70% of Panama's native forests. The main reasons for the ongoing expansion of cattle farming are the favorable markets for meat, state credit programs for cattle ranching, the rising demand for meat and milk and the low labor requirements along with limited risks of livestock ranching (Heckadon and Espinosa 1985, Love and Spaner 2005, Siegmund-Schultze et al. 2010). For these reasons cattle population annually increased by 0.2 Mio heads between 1993 and 2010 (INEC 2011) resulting in increasing land degradation because of continuous burning of pastures, overgrazing and damages through trampling (Kaimowitz 1996, Heckadon and Espinosa 1985). ANAM (2011) states that 27% of Panama's national territory have been degraded and thus become unproductive through unsustainable land use, especially cattle farming. Today, Panama counts a remaining forest area of 3.25 Mio ha while deforestation continues, especially in the eastern part of Panama, at a rate of 0.36% (FAO 2010b).

Forestry sector and agroforestry uses in the study site

While the forest area is decreasing, the yearly consumption of timber increases and currently accounts for 120,000 m³ without considering wood used for handicraft and fire wood (ANAM 2010). Taking into account that 13% of Panamanian households use fire wood as their primary energy source (INEC 2010) the actual demand is likely to be considerably higher. This situation, together with increasing environmental problems and the lack of employment opportunities in rural areas led to a shift in policy from the primary support of cattle farmers to incentives for reforestation. On the 23rd of November 1992 the federal law 24 and shortly after, the executive decree 89 (from the 8. 6. 1993) were passed, which promote reforestation and support all linked industries by tax exemptions in investments, imports, property or income related to tree plantings and their processing. Furthermore, loans at preferential rates are offered to reforestation-related investments. Foreigners are offered a permanent residential visa when investing more than B/. 40,000[26] in reforestation or related activities. These incentives led to a considerable increase in reforestation activities, especially by foreign companies and investors. Today, Panama counts a reforested area of 73,257 ha (ANAM 2010), which corresponds to an annual rate of 3900 ha per year between 2000 and 2009. More than half of this area is planted with *T. grandis* (see Table 3.3) and less than 10% using native tree species as e.g. *Bombacopsis quinatum* (ANAM 2010).

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[26] The currency in Panama is the Balboa (B./), which is fixed at parity with the United States Dollar (US$) since independence in 1903. Therefore only US$ will be used in all following calculations of this thesis.

Table 3.3: Tree species used for reforestation in the Republic of Panama and their share of replanted area according to ANAM (2010)

Tree species	% of reforested area
Tectona grandis	65.7
Pinus caribaea	15.3
Bombacopsis quinatum	2.6
Khaya senegalensis	1.8
Acacia mangium	1.9
Others[1]	12.7

[1] e.g. *Swietenia macrophylla, Cordia alliodora, Eucaliptus spp.*

The use of these mostly exotic tree species has also been promoted by a range of rural development and research projects since the 1990s (Current 1995, Simmons et al. 2002), while the systematic testing of native species for the use in reforestation has only started in the last decade (e.g. Hooper et al. 2002, Jones et al. 2004, Wishnie et al. 2007, Griscom et al. 2005, van Breugel et al. 2011). While large-scale reforestation is still mainly carried out using exotic tree species (ITTO 2011), studies have shown that small-scale farmers in Panama traditionally plant, protect and use rather native multipurpose tree species (Aguilar and Condit 2001, Love and Spaner 2005, Garen et al. 2011). Garen et al. (2009) and Schuchmann (2011) have shown that in Panama, the main reason for farmers to plant trees is to harvest fruits for human consumption. However, 40% of farmers in Tortí answered that they also planted or protected trees for selling wood (Schuchmann 2011), illustrating the general interest in forest plantations.

Accordingly, agroforestry has also already been applied: The most frequently used practices are trees on pastures or in living fences, which were mentioned by 52% and 48% of interviewed farms, respectively. 16% of farmers already dedicated part of their farm to reforestation with hardwoods and the same proportion of respondents even mixed trees with agricultural crops, while 12% used trees as shade for perennial crops. Chapter 2 has shown that information on timber-based agrosilvicultural systems in Panama is scarce, while farmers obviously do have an interest in planting trees (Garen et al. 2009) or already actively combine them with crops (Garen et al. 2011). However, systematic studies on possible tree-crop combinations and recommendations for improved management practices are missing.

3.2 Experimental design

The experiment to be described was designed to allow the testing of four crops in combination with six different valuable exotic and native tree species. The tree crop combinations are compared with monocultures of trees and crops respectively using ecological and socioeconomic criteria. In the following chapter, the species used in this study and the reasons for their selection will be described. Subsequently the design of the agroforestry trial and control treatments will be presented.

3.2.1 Species Selection

3.2.1.1 Tree species

For the overstory, tree species were selected which are typically used for reforestation by the Forest Finance Group (Table 3.4). Thus, seedlings of the same provenience and quality were available to the research project in the necessary amount. These tree species have been proven to be suitable species for reforestation projects in Panama with high market potentials (see Table 3.5). An extensive literature research on the selected tree species and their use in agroforestry systems has been carried out by Waltenberger (2010).

Table 3.4: Selected trees species

Botanical name	Spanish name	Commercial name	Abbreviation
Astronium graveolens Jacq.	Zorro, Ronrón	Tigerwood, Glassywood	Ag
Cedrela odorata L.	Cedro amargo	Spanish Cedar	Co
Dalbergia retusa Hemsl.	Cocobolo	Rose Wood	Dr
Hieronyma alchorneoides Allemao	Zapatero	Zapatero	Ha
Tectona grandis L.f.	Teca	Teak	Tg
Terminalia amazonia (J.F.Gmel.) Exell	Amarillo	Yellow Wood	Ta

Table 3.5 reveals that the few experiences in agroforestry systems rather focus on silvopastoral systems or on the use of these tree species for shade in perennial crop plantations. Among the selected tree species Schuchmann (2011) found that around Tortí *C. odorata* was most frequently planted, with 30% of respondents having it on their farms. *T. grandis* and *T. amazonia* are also already actively planted by farmers in the region.

Table 3.5: Description of selected tree species. General descriptions were taken from Vozzo (2002), Cordero and Boshier (2003), Carrasquilla R. (2006), Chizmar et al. (2009) and Condit et al. (2011). Additional sources are shown in the table.

	Astronium graveolens	*Cedrela odorata*	*Dalbergia retusa*
Botanical family	Anacardiaceae	Meliaceae	Fabaceae (Papilionoideae)
Distribution	Mexico to Paraguay	Mexico to Brazil and West Indies	Mexico to Panama
Habitat (Panama)	Mature and secondary forest on the pacific slope, common on farmland	Primary to late secondary forests, common on farmland and living fences	Common in remaining open dry forest, hardly regenerates in closed forests
Successional status	Pioneer (Griscom and Ashton 2011), subcanopy or canopy species but saplings grow best under full light (Marin and Flores 2002a)	Light demanding long-lived pioneer (Delagrange et al. 2008)	Long-lived, light demanding pioneer (Griscom and Ashton 2011, Cordero and Boshier 2003)
Description	Up to 35 m high, bark dark grey, peels off, leaves compound without stipules, alternate, imparipinnate, leaflets 9-15, strongly aromatic, elliptic to oblong-lanceolate, assymetric, margin serrate, inflorescences terminal, flowers light-green	Up to 40 m high, bark grayish brown and fissured; leaves compound, with stipules, paripinate, alternate, leaflets 10-22, lanceolate to ovate, margin entire, Inflorescences terminal, flowers white to creamy-white	Medium sized to small tree up to 20 m high, bark grayish brown, fissured, leaves compound, alternate, imparipinnate, leaflets 7-5, oblong to ovate-oblong, leaf surface appears leathery and shiny, flowers white
Crown structure[1]	Conical to columnar, spreading to round dense crown	Compact, conical	Sympodial growth developing a flat-topped spreading crown
Fruit	Nut	Capsule	Flat, winged legume pods with one to three seeds
Seed dispersal agent	Wind/birds (Griscom and Ashton 2011)	Wind (Griscom and Ashton 2011)	Wind/Water
Site requirements	Wide range of soils, is also found on rocky and poorly drained limestone soils, but grows best on sandy soils with good drainage	Require deep fertile soils (especially rich in phosphorus, potassium and calcium), does not tolerate high levels of aluminum, iron and zinc or ponding water	Found on a wide range of soils
Elevation [m]	0- 1500	0 - 1200	50 - 700
Precipitation [mm]/maximal length of dry season	750- 3500 / 3-6 months	1200 – 3000 / 0-6 months	< 2000 / ≥ 3 months
Mean annual temperature [°C]	18 – 22	20-32	25 - 35
Drainage	Good to inhibited	Good	Good
Soil ph	neutral	Acid to neutral	varying
Slope	flat to moderate		Below 15%
Phenology	Partly deciduous mainly during dry season, flowering between December and March, fruits ripen between February to June	Partly deciduous during dry season, flowering occurs from the end of the dry season to the beginning of the rainy season, fruits ripen from the end of the rainy season to the beginning of the dry season	Partly deciduous during the dry season, between march and may the flowers are produced, ripe fruits develop between September and November
Wood description	Decorative through vivid stripes, high natural polish, moderate shrinkage	Fine, light but strong wood, easy to work and low shrinkage, wood is naturally resistant against termits and rot	Heartwood is dark brown to almost black and shiny, wood is hard, heavy and strong, low shrinkage, resistance against marine borer and other wood pests
Specific gravity[2]	0.75-0.78	0.42-0.63	0.80 – 0.98
Protection status	Heavily exploited in natural forests	considered to be endangered in Mesoamerica (Grogan et al. 2011)	Listed as vulnerable by the IUCN
Other considerations	Contains acid resin which can lead to persistent dermatitis, therefore protection is recommended when working the wood	High susceptibility to the moth *Hypsipyla grandella* often prevents use in forest plantations[3]	Bole grows irregular and crooked and ramifies already at small heights, leguminous tree species
Experiences in Agroforestry Systems	-	Used as shade tree in agroforestry systems alongside coffee (Beer et al. 1997, Viera and Pineda 2004) or cacao (Yamada and Gholz 2002, Villarreal et al. 2006), in pastures (Cordero and Boshier 2003), and in living fences (Love and Spaner 2005a, León and Harvey 2006)	Used in silvopastoral systems (Andrade et al. 2008) and tested in combination with annual crops (Espino 1975)
Experiences in Reforestation (examples from Panama + Costa Rica)	Piotto et al. (2004), Wishnie et al. (2007), Park et al. (2010),	Piotto et al.(2004), Wishnie et al. (2007), Potvin and Gotelli (2008), Plath et al. (2011a), Plath et al. (2011b), van Breugel et al. (2011)	Tilki and Fisher (1998), Piotto et al. (2004), van Breugel et al. (2011), in enrichment plantings (Paquette 2009)

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[1] based on general canopy shapes described by Wilkinson and Elevitch (2000)

[2] all taken from Vozzo (2002)

Table 3.5 (continued)

	Hieronyma alchorneoides	*Terminalia amazonia*	*Tectona grandis*
Botanical family	Euphorbiaceae	Combretaceae	Verbenaceae
Distribution	Mexico to Brazil	Mexico to Peru	Southeast Asia
Habitat (Panama)	Late secondary forests	Widespread in secondary forests, does not invade roadsides or fields but establishes when forest is young, often found along rivers	Planted in forest plantations, now also found along streets
Successional status	Light-demanding non-pioneer to late-successional, (Butterfield and Mariano 1995), lower crown is shade tolerant, germinates and grows in clearings and well-illuminated places, seedlings and saplings are not common in the forest understory (Flores 2002a)	Pioneer, emergent tree in the canopy of the humid tropical forests (Flores 2002b)	Pioneer, shade tolerant during youth, (Griscom and Ashton 2011, ICRAF 2013)
Description	Up to 50 m high, bark brownish-red, fissured, corky, leaves simple, alternate, lepidote, elliptic, inflorescences axillary, flowers pale green to creamy-green	Up to 50 m high, bark grayish brown, heavily fissured, leaves simple, alternate, obovoid, margin entire, infloresceses axillary, flowers small white on long spikes	Up to 40 m high, large leaves are ovate-elliptic to ovate and 15-45 cm long and 8-23 cm wide with an entire margin, leaf surface is rough, small white flowers arranged in large flowering heads, about 45 cm long, located on the uppermost branches of the crown
Crown	Rounded to conical crown, wide and extended, large leaves, branches subterete and angulous	Branches and trees from flattened dense layers up the crown, pagoda-like, called terminalian, axis monopodial, branches sympodial and olagiotropic	First monopodial later sympodial growth, first narrow columnar crown later developing a rounded crown
Fruit	Drupe, one seed	Tiny drupe with two little wings	Dry green capsules
Seed dispersal agent	Birds/monkeys and other animals	Wind	Wind/gravity
Site requirements	Grows on wet alluvial soils with loamy and clayey texture	Grows well in red or dark soils that are lateritic, deep and derived from alluvial or igneous materials, reaches best growth in clay soils, also grows on nutrient-poor and degraded soils	deep, well-drained, fertile alluvial-colluvial soil, high calcium and phosphorous content, does not tolerate waterlogging and infertile lateritic soils, susceptible to damage by wind, is not adequate for over-pastured soils
Elevation [m]	0 - 900	0-1200	0 - 1200
Precipitation [mm]/maximal length of dry season	2000 – 5000 0-2 months	1800 – 5000 / 0-3 months	1200 – 2500 / 3-7 months
Mean annual temperature [°C]	24-30	18 – 22	14 - 36
Drainage	Good to inhibited	Good	Good
Soil ph	acid	Acid to neutral	6.5-8
Slope	Plain to strongly inclinated	Flat to medium	Flat to medium
Phenology	Evergreen, flowering and fruit bearing occurs from March to June and through the rainy season	Evergreen, flowering during dry season, fruits are produced from March to beginning of June	Deciduous in Panama during the dry season, flowering between June and September
Wood description	Heartwood is dark red to brown, wood is robust and heavy but shrinkage is high, resistant to termites and fungal diseases	In dry conditions wood turns yellowish, wood has high quality and good physical and mechanical properties but susceptible to fungal and termite attacks	Medium weight timber, very durable, resistant against termites and toredo activity and chemicals
Specific gravity[2]	0.59 – 0.86	0.51 – 0.7	0.55
Protection status	-	-	-
Other considerations	-	-	Tends to develop forked trunks
Experiences in Agroforestry Systems	Tested in silvopastoral Systems (Tornquist et al. 1999, Montagnini et al. 2003), tested for use as shade tree for perennial crops (Bellow and Nair 2003)	Tested in silvopastoral systems: (Nichols et al. 2001, Montagnini et al. 2003), tested with perennial crops (Dzib 2003)	See chapter 2.1.3 and 2.1.4
Experiences in Reforestation (examples from Panama + Costa Rica)	Piotto et al. (2003b), Jiménez et al. (2007), Wishnie et al. (2007), Piotto et al. (2010),	Haggar et al. (1998), Piotto et al. (2003b), Carpenter et al. (2004), Montero M. and Kanninen (2005), Redondo-Brenes and Montagnini (2006), Piotto et al. (2010), van Breugel et al. (2011)	e.g., Bermejo et al. (2004); Keogh (1982), Piotto et al. (2004), Kanninen et al. (2004), Pérez and Kanninen (2005), van Breugel et al. (2011)

[3] more information is given in chapter 3.3.1

3.2.1.2 Crop species

The selection of crop species was restricted to such that can be harvested within one year. Furthermore, in an attempt to meet the problem of rural food scarcity and the resulting high food prices staple food crops that are commonly grown by farmers of the region were selected (Schuchmann 2011). Exclusion criteria for species selection were invasive (e.g. *Dioscorea spp.*) and wining species. All of the crops are found throughout the tropics and don't require intensive processing for selling.

Table 3.6: Selected crop species. General descriptions are taken from Norman et al. (1995), Lieberei and Reisdorff (2012) and FAO (2013a).

Common name	**Maize**	**Bean**	**Cassava**	**Rice**	**Pigeon pea**	**Ginger**	**Soy beans**
Latin Name	*Zea mays* L.	*Phaseolus vulgaris* L.	*Manihot esculenta* CRANTZ	*Oryza sativa* L.	*Cajanus cajan* (L.) HUTH	*Zingiber officinale* ROSCOE	*Glycine max* (L.) MERR.
Origin	Central and South America	Central America	Brazil	Southeast Asia	Probably Africa	Southeast Asia	East Asia
Life form	Grass	Herb	Shrub	Grass	Shrub	Herb	Herb
Life span	Annual	Annual	Perennial	Annual	Perennial	Annual/perennial	Annual
Time until first harvest	2-3 months	~3 months	10-12 months	~3 months	> 6 months	~10-12 months	~3-4 months
Max. Height [m]	2.4 m	1 m	3 m	1.5 m	4 m	1.5 m	1 m
Used parts	seeds	Pods/seeds	Roots/tubers	seeds	Pods/seeds, firewood, leaves as forage	Roots/rhizome	Pods/seeds
Altitude [m a.s.l.]	0-4000	0-3000	0-2000	0-2500	0-3000	0-1900	0-3000
Optimal temperature range [°C]	18-33	16-25	20-29	20-30	18-38	19-29	20-33
Optimal range of annual rainfall [mm]	600-1200	500-2000	1000-1500	1500-2000	600-1500	1400-3000	600-1500
Soil pH (optimal)	5-7	5.5-7.5	5.5-8	5.5-7	5-7	6-7	5.5-6.5
Soil requirements	fertile and well drained soils, best on loam	Does not tolerate excessive water	Light, well-drained soils	Wet, fertile soils	No waterlogging, grows on a wide range of soils, legume	No waterlogging, grows on a wide range of soils	prefers good drainage and medium deep soils
Photosynthesis	C4	C3	C3	C3	C3	C3	C3
Light requirement	Full sun	Full sun	Full sun, but tolerates light shade	Full sun	Full sun, shade tolerant during youth	Shade tolerant	Full sun, short day plant

Maize and beans have already been used in timber based agrisilvicultural practices and are also frequently used in alley cropping systems throughout the world (Verinumbe and Okali 1985, Kapp and Beer 1995, Heineman et al. 1997, Miller and Pallardy 2001, Schlönvoigt and Beer 2001, Henriksen et al. 2002, Friday and Fownes 2002, Ceccon 2005, Kang et al. 2008, Martin and van Noordwijk 2009). As a major food crop cassava has been introduced into a range of agrisilvicultural systems with differing success (Lose et al. 2003, Schlönvoigt and Beer 2001, Haggar et al. 2003). Dry rice was selected for this study as waterlogged soils favored this crop species. It has also been proposed for intercropping trees (Khybri et al. 1992, Jordan 1992, Ceccon 2005). Pigeon pea is a leguminous shrub species that is less known on global markets but is receiving growing agronomic and scientific attention. In Panama, it is used for a traditional Christmas dish, and the leaves are used as fodder for cattle due to their high nutritional value and are also frequently processed to make medicinal ointments. These multiple purposes, along with its ability to fix nitrogen make pigeon pea a desirable plant for agroforestry systems (Nene et al. 1990, Vieira et al. 2009). Ginger has been used in agroforestry due to its shade tolerance and relatively easy management (Kapp and Beer 1995). Expert interviews carried out in Panama also supported its potential in agroforestry systems, during early but also later stages of tree development (Ewers 2013). Soy beans were included in this trial to demonstrate the potential of the agrisilvicultural system for production of renewable energy resources. The selected crops were combined in four different crop rotations:

Table 3.7: Selected crop rotations

Crop rotation	Abbreviation
Ginger – Pigeon pea	G-P
Maize – Beans – Maize – Maize	M-B-M-M
Beans – Rice – Rice	B-R-R
Cassava – Soy beans	C-S

More information on the exact planting sequence of the crop rotations will be given in the following chapter.

3.2.2 Agroforestry trial

In order to allow for inclusion of the experimental factors tree species, tree spacing and crop rotation on a limited area the following experimental design has been developed (Figure 3.5). This design was derived and modified from the mixed fan and parallel row design (Nelder 1962, Bleasdale 1967, Huxley 1985a) described in chapter 2.2.2.

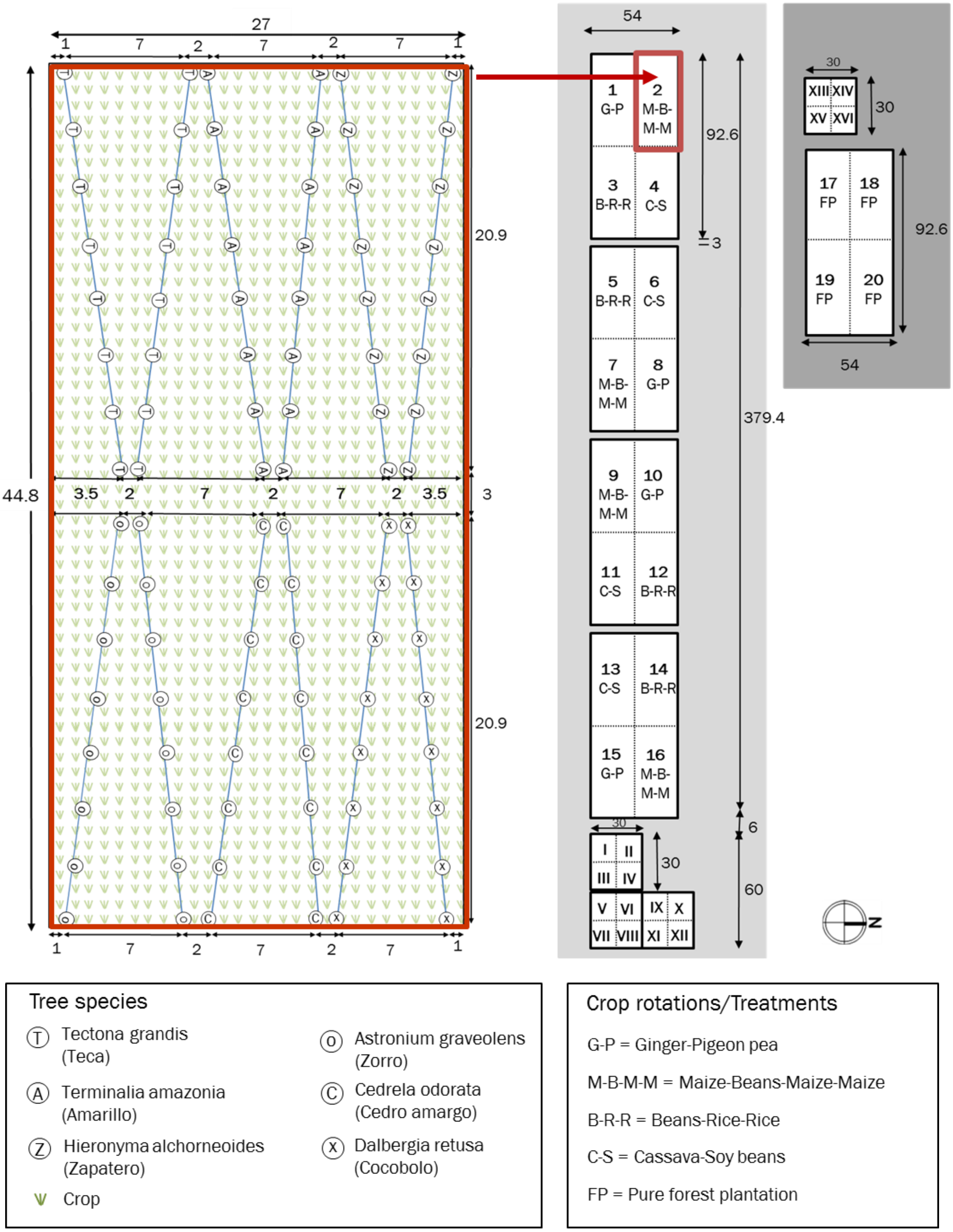

Figure 3.5: Experimental layout of one plot (left side) and layout of plots (right side). Dark grey shaded plots were situated 230 m east of the light grey shaded plots. Each plot is labeled by plot number, followed by the treatment assigned (see right box for abbreviations). To improve readability, plots with pure crop plantations (CP see Table 3.9) are numbered with Roman numerals, which include the identification of the assigned crop rotation (I = M-B-M-M, II = G-P, III = C-S, IV = B-R-R, V = C-S, VI = B-R-R, VII = GP, VIII = M-B-M-M, IX = B-R-R, X = C-S, XI = M-B-M-M, XII = G-P, XIII = G-P, XIV = M-B-M-M, XV = B-R-R, XVI = C-S).

According to this design, each of the four crop rotations (see Table 3.7) was tested under six different tree species within one experimental plot. Each of the six tree species was represented by 16 trees, each. Hence, one plot contained 96 trees and covered an area of 1,209.6 m^2. As shown in the experimental layout, planting distance between rows varied from 2 to 7 m. This was done to create different regimes of above- and belowground competition. The planting distance within one tree line (marked in blue) was held constant at 3 m. The triangle resulting from two lines of one tree species (e.g. *T. grandis*) or two adjacent species (e.g. *T. grandis* and *T. amazonia*) and the eight different planting distances[27] will be referred to here as a "light gradient". Hence, the design allowed for the monitoring of crop productivity between the same and two different tree species within ten light gradients (Table 3.8).

Table 3.8: Denomination of light gradients

Abbreviation of light gradient	Combination of tree species
TgTg	*T. grandis x Tectona grandis*
TgTa	*T. grandis x T. amazonia*
TaTa	*T. amazonia x T. amazonia*
TaHa	*T. amazonia x H. alchorneoides*
HaHa	*H. alchorneoides x H. alchorneoides*
AgAg	*A. graveolens x A. graveolens*
AgCo	*A. graveolens x C. odorata*
CoCo	*C. odorata x C. odorata*
CoDr	*C. odorata x D. retusa*
DrDr	*D. retusa x D. retusa*

Crops were planted between the trees in a regular grid based on the commonly used planting distance for each individual crop. In contrast to more complex spacing designs, such as the Nelder Fan Design (Nelder 1962), the distance between crops did not vary. The simplified design enabled ease of harvesting and sowing of crops and facilitated the economic evaluation of different treatments (cf. Schlönvoigt 1993a). Compared to conventional designs, this geometric design allowed for the observation of six different tree species (and ten tree species combinations) (Table 3.8) under eight different planting distances on a relatively small area. Furthermore, rather uncommon tree planting distances of 2 and 7 m could be incorporated to obtain a better appreciation of crop responses to competition with trees (Huxley 1985a).

Each tree-crop combination had four replications, and thus 16 adjacent experimental plots of 1,209.6 m^2 were established. One of the four crop rotations was randomly assigned to each of these plots (Figure 3.5). The whole agroforestry trial was established on a total area of 2.0 ha, surrounded by the reforestation project, "Playa Chuzo", implemented by Forest Finance (see Figure 3.6). On the border between the experimental design and this commercial tree plantation, an additional line of trees was planted as a buffer strip to assure the same neighbor effects for each tree (cf. Langton 1990). This additional tree line simulated an additional plot, with the corresponding tree species and the corresponding spacing design.

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[27] Planting distances are shown in Table 3.9

Figure 3.6: Picture of the agroforestry trial. Picture was taken in November 2010. Therefore, the only crop present is pigeon pea (see shrubs on the right side of the picture) (picture taken by Forest Finance S.A.)

The entire design was oriented from west to east, which meant that the irregular spacing design is oriented towards north-south providing a realistic light situation under the assumed simulated tree density and a more homogeneous light transmittance throughout the year (Leroy et al. 2009).

3.2.3 Control treatments

In order to compare tree and agricultural crop growth in the agroforestry trial with monocultures of crops and trees, control plots were established for each component. Tree monocultures were monitored in two different types of control plots:

- First, tree performance was documented on 4 plots using the same design as for the agroforestry trial but without integrating crops in the understory. Hence each of these four control plots was 5000.4 m^2. The plots were adjacent to one another and situated within 300 m of the agroforestry trial.
- Second, for the purpose of evaluating differences in tree growth between trees planted using the experimental design and those in plantations with the commonly used spacing design of 3 x 3 m[28], additional monitoring plots were established in the adjacent Playo Chuzo tree plantation among trees of the same age and the same species. Four plots of 21 x 21 m for each tree species containing 49 trees each were thus monitored in the surrounding plantation. One exception was *D. retusa,* which was planted in a grid of 3 x 2 m, and hence, 70 trees were monitored in each plot. Only *C. odorata* could not be monitored in a forest monoculture setting, as this species was not planted in the surrounding forest plantation. In order to minimize site effects, the stands located closest to the trial were chosen for comparison of tree growth. Within these stands, monitoring plot locations were selected randomly.

To document production of pure crops (without trees), four plots of 15 x 15 m were established for each crop rotation and managed in the same way as those under the trees. These crop monocultures were also planted in a randomized plot design, located between the agroforestry

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[28] This spacing design is commonly used in hardwood plantations in the tropics (Evans and Turnbull 2004) and also corresponds to the planting distance of trees used in the original Taungya system (Jordan 1992).

trial plots and the sole tree plots (in a simplified fan design). Table 3.9 sums up the treatments investigated:

Table 3.9: Overview of treatments and their sample sizes. Crop rotation in the AF sampling type corresponds to "Intercropping Treatment".

Sampling Type	Abbr.	Crop rotation	No. tree species per plot	Tree distances [m]	Trees per plot	Amount of plots	Area per plot [m^2]	Total No. of trees per sampling type	Total Area [m^2]
Agroforestry (trees with crops)	AF	G-P M-B-M-M B-R-R C-S	6	2.0 x 3 2.7 x 3 3.4 x 3 4.1 x 3 4.9 x 3 5.6 x 3 6.3 x 3 7.0 x 3	96	16	1,209.6	1,536	20,487
Pure forest plantations in AF planting design	FP	FP[3]	6	2.0 x 3 2.7 x 3 3.4 x 3 4.1 x 3 4.9 x 3 5.6 x 3 6.3 x 3 7.0 x 3	96	4	1,209.6	384	5,000
Monitoring plots in common plantation design	FP 3x3	-[4]	1	3 x 3 (3 x 2)[1]	49 (70)[1]	20[2]	441	1,064	8,820
Pure crop plantations	CP	G-P M-B-M-M B-R-R C-S	0	-	0	16	225	0	3600
Total								2,984	37,907

[1] *D. retusa* was planted 3 x 2 m in the surrounding plantation

[2] *C. odorata* could not be monitored for this treatment

[3] Control treatment for evaluating tree performance compared to intercropping treatments

[4] This sampling type was not included as control group for intercropping treatments for reasons delineated in chapter 4.2.2

Table 3.9 shows that the entire area under investigation was 3.7 ha. An area of 2.9 ha was planted with trees and/or crops exclusively for this trial, and an area of 0.9 ha was monitored in the surrounding plantation. Each crop rotation includes a trial area of 6040.8 m^2. The entire research project accounts for 3360 trees. Table 3.10 shows the number of trees investigated by tree species and treatment.

Table 3.10: Number of trees per tree species and treatment

Tree species	Sampling type (ST)								
	AF			FP		FP 3x3		CP	Total
	N per sample	N per intercropping treatment	N per ST	N per sample	N per ST = intercropping treatment	N per sample	N per ST	N per ST	
A. graveolens	16	64	256	16	64	49	196	0	516
C. odorata	16	64	256	16	64	0	0	0	320
D. retusa	16	64	256	16	64	70	280	0	600
H. alchorneoides	16	64	256	16	64	49	196	0	516
T. grandis	16	64	256	16	64	49	196	0	516
T. amazonia	16	64	256	16	64	49	196	0	516
Total	**96**	**384**	**1536**	**96**	**384**	**266**	**1064**	**0**	**2984**

3.3 Trial establishment and management

The agroforestry trial was established in August 2009 simultaneous to the planting of the surrounding commercial reforestation project by Forest Finance. The crop cycles started upon completion of tree planting - between September and October 2009. The overall approach of the trial was to manage trees in accordance to the practical guidelines of the reforestation company and to manage the crops in a manner as close as possible to the traditional agricultural practices of local farmers[29].

3.3.1 Tree management

Tree seedlings were provided by BARCA S.A., in Tortí. All of the management steps to be described in the following sections were carried out by BARCA staff following the instructions of the author. All tree seeds, with the exception of *T. grandis* and *A. graveolens* seeds were collected in forests in the provinces of Panamá and Darién, within a distance of 80 km from the trial area (see Table 3.11). Certified[30] seeds were imported for *T. grandis* and *A. graveolens* from the forest seed bank of CATIE (Tropical Agricultural Research and Higher Education Centre) in Costa Rica.

Table 3.11: Origins of the tree seeds used in the trial

Tree species	Number of mother trees	Location of trees (community)	District
T. amazonia	6	Madroño	Chepo
H. alchorneoides	3	Piriatí, Calí	Chepo
D. retusa	5	La Relojera	Pinogana
C. odorata	3 + 2	Playa Chuzo + Agua Fría	Chepo + Chepigana
A. graveolens	Seeds imported from CATIE, Costa Rica		
T. grandis	Seeds imported from CATIE, Costa Rica		

Seedlings were grown in a nursery using a substrate containing 90% alluvium soils, 6% rice husk and 4% organic fertilizer. Before planting the tree seedlings, the entire plantation, including all treatment areas, was prepared for planting by cutting high bush and herb vegetation with a tractor, and applying herbicide[31]. All cut biomass was left in the field as mulch. Containerized seedlings were then planted at the end of August 2009 using spades. One week after planting, 20 g of fertilizer (NPK 15-30-8) was divided among three holes, placed at a distance of 15 cm from each tree.

Beginning three weeks after planting, competing grass was repeatedly cut in a circle of one meter around each tree using machetes. According to Evans and Turnbull (2004) this technique will be referred to from here on as “spot-ringed weeding”. In the agroforestry trial, subsequent weed control was carried out in the course of crop planting. The control plots of trees planted in the simplified fan design (FP) were cleared manually of competing vegetation by workers approximately every 4 weeks during the first 4 months, and subsequently once every 4 months. In the FP and FP 3 x 3 m plots were cleared manually of competing vegetation every 4 months and additionally treated with Glyphosate, according to the common practice in forest plantations in eastern Panama.

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[29] These practices were documented by Schuchmann (2011) using a seasonal work calendar.

[30] Certified by the National Seed Office of the Government of Costa Rica

[31] The herbicide used is known under the trade name “Glyphosate” (*N*-(phosphonomethyl)glycine).

Replanting of dead trees was carried out three times - two weeks after planting in September 2009, again at the beginning of December 2009 and finally in May 2010. There were no seedlings of *T. grandis* and *D. retusa* available to replant in the second phase. Therefore, any dead *D. retusa* trees were not replaced until May 2010. *T. grandis* could not be replanted until July 2010 because of problems with the delivery from Costa Rica.

The first pruning and singling of *D. retusa* and *T. grandis* was carried out in May and August 2010, respectively. Low branches of all tree species were cut in October 2010. *T. grandis* was pruned again in September 2011. The upper third of the crown was left untouched.

As mentioned in Table 3.4 the mahogany shoot borer (*Hypsipyla grandella* Zeller*)* can cause serious damage to *C. odorata*. This insect is a small moth (Pyralidae) that bores into the pith of terminal shoots, ultimately resulting in multiple shoot growth and forked trunks of little economic value (Newton et al. 1993). Once a plantation is invaded by the insect, nearly all trees are attacked, thus rendering the production of this species and other hardwoods of the *Meliaceae* family (e.g. *Swietenia macrophylla*) in pure stands too risky. Up to now, neither the development of insecticides (Ohashi et al. 2011), pest-resistant planting stock (Navarro et al. 2004, Soto et al. 2007, Ward et al. 2008) nor the introduction of parasitoids, predators or viruses (Wylie and Speight 2012) have proven effective in preventing damages by *H. grandella*. The only effective method for reducing damages to invaded tree plantations is to cut the infected, mostly apical, part of the tree and burn it. In this trial, trees were monitored and cut every 3 months beginning at the end of the first dry season in February 2010.

3.3.2 Crop management

Based on the species selection and associated recommended planting periods the following crop rotations were chosen:

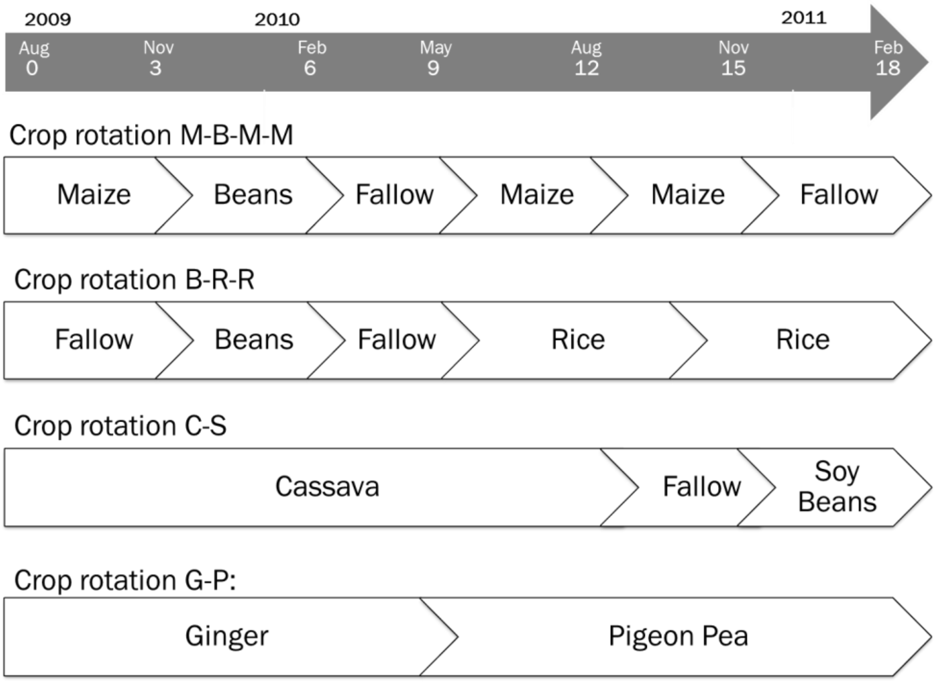

Figure 3.7: Selected crop rotations and their abbreviations by year, calendar month (Aug = August, Nov = November, Feb = February) and month after tree establishment (see numbers below calendar month).

No crop cultivation was carried out during the dry season between December and May. Beans were planted in rotation with maize to improve soil fertility. In the B-R-R rotation (Figure 3.7), beans were planted at the same point in time as in the rotation M-B-M-M, but without any previous planting of grain, in order to compare the nutrient cycle between these two treatments.

Previous to the planting of pigeon pea, ginger was planted. However, as this crop did not germinate in the trial, the management in these plots can be considered identical to that undertaken in the control plots (FP) during the first 9 months. Due to the intensive rainfall during November and December 2010, soybeans also did not germinate. Neither ginger nor soybeans will therefore be considered in the results.

In accordance to local agricultural practices establishment and management of crops were carried out manually, and seeds were obtained from local farmers. To meet certification standards of the Forest Stewardship Council (FSC) (cf. Willoughby et al. 2009) no pesticides were applied, even though they are frequently used by local farmers.

All crops were planted in parallel lines between the trees without regard for the light gradients (see Figure 3.5). Marked ropes were used during planting to ensure a uniform planting grid. A radius of 50 cm around each tree was left free of crops. If this circle coincided with a regular planting position of the crop as determined by the planting grid, planting was continued on the next marked position on the rope outside of the circle.

Management of maize

Three rotations of maize were planted - once at the end of August 2009, again at the beginning of June 2010 and finally, at the beginning of August 2010. Maize sowing was carried out with a distance of 30 cm within rows and 90 cm between rows. The seed was hand drilled, with three seeds per hole at a depth of 5 cm. In accordance with local tradition, these holes were made using a wooden stick called a“chuzo,” or “coa”. Eighteen kg of Hybrid-seeds, DK 1040 (Dekalb), were sown. The same hybrid was used for all rotations. Two weeks after both the first and the third maize sowing, 184 kg/ha of fertilizer (NPK 15-30-8) was applied manually in holes between the maize plants. No fertilizer was used after the second sowing, as beans had been planted beforehand to improve the nitrogen content of the soil. The maize cops were harvested as “maize nuevo”, which means during the time when the maize seeds are still slightly soft and the cornsilk is dark, but not yet dry. Harvesting of the three rotations was carried out in the middle of November 2009, the middle of August 2010 and in November 2010, respectively. The period from sowing to harvest was 9-10 weeks. The maize cobs were sold by the bag for human consumption in Tortí, with each bag containing 100 cobs.

Management of beans and rice

Bean seeds were acquired from a local farmer in Tortí, who has been cultivating the variation, “Chiriquano,” for 30 years. Beans were sown in the B-R-R rotation in the second week of October 2009, and shortly after, also in the M-B-M-M rotation at the end of November 2009, after the first maize harvest. In the latter rotation, plots were prepared both manually and chemically, using 4 l/ha of Glyphosate previous to sowing. In contrast, competing vegetation on B-R-R plots was slashed to ground level without application of herbicides. For this reason, an additional manual weed control was conducted during November 2009 in the B-R-R plots. Dried bean pods were harvested four months after sowing, starting in the B-R-R plots in the second week of February 2010, and continuing in the M-B-M-M plots in the first week of March 2010. After picking, beans were threshed manually and cleaned using wind[32].

In the B-R-R rotation, dry rice was sown in both May and September 2010, at a distance of 30 by 30 cm, again using the traditional “chuzo” technology, as suggested by local farmers. Seeds were acquired from a farmer[33] in Tortí. Fields were prepared for sowing using both mechanical and chemical weed control. No pesticides were used during the growing phase. Protection from birds

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[32] Beans are carefully tossed into the air, and through the differing weight of the beans and the shredded pods even a light wind will separate them.

[33] Special thanks go to Ismael Rivera a local farmer, who not only provided rice seeds but also voluntarily spent a couple of days on the trial to help with the selection of crop species and the correct planting techniques.

was carried out manually[34]. Harvesting was also carried out manually. Seeds were sold in the husk.

Management of cassava and soy beans

Cassava was cultivated using stem cuttings, which were collected near Agua Fría, a township located approx. 20 km east of Tortí. Using local plant material adaptability to local climate and native pests was ensured. According to the traditional practice, shoots 15-20 cm long with a diameter of 2-3 cm were cut to use as seedlings. Stem cuttings were then planted in holes 15-20 cm deep at an angle of approximately 40°. The spacing between plants was one by one meter and no fertilizer or pesticides were used. Competing vegetation was cut back both in October and December 2009 as well as in June and August 2010. No weed control was necessary during the dry season. The time period between planting and harvest was 9 months. In September 2010, cassava roots were pulled out of the soil, superficially cleaned and sold without any further processing in the community of Tortí.

Following a short fallow period after the cassava harvest, soybeans were sown. Seeds were acquired from the “Asociación Afro-Darienta Forestal de Zapallal de Darién”. Sowing, management and harvesting was carried out as described for common beans (see above)

Management of pigeon pea

The seeds for pigeon pea were bought at the central market in Panama City. Field preparation prior to planting included both manual weeding and application of Glyphosate. Pigeon pea was sown “by chuzo” during the first two weeks of May 2010 in a grid of one by one meter, with 4 - 6 seeds per hole. The first two weeks of May were recommended by local farmers for sowing. Manual weed control was necessary only once - in August 2010 – as after 5 months, herbaceous vegetation was shaded out by the crowns of pigeon pea. The peas were picked manually in January 2011, when the majority of pigeon pea was producing green pods. Pods that had already dried out by that time were harvested separately and processed as described for common beans (see above)

3.4 Data collection

Data collection in the agroforestry trial focused on the biophysical and economic performance of the different tree-crop combinations. However, to assess the suitability of the agrisilvicultural option as a sustainable land use concept, other factors influencing the potential for adoption, such as political limitations, and preferences and perceptions of farmers needed to be evaluated as well (Montambault and Alavalapati 2005, McGinty et al. 2008). Data collected concerning these aspects are not presented as results here, but will however, be discussed in chapter 5.2.5. Data on current land uses and integration of trees in farms can be found in the thesis of Schuchmann (2011).

3.4.1 Growth performance of trees

During the time of intercropping from August 2009 to March 2011, tree growth was monitored every three months. This time period represents the first 18 months after tree planting. After 24 months, a final growth performance survey was done in order to evaluate possible long-term effects of intercropping.

The target response variables of trees measured every three months are shown in Table 3.12. Height and diameter were selected as the main indicators for tree growth. Height was measured as the shortest distance between the highest tissue in the canopy and ground level. As proposed

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[34] Blank CDs fixed on sticks showed the best success.

by Cornelissen et al. (2003), any exceptional branches, inflorescences or infructescenses were ignored to reflect the general canopy of the plant. If a tree's stem was bent, the length of the crooked stem was registered. Total height and crown height were measured with a measuring pole or folding rule. Heights over 3.5 m were measured using a hypsometer (Forestor Vertex, Haglöf, Sweden). If tree diameter was smaller than 10 cm, both root collar diameter and diameter at breast height (dbh) were quantified using a caliper. Trees with a larger diameter were measured using a diameter tape. The position of the root collar diameter was chosen as proposed by van Kanten and Beer (2005). Dbh was recorded only for trees taller than 2 m. For individuals with multiple stems, the tallest stem was chosen for diameter measurements. A tree was characterized as dead when no green parts were evident and the stem had already dried out. All management activities such as replanting or pruning which had occurred since the last data collected were noted.

In the first three months after plantation establishment, it was observed that the planting position relative to the microrelief strongly affected seedling development. While small depressions quickly filled with water during the rainy season, deep cracks developed in them during the dry season, making those planting positions unsuitable for tree seedlings. The relative planting positions was therefore recorded beginning three months after planting.

Table 3.12: Measured variables for tree performance

Test variable	Abbr.	unit	Measuring technique	Instruments used	Scale
Height	h	cm	Top height (from the soil surface to the highest point of the tree)	measuring pole, folding rule, hypsometer	metric
Root collar diameter	rcd	mm	Diameter at the thinnest part of the trunk between 0-15 cm above soil and under the first stem fork	caliper, diameter tape	metric
Breast diameter	dbh	mm	Stem diameter at breast height (= 1.3 m)	caliper, diameter tape	metric
Crown height	ch	cm	Distance from soil surface to lowest green branch	measuring pole, folding rule, hypsometer	metric
Crown diameter	Cd	cm	Measure of the projection of the widest branch range in two perpendicular directions (north-south and east-west). For further analysis the average of the two measurements was used	Measuring tape	metric
Growth form			0 = good 1 = crooked stem or shrubby growth form	Categories	nominal[1]
Quality			0 = good 1 = bad (forked and multiple-stemmed trees)	Categories	nominal[1]
Abiotic Damages			1 = bent down 2 = tendriled 3 = broken top 4 = damage at bark (not caused by animals) 5 = deformation of root collar (caused by planting mistakes)	Categories	nominal
Biotic damages			1 = damages by insects 2 = damages by rodents 3 = damages by fungi	Categories	nominal
Vitality			0 = dead 1 = alive	Categories	nominal[1]
Microrelief			0 = planting position on flank or top of mound 1 = planted in a relative depression	Categories	nominal[1]

[1] considered as metric in the regression

3.4.2 Crop production and growth

In an attempt to evaluate crop production as a function of tree species and tree distance trapezoidal subplots were derived from the experimental design:

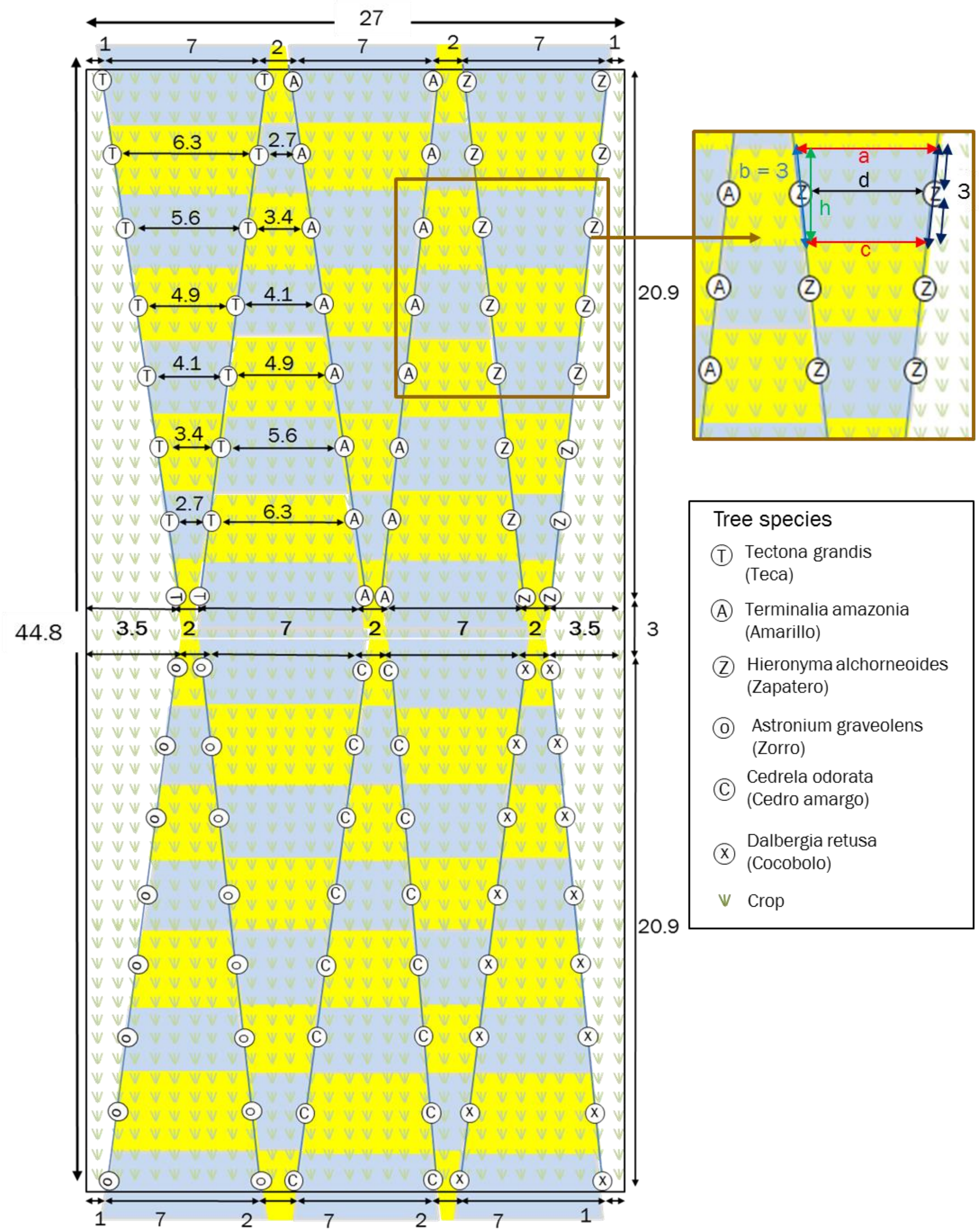

Figure 3.8: Sampling design for crop yield measurements for one plot. The alternating blue and yellow trapezoidal forms represent the subsampling units for crop yield measurments between one tree pair. See text for details. All distances are given in [m].

The trapezoidal areas marked in blue and yellow in Figure 3.8 represent the experimental unit applied to all measurements related to crop production between each tree pair at a particular planting distance. Examples of planting distances are denoted for the light gradient between *T. grandis* (TgTg, see table Table 3.8) and *T. grandis* and between *T. grandis* and *T. amazonia* (TgTa), respectively. The right side of the figure represents one example of a subsample unit for crop production. The trapezoidal surface area of one sample is defined by the virtual line linking the trees of one arm of the light gradient (blue line) and two lines (a, c) located 1.5 m (on the gradient line) parallel to the planting distance d of a pair of trees. The surface area of this trapezoid is defined by the planting distance d and the height h of 2.99 m[35], which is constant for all subsamples. This area was however not completely planted with crops as a circle of 0.5 m around each tree was left free of crops. Table 3.13 shows the derived sample surface for each planting distance and the potential area available for crop planting.

Table 3.13: Planting distances and corresponding area of trapezoidal subplots for crop production between trees. Third column shows the area available for crop planting.

Planting distance [m]	Surface area of subsample [m²]	Surface area planted with crops [m²]
2.0	6.1	5.3
2.7	8.2	7.4
3.4	10.3	9.5
4.1	12.4	11.6
4.9	14.6	13.8
5.6	16.7	15.9
6.3	18.8	18.0
7.0	20.9	20.1

During harvest the trapezoids were circumscribed by ropes. For all crops the following parameters were measured in each subplot:

- Number of crop plants per subplot
- Weight of marketable plant parts per subplot
- Number of marketable plant parts (e.g. pods, cobs, counted while picking)
- Weight of non-marketable products due to poor quality
- Number of non-marketable products due to poor quality
- Weight of remaining aboveground biomass

All production data for pigeon pea, beans and soybeans was recorded separately for fresh and dried pods, whereas for pigeon pea mainly green pods were sold and for beans and soy beans dried and threshed beans were brought to market. In all cases, the whole pods were picked and measured in the field. Green pods were sold on the same day, while the mature brown pods were dried in the sun, threshed and cleaned by hand. Based on subsamples, we calculated the weight fractions of the pod and the seeds to obtain the respective real weight of the marketable seeds. In order to measure crop yields of rice, the whole panicles were weighed and counted. Afterwards they were processed in the same way as the beans. Accordingly, subsamples were taken to compute the weight of the end product. As maize cobs were sold as “maíz nuevo” (see 3.4.1) no processing of the cobs was necessary. To compare the yields of “maíz nuevo” with threshed and dried maize seeds the “rule of thumb” according to INEC (2011) was used, where the number of corn cobs was multiplied by 0.092 to obtain an approximate value of dried seed yield in [kg]. For cassava, the belowground biomass was weighed, as it represents the marketable part of the plant. Cassava tubers were superficially cleaned in the field before weighing. To obtain the real weight of the tubers, a correction factor was calculated based on a water-cleaned subsample.

Aboveground biomass for all crops was measured by cutting the remaining plants and weighing them in the field per subplot, using a hanging scale. Only in the case of pigeon pea subsamples within subplots were used to estimate aboveground biomass to reduce measurement effort: One shrub was cut in the center of every second trapezoidal subsample at soil level and weighed using a hanging scale. Additionally, five shrubs were cut and weighed in each of the four pure

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[35] Height h is defined by the angle between a and b (Figure 3.8), which is 83.16 °.

crop plantation plots. The mean aboveground biomass weight per shrub was then multiplied by the number of shrubs per subplot. In order to obtain dry matter weight, samples were taken separately from the marketable products and the remaining aboveground biomass (where applicable, also belowground biomass). In the case of the three leguminous crops, fresh and dried pods were measured separately. For this purpose, parts of randomly selected plants from different plots were pooled together and cut into small pieces to obtain representative samples. At least 6 subsamples of between 100 - 300 g, depending on plant part, were weighed in the field and again after drying at 60°C for more than 72 hours using a drying oven. Biomass samples were taken and measured on dry days after noon to avoid the presence of surface water on the tissue. To obtain the different water contents for the woody pigeon pea, plants were divided into 3 fractions - leaves, stem with a diameter of larger than 4 cm and woody debris with a diameter less than or equal to 4 cm. Fifteen of the cut shrub samples were used to estimate the weight proportion of each fraction[36].

3.4.3 Characterization of tree-crop competition at the single tree level

Two forms of tree-crop interactions with potential to affect individual tree performance were studied:

- Competition for belowground resources and space (represented by distance to neighbors and height of neighbors) and
- Competition for light.

Competition for belowground resources and lateral space

Most experiments on interspecific interaction focus on the mean population responses of species (e.g. yield) under varying densities and species proportions (e.g. Schwinning and Weiner 1998, Park et al. 2002). However, Gibson et al. (1999) states that “an important feature of plants and other sessile organisms is that they do not sense or respond to overall population density or frequency, but only interact with their immediate neighbors”. Hence, additional information about the three crop plants closest to each tree was collected in order to more thoroughly analyze the effects of crops on individual tree performance. The parameters of the three closest neighbors surveyed were:

- distance to the stem of the tree
- distance from the stem of the tree to the closest crown tissue of the crop
- height

The overall aim was to describe individual tree growth as a function of the size of and distance to neighboring crops. These measurements were carried out for each crop shortly before its harvest. In the case of pigeon pea and cassava, measurements were carried out twice - once approximately halfway through the growth period, and again shortly before harvest. By carrying out two measurements, we were able to detect the changing dynamics of species interaction (cf. Gibson et al. 1999)[37].

Competition for light

Shading is a commonly used concept to assess aboveground competition, but there is a great deal of variation in both the definition of the term and the evaluation methods used (Bellow and Nair 2003, cf. chapter 2.2.1). Forest ecologists agree upon the importance of light as a limiting factor for tree growth (e.g. Coomes and Allen 2007, Pretzsch 2009). For the purpose of this study, shading is defined as the fraction of photosynthetically active radiation (PAR) transmitted to the height of the tree from the PAR on an open field. Measurements were carried out using a PAR

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[36] Biomass production of pigeon pea is reported in detail in the thesis of Kreuzer (2013).

[37] More detailed information is given in chapter 4.3.1.2

sensor from a company called Field Scout[38]. The device includes six PAR sensors which are fixed on a bar with a length of 60 cm, and records the average of light readings from the six sensors. Photosynthetically active radiation - also referred to as quantum light - can range from 400 – 700 nm and represents the moles of light energy striking an area over time (unit: [μmol/s*m^2]). Measurements were taken between 10 am and 2 pm and preferably on sunny days with clear sky to ensure comparability of data, as suggested by Bellow and Nair (2003). To improve data quality, PAR measurements under open conditions were taken every 5 minutes. All readings were carried out in both a north-south and an east-west direction.

3.4.4 Soil samples

Soil samples were taken in order to characterize soil properties and identify possible differences between plots, as well as to provide a baseline for later studies on tree species and intercropping effects. In the course of this thesis, results of soil samples were primary used to identify pedological differences between plots that might mask treatment effects.

Soil samples were taken in November 2010 using an Edelmann auger (combination type). The Edelmann auger (combination type) was chosen, as it allows for a minimum of friction during both penetration of the soil and extraction of the sample, which also means less physical effort, which is especially important in a high clay content soil (Bacon and Hudson 2001). A composite sample of 250 g was taken out of the approx. 300-600 g of soil extracted by the auger. Sampling depth was 0-15 cm, due to the shallow rooting system of crops and tree seedlings. Accordingly, Oelmann et al. 2010 found in Panama that even after six years, the main rooting zone of trees was between 0 and approx. 30 cm, because of the periodically high groundwater levels.

Soil samples were taken at the halfway point between the trees spaced at 2 m, and hence at 1 m distance to each tree. Mixed gradients (e.g. TaHa.) were excluded. We thus obtained 6 soil samples per agroforestry plot. The same sampling grid was applied to the FP plots. Additionally, two soil samples were taken in each of the 16 pure agriculture plots. Ten control samples were taken in the surrounding forest plantation (Table 3.14). The distance between these control samples and the closest samples within the established trial was 12 m. This distance was chosen as it was assumed to be far enough to eliminate any possibility of influence of crops on the soil in the control samples, while still being close enough to assume the same initial soil conditions.

While taking the soil samples, the soil color of each sample was determined using Munsell soil charts (Munsell 2000). If more than one color was detected, all were noted. Munsell values were then converted to numerical values using the formula for Redness Rating (RR), according to Torrent et al. (1983):

$$\mathrm{RR}=\frac{(10-\mathrm{H})\cdot\mathrm{C}}{\mathrm{V}}$$

Equation (3.1)

where C and V correspond to chroma and value respectively and H corresponds to the number preceding the yellow-red hue in the soil color classification. Redness Rating can be used to quantify the hematite content of soil (Scheffer et al. 2010).

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[38] Quantum Light 6 Sensor Bar and Field Scout External Light Sensor Meter by Spectrum Technologies, Illinois, USA

Table 3.14: Number of soil samples per sampling type and intercropping treatment (see Table 3.7 and Table 3.9 for abbreviations)

Sampling type	Intercropping treatment	No. of soil samples per plot	No. of plots	No. of samples per treatment
AF	G-P	6	4	24
AF	M-B-M-M	6	4	24
AF	B-R-R	6	4	24
AF	C-S	6	4	24
FP	FP	6	4	24
CP	G-P	2	4	8
CP	M-B-M-M	2	4	8
CP	B-R-R	2	4	8
CP	C-S	2	4	8
	Control samples outside of agroforestry trial			10
Total				**162**

Chemical analysis of soil samples was carried out in the laboratories of the Chair of Soil Science at the Technische Universität München in Weihenstephan. The potentiometric method in a $CaCl_2$ solution[39] was used to determine pH. Exchangable Ca, Mg, Na, K, Mg, Mn, Na, Fe and Al were determined by displacement with 0,5 M NH_4Cl and subsequent emission spectroscopy (ICP-OES[40]). Cation exchange capacity was determined by summation of exchangeable base cations and exchangeable acidity. Phosphate was extracted using a 0.5 M sodium bicarbonate ($NaHCO_3$) solution at a pH of 8.5, as proposed by Olsen et al. (1954). Colorimetric estimation of Olsen P content was carried out using an ascorbic working solution and a wave length of 882 nm[41], as proposed by John (1970).

The bulk density of all 162 samples was assessed using cylindrical cores with a volume of 100 cm^3. Three sampling depths of 0-5, 5-10 und 10-15 cm were surveyed. Samples were dried at 105 °C and weighed at the Instituto de Ciencias Agropuecarias of the Universidad Nacional de Panamá. Soil moisture was assessed in May 2010 using the Time-Domain-Reflectometrie (TDR) method and a TDR meter[42]. Soil moisture is one of the limiting factors for growth during the dry season from December to April. After the first dry season, the volumetric water content (VWC) in the upper 10 centimeters of the soil was measured. The VWC is the ratio of the volume of water to the total soil volume in a given volume of soil. At saturation, the volumetric water content (expressed as a percentage) is equal to the percent pore space of the soil. TDR measurements were carried out in the center of each tree pair. Follow-up studies will investigate the change in VWC at the end of the dry season in later stages of stand development. For this study, these measurements were used only to characterize soil moisture in the different plots.

3.4.5 Economic survey

All labor and input costs for tree and crop production were recorded over the entire 2 year observation period. All crops harvested were sold in and around Tortí to obtain real prices. A market study, including interviews of 10 restaurants and shops in Tortí and 28 restaurants and shops in Panama City, was also carried out to improve data quality about prices received by

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[39] The handheld pH meter WTW ph 340i was used in combination with a Hamilton electrode.

[40] Inductively coupled plasma-optical emission spectrometry using the VISTA-PRO CCD Simultaneous ICP-OES by Varian Inc.

[41] The spectrophotometer Spectronic 601 by Milton Roy was used.

[42] Field Scout™ TDR Soil Moisture Meter 100 using the 7.9'' rods and readings for high clay soil

farmers in Tortí in comparison to data from the central market[43] (Dey, unpublished data). All costs and revenues were tested for plausibility by comparing them to data from INEC 2006, INEC 2011 and average production costs for crops provided by the Ministry for Agricultural Development of Panama (MIDA)[44].

Costs for tree establishment and management were also recorded and compared to long term experiences from the two cooperating companies, interviews with local small-scale forest enterprises and ANAM (2010). Inventory data from older plantations, provided by the Forest Finance Group and further data from literature were used to predict tree growth. As the input data for the economic analysis was mainly derived from real tree and crop production measured in the trial, the cash in- and outflows will not be presented in the materials and methods section, but in the results section (chapter 4.5) to avoid repetitions. In order to improve readability, assumptions made based on literature will also be presented in chapter 4.5.

3.5 Data Analysis

3.5.1 Analysis of tree growth

In order to compare tree growth parameters between treatments, a linear mixed model (LMM) was built. Mixed Models are frequently used in agricultural and forestry research, as they allow for the inclusion of random environmental effects (Piepho et al. 2003). In this study, the mixed model approach was used as the assumption of independence of observations was violated due to the fact that trees are spatially clustered within plots. This means that trees standing close to one another are more likely to be related (in the statistical sense) due to soil conditions, for example. Clustering often results in Type I errors (meaning the false rejection of the null hypothesis) if not properly taken into account (Field 2009). In order to reflect the clustered nature of trees in the samples, plot number was included in the model as a random factor, allowing intercepts to vary across plots. This means that there was a random effect in the model associated with the intercept for each level of plots. The four different crop rotations and the pure forest plantation (FP) were included as the “treatment” factor with 5 levels. This was true for all tree-related analysis to follow[45]. Additionally, the microrelief for each tree was included as a binary covariable - coded as 1 if the tree was growing in a relative depression and 0 if the tree was growing on the flank or on the top of a mound. All analyses were carried out separately for each tree species for reasons to be described in 4.2.2. The linear mixed model is represented by the following formula:

$$LNheight_i = b_{0j} + b_1 Treatment_{ij} + b_2 microrelief_{ij} + \varepsilon_{ij} \qquad \text{Equation (3.2)}$$
$$b_{0j} = b_0 + u_{0j}$$

where
b_0 = intercept
b_1 = fixed effect of treatment
b_2 = fixed effect of microrelief
u_{0j} = variability of intercepts
i = Individual tree
j = plot
ε_{ij} = Error

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[43] Data on prices from the central market are available on the webpage of the Instituto de Mercadeo Agropuecario (http://www.ima.gob.pa).

[44] The author would like to thank Nidia Romero Ruiz from MIDA for providing the data and for her help with interpretations. Some of the production cost calculations are also available on http://www.ima.gob.pa.

[45] The reasons for excluding the FP 3x3 were derived from results presented in chapter 4.2.2

The distribution of the random effect is $u_{0j} \sim N(0,\sigma^2_{plot})$, where σ^2_{plot} represents the variance of the random plot effects. The distribution of the residual, ε_{ij}, associated with the observation on an individual tree, i, within plot j was assumed to be the same for all levels of treatments ($\varepsilon_{ij} \sim N(0,\sigma^2)$).

The same model was used for the final status of height (h), root collar diameter (rcd) and slenderness – the ratio of height and root collar diameter (h/rcd [cm/cm]) - after 24 months, as well as for the increment of height and root collar diameter during different time periods. The alternative approach of using a longitudinal linear mixed model to include the factor time was rejected, as nonlinear growth trajectories were observed. Hence, forcing the data into a longitudinal linear mixed model by assigning a random time effect to each tree within plot and/or applying repeated measures (in order to identify the covariance matrix for the residuals (cf West et al. 2007) resulted in a severe violation of model assumptions, such as the occurrence of non-normally distributed residuals, and clear nonlinear patterns of residuals plotted against predicted values. Therefore, the observation period was split up into separate time periods and the increment of trees between treatments was compared for each of these periods. This approach met model assumptions, improved model fit and facilitated an easier allocation of effects to specific crops, due to the differing planting and harvesting periods. Time intervals for the purpose of analysis were defined as follows: The first three months were examined to investigate the initial growth phase of the trees. Next, the first 18 months (including the previously examined initial three-month period) during which enrichment planting was carried out, were divided into two time periods - before and after the first dry season – at 9 months. These intervals corresponded to the main sowing and harvesting periods for all crops, with the exception of cassava (Figure 3.7, page 33). These time intervals were furthermore chosen, as the first dry season is critical in tree plantation establishment. Finally, the growth increment in the period between 18 and 24 months was analyzed in detail to investigate the development of trees after enrichment planting had stopped. To achieve normality, root collar diameter and height (respectively increment) were transformed using the natural logarithm. No transformation was necessary for the slenderness (h/d). The Null-Hypothesis (H_0) and alternative Hypothesis (H_A) to be tested for all dependent variables were

H_0: $b_1 = 0$ Equation (3.3)

H_A: $= b_1 \neq 0$,

representing the question of whether there is a treatment effect (b_1 see Equation (3.2) unequal to zero) on tree growth parameters. This question was tested using an F – Test, as the factor treatment contained more than two levels. As the model was only composed of one random effect, a simple variance component matrix (with assumed independent random effects) which assigned a scaled identity structure to each of the random effects was used. The Residual Maximum Likelihood Estimation (REML) was applied to estimate the covariance parameters, because it produces unbiased estimates by taking into account the loss of degrees of freedom that results from estimating the fixed effects (Heck et al. 2010). For this purpose, the Satterthwaite approximation was used to calculate the degrees of freedom. In order to adjust for all other fixed effects in the model, Type III Sum of Squares was used to estimate fixed effects (West et al. 2007). The assumption of normally distributed residuals was checked using the Kalmogorov-Smirnov-Test. Other model assumptions (e.g. nonlinear patterns) were revised visually using Q-Q-Plots and scatter plots of conditional residuals plotted against predicted values. Pairwise comparisons using Least Significant Differences (LSD) were used to test for significant differences between treatments when the Type III Test of fixed effects was significant. Error probabilities below 5% ($p < 0.05$) were accepted as statistically significant. In order to standardize sample size - and for other silvicultural considerations explained in chapter 4.2.2 - only the trees with the best height performance after 24 months were included in the growth analyses. Plots with a sample size of less than 3 trees per tree species were excluded from the analysis[46].

The analysis was carried out using the statistical software package SPSS 20 using the MIXED command.

In order to compare performance of different tree species without considering treatment effects, the same model was applied for the final status of trees after two years (height, diameter, slenderness) with the factors tree species and microrelief.

3.5.2 Analysis of tree survival

One common problem when analyzing survival data is that they are generally not symmetrically distributed. Instead, data tends to be positively skewed, typically with some survival times much longer than others (Clark et al. 2003). As a consequence, it is not reasonable to assume that data of this type have a normal distribution. This difficulty can be resolved by transforming the data, for example with an arcsine squareroot transformation, as proposed by El Kateb et al. (2004). However, in the present study, transformation still did not achieve a normal distribution. Therefore, a more satisfactory approach was to adopt an alternative distributional model for the original data (Collett 2003).

Another problematic feature of survival data is that survival times are frequently censored. “The survival time of an individual is said to be censored when the end-point of interest (e.g. death) has not been observed for that individual” (Collett 2003). In order to deal with this problem, a Cox Proportional Hazard Model was fitted to the data. The Cox Proportional Hazard Model is a semi-parametric model of a survival curve that, in contrast to Kaplan Meier curves and the log rank test, allows the incorporation of multiple covariates - in this case treatment and microsite (Bradburn et al. 2003):

$$h_i(t)=h_0(t)\, e^{\beta_1 \mathrm{Treatment}_i+\beta_2 \mathrm{microrelief}_i} \qquad \text{Equation (3.4)}$$

$h_i(t)$ is the hazard or probability of death for an individual tree at time t. $h_0(t)$ is the baseline hazard function, which in this analysis, corresponds to a tree growing on a control plot situated on the top or flank of a mound. Because, under these conditions, treatment = 0 and microrelief = 0, e^{β} can be interpreted as the change in the hazard between a certain treatment or microrelief (unequal to zero) and the baseline treatment or microrelief (equal to zero), it is therefore referred to as the hazard ratio (HR) (Hosmer et al. 2008). The hazard ratio for the purposes of this analysis can be written as

$$\mathrm{HR}=\frac{\mathrm{P(fail\ at\ t\ |\ still\ alive\ up\ to\ t,\quad Treatment=1)}}{\mathrm{P(fail\ at\ t\ |\ still\ alive\ up\ to\ t,\quad Treatment=0)}}=\frac{h_0(t)\, e^{\beta_1(\mathrm{Treatment}+1)}}{h_0(t)\, e^{\beta_1(\mathrm{Treatment})}}=\frac{h_0(t)\, e^{\beta_1(1)}}{h_0(t)\, e^{\beta_1(0)}}=e^{\beta 1}$$

Equation (3.5)

The hazard ratio of one indicator treatment (e.g. control plot = 0) is proportional to the hazard of trees in treatment i (e.g. i = 1 = M-B-M-M). In other words, the ratio of hazards for two groups is constant with time. All other covariates are kept constant (i.e. microrelief = 0) when calculating the hazard ratio between groups of one covariate, and are therefore independent. The HR of the microrelief was therefore calculated according to the formula displayed above, while holding the treatment constant (0). The β coefficients were estimated using Maximum Likelihood. The Wald statistic, which is the parameter estimate divided by the standard error of the parameter estimate, was used for the hypothesis tests, by comparing it to the standard normal z distribution (Quinn and Keough 2002). Model comparison was conducted using the -2 log Likelihood statistic

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[46] This applies to one plot of *T. grandis* and three plots of *H. alchorneoides*

(Hosmer et al. 2008). Analysis was carried out separately for each tree species using the "COXREG" command in SPSS 20.

3.5.3 Analysis of insect damages and tree quality

In order to make comparisons between treatments regarding damages to *C. odorata* caused by the insect *H. grandella,* the infestation rate was calculated per plot and time period as the number of trees with visible signs of *H. grandella* divided by the number of trees alive. As only the tree species *C. odorata* was affected by *H. grandella,* the total number of trees per plot was equal to one gradient, or 16 trees, if no mortality occurred. Infestation rate was compared between treatments using a Generalized linear Model with a binomial probability distribution and the logit link function. Logistic regression testing of binomial or proportional outcomes requires that the probability of an outcome Y (i.e. the probability of an "event", in this case, insect attack) be related to the covariate value for an individual (in this case, a treatment coded either 0 or 1) using a formal model that has parameters that reflect the direction and size of the effect of each predictor – the so called "link function". The logit transformation, or logit link function g(x), is defined as the natural log of the odds of an event, which is the probability that an event occurs - Y equals 1 - relative to the probability that it does not - Y equals 0 (Quinn and Keough 2002):

$$g(x)=\ln\left[\frac{P(Y=1)}{1-P(Y=1)}\right]=\beta_0+\beta_1 x_i \qquad \text{Equation (3.6)}$$

The resulting logistic regression model is the natural log of the odds set equal to the constant (β_0), plus the product of the regression coefficient β_1 multiplied by the value of the predictor variable, x_i, which is, in this case, the treatment. The value of the log of the odds can be compared for different values of the predictor variable x_i, i.e. x = 0 and x +1 = 1, in this case Treatment = 0 (e.g. FP treatment) vs. Treatment = 1 (e.g. M-B-M-M treatment). The ratio of these two odds is called the odds ratio (OR), and is written and interpreted using the same logic as the Hazard Ratio described for the Cox regression (chapter 3.5.2):

$$OR = \frac{\frac{P(Y=1 \mid Treatment=1)}{P(Y=0 \mid Treatment=1)}}{\frac{P(Y=1 \mid Treatment=0)}{P(Y=0 \mid Treatment=0)}} = \frac{e^{\beta_0}\, e^{\beta_1 (Treatment+1)}}{e^{\beta_0}\, e^{\beta_1 (Treatment)}} = \frac{e^{\beta_1 (1)}}{e^{\beta_1 (0)}} = e^{\beta_1} \qquad \text{Equation (3.7)}$$

This approach was chosen because data transformation, including arcsine squareroot transformation which is frequently used for proportions (e.g. Quinn and Keough 2002, El Kateb et al. 2004), did not achieve normally distributed data. Time periods were analyzed separately, according to the time intervals described in the discussion of the analysis of tree growth (3.5.1). The model fit was best when treatment was included as a single fixed effect. Fisher scoring was used for parameter estimation. The robust Huber/White/Sandwich method offered by SPSS 20 for estimating variance parameters was used to control for possible departures from normality due to for example, dependence of observations (Heck et al. 2012). Analysis Type III was used to estimate model effects. Chi-square Statistics for fixed effects were calculated using the Wald method, which is the squared form of the z-statistic, where z refers to the standard normal distribution (Heck et al. 2012). As the Wald test can be unreliable in small samples, a likelihood ratio statistic was also carried out (Hox 2010). This test was used to compare the model with one predictor to the baseline model, only including the intercept. The result represents the difference in -2 *Log likelihoods (-2LL) between the two models. As only one predictor was used (treatment with 5 levels) this analysis can also be used to test for a significant treatment effect. Cookes distance was calculated for all samples. None of the samples showed influential cases with a Cookes distance smaller than one (cf. Quinn and Keough 2002).

In order to investigate differences in tree quality, a "bad quality rate" was calculated for each tree species in each plot. For this purpose, the number of forked or multiple-stemmed trees was divided by the total number of trees alive at the time of observation. The statistical comparison of bad quality rate between treatments was carried out separately for each tree species in accordance to the analysis described above. The same applies to the analysis of the rate of bad growth forms in *D. retusa*. All analyses were carried out using the “GENLIN” command in SPSS 20.

3.5.4 Analysis of tree-crop interactions on the single tree level

In order to characterize the competition situation of each tree an index was computed from the measured parameters described in chapter 3.4.3. A range of indices has been developed in plant sciences in order to quantify the spatial structure of competition effects (e.g. Silander and Pacala 1985, Connolly et al. 2001a, Connolly et al. 2001b, Armas et al. 2004, Kristensen et al. 2006, Pugnaire 2010, Pretzsch 2009). The index used here was slightly modified from the well-acknowledged index of Hegyi (1975), which is originally based on a virtually drawn circle around the focal tree with a fixed radius in which all neighbors are counted. The index is then defined as the sum of the ratios between the diameter of each neighbor, j, and the diameter of the focal tree, i, which is then multiplied by the distance between the focal tree and the neighbor - ($dist_{ij}$). In the present study, instead of the fixed search radius, a fixed number of three crops around each tree was used. Furthermore, instead of the diameter relation, the sum of the relative heights (h_j/h_i) divided by the distance were used, as already applied by Vanclay (2006), Bristow et al. (2006) among others. The competition index (CI) used was therefore defined as:

$$\mathrm{CI}=\sum_{j=1}^{3}\frac{h_j}{h_i \cdot dist_{ij}}$$

Equation (3.8)

This competition index was chosen, as other indices tested - for example, the neighborhood index as proposed by Nagashima (1999) and Thomas and Weiner (1989) as well as more simple measures, like the sum, mean, minimum or maximum of height/distance ratios or the sum of height divided by the square of distance - tended to have a weaker correlation with growth. In contrast, the index of Hegyi (1975) has been proven to show good correlation with increment (e.g. Holmes and Reed 1991, Ammer et al. 2005), is relatively easy to measure, and also takes into account effects of size asymmetry (cf. Schwinning and Weiner 1998).

Relationships between height and diameter increment and the competition index were evaluated using linear regression. Only trees that had not been replanted during the observation period were included in the analysis. Increment was included as the dependent variable, and CI as the independent variable. CI was transformed using the natural log in order to meet model assumptions. The same transformation was also used for the dependent variable in some cases. Assumption of normally distributed residuals was checked using the Shapiro-Wilk Test. Influential cases with values of Cook’s distance above 1 and DFBeta above 1 were excluded from the analysis as proposed by Field (2009). Regression plots of residuals against predicted values were used to detect heteroscedasticity and non-linearity (cf. Quinn and Keough 2002). Regression analysis was carried out using the “REGRESSION” command in SPSS 20.

Regression analysis was also used to investigate the influence of shading on height and diameter increment. A square root transformation was applied to the percentage of shading to achieve a normal distribution. Further assumptions were tested as described above.

3.5.5 Analysis of crop production

In a first step, the yield and biomass of each crop was compared between pure crop plantations (CP) and agroforestry plots (AF). For this purpose, the total yield and biomass per square meter on each plot of these two sample types was considered as one sample. In the AF sampling type, the area available for crop plantings was used as the reference area (see Table 3.13). Hence, four samples were available for the two sampling types, AF and CP, for each crop. Yield and biomass per square meter were compared between sampling types using an independent T-Test. If the Levene-Test for homogeneity of variances was significant, the separate-variance T-Test provided by SPSS 20 (Brosius 2011) was used. In all other cases, the pooled-variance T-Test was applied. The assumption of normally distributed data was checked using the Kalmogorov-Smirnov Test. As the sampling area of plots was large[47] in both sampling types - as compared to common sampling area sizes in yield experiments - the difference in plot size between sampling types was assumed to be negligible. This assumption was supported by the similar standard errors of the two sampling types.

In order to explore possible effects of tree species and planting distance on the dependent parameters - yield/m², yield/plant and biomass/m² - a stepwise approach was chosen. First, the effect of tree species combination (or light gradients, see Table 3.8, page 29) on crop production parameters was tested separately for each planting distance, using an Oneway ANOVA. The Levene-Test was used to test for the assumption of homogeneous variances. Dependent parameters of all crops were square root transformed prior to this, and all subsequent analyses in order to obtain normally distributed data. Data from the first maize rotation was not included in the analysis of tree species and planting distance effects, as it did not seem plausible that trees would affect maize yields during the first three months of tree development.[48] The Tukey Post-hoc procedure was used to carry out pairwise comparisons between tree species combinations. In the following step, the question of whether the effect of planting distance on crop production differed between light gradients was tested – or in other words, whether the slope significantly varied between factor levels of "tree species combination". As homogenous slopes across factor levels represent a basic assumption of covariance analysis, this assumption was tested by running a model with the factor, light gradient identity (df = 9), and the covariable, planting distance (df = 1), and by additionally integrating the interaction between light gradient identity and planting distance (df = 9), as suggested by e.g. Field (2009) (p. 413). As the interaction was significant for some of the crops investigated, the effect of planting distance on crop production was further analyzed separately for each tree species combination using regression analysis. As the size of the trapezoidal sample area increases with planting distance (see Figure 3.8), sampling errors differed between the levels of the predictor variable. This might lead to departure from the assumption of homoscedasticity - an effect that is often present in systematic designs due to differing surface areas of sample units (Mead and Stern 1980, Mead and Riley 1981). In order to solve this problem Lin and Morse (1975b) and Mead and Riley (1981) suggested applying a weighted regression. The concept of weighted regression is that before minimizing the squared sum of residuals – as in Ordinary Least Squares Regression (OLS) - residuals are weighted by a factor (Quinn and Keough 2002, p. 99). In the present trial, yields/m² measured at small tree distances and therefore on a small trapezoidal subsample area, tended to have higher variances than yields measured at a higher tree planting distance. Therefore residuals were weighted by the square root transformed value of tree planting distance. This theoretic consideration was proven by the Weight Estimation procedure offered by SPSS 20 ("WLS" command). This procedure uses the log-likelihood estimation to iteratively determine a weight in relation to a defined independent variable (see also Urban and Mayerl 2011). This weight was then included in the Weighted Least Squares Regression, using the "REGWGT" command. Even though weighted regression did not significantly change p-values - and hence, statistical inferences on effects of planting density - the

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[47] Yield was measured on a total plot size of 225 m² for pure crop production (sampling type CP) and on 1241 m² on the agroforestry plots (sampling type AF). The size of the agroforestry plot only refers to the area within light gradients. The buffer area outside of light gradients displayed in Figure 3.8 was excluded.

[48] This was proven by insignificant results for both tree species and planting distance, which will however, not be presented here.

weighted regression offered more efficient estimations of coefficients. Assumptions of homogeneity of variances, linearity and normal distribution of residuals were visually checked in residual plots[49]. Normal distribution of residuals was furthermore tested by the Kalmogorov-Smirnov Test.

In both the ANOVA and regression analyses, subsamples without any crop plants were not included in the analysis. Due to the low germination rate of some of the crops, the high number of zero yields led to severe patterns in residual plots. Moreover it is more likely that individual site conditions as for example, paddles, led to a germination rate of 0%, rather than the effect of trees. Another reason for omitting these samples was that the probability for a germination rate of 0% was higher on small plots compared to larger plots and might therefore lead to biased results.

3.5.6 Economic analysis

Although there are many personal and environmental factors involved in land use decisions (McGinty et al. 2008), financial factors are considered to be the essential driver (Buongiorno and Gilless 2003). Scientists have shown how economic theory may be applied to the study of agroforestry systems (Mercer and Miller 1997, Alavalapati and Mercer 2005, Knoke et al. 2009a, Knoke et al. 2012, Castro et al. 2012 among others). In this study, methods of investment appraisal were used in order to quantify the economic viability of agroforestry, and to allow comparison with other land use alternatives. For this purpose, the Net Cash Flow, Net Present Value, Internal Rate of Return and Land Expectation Value were used as financial indicators.

The Net Cash Flow (NCF) is the difference between revenue, or income (cash inflows) and the payments, or expenses (cash outflows) that are a normal part of any business operation (Thompson and Brendan 2009). The NCF was calculated for each year, in order to answer the question of whether positive Net Cash Flows can be obtained from a juvenile forest plantation through an initial interplanting with crops. This measure does not however, include the “time value of money,” which refers to the fact that most individuals prefer to consume now rather than later. Because forestry and agroforestry practices involve investments over a long time horizon, it is important to compare future costs and benefits in present value terms. Therefore, the Net Present Value (NPV) was calculated to compare the economic performances of different intercropping treatments over the entire rotation period, based on Thommen and Achleitner (2003) with

$$NPV = \sum_{t}^{T} NCF_t \cdot (1+i)^{-t}$$

Equation (3.9)

where NCF_t is the Net Cash Flow in year t after stand establishment[50], T is the period of consideration - in this case the rotation length - and i is the decimal discount rate. The discount rate is generally set based on the costs of borrowing money and/or the return from alternative investments (Davis 2005, p. 318). For small-scale farmers in developing countries, relatively high interest rates are usually applied, as they favor quick profits over future profits, even if the latter are potentially higher (eg. Benítez et al. 2007). These farmers’ preferences for short-term profits are mainly due to insecure land tenure and limited access to funding (Hildebrandt and Knoke 2011, Knoke et al. 2012). The value of profits in the near future, represented by a high interest rate, is even greater for subsistence farmers, who depend on their yields for their livelihood. Therefore the NPV was calculated for a range of interest rates of up to 20%. A more detailed

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[49] SPSS 20 cannot directly graph residual plots when applying the “REGWGT” command. Residuals and predicted values were therefore transformed by multiplying them with the square root of the weight, prior to plotting, as suggested by Urban and Mayerl (2011).

[50] Hence, year of plantation establishment is considered to be year 0 and is not discounted.

comparison of land use systems in terms of NPV was carried out based on an interest rate of 6%. This interest rate was selected, as it is generally assumed for investments in agriculture by the Panamanian Ministry of Agricultural Development (MIDA 2011), as well as local landowners (Lopez, personal communication). A moderate interest rate of 5 - 6% has also been recommended and applied for studies in Latin America by Pearce et al. (2003), Knoke et al. (2009a), Knoke et al. (2009b) and Castro et al. (2012), among others. The discount rate at which the NPV is equal to zero is known as the Internal Rate of Return (IRR), and is furthermore used to compare financial viability between different land uses.

While the NPV only assesses the economic performance of one tree rotation – or other land uses during the same period of time – the Land Expectation Value (LEV)[51] considers an infinite iteration of the same management regime - e.g. successive rotations of even-aged timber at a particular rotation length. The LEV was developed by Martin Faustmann in 1849 (see Faustmann 1995) and can be thought of as the value of bare land which will be indefinitely used for a specific type of silviculture or other land use (Buongiorno and Gilless 2003). This means that in financial terms, the LEV is a present value of annuity. The perennial periodic annuity used for its calculation is made up by the NCFs of one rotation compounded up to the year of final harvest. Hence, the LEV can be derived by multiplying the NPV by an eternity factor, as described by Knoke (2012, p. 67):

$$\text{LEV}= \text{NPV} \cdot \frac{(1+i)^T}{(1+i)^T-1}$$

Equation (3.10)

with T being the rotation length. Due to the consideration of the time period that defines the regular occurrence of a distinct cash flow, this formula allows for investigating different rotation lengths.

Furthermore, a sensitivity analysis was conducted to determine how changes in key parameters, would affect the results. For this purpose, the effect of varying cash in- and outflows on the NPV was calculated according to Current et al. (1995b), Alavalapati and Mercer (2005) and Griess and Knoke (2011).

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[51] Synomyms: “Soil Expectation Value”, “Willingsness to pay for land” (Knoke and Hahn 2007)

4 Results

4.1 Soil analysis

Analysis of chemical soil characteristics at the study site revealed a high soil fertility level with a base saturation (BS) of 99.4% (± 0.4%), a high Cation Exchange Capacitiy (CEC) of 932.8 µmol IE/g (± 104.6 µmol IE/g) and a relatively high pH of 5.6 (± 0.4). Values in this range are not uncommon for Vertisols (Coulombe et al. 1996, Brady and Weil 2008 p. 348). The C/N ratio was 11.1 (± 1.3). Similar values for this ratio have been reported by Schwendenmann and Pendall 2006 in both forests and grasslands in Panama. The bulk density value was 0.91 (± 0.11) in the first 5 cm, 1.01 (± 0.09) in 5 to 10 cm and 1.00 (± 0.09) in 10 to 15 cm. These values are rather low for Vertisols (Brady and Weil 2008, p. 138), while Healy et al. (2008) report values of around 0.6 for soils in Panama with comparable parent material, and Yavitt et al. (2004) also report comparable values. The volumetric water content (VWC) at the end of the first dry season was 63.6% (± 7.8%). Despite the high chemical soil fertility, physical conditions generally found in Vertisols - particularly the high clay content (cf. Table 3.1) - often impede their agronomic use. The high clay content results in changes in volume and other physical properties when these soils are subject to alternating wet-dry cycles, which then leads to extensive cracking (Coulombe et al. 1996). The consequences of this are the translocation and loss of both solutes and fertilizer (Coulombe et al. 1996). In addition to the shrink-swell phenomena, Vertisols are hard to work, and thus tillage is very difficult. In the trial site, soils were waterlogged during most of the wet season, which was reflected in the soil color. Accordingly, the hue identified in the present soils was 10 YR and 7.5 YR, suggesting high organic matter content and chemically reduced conditions. Soil color ranged from black to yellow reflecting, the seasonal change in water content[52]. Redness rating revealed a hematite content of less than 1%. Only six samples showed RR values between 1 and 1.88. Charcoal concretions found in the soil samples furthermore indicated previous burning for conversion of forest to agricultural land and the subsequent use of slash and burn practices.

Spatial variability of soil has been observed to be particularly high in the tropics (Barthold et al. 2008, Günter et al. 2009). This is important because as Huxley and Maingu (1978) and Mead and Stern (1980) among others, argue, homogeneity of within-plot soil conditions is vital in systematic intercropping designs. Furthermore differences in soil conditions that might mask treatment effects should be avoided in research plots (Healy et al. 2008). Table 4.1 (page 52) and Table 4.2 (page 53) show the results from the analysis of chemical and physical soil conditions by plot. Confidence intervals of the parameters show that the variation in soil characteristics among plots was low in the trial site. Though some plots showed a particularly high level of fertility - for instance, plot 13 - the random allocation of treatments to plots succeeded in reducing site effects. Hence soil conditions also did not differ between treatments, as illustrated by the CEC and bulk density in Figure 4.1 and Figure 4.2 respectively. It should be noted that soil sampling was carried out after 15 months, and hence, various crops were either still growing or had already been harvested from the different treatment plots at the time of measurement. This implies possible influences of the treatment on soil conditions, particularly the C/N ratio in the upper soil. However, no differences between treatments were proven. Table 4.2 reveals that only in the case of the volumetric water content – where plots 17 – 20 showed higher values than all other plots - any difference between plots was found. All of these plots were assigned to the pure forest plantation (FP) treatment. While this result suggests possible differences between the FP plots and the Agroforestry plots with regard to soil, other parameters indicate very similar chemical and physical conditions.

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[52] Soil samples were taken in November 2010 during the rainy season and thus, soils might have appeared darker due to water saturation. However, H. Thile reported the same soil colors from the two soil profiles (Figure 3.4) in January 2009.

As soil sampling was mainly carried out to establish a baseline for later studies on tree species and intercropping effects on soil conditions – which as expected, were not yet present during the first 15 months – soil data was not analyzed in more detail. However, due to small differences in soil conditions between plots, the plot number was included in the statistical model to test for differences in tree growth performance between treatments. In this manner the fact that trees might grow more homogenously within a single plot due to similar soil conditions was taken into account.

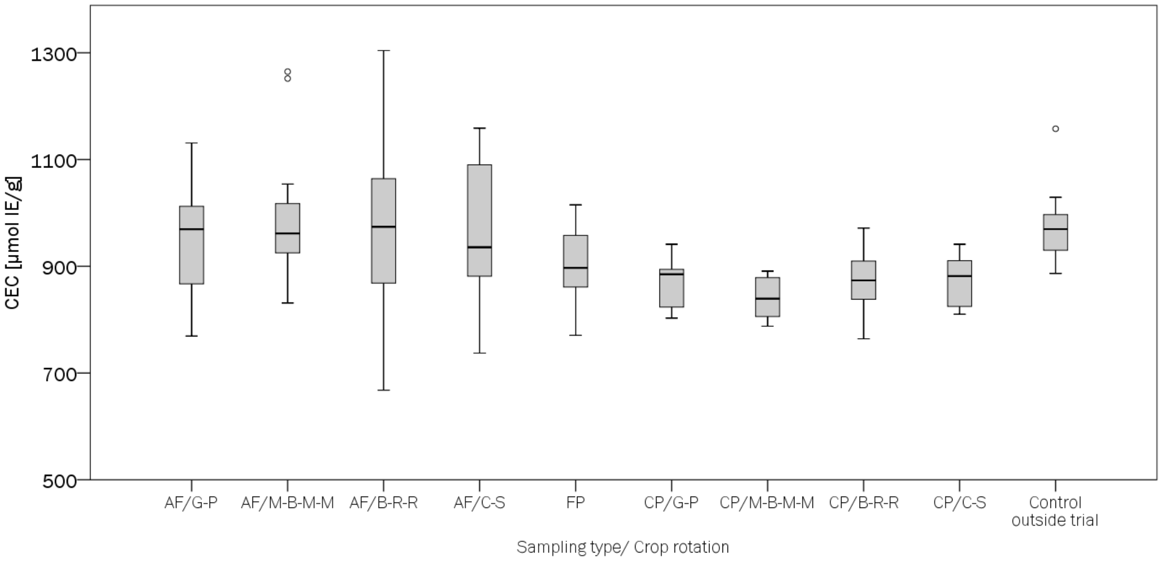

Figure 4.1: Cation Exchange Capacity (CEC) by treatment (AF = Agroforestry, FP = Forest plantation, CP = Crop plantation, M-B-M-M = Maize-beans-maize-maize rotation, B-R-R = Beans-rice-rice rotation, C-S = Cassava-soy beans rotation, G-P = Ginger-pigeon pea rotation)

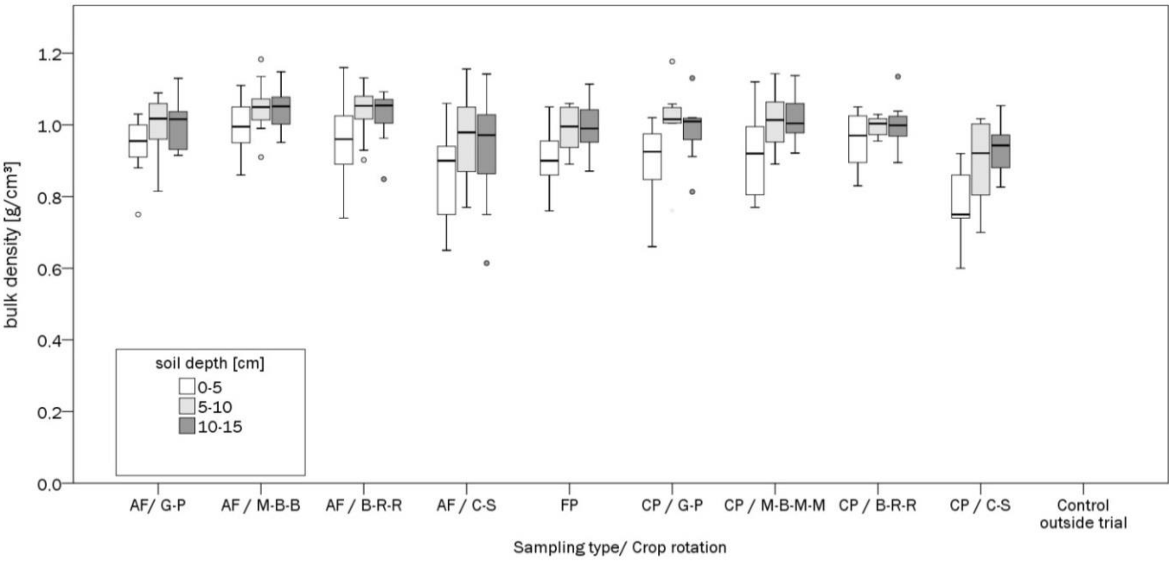

Figure 4.2: Bulk density by soil depth and treatment (see Figure 4.1 for abbreviations).

Table 4.1: pH-values, cation exchange capacity (CEC), base saturation (BS) and carbon/nitrogen ratio (C/N) by plot, sampling type (ST) and intercropping treatment (Treatment). 95% confidence intervals are given in brackets (AF = agroforestry, FP = pure forest plantation, CP = pure agriculture, N = sample size, for abbreviations for treatments see Table 3.7) (See also Table 11.1 in the appendix).

Plot #	ST	Treatment	Plot size [m²]	N	pH		CEC [µmol IE/g]		BS [%]		C/N	
1	AF	G-P	1204	6	5.6	(5.4 - 5.8)	844.9	(766.7 - 923.1)	99.3	(98.9 - 99.7)	10.8	(10.4 - 11.1)
2	AF	M-B-M-M	1204	6	5.7	(5.4 - 6.1)	920.6	(855.0 - 986.2)	99.4	(99.0 - 99.8)	11.0	(10.2 - 11.9)
3	AF	B-R-R	1204	6	5.4	(5.1 - 5.6)	785.2	(706.0 - 864.4)	99.2	(98.6 - 99.8)	10.9	(10.4 - 11.4)
4	AF	C-S	1204	6	5.8	(5.4 - 6.1)	862.1	(794.7 - 929.6)	99.4	(99.0 - 99.8)	11.1	(10.5 - 11.7)
5	AF	B-R-R	1204	6	5.9	(5.7 - 6.0)	936.9	(885.9 - 987.8)	99.6	(99.4 - 99.7)	11.2	(10.9 - 11.5)
6	AF	C-S	1204	6	5.4	(5.2 - 5.6)	925.4	(842.5 - 1008.4)	99.3	(98.7 - 99.9)	11.1	(10.4 - 11.8)
7	AF	M-B-M-M	1204	4	5.6	(4.8 - 6.4)	971.4	(864.1 - 1078.7)	99.7	(99.2 - 100.2)	11.3	(10.8 - 11.7)
8	AF	G-P	1204	6	5.9	(5.7 - 6.1)	1027.0	(956.2 - 1097.8)	99.7	(99.6 - 99.8)	11.3	(10.8 - 11.8)
9	AF	M-B-M-M	1204	6	5.5	(4.8 - 6.2)	972.7	(922.6 - 1022.8)	99.1	(98.2 - 99.9)	12.0	(10.2 - 13.8)
10	AF	G-P	1204	6	5.7	(5.0 - 6.4)	1017.0	(952.3 - 1081.8)	99.5	(99.1 - 99.9)	11.6	(10.6 - 12.6)
11	AF	C-S	1204	6	5.4	(4.9 - 5.8)	1036.0	(900.5 - 1171.6)	99.3	(99.0 - 99.5)	11.5	(10.7 - 12.2)
12	AF	B-R-R	1204	6	5.6	(5.1 - 6.2)	1084.4	(1021.9 - 1146.9)	99.5	(99.3 - 99.7)	11.0	(10.4 - 11.7)
13	AF	C-S	1204	6	6.0	(5.4 - 6.6)	1096.2	(1044.7 - 1147.7)	99.7	(99.5 - 99.8)	10.6	(10.0 - 11.2)
14	AF	B-R-R	1204	6	5.4	(4.9 - 6.0)	1048.6	(892.0 - 1205.3)	99.4	(99.0 - 99.8)	10.7	(10.3 - 11.1)
15	AF	G-P	1204	6	5.3	(5.2 - 5.3)	901.3	(817.1 - 985.4)	99.0	(98.4 - 99.6)	10.9	(10.5 - 11.2)
16	AF	M-B-M-M	1204	6	5.6	(5.1 - 6.1)	969.5	(900.9 - 1038.0)	99.4	(99.2 - 99.7)	11.1	(10.3 - 12.0)
17	FP	FP	1204	6	5.7	(5.5 - 5.9)	933.7	(876.8 - 990.7)	99.6	(99.5 - 99.8)	11.4	(10.5 - 12.2)
18	FP	FP	1204	6	5.5	(5.1 - 5.8)	872.2	(784.0 - 960.4)	99.4	(99.0 - 99.8)	10.5	(10.2 - 10.9)
19	FP	FP	1204	6	5.5	(5.2 - 5.8)	911.1	(855.6 - 966.5)	99.6	(99.4 - 99.7)	10.6	(10.0 - 11.3)
20	FP	FP	1204	6	5.8	(5.7 - 5.9)	925.3	(852.6 - 997.9)	99.5	(99.4 - 99.7)	11.4	(10.6 - 12.2)
I	CP	M-B-M-M	225	1	5.2		890.8		99.5		11.9	
II	CP	G-P	225	2	5.9	(3.7 - 8.2)	915.7	(589.3 - 1242.0)	99.9	(98.5 - 101.3)	10.5	(9.7 - 11.4)
III	CP	C-S	225	2	5.7	(3.6 - 7.8)	810.2	(809.4 - 811.1)	98.8	(96.3 - 101.4)	11.1	(11.1 - 11.2)
IV	CP	B-R-R	225	2	6.2	(6.0 - 6.3)	872.4	(612.1 - 1132.6)	99.4	(96.1 - 102.8)	11.0	(4.1 - 17.8)
V	CP	C-S	225	2	5.5	(1.1 - 9.8)	856.8	(632.7 - 1081.0)	99.5	(99.5 - 99.5)	10.5	(9.3 - 11,6)
VI	CP	B-R-R	225	2	5.2	(3.9 - 6.6)	847.8	(549.0 - 1146.7)	98.9	(98.8 - 99.0)	10.3	(7.4 - 13.2)
VII	CP	G-P	225	2	5.5	(1.5 - 12.6)	823.6	(705.2 - 942.0)	98.9	(88.4 - 109.4)	12.0	(1,3 - 25.4)
VIII	CP	M-B-M-M	225	2	5.4	(5.1 - 5.7)	802.9	(609.7 - 996.2)	98.4	(92.0 - 104.7)	11.0	(10.1 - 11.9)
IX	CP	B-R-R	225	2	5.6	(3.1 - 8.2)	923.8	(315.0 - 1532.6)	99.4	(95.0 - 103.8)	10.8	(8.1 - 13.5)
X	CP	C-S	225	2	5.7	(5.1 - 6.2)	920.3	(654.7 - 1185.9)	99.6	(98.0 - 101.1)	11.4	(6.4 - 16.4)
XI	CP	M-B-M-M	225	2	5.7	(3.5 - 7.9)	878.7	(808.0 - 949.5)	99.4	(98.4 - 100.4)	10.6	(9.4 - 11.9)
XII	CP	G-P	225	2	5.4	(4.8 - 6.1)	885.0	(838.6 - 931.5)	99.2	(95.9 - 102.6)	10.4	(9.7 - 11.1)
XIII	CP	G-P	225	2	5.6	(4.1 - 7.2)	850.7	(244.6 - 1456.7)	99.3	(96.3 - 102.4)	10.7	(10.6 - 10.7)
XIV	CP	M-B-M-M	225	2	5.6	(4.4 - 6.7)	816.3	(525.3 - 1107.4)	99.2	(98.9 - 99.4)	11.8	(10.3 - 13.3)
XV	CP	B-R-R	225	2	5.6	(3.7 - 7.5)	845.5	(188.5 - 1879.4)	99.4	(97.8 - 101.1)	10.6	(8.7 - 12.6)
XVI	CP	C-S	225	2	6.2		905.4	(694.4 - 1116.3)	99.6	(97.2 - 102.1)	10.3	(10.1 - 10.5)
outside trial			-	10	5.8		969.9		99.5		10.8	
Total				*159*	*5.6*	*(5.6 - 5.7)*	*932.8*	*(916.4 - 949.2)*	*99.4*	*(99.3 - 99.5)*	*11.1*	*(10.9 - 11.3)*

Table 4.2: Bulk density and volumetric water content (VWC) by plot, sample type (ST) and intercropping treatment (Treatment). 95% confidence intervals are given in brackets (AF = agroforestry, FP = pure forest plantation, CP = pure agriculture, N = sample size, for abbreviations of Treatment see Table 3.7)

Plot #	ST	Treatment	Plot size [m²]	bulk density [g/cm³]				VWC [%]	
				N	0-5 cm	5-10 cm	10-15 cm	N	0 - 10 cm
1	AF	G-P	1204	1	1.01 - -	1.05 - -	1.04 - -	80	63.1 (61.3 - 64.8)
2	AF	M-B-M-M	1204	6	1.02 (0.95 - 1.09)	1.11 (1.05 - 1.16)	1.08 (1.02 - 1.13)	80	63.3 (61.4 - 65.1)
3	AF	B-R-R	1204	6	1.00 (0.94 - 1.07)	1.07 (1.02 - 1.12)	1.06 (1.03 - 1.10)	80	58.0 (56.1 - 59.9)
4	AF	C-S	1204	6	0.91 (0.81 - 1.01)	1.06 (0.95 - 1.16)	1.05 (0.98 - 1.11)	80	59.8 (57.8 - 61.7)
5	AF	B-R-R	1204	6	0.92 (0.87 - 0.98)	1.06 (1.02 - 1.10)	1.07 (1.05 - 1.09)	80	63.2 (61.9 - 64.6)
6	AF	C-S	1204	6	0.91 (0.85 - 0.97)	1.03 (0.98 - 1.08)	0.98 (0.93 - 1.02)	80	58.3 (56.4 - 60.1)
7	AF	M-B-M-M	1204	6	1.01 (0.93 - 1.08)	1.03 (1.00 - 1.07)	1.05 (1.02 - 1.07)	80	67.4 (66.1 - 68.7)
8	AF	G-P	1204	6	0.92 (0.81 - 1.02)	1.03 (0.97 - 1.09)	1.03 (1.01 - 1.06)	80	64.7 (63.6 - 65.9)
9	AF	M-B-M-M	1204	0	- - -	- - -	- - -	79	62.9 (61.4 - 64.4)
10	AF	G-P	1204	0	- - -	- - -	- - -	80	61.8 (60.4 - 63.2)
11	AF	C-S	1204	5	0.80 (0.66 - 0.94)	0.89 (0.77 - 1.00)	0.82 (0.62 - 1.02)	80	60.0 (57.8 - 62.2)
12	AF	B-R-R	1204	6	0.86 (0.77 - 0.95)	0.97 (0.90 - 1.05)	0.98 (0.91 - 1.06)	80	64.3 (62.5 - 66.1)
13	AF	C-S	1204	5	0.78 (0.62 - 0.95)	0.90 (0.80 - 0.99)	0.90 (0.81 - 0.99)	80	61.5 (59.7 - 63.4)
14	AF	B-R-R	1204	5	1.00 (0.87 - 1.13)	1.06 (1.02 - 1.09)	1.03 (1.00 - 1.07)	80	63.0 (61.1 - 64.8)
15	AF	G-P	1204	6	0.97 (0.92 - 1.01)	1.00 (0.95 - 1.04)	0.94 (0.91 - 0.97)	80	62.9 (61.6 - 64.2)
16	AF	M-B-M-M	1204	6	0.95 (0.89 - 1.02)	1.01 (0.95 - 1.07)	1.02 (0.94 - 1.09)	80	63.9 (62.5 - 65.3)
17	FP	FP	1204	1	0.86 - -	1.02 - -	1.04 - -	79	71.1 (70.0 - 72.1)
18	FP	FP	1204	5	0.88 (0.79 - 0.98)	0.96 (0.88 - 1.04)	0.99 (0.83 - 1.15)	80	65.4 (64.0 - 66.7)
19	FP	FP	1204	5	0.86 (0.75 - 0.96)	0.97 (0.89 - 1.05)	0.97 (0.90 - 1.04)	80	70.3 (69.4 - 71.1)
20	FP	FP	1204	5	0.95 (0.88 - 1.02)	1.01 (0.97 - 1.06)	0.97 (0.86 - 1.08)	80	68.2 (67.1 - 69.3)
I	CP	M-B-M-M	225	2	0.91 (0.49 - 2.31)	1.07 (0.19 - 1.96)	1.03 (0.44 - 1.63)	-	- - -
II	CP	G-P	225	2	0.95 (0.70 - 1.20)	1.01 (0.95 - 1.07)	1.01 (0.98 - 1.03)	-	- - -
III	CP	C-S	225	2	0.79 (0.15 - 1.43)	0.91 (0.26 - 2.08)	0.97 -(0.07 - 2.01)	-	- - -
IV	CP	B-R-R	225	2	1.01 (0.43 - 1.58)	1.02 (0.86 - 1.17)	0.97 (0.74 - 1.20)	-	- - -
V	CP	C-S	225	2	0.82 (0.01 - 1.64)	0.85 (1.07 - 2.77)	0.95 (0.92 - 0.99)	-	- - -
VI	CP	B-R-R	225	2	0.97 (0.77 - 1.16)	0.97 (0.96 - 0.99)	1.02 (0.76 - 1.28)	-	- - -
VII	CP	G-P	225	2	0.82 (1.21 - 2.85)	0.97 (1.67 - 3.61)	1.02 -(0.37 - 2.41)	-	- - -
VIII	CP	M-B-M-M	225	2	0.87 (0.40 - 2.14)	1.03 (0.29 - 1.78)	1.03 -(0.34 - 2.40)	-	- - -
IX	CP	B-R-R	225	2	0.94 (0.46 - 2.34)	1.02 (0.84 - 1.19)	0.95 (0.28 - 1.62)	-	- - -
X	CP	C-S	225	2	0.84 (0.25 - 1.92)	0.99 (0.65 - 1.33)	0.90 (0.50 - 1.30)	-	- - -
XI	CP	M-B-M-M	225	2	0.88 (0.05 - 1.70)	0.91 (0.66 - 1.16)	1.01 (0.62 - 1.40)	-	- - -
XII	CP	G-P	225	2	0.96 (0.13 - 1.78)	1.03 (0.69 - 1.37)	1.01 (0.96 - 1.06)	-	- - -
XIII	CP	G-P	225	1	0.81 - -	1.03 - -	0.92 - -	-	- - -
XIV	CP	M-B-M-M	225	2	1.01 (0.39 - 2.41)	1.03 (0.95 - 1.11)	1.00 (0.75 - 1.25)	-	- - -
XV	CP	B-R-R	225	2	0.92 (0.10 - 1.94)	0.98 (0.66 - 1.30)	1.07 (0.28 - 1.87)	-	- - -
XVI	CP	C-S	225	2	0.67 (0.22 - 1.56)	0.83 (0.27 - 1.39)	0.91 -(0.11 - 1.93)	-	- - -
	outside trial			-	- - -	- - -	- - -		- - -
Total			-	*123*	*0.91 (0.89 - 0.93)*	*1.01 (0.99 - 1.02)*	*1.00 (0.98 - 1.01)*	*1598*	*63.6 (63.3 - 64.0)*

4.2 Tree performance

4.2.1 Initial conditions of seedlings

At the time of planting, there were differences in height and diameter among the seedlings of the various tree species. Therefore, the height and height/root collar diameter relationship measured two weeks after planting are displayed in Figure 4.3 and Figure 4.4. At this time, *C. odorata* seedlings were the largest (40 cm ± 8.4 cm), while *H. alchorneoides* seedlings were the smallest, with heights of less than 15 cm (8 cm ± 2.1 cm). The range of heights was extremely wide for *T. amazonia*, while *T. grandis* and *H. alchorneoides* seedlings were characterized by rather homogenous heights.

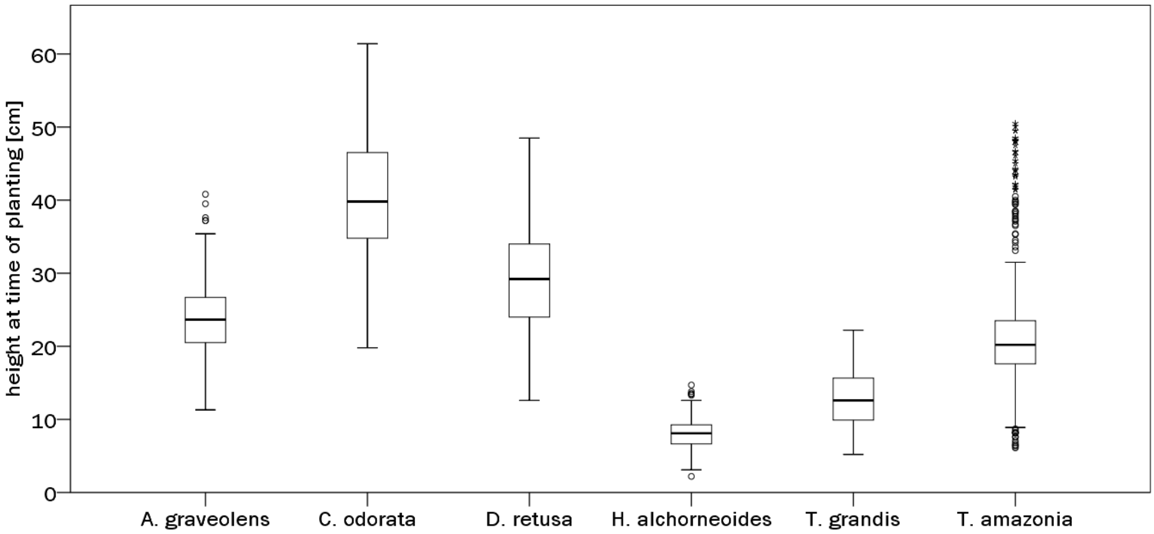

Figure 4.3: Heights of the six investigated tree species at time of planting

The relatively low h/rcd values for *H. alchorneoides* indicate a balanced growth form at the time of planting (Figure 4.4). In contrast, *A. graveolens* was characterized by a high slenderness value, and hence, a superior height growth relative to diameter growth during the first weeks after germination. This growth form is typical for young tree seedlings that follow the “survival strategy” (Pretzsch 2009).

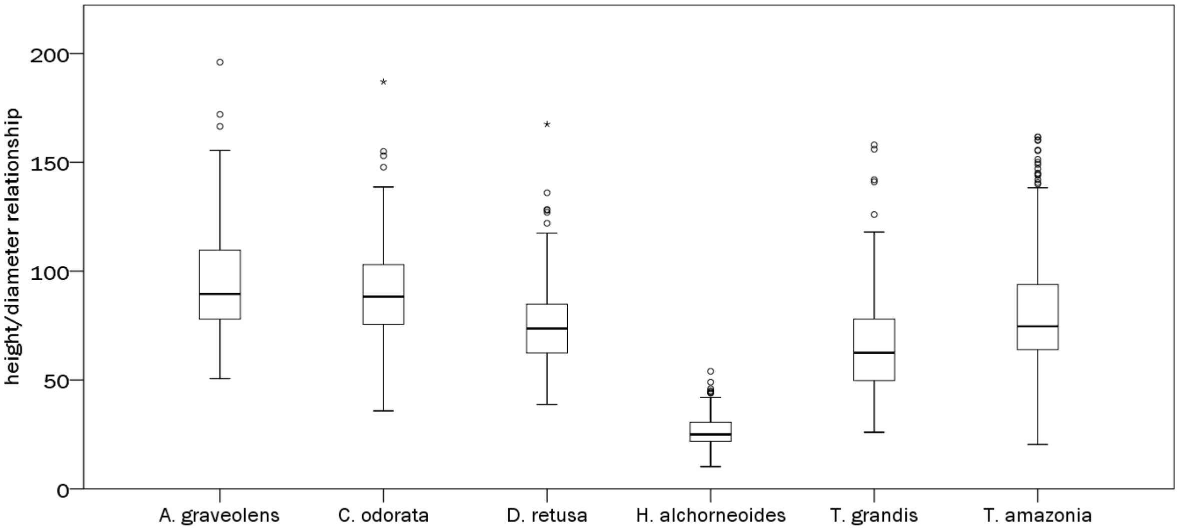

Figure 4.4: Slenderness (h/d) in [cm/cm] of the six investigated tree species at time of planting

The differences in initial heights and diameters[53] of tree seedlings were taken into account by analyzing the increment of these parameters (chapter 4.2.3.1.1)

4.2.2 Overall status of the reforestation after 24 months

In this section the general status of the reforestation after two years will be presented. The literature review presented in chapter 2 and Table 3.5 revealed a considerable lack of knowledge concerning the growth performance of native tree species in forest plantations in Central America. This deficit of experience might be one of the main reasons farmers and forest investment companies favor the use of exotic, widely tested tree species. This chapter will therefore describe the initial performance of the six different tree species, pooling together all 400 (approximately) trees per species, and ignoring different treatments and planting designs. General experiences with the management of the tree species planted and implications for further statistical analysis will be reported. The focus will be on the overall comparison of tree species.

In the following sections, we distinguish between three groups of "populations":

- **"Commercial status"** refers to the collective of individuals that includes all trees present after two years.
- **"Biological status":** As the "commercial status" population includes tree seedlings which died and were at some point replaced with younger and smaller seedlings, actual biological growth might be underestimated. To avoid age differences due to replanting activities - that were carried out during the first year, the "biological status" collective includes only trees from the initial planting that were still alive after two years.
- The last group includes the five most vital trees of each tree species per plot (**"target trees"**). In this context, the most vital trees were defined as the trees with the best height growth performance after two years. In young tree plantations, tree height is a good indicator for future growth expectations, as trees that show good development in height growth usually develop larger crowns, thus allowing them to intercept more light. Consequently there is usually a linear relationship between crown size and other tree traits, such as diameter and volume (Evans and Turnbull 2004, p. 254). As a result, these trees usually have a competitive advantage over others, and the highest probability of reaching maturity (Aguirre 2007). Trees which are inferior at the time of canopy closure usually do not succeed in reaching a dominant position (cf, scale of Kraft in Burschel and Huss 2003, Evans and

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[53] In the following diameter refers to root collar diameter

> Turnbull 2004 p. 255). Furthermore, quantifying the diameter structure of (old-growth) stands by measuring the 100 largest trees ("top height tree collective") is a generally acknowledged approach in forestry (see Pretzsch 2009, p. 200). This method is based on the idea that the final stand will consist of only a percentage of the largest, and therefore usually the most vital trees, which will then be harvested at the end of the rotation period (in this case: 25 years). The chosen top five trees per species and plot accounted for approx. 30% of the initial stem number, which is a greater percentage than the final stocking of tree plantations that is usually applied in the tropics (Evans and Turnbull 2004 p. 254, Griess and Knoke 2011).

Figure 4.5 illustrates the different sample sizes for each collective of trees, pooling together all sampling types (see also Table 3.9).

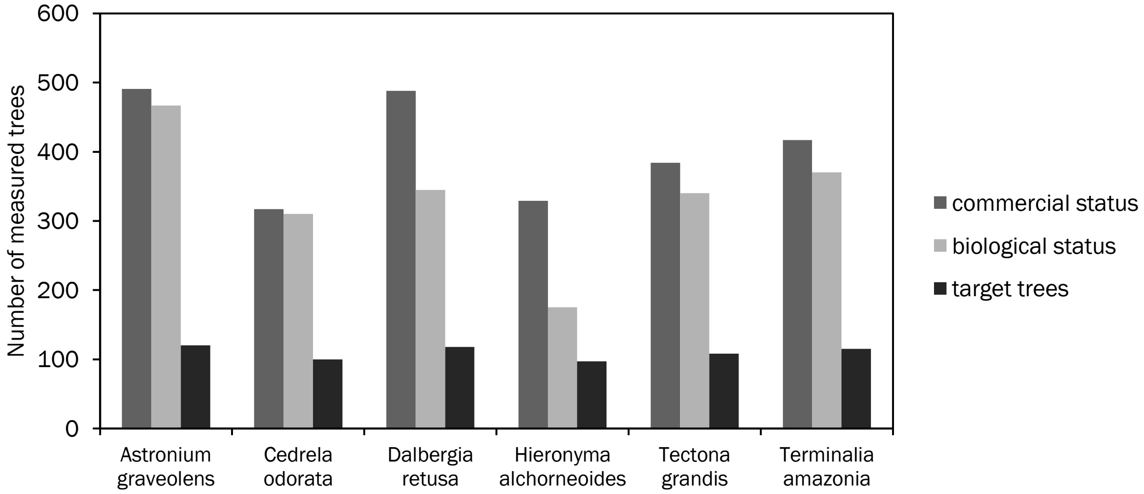

Figure 4.5: Sample size (number of measured trees) of all treatments pooled together (including AF, FP and FP 3x3) by tree species and population type.

Figure 4.6 a) and b) (see next page) demonstrate the overall superior growth of the exotic, *T. grandis,* during the first two years as compared to the native species ($p < 0.001$). Focusing on the biological growth[54] - i.e. excluding the trees replaced by replanting new seedlings - the maximum tree heights of the native tree species ranged between 370 (*H. alchorneoides*) and 680 cm (*T. amazonia*), while *T. grandis* reached a maximum height of 990 cm after 24 months. Growth performance of the biological status population differed significantly between tree species ($p < 0.001$). The best height performance among native tree species was observed for *T. amazonia,* with 301 cm (± 110 cm, $p < 0.001$). *H. alchorneoides* trees were significantly smaller (208 cm ± 62 cm) compared to all other tree species ($p < 0.001$). These differences are consistent between tree collectives. However, when investigating the population of target trees, the height after 24 months did not differ between *D. retusa* and *T. amazonia* ($p = 0.951$), but both were significantly taller than the other native tree species ($p < 0.001$).

Regarding the diameter growth, *C. odorata* showed the best performance with a mean of 6.9 cm (± 18) and p-values smaller than 0.001 compared to all other tree species. *H. alchorneoides* and *A. graveolens* reached the lowest mean root collar diameter with 4.5 cm (± 1.4 cm) and 4.3 cm (± 1.5 cm), respectively, compared to all other tree species ($p < 0{,}001$ for both species), indicating small h/rcd values as displayed in Figure 4.6 c).

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[54] In this section, results refer to the biological status, to give data on the physiological performance of trees. For silvicultural reasons to be presented later, the focus in the following sections will be on target trees and commercial status of the plantation

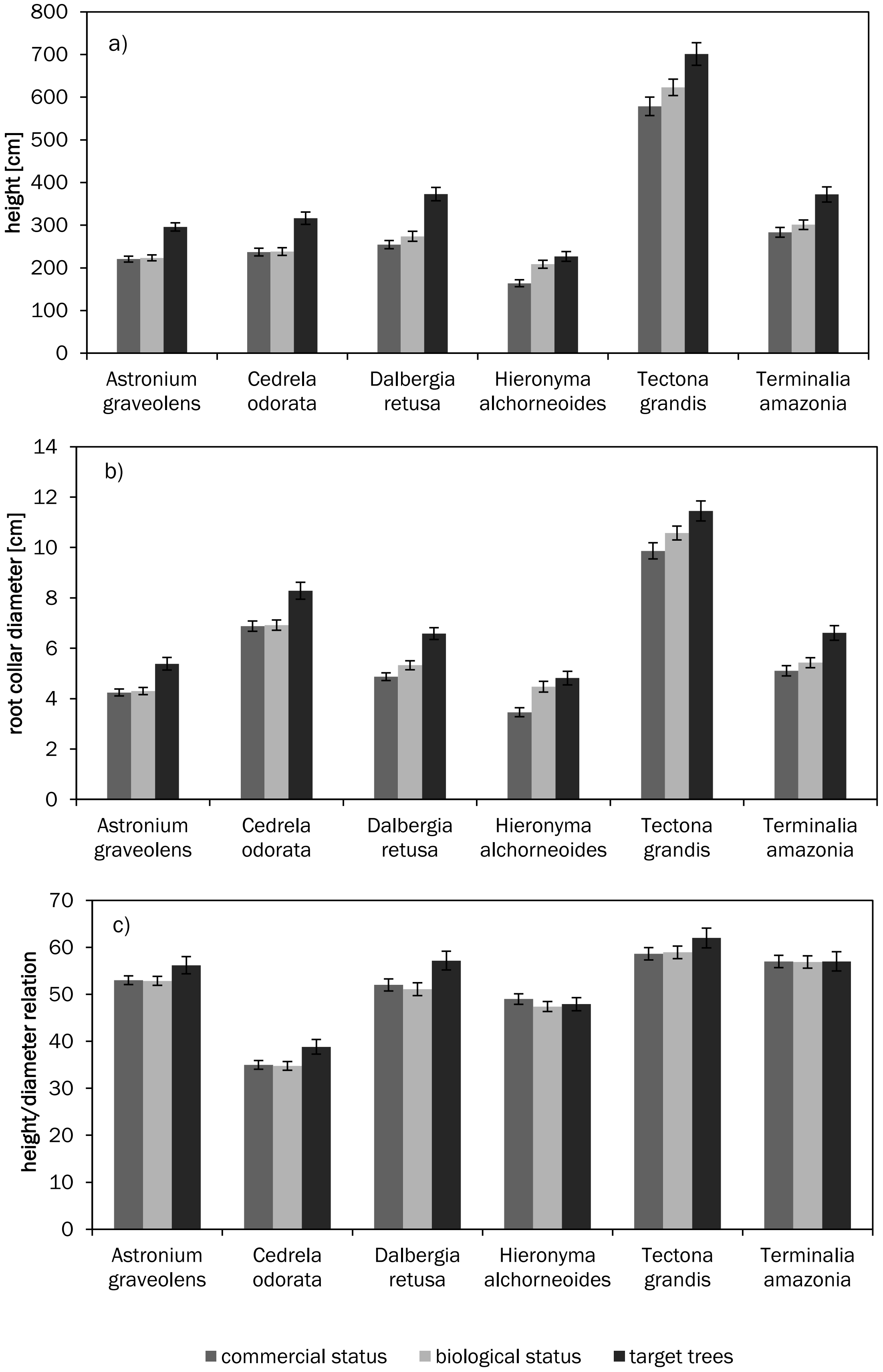

Figure 4.6 a-c: Height, root collar diameter and slenderness (height/diameter ratio) after 24 months for all sampling types pooled together, by tree species and population type. Bars denote 95% confidence intervals.

Regarding differences between the three tree collectives described above, the initial performance of the target trees was, as expected, higher than that of other groups. After two years, the mean height of target trees was more than 20% larger than that for the commercial status group and more than 10% larger than for the biological status group. This was true for all tree species. *D. retusa* showed the largest difference between the target trees group and the other two population types, with 46 and 36% greater heights than the commercial and the biological status groups, respectively. In the case of *T. grandis,* the differences were surprisingly small. Generally the two collectives including and excluding replanted trees hardly differed. Only for *H. alchorneoides* was the mean height 27% greater when replaced trees were not considered. This large difference was due to the high mortality rate of this species which will be discussed later. Results for root diameter were consistent with the results for height. But, differences in root collar diameter were generally smaller.

Table 4.3 presents the crown characteristics after 24 months for the biological status collective of the six tree species investigated. After 2 years, *T. amazonia* had the largest crown ratio, with 59% (± 14%) of the stem carrying branches. This species also had large crown diameters, due to its sympodial growth pattern with horizontal branches forming on different levels[55]. The only species that showed a greater mean crown diameter was *D. retusa* with 2.35 m (± 1.11 m). This can be attributed to its generally shrubby growth form with mostly inclined branches on multiple stems. In contrast to all native tree species, *T. grandis* was the only species that had a length-to-diameter ratio of the crown of more than 1, representing a slender crown (ci in Table 4.3). In relation to root collar diameter, crowns were broad, as shown by the high cd/rcd ratio (Table 4.3) with values greater than 24 for the native species and 16 for *T. grandis*. The relatively high cd/rcd ratios are consistent with the light-demanding character of these tropical hardwood species during the juvenile stage (Evans and Turnbull 2004, p.256). The values of the crown diameters (cd) suggest that after two years, the crowns of only a very few trees touched, as during the active intercropping period in the first 18 months, tree crowns all had a diameter of less than 2 m - the smallest planting distance.

Table 4.3: Crown characteristics (of biological status – i.e. replanted trees are excluded) of different tree species after 24 months: crown diameter (cd), crown index (ci = crown length/crown diameter), live crown ratio (LCR = 100*crown length/height), and crown diameter to root collar diameter ratio (cd/rcd). (N = sample size, SD = standard deviation)

Tree species		cd [cm]	Ci [cm/cm]	LCR [cm/cm]	cd/rcd [cm/cm]
A. graveolens	N	467	466	466	467
	mean	152	33	0.5	35
	SD	72	12	0.2	8
C. odorata	N	310	310	310	310
	mean	162	46	0.7	24
	SD	38	10	0.2	5
D. retusa	N	342	342	342	345
	mean	235	43	0.6	43
	SD	110	12	0.2	15
H. alchorneoides	N	175	175	175	175
	mean	136	48	0.8	31
	SD	50	12	0.4	7
T. grandis	N	340	340	340	340
	mean	165	40	1.8	16
	SD	84	11	0.8	8
T. amazonia	N	370	370	370	370
	mean	233	58	0.8	44
	SD	77	13	0.3	9

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[55] See chapter 3.2.1.1 for more information

While the previous comparison of tree species in terms of growth performance and growing habit included all sampling types, the following presentation of survival rates will exclude the FP 3x3 treatment, because these monitoring plots lack precision in terms of seedling survival. As they were managed by the cooperating companies and only monitored every three months, exact data on replanting is not available and might lead to erroneous results. Figure 4.7 illustrates the large differences in total survival rates between tree species. Survival was lowest for *H. alchorneoides* on this site with only 37%, whereas 97% of *C. odorata* trees survived the first 24 months. Overall, 61% of all trees in the trial survived the first 24 months. The rather low survival rates might also have been influenced by the very hot and dry weather conditions shortly after planting and the low precipitation during the first rainy season, followed by a long and extreme dry season due to the El-Niño-phenomenon in 2009. The low rainfall in combination with the high clay content of the soil obviously caused problems for some species.

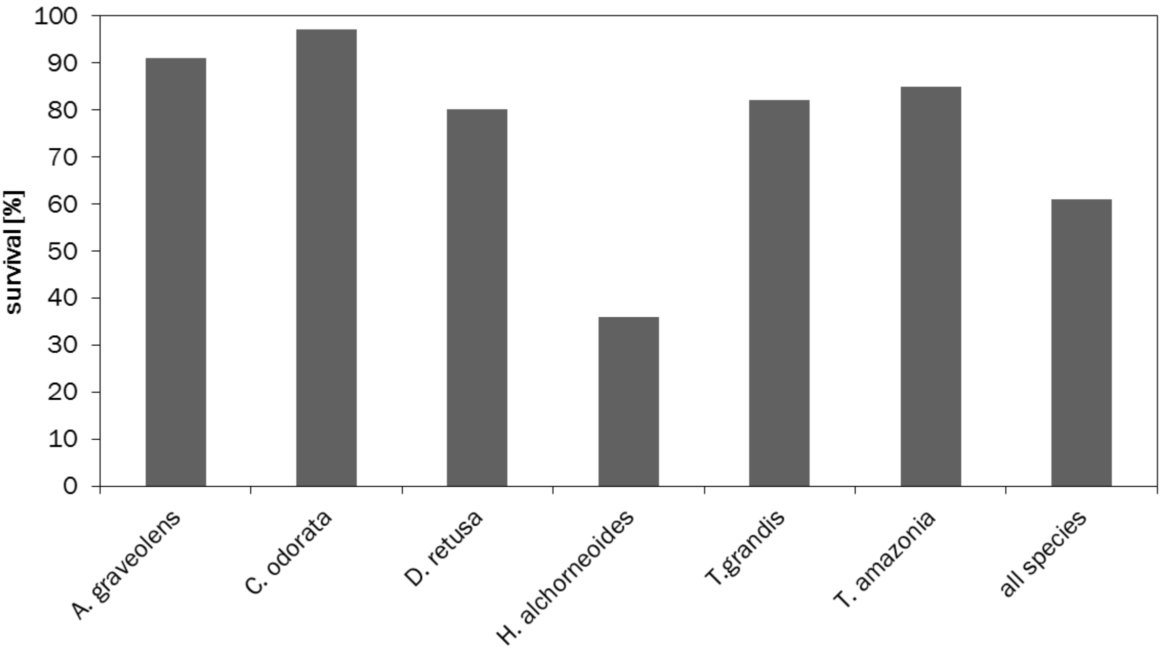

Figure 4.7: Mean survival rate by tree species of all measured trees 24 months after planting by tree species. All treatments are pooled together, with the exception of FP 3x3 sampling type (N = 320 per tree species).

During the first months after planting, trees were furthermore observed to suffer from water paddles. Even though the trial was established on a plain, small differences in the microrelief were detected, which could be attributed to the soil type present (see chapter 3.1.1). Figure 4.8 illustrates that survival of trees growing in depressions was up to 100% lower compared to trees growing on the flank or top of a mound (see dotted fraction of bar). By comparing survival on different relative planting positions, using the cox regression, controlling for tree species, it was proven that the hazard for mortality was 2.2 times higher (95% confidence interval = (2.0 – 2.4) $p < 0.001$) for trees growing in a relative depression compared to trees growing on a flank or top of a mound.

When comparing survival of tree species and controlling for microrelief, it was found that the hazard of mortality ((e^{β}) see Equation (3.5)) of *H. alchorneoides* was between 3.4 (vs. *T. grandis*[56], 95% confidence interval = (3.0 – 3.9)) and 19.7 times (vs. *C. odorata*, 95% confidence interval = (15.1 – 25.7)) higher than that of the other tree species. The difference to

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[56] The tree species after the expression “vs.” was the redundant parameter in the estimation algorithm, coded 0. The reciprocal value of e^{β} can be used to converse comparison.

all other species combined was significant, with $p < 0.001$. Excluding *H. alchorneoides*, the exotic tree species *T. grandis* showed a higher risk for mortality than all native species, with e^{β} ranging from 5.8 (vs. *C. odorata*) to 1.1 (vs. *D. retusa*). The difference to the latter tree species was the only result that was not significant at the $p < 0.01$ level ($p = 0.236$). *C. odorata* was statistically proven to have the highest cumulative survival rate among native tree species ($p < 0.001$ compared to all other tree species) followed by *A. graveolens* ($p < 0.001$ compared to all other tree species). Differences between *D. retusa* and *T. amazonia* were proven not to be significant ($p = 0.193$) with *D. retusa* having a slightly higher hazard of mortality than *T. amazonia,* with e^{β} equaling 1.1 (95% confidence interval = (0,95 -1.32). *H. alchorneoides* and *D. retusa* obviously seem to be less suitable for this particular site.

Figure 4.8 also holds information on the success of the replanting activities carried out during the first 12 months: In the case of *A. graveolens* and *C. odorata,* all tree seedlings on the flank or top of a mound that died and were subsequently replaced, survived during the first two years, while the success of replacement seedlings in relative depressions was very small. For other tree species, replacement success was also generally low but still higher on the tops or flanks of mound. Over all tree species, replanting success was only 45% in relative depressions compared to 60% on all other planting positions combined. This indicates that activities to replace dead seedlings should be planned carefully, and that even small differences in microrelief should be taken into account in order to reduce replanting losses.

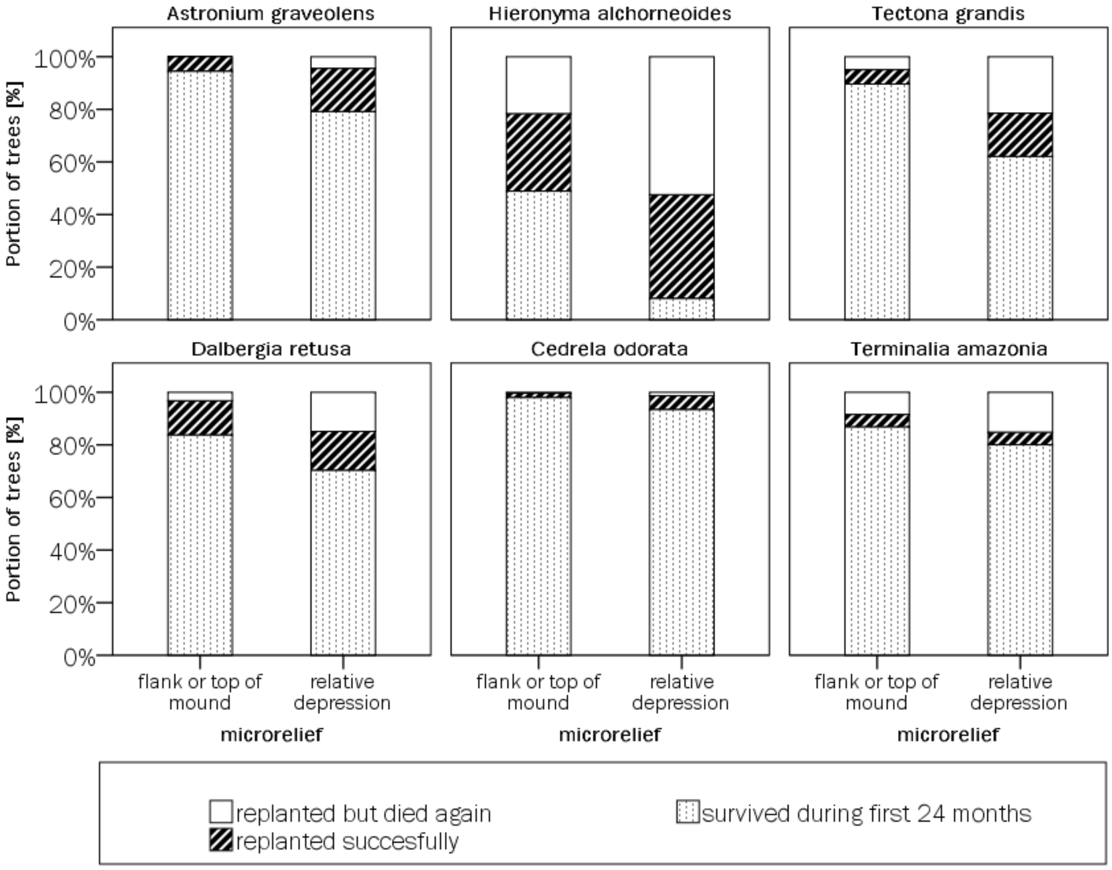

Figure 4.8: Portion of trees that survived and those that had to be replanted by relative planting position. Replanted trees are split up into those that were still alive after two years and those that died before that time. Treatment FP 3x3 was excluded and hence, the original total number of trees accounts to 320 per tree species.

These general observations made on the overall performance of the six tree species, without considering other experimental factors, led to the following consequences with regard to the analysis of treatment effects in the chapters to follow:

- Growth and mortality strongly differed between tree species, suggesting a separate analysis for each tree species, in order to avoid treatment effects being masked by dominant species effects.
- A higher survival for a particular species inherently means a wider range of heights and diameters as for a species with a low survival rate, because in the latter case, the most vital trees with the best genetic characteristics for a particular site are the most likely survivors. Thus, in order to improve comparability in the presence of strongly differing survival rates between tree species and treatments, only the collective of the "target trees" per tree species and plot was used. Furthermore, from a silvicultural perspective, only the future target trees are of interest.
- Due to different sampling designs and missing continuous survival data the monitoring plots in the surrounding plantation (FP 3x3) were not included in the following analysis of treatment effects on tree growth and survival. This data was, however used for calculations of the economic performance of tree plantations as a reference for common plantation practices.
- Planting position relative to microrelief seemed to influence growth performance and survival of trees. It was therefore included as a covariable.
- Crown diameter development during the intercropping phase (first 18 months) indicated that the effect of planting distance on tree growth was not important. It was therefore assumed that there was no inter or intra-specific competition between trees.

4.2.3 Effect of intercropping treatment on tree performance

4.2.3.1 Tree growth

4.2.3.1.1 Development of trees during the observation period

In the following section, the development of seedling growth in association with different crops is compared. If not otherwise noted, all data cited in the text refer to the best 5 trees per tree species and plot ("Target trees" see chapter 4.2.2). For comparison, growth parameters for all trees excluding those replaced ("biological status") are listed in Table 4.4.

Figure 4.9 reveals the nonlinear growth trajectories of the trees. During the first 9 months, height growth resembled a (more or less) linear function of time. This interval corresponds to the phase from planting until the end of the first dry season. However, with the onset of the rainy season, growth accelerated until the next dry season (months 17-19[57]) resulting in an overall s-shaped curve. This growth pattern was one of the main reasons for investigating the increment during different time intervals – namely 0-3, 0-9, 9-18 and 18-24 months as described in chapter 3.5.1 - rather than comparing growth curves of the entire observation period.

First, the effect of intercropping treatment on height growth in different time intervals will be described, followed by diameter growth and finally, the effect of microrelief on both parameters. For reasons discussed in the previous chapter, treatment effects were tested separately for each tree species.

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[57] Due to the "La Niña" phenomenon and the resulting long and intensive rainy season in 2010, the following dry season was shifted to January instead of end of November corresponding to month 17-19 instead of 15-18

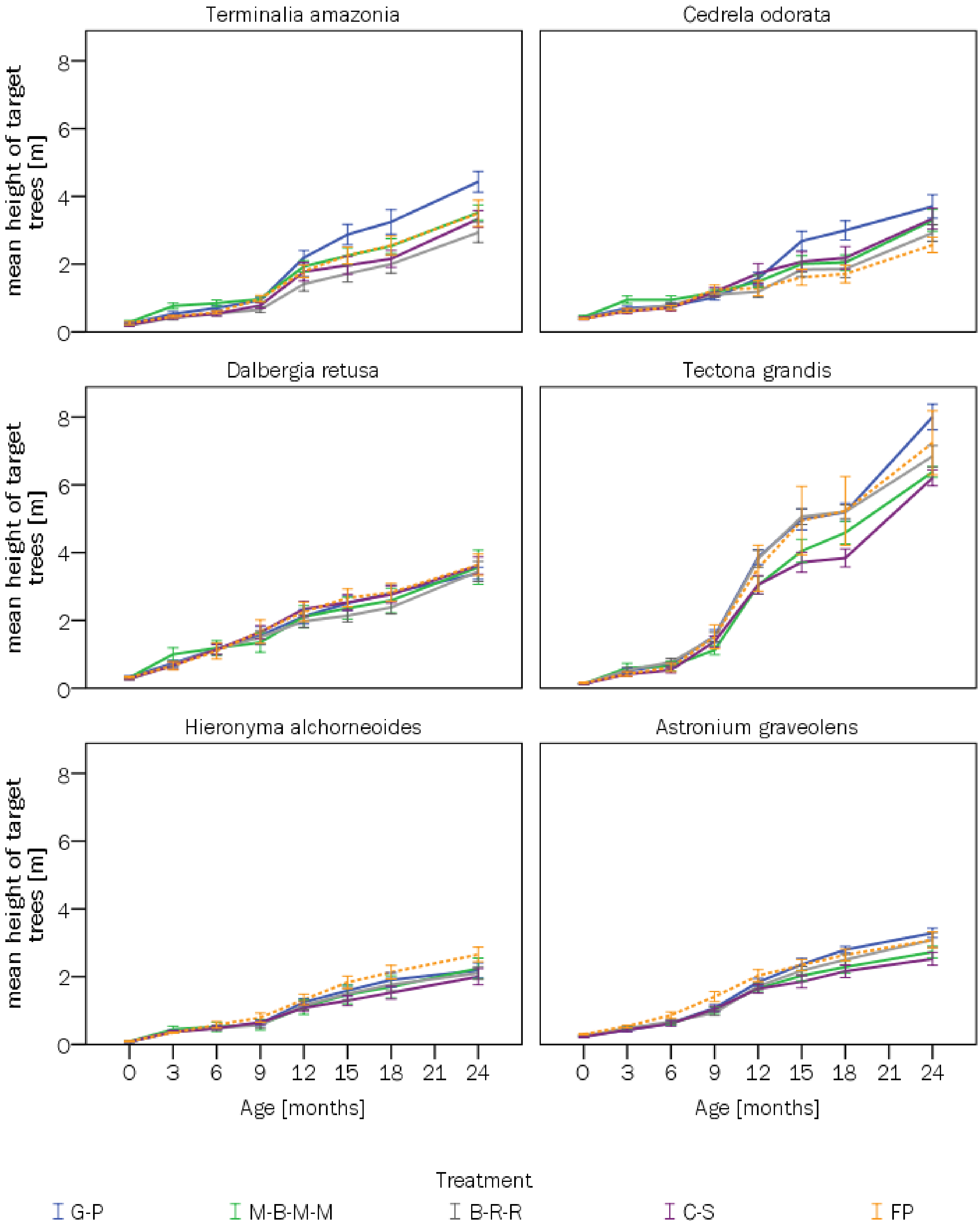

Figure 4.9: Development of mean height of target trees in association with different crop rotations during the observation period. Error bars denote 95% confidence interval (N = 20 per treatment and tree species).

Table 4.4: Mean height (h) and root collar diameter (rcd) of all trees excluding replanted seedlings ("biological status") by tree species, age (A) (in months after planting), and treatment (T). See Table 3.7 and Table 3.9 for abbreviations. Standard deviation is given in parentheses.

		Tree species																	
		Terminalia amazonia			*Cedrela odorata*			*Dalbergia retusa*			*Tectona grandis*			*Hieronyma alchorneoides*			*Astronium graveolens*		
A	T	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]
0	G-P	64	24 (10)	0.3 (0.1)	64	41 (10)	0.5 (0.1)	64	29 (7)	0.4 (0.1)	64	12 (3)	0.2 (0.1)	64	7 (2)	0.3 (0.1)	64	24 (4)	0.3 (0.1)
	M-B-M-M	64	23 (11)	0.3 (0.1)	64	45 (9)	0.5 (0.1)	64	29 (6)	0.4 (0.1)	64	13 (4)	0.2 (0.0)	64	8 (2)	0.3 (0.1)	64	23 (4)	0.2 (0.1)
	B-R-R	64	20 (5)	0.3 (0.1)	64	40 (8)	0.5 (0.1)	64	28 (7)	0.4 (0.1)	64	12 (3)	0.2 (0.0)	64	8 (2)	0.3 (0.0)	64	23 (4)	0.3 (0.1)
	C-S	64	20 (8)	0.3 (0.1)	64	39 (8)	0.4 (0.1)	64	28 (7)	0.4 (0.1)	64	12 (4)	0.2 (0.0)	64	8 (2)	0.3 (0.1)	64	21 (4)	0.3 (0.1)
	FP	64	26 (11)	0.3 (0.1)	64	37 (6)	0.5 (0.1)	64	32 (5)	0.4 (0.1)	64	15 (3)	0.2 (0.1)	64	10 (2)	0.3 (0.1)	64	28 (5)	0.3 (0.1)
	FP-3x3m	-	- -	- -	-	- -	- -	-	- -	- -	-	- -	- -	-	- -	- -	-	- -	- -
3	G-P	61	44 (14)	0.9 (0.3)	64	65 (12)	1.9 (0.5)	64	61 (19)	1.4 (0.4)	63	43 (19)	1.6 (0.7)	61	34 (11)	1.0 (0.3)	60	41 (11)	0.8 (0.3)
	M-B-M-M	62	63 (26)	0.7 (0.3)	62	90 (24)	1.5 (0.4)	63	89 (38)	1.3 (0.4)	61	57 (22)	1.4 (0.5)	62	42 (15)	0.8 (0.2)	61	42 (10)	0.7 (0.2)
	B-R-R	63	40 (13)	0.9 (0.3)	63	61 (12)	1.9 (0.6)	63	62 (19)	1.3 (0.4)	62	45 (21)	1.7 (0.8)	63	32 (9)	0.9 (0.3)	60	42 (9)	0.8 (0.2)
	C-S	63	38 (11)	0.9 (0.3)	64	56 (14)	1.6 (0.6)	64	56 (19)	1.4 (0.5)	59	33 (17)	1.2 (0.7)	60	33 (9)	1.0 (0.3)	62	37 (11)	0.8 (0.2)
	FP	62	41 (11)	0.9 (0.3)	63	58 (12)	2.1 (0.5)	64	58 (20)	1.5 (0.3)	63	37 (14)	1.7 (0.6)	61	32 (7)	1.1 (0.3)	64	48 (11)	1.1 (0.2)
	FP-3x3m	168	34 (17)	0.7 (0.4)	-	- -	- -	150	53 (19)	1.3 (0.4)	164	33 (13)	1.4 (0.6)	153	33 (11)	0.9 (0.3)	191	40 (11)	0.9 (0.2)
6	G-P	59	57 (18)	1.2 (0.4)	64	71 (17)	2.9 (0.9)	62	94 (34)	2.2 (0.7)	62	58 (24)	2.4 (0.9)	41	44 (14)	1.2 (0.3)	60	56 (16)	1.2 (0.3)
	M-B-M-M	49	72 (26)	1.1 (0.4)	61	86 (24)	2.2 (0.6)	44	104 (46)	2.0 (0.8)	56	59 (27)	1.9 (0.8)	19	50 (15)	1.2 (0.3)	58	53 (13)	1.1 (0.3)
	B-R-R	60	52 (15)	1.1 (0.4)	63	74 (20)	2.8 (0.9)	61	96 (31)	2.1 (0.6)	60	66 (29)	2.5 (0.9)	37	41 (10)	1.1 (0.3)	60	57 (13)	1.1 (0.2)
	C-S	63	47 (14)	1.1 (0.4)	63	66 (19)	2.4 (0.9)	61	91 (34)	2.2 (0.8)	52	46 (20)	1.9 (0.8)	39	44 (10)	1.1 (0.2)	61	50 (15)	1.0 (0.3)
	FP	54	52 (12)	1.2 (0.3)	63	67 (16)	3.0 (1.0)	57	94 (40)	2.5 (0.7)	44	54 (28)	2.3 (1.0)	36	46 (17)	1.3 (0.4)	59	76 (21)	1.5 (0.4)
	FP-3x3m	145	48 (24)	1.1 (0.6)	-	- -	- -	100	85 (42)	2.2 (0.8)	129	44 (20)	2.0 (0.8)	87	50 (20)	1.3 (0.5)	178	51 (17)	1.2 (0.4)
9	G-P	56	77 (27)	1.7 (0.4)	64	98 (19)	3.5 (0.8)	61	114 (52)	2.9 (0.8)	62	135 (46)	3.8 (1.1)	30	56 (16)	1.4 (0.5)	60	92 (24)	1.8 (0.4)
	M-B-M-M	47	82 (23)	1.3 (0.5)	59	106 (23)	2.9 (0.6)	39	119 (69)	2.7 (1.3)	53	96 (36)	2.8 (1.0)	14	56 (20)	1.4 (0.4)	58	87 (24)	1.6 (0.4)
	B-R-R	57	59 (17)	1.4 (0.5)	62	102 (23)	3.2 (0.9)	61	116 (42)	2.6 (0.7)	60	134 (47)	3.7 (1.0)	21	53 (14)	1.4 (0.4)	60	82 (19)	1.6 (0.4)
	C-S	63	66 (18)	1.4 (0.4)	63	102 (26)	2.9 (0.9)	60	118 (52)	2.7 (0.8)	52	120 (42)	3.1 (0.9)	29	59 (15)	1.4 (0.4)	60	85 (22)	1.5 (0.4)
	FP	54	83 (25)	1.9 (0.6)	63	114 (30)	3.8 (1.0)	56	135 (66)	3.1 (1.0)	41	131 (75)	3.6 (1.5)	26	71 (23)	2.0 (0.5)	58	127 (35)	2.5 (0.5)
	FP-3x3m	132	64 (28)	1.6 (0.7)	-	- -	- -	93	109 (58)	2.6 (0.9)	125	88 (49)	2.7 (1.1)	63	67 (22)	1.7 (0.6)	176	74 (23)	1.5 (0.5)
12	G-P	56	179 (54)	2.6 (1.0)	64	134 (41)	3.8 (0.9)	59	157 (60)	3.5 (1.1)	62	337 (101)	6.9 (1.7)	29	114 (31)	2.3 (0.8)	60	163 (28)	2.8 (0.7)
	M-B-M-M	46	159 (47)	2.5 (0.8)	59	124 (39)	4.3 (1.2)	37	177 (80)	3.5 (1.4)	53	252 (91)	5.7 (1.7)	13	105 (29)	2.3 (0.6)	58	141 (32)	2.7 (0.6)
	B-R-R	56	110 (45)	2.3 (0.8)	62	103 (36)	4.3 (1.2)	61	148 (54)	3.6 (1.0)	60	334 (101)	6.8 (1.5)	21	101 (29)	2.3 (0.8)	60	143 (35)	2.9 (0.6)
	C-S	63	144 (52)	1.9 (0.5)	63	138 (50)	3.8 (1.0)	59	172 (67)	3.4 (1.1)	52	263 (87)	5.3 (1.2)	28	98 (25)	1.8 (0.5)	60	135 (35)	2.3 (0.6)
	FP	54	145 (53)	2.9 (0.9)	63	98 (46)	4.1 (1.2)	56	176 (72)	3.8 (1.2)	41	287 (151)	5.9 (2.4)	26	121 (29)	2.9 (0.7)	58	182 (41)	3.9 (0.9)
	FP-3x3m	131	127 (56)	2.7 (1.1)	-	- -	- -	91	171 (78)	3.8 (1.4)	125	241 (121)	5.1 (1.8)	60	107 (34)	2.8 (0.9)	176	117 (41)	2.4 (0.8)

Table 4.4 (continued): Mean height (h) and root collar diameter (rcd) of all trees excluding replanted seedlings ("biological status") by tree species, age (A) (in months after planting), and treatment (T). See Table 3.7 and Table 3.9 for abbreviations. Standard deviation is given in parentheses.

		Tree species																	
		Terminalia amazonia			*Cedrela odorata*			*Dalbergia retusa*			*Tectona grandis*			*Hieronyma alchorneoides*			*Astronium graveolens*		
A	T	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]	N	h [cm]	rcd [cm]
15	G-P	56	236 (73)	3.1 (1.0)	64	215 (69)	5.0 (1.3)	59	176 (71)	3.5 (1.2)	60	445 (112)	8.3 (1.6)	29	148 (44)	2.7 (0.7)	60	205 (40)	3.3 (0.7)
	M-B-M-M	46	180 (58)	3.2 (0.9)	59	159 (52)	5.1 (1.3)	35	200 (83)	4.0 (1.5)	53	343 (110)	7.2 (1.8)	13	138 (35)	3.3 (0.8)	57	170 (41)	3.4 (0.7)
	B-R-R	56	133 (52)	2.9 (1.0)	62	152 (47)	5.4 (1.4)	60	157 (58)	3.7 (1.1)	60	429 (125)	7.8 (1.7)	21	130 (38)	3.1 (0.9)	60	181 (40)	3.7 (0.8)
	C-S	63	157 (56)	2.4 (0.7)	63	159 (59)	4.5 (1.3)	59	182 (75)	3.6 (1.2)	52	304 (104)	6.3 (1.5)	28	120 (31)	2.5 (0.6)	60	149 (42)	2.7 (0.7)
	FP	54	184 (67)	4.1 (1.4)	63	125 (45)	5.3 (1.6)	56	197 (81)	4.4 (1.4)	41	396 (209)	7.4 (2.6)	26	169 (34)	4.0 (1.0)	58	205 (43)	4.9 (1.1)
	FP-3x3m	131	175 (73)	3.7 (1.6)	-	- -	- -	90	210 (96)	4.5 (1.5)	125	355 (174)	6.9 (2.3)	59	152 (43)	3.6 (1.2)	176	142 (55)	3.1 (1.1)
18	G-P	56	272 (85)	3.5 (1.1)	64	235 (75)	6.0 (1.4)	59	193 (80)	4.0 (1.1)	60	459 (102)	8.4 (1.6)	29	177 (55)	3.0 (1.0)	60	243 (44)	3.6 (1.0)
	M-B-M-M	46	201 (63)	3.8 (1.2)	59	165 (55)	6.2 (1.6)	35	215 (98)	4.6 (1.5)	52	391 (119)	7.8 (1.5)	13	161 (42)	3.6 (1.0)	57	190 (45)	3.7 (0.8)
	B-R-R	56	154 (63)	3.3 (1.2)	62	155 (51)	6.3 (1.5)	60	172 (65)	4.0 (1.2)	60	457 (120)	8.3 (1.5)	21	152 (48)	3.4 (1.1)	60	204 (48)	4.0 (1.0)
	C-S	63	166 (58)	2.8 (0.9)	63	163 (64)	5.7 (1.5)	59	191 (84)	4.1 (1.2)	52	319 (105)	6.9 (1.5)	28	141 (38)	3.1 (1.0)	60	167 (50)	3.0 (0.8)
	FP	54	206 (75)	4.6 (1.5)	63	134 (48)	6.0 (1.5)	56	216 (86)	5.1 (1.5)	41	421 (213)	7.8 (2.5)	26	194 (42)	4.5 (1.2)	58	230 (46)	5.3 (1.2)
	FP-3x3m	130	217 (90)	4.2 (1.8)	-	- -	- -	90	251 (106)	5.1 (1.5)	122	406 (196)	7.4 (2.2)	59	171 (48)	4.0 (1.3)	176	158 (64)	3.3 (1.4)
24	G-P	56	348 (105)	6.1 (1.9)	64	276 (93)	7.1 (2.0)	57	241 (91)	4.7 (1.5)	60	696 (143)	12.6 (2.5)	29	192 (58)	3.7 (1.2)	60	279 (52)	4.7 (1.1)
	M-B-M-M	46	293 (73)	5.4 (1.4)	59	244 (83)	7.2 (1.8)	35	297 (131)	5.5 (2.1)	52	576 (89)	10.4 (2.0)	13	207 (49)	4.4 (1.1)	57	225 (51)	4.1 (1.0)
	B-R-R	54	228 (76)	4.4 (1.8)	62	229 (62)	6.8 (1.6)	57	248 (96)	4.9 (1.5)	60	574 (119)	10.7 (2.2)	20	184 (49)	4.0 (1.1)	59	241 (66)	4.5 (1.3)
	C-S	62	255 (82)	4.4 (1.6)	62	251 (76)	7.0 (2.0)	53	263 (100)	5.2 (1.5)	52	539 (112)	9.8 (1.8)	28	184 (47)	3.8 (1.0)	58	204 (51)	3.6 (0.9)
	FP	54	287 (91)	6.1 (1.9)	63	190 (59)	6.6 (1.7)	56	270 (104)	5.8 (1.7)	41	601 (206)	10.4 (3.1)	26	238 (54)	5.4 (1.3)	58	257 (60)	6.1 (1.4)
	FP-3x3m	98	354 (131)	5.9 (2.2)	-	- -	- -	87	312 (124)	5.7 (1.6)	75	708 (249)	9.5 (2.6)	59	224 (70)	4.9 (1.5)	175	192 (88)	3.8 (1.6)

Figure 4.10 illustrates the crop rotation and crop heights[58] during the time intervals investigated. This figure is intended to guide the reader through the results section.

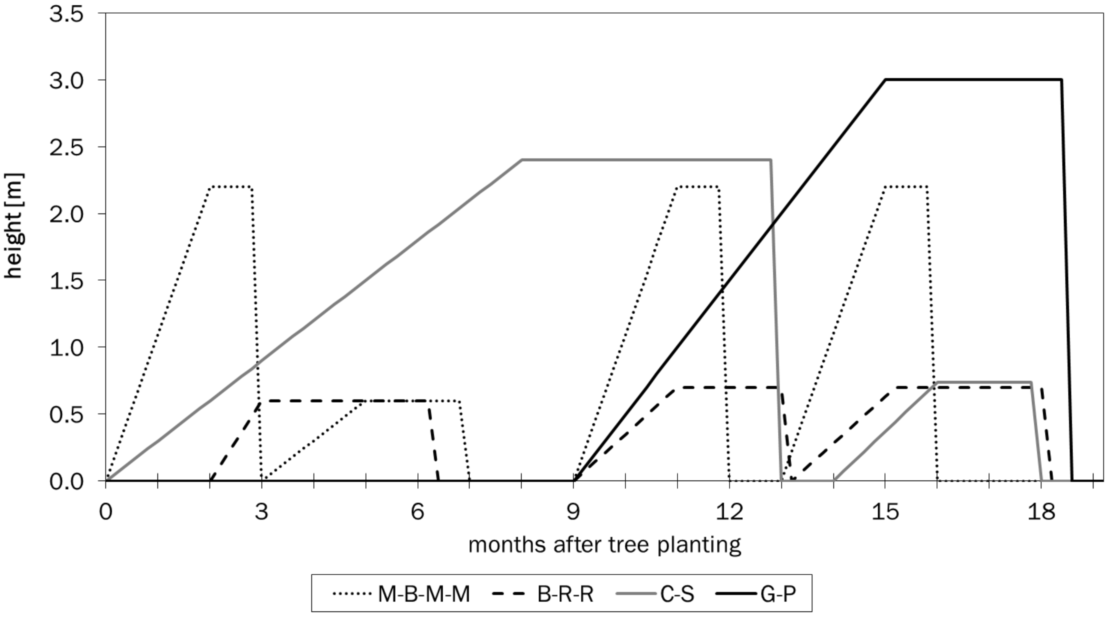

Figure 4.10: Heights of crops during different crop rotations in the agroforestry treatments (see also Figure 3.7, page 33). (M-B-M-M = Maize-beans-maize-maize rotation, B-R-R = Beans-rice-rice rotation, C-S = Cassava-soy beans rotation, G-P = Ginger-pigeon pea rotation).

Table 4.5 shows that the type of intercropping, i.e. different crop rotations and pure forest plantation[59], had a significant effect on growth performance for most tree species. During the first 3 months after planting, trees growing in maize fields showed a superior height increment (Figure 4.9, see also Table 4.4). Initial height growth of *C. odorata*, *D. retusa*, *H. alchorneoides* and *T. amazonia* was significantly higher in the maize fields (M-B-M-M treatment) compared to all other treatments (Figure 4.11 a). For *C. odorata*, all pairwise comparisons of the M-B-M-M with other treatments were even more highly significant, with p-values below 0.007. Trees of *T. grandis* and *A. graveolens* also tended to have higher increments in the maize plots during the first 3 months, however, the differences were not significant. Yet, during subsequent months, trees that were previously intercropped with maize showed a rather inferior height growth. For instance, after six months – 3 months after the maize harvest (Figure 4.10) - trees of *T. amazonia* were still taller in the former maize fields compared to other treatments, but by less than 40%, as opposed to the 65% height difference measured after 3 months (Table 4.4). Nine months after planting, when the next maize rotation of the M-B-M-M treatment started, trees in this treatment were overtaken in height by trees growing in the FP treatment. The same pattern was observed for *C. odorata* and D retusa. It might be argued that the strong effect of maize on growth performance of trees in the first 3 months was due to fertilization of maize. However, fertilizer was applied at a distance of at least 50 cm from the newly planted trees, which themselves had received the same fertilizer a week before the maize plants were treated. Hence, it is rather unlikely that tree seedling growth was influenced by the additional fertilization. A more plausible explanation could be that competition for light with the maize plants might have stimulated the height growth of the tree seedlings in the maize treatments.

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[58] Heights were only measured before harvest, growth curve is therefore displayed in a simplified linear shape

[59] In this chapter the phrase "pure forest plantation" always refers to the FP treatment, where trees were not intercropped, but planted in the simplified fan design (see chapter 3.2.3).

Table 4.5: P - values of fixed effects tested by a linear mixed model with the transformed dependent variables height increment (ln(h)) and root collar diameter increment (ln(rcd)) of target trees within different time periods (fixed factors: Treatment, covariable: microrelief, random intercept for plots, controlling for cluster- effect of trees nested in plots; analysis was carried out separately for each tree species). Significant differences are presented in bold.

		time period [months after planting]							
Tree species	Factor	0-3		0-9		9-18		18-24	
		ln(h)	ln(rcd)	ln(h)	ln(rcd)	ln(h)	ln(rcd)	ln(h)	ln(rcd)
A. graveolens	Treatment	0.051	0.106	**0.002**	**<0.001**	**0.002**	**0.003**	0.606	0.157
	microrelief	0.428	0.744	0.791	0.380	0.461	0.562	0.595	0.057
C. odorata	Treatment	**0.003**	**0.043**	0.191	0.103	**<0.001**	**0.241**	0.353	0.565
	microrelief	0.097	0.150	**0.023**	0.177	**0.016**	0.272	0.052	0.971
D. retusa	Treatment	**0.037**	0.350	0.539	0.695	**0.024**	**0.042**	0.436	0.238
	microrelief	0.172	**0.028**	**0.038**	**0.038**	**0.001**	**0.753**	0.196	0.896
H. alchorneoides	Treatment	**0.030**	0.126	0.098	0.051	0.071	0.389	0.169	0.571
	microrelief	0.651	0.099	0.115	0.377	0.893	0.318	0.705	0.714
T. grandis	Treatment	0.373	0.334	0.276	0.213	**0.014**	0.073	**0.023**	0.360
	microrelief	**0.039**	**0.006**	**<0.001**	**0.007**	0.145	0.449	0.081	0.607
T. amazonia	Treatment	**0.043**	0.723	**0.043**	**0.005**	**0.046**	**0.033**	0.640	**0.004**
	microrelief	0.488	0.168	0.873	0.158	0.645	0.975	0.304	0.766

After 9 months, the highest mean tree heights were observed in the pure forest plantation plots (FP) for all tree species, ranging between 71 cm (± 23 cm) (*H. alchorneoides*) and 135 cm (± 66 cm) (*D. retusa* and *T. grandis*) (Table 4.4). But, compared to the first 3 months, differences between treatments were small, which was also true for the target trees. Significant treatment effects on height increment during the first 9 months were detected only for *T. amazonia* ($p = 0.043$) and *A. graveolens* ($p = 0.002$). Until the end of the first dry season, *T. amazonia* trees associated with beans grew significantly slower than trees intercropped with ginger (which can be regarded as no crop, see Figure 4.10) ($p = 0.012$) or with maize ($p = 0.014$) and those without any intercropping ($p = 0.009$) (Figure 4.11 b). A clearly superior growth of trees in the FP plots was detected for *A. graveolens* compared to all other treatments (pairwise comparisons $p < 0.009$). While trees in the agroforestry treatments showed a rather homogenous increment of between 8 and 9 cm per month, height growth on the FP plots was 50% superior (12 cm per month (± 3.6 cm month). This effect is most likely to be explained by small site differences which might particularly favor the growth of this tree species. The surprisingly small differences in height growth in the first 9 months show that the maize had a very short-term positive impact on growth performance.

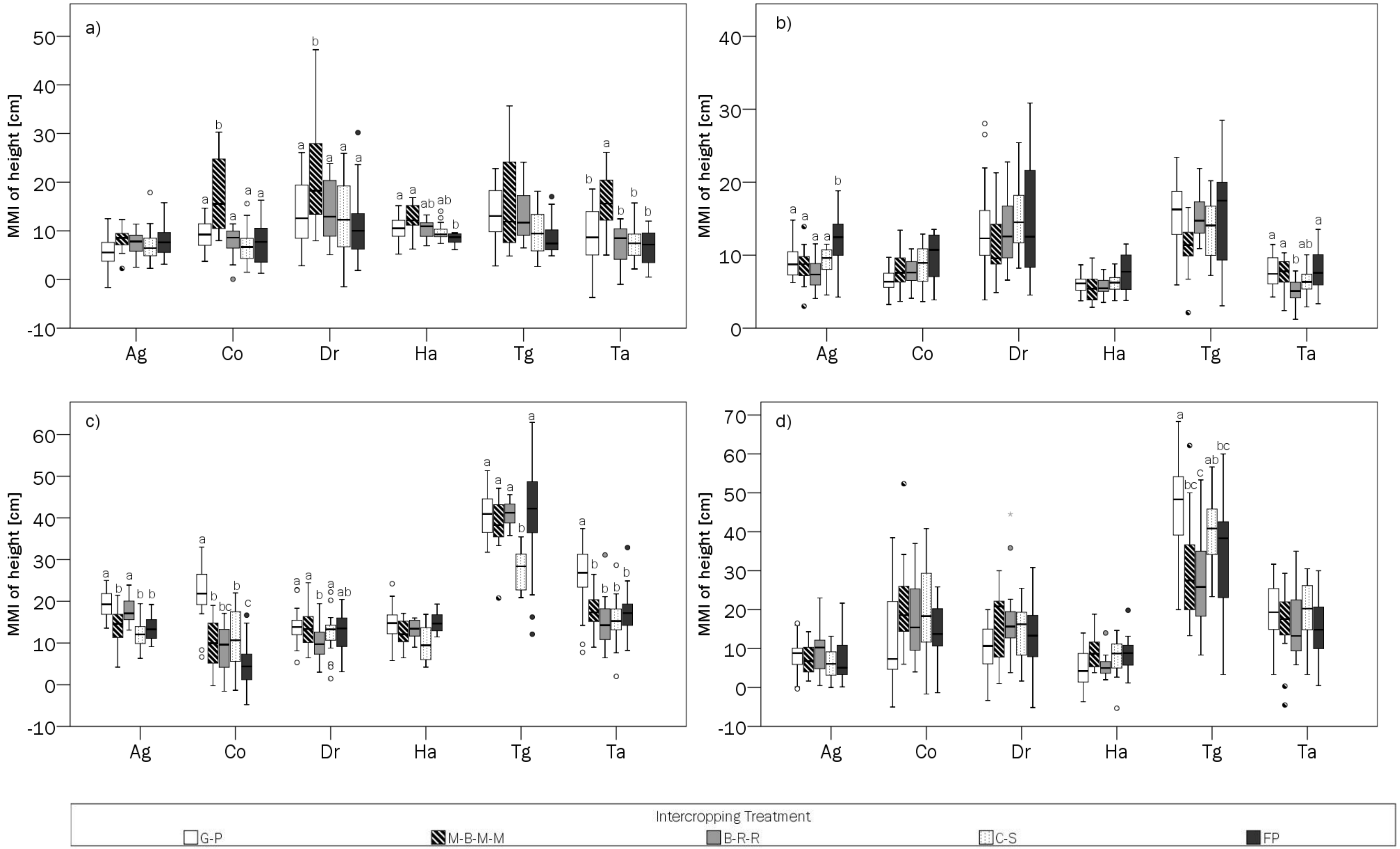

Figure 4.11 a-d: Mean monthly height increment (MMI) of target trees during the first 3 months (a), 0-9 months (b), 9-18 months (c) and 18-24 months (d) by tree species and intercropping treatment. Different letters denote significant differences between treatments within tree species according to the LSD test ($p < 0.05$), if fixed effect “treatment” was significant (see table Table 4.5). Please note that the scale of the y-axis differs between time intervals in order to improve readability. See Table 3.4, page 23 for abbreviations of tree species and Table 3.7 page 27 for abbreviations of treatments.

After the first dry season, tree growth started to accelerate, especially during months 9 to 12. During this phase, the highest increments of the entire observation period were measured. This was true for all species with the exception of *C. odorata.* The mean increments of the target trees per treatment and tree species ranged from 14 cm per month (*H. alchorneoides* in the C-S treatment) to 78 cm per month (*T. grandis* in G-P treatment). The maximum height increment was found for one teak tree (FP treatment), which grew 123 cm per month during these three months. The biggest increment for a native species was also found in this time period, for a *T. amazonia* tree in the C-S treatment which grew 77 cm per month. Referring to the entire time interval from 9 - 18 months one trend was observed for all species except *H. alchorneoides* and *D. retusa* - the striking height growth of trees associated with pigeon pea (see blue line in Figure 4.9). Pigeon pea was planted after 9 months but took until month 12 to reach its final height of about 3 m (Figure 4.10). It seems as if the intercropping with pigeon pea induced a greater investment by the trees in height growth. For instance, *T. amazonia* showed an average growth of trees in the ginger fields compared to the other treatments. As the ginger seedlings were lost, trees in this treatment grew without association of crops until month 9, when pigeon pea was sown. At age 12 months *T. amazonia* trees in association with pigeon pea were already 10 to 60% taller than those intercropped with other crop rotations, and after 15 months their heights exceeded those of other treatments by 28 to 77%. At the time of the pigeon pea harvest, trees that had grown associated with the leguminous shrubs were between 66 cm (32%) and 118 cm (76%) taller compared to those in the FP and B-R-R treatments, respectively.

Between month 9 and 18, the height increment of *T. amazonia*, *C. odorata* and *A. graveolens* was significantly higher in association with pigeon pea compared to all other treatments with the exception of the B-R-R treatment (Figure 4.11 c). Pairwise comparisons between treatments within the tree species *C. odorata* and *A. graveolens* were highly significant, with $p < 0.008$. For *C. odorata, the* height increment between 9 and 18 months was four times superior in the G-P treatment compared to the FP treatment, and over two times higher than that for the other agroforestry treatments. The low increment on the control plots of this species can be explained by the high infestation rate with *H. grandella* (to be presented in chapter 4.2.3.3.1). Significant treatment effects in this time period were also detected for *D. retusa* ($p = 0.024$) and *T. grandis* ($p = 0.014$) (Table 4.5). While the increment of *D. retusa* trees in the B-R-R treatment had been average during the first 9 months ($p > 0.229$ compared to other treatments), height growth decreased from 14 cm (± 5 cm) to 9 cm (± 4 cm) per month during the period from 9 - 18 months when the trees were intercropped with rice. Accordingly, the B-R-R treatment showed a significantly lower height growth in months 9 - 18 compared to the G-P ($p = 0.002$), the M-B-M-M ($p = 0.01$) and the C-S treatments ($p = 0.039$). For *T. grandis* a similar effect was detected in the C-S treatment. During month 12 and 15, after the cassava harvest, height growth slowed down considerably compared to other treatments. As a consequence, the height increment between 9 and 18 months was 40 – 50 % lower than that in the other treatments ($p < 0.011$). Obviously, the increment of associated trees was higher when cassava had reached its final height compared to the time after crop harvest.

During the last phase, between 18 and 24 months, intercropping did not show any long-term effect on height growth (Table 4.5). The one exception was that for *T. grandis*, a significantly higher increment was recorded in the former G-P plots compared to the former M-B-M-M ($p = 0.011$), the B-R-R ($p = 0.003$) and the FP treatments ($p = 0.024$). Despite the small differences in height increment between treatments, all tree species still tended to be highest in the former G-P treatment, even 6 months after the harvest of pigeon pea. The status after 24 months will be described in more detail in the following chapter.

Diameter growth showed an overall similar pattern to that of height growth, with peaks between 9 and 12 months. However, differences were generally smaller and some opposite patterns were detected: In contrast to height increment, diameter growth did not increase during intercropping with maize. Trees of all species showed lower diameters at the end of the first maize rotation compared to other treatments (Figure 4.13, see next page). However, differences were generally small, only proven to be statistically significant for *C. odorata* ($p = 0.043$) (Table 4.5). As previously mentioned, it is not surprising that trees seemed to invest in height growth at the expense of diameter growth due to competition for light. This is also supported by the fact that trees in treatments without associated crops - i.e. FP and the initial phase of the G-P treatment - tended to have a higher root collar diameter after 9 months than those who had to compete with maize or other crops during the first months after establishment. However, differences between treatments were – as in the case of height growth - relatively small during the first 9 months. An influence of treatment on diameter increment was proven only for *T. amazonia* ($p = 0.005$) and *A. graveolens* ($p < 0.001$). *T. amazonia* showed a larger diameter increase on FP plots compared to M-B-M-M ($p = 0.001$), B-R-R (0.001) and C-S plots ($p = 0.006$). Accordingly, the G-P treatment – which can be considered a treatment without association of crops during the first nine months – showed larger diameter increments than both the M-B-M-M ($p = 0.031$) and the B-R-R ($p = 0.042$) rotations. This effect was even more evident for *A. graveolens,* which performed 50% better in terms of diameter growth on the FP plots compared to treatments with intercropping ($p < 0.002$). However, even the G-P treatment, in which management was identical to the FP treatment at that time, performed worse ($p = 0.002$), indicating that more favorable site conditions for *A. graveolens* on the FP plots might explain these differences better than differences in management practices or competition with crops. This is supported by the non-significant pairwise comparisons between the G-P treatment and the other agroforestry treatments ($p = 0.107$).

During the last phase of observation, only for *T. amazonia* was a significant effect of the experimental factor treatment in terms of diameter increment proven. Surprisingly, the diameter increment was larger on former G-P plots compared to former M-B-M-M ($p = 0,002$), B-R-R ($p = 0.001$) and FP plots ($p = 0.007$), although the increment had been smaller in the G-P treatment during the period from 9 - 18 months ($p > 0.053$) (Figure 4.13). Other tree species reacted similarly – yet not significantly.

The **microrelief** was proven to play an important role in growth performance. Trees planted in relative depressions were generally associated with smaller heights and diameters. This effect was proven to be significant for *C. odorata, D. retusa* and *T. grandis*[60]. For instance, during the first nine months, microrelief had a significant effect on the height growth of *T. grandis*, *C. odorata* and *D. retusa* ($p < 0.001$). The estimation of the fixed effect for microrelief (i.e. b_2 see Equation (3.2) ranged between -0.44 (*T. grandis*) and -0.014[61] (*T. amazonia*), indicating that trees growing in a relative depression - in this case coded as 1 - showed a smaller increment compared to trees growing on the flank or top of a mound (coded 0). The single exception was *A. graveolens,* for which a slightly positive ($b = 0.032$) yet not significant ($p = 0.79$) effect of the microrelief on height increment was found. A similar pattern was found, for both diameter and height increment during both the first three months and the period between 9 and 18 months (Table 4.5). No effect of microrelief on either height or diameter growth was observed during the period from 18 – 24 months. The results indicate that *T. grandis*, *D. retusa* and *C. odorata* tended to be more sensitive to differences in microrelief than other tree species, when controlling for treatment and time effects. *T. amazonia* and *A. graveolens* also seemed to be less sensitive towards differences in the microrelief on soils with high clay content. The interaction between microrelief and treatment was not significant for any tree species or time interval, and was therefore omitted from the model. This also indicates that the growth of trees on difficult microreliefs was neither impeded nor improved by intercropping

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[60] Even though the effect of microsite was not significant for any of the tree species it was not omitted from the model, as it significantly improved model fit, which was assessed using the Bayesian Information Criteria (BIS)

[61] These b-values are based on transformed outcome variables and can therefore not be interpreted directly (see chapter 3.5.1. Entire estimation of fixed effects are given in (Table 11.3 ff. in the appendix)

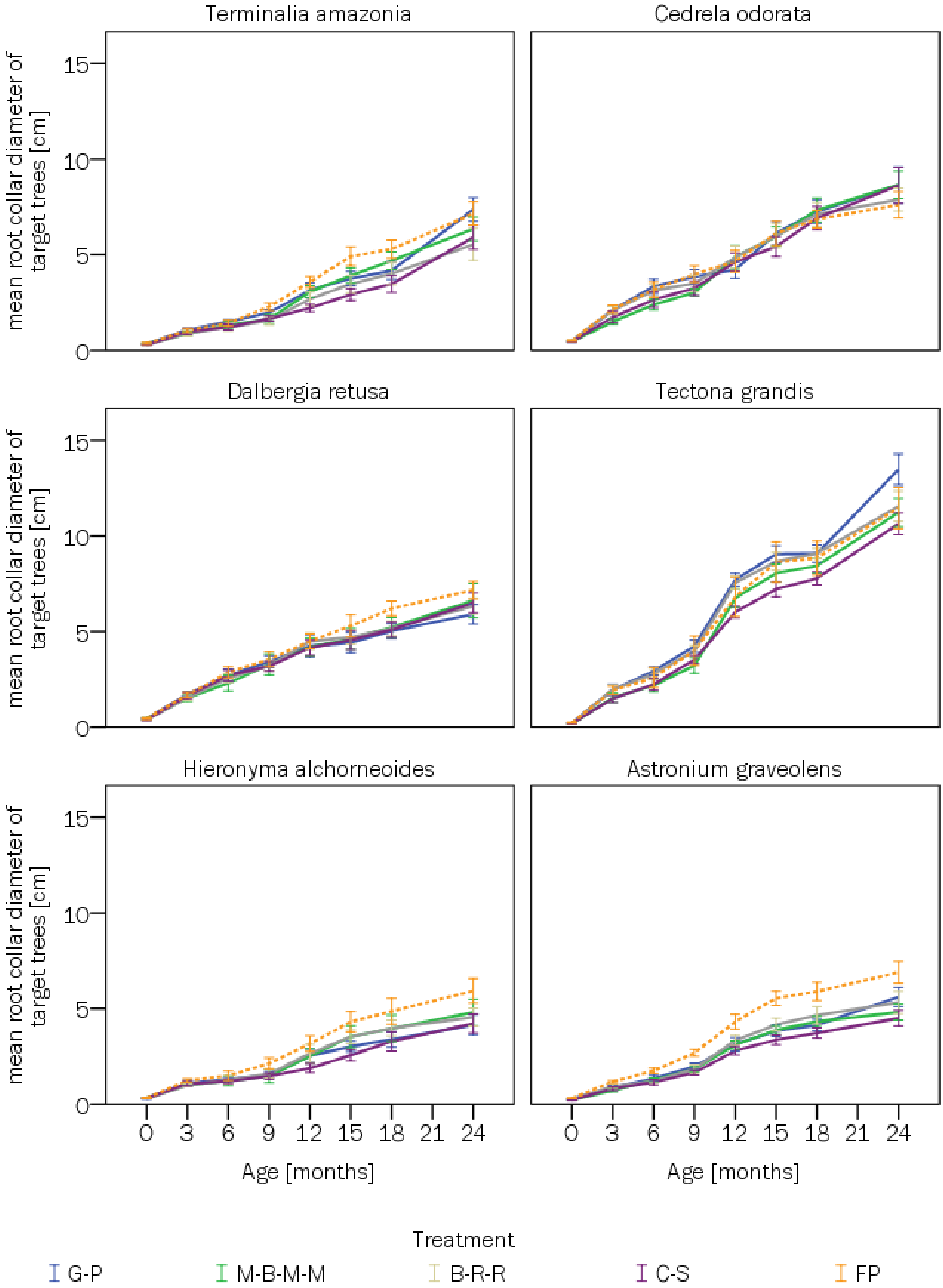

Figure 4.12: Development of root collar diameter of target trees in association with different crop rotations during the observation period. Error bars denote 95% confidence interval (N = 20 per treatment and tree species).

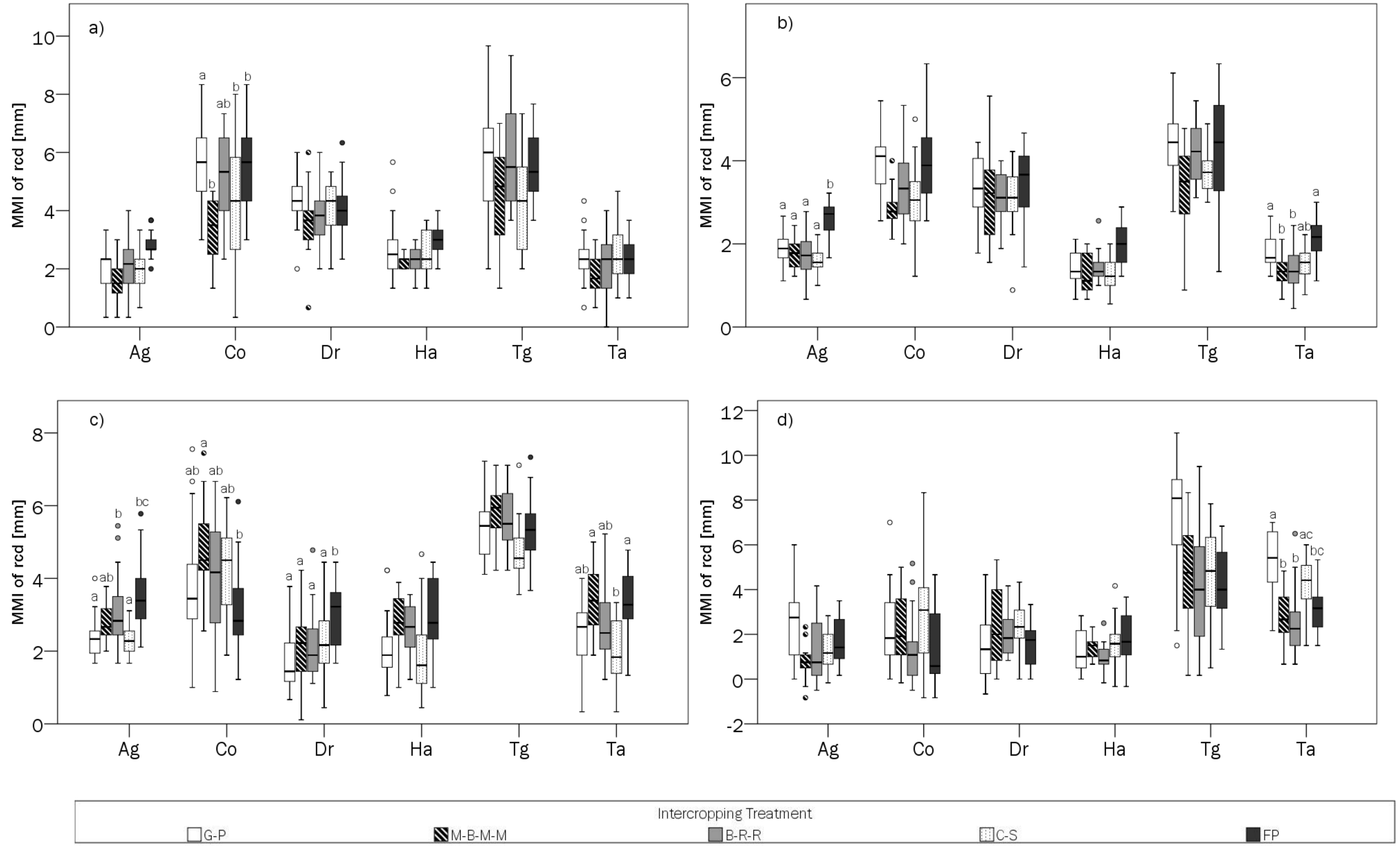

Figure 4.13: a-d: Mean monthly root collar diameter (rcd) increment (MMI) of target trees during the first 3 months (a), 0-9 months (b), 9-18 months (c) and 18-24 months (d) by tree species and intercropping treatment. Different letters denote significant differences between treatments within tree species according to the LSD test ($p < 0.05$), if fixed effect “treatment” was significant (see table Table 4.5). Please note that the scale of the y-axis differs between time intervals in order to improve readability. See Table 3.4, page 23 for abbreviations of tree species and Table 3.7 page 27 for abbreviations of treatments.

4.2.3.1.2 Status after two years

In this chapter, the final status of the trees after 24 months will be described to evaluate the effects of the crop rotations and their associated management practices on tree performance. The discussion in the previous chapter showed that the differences between treatments decreased in the period between 18 and 24 months when intercropping was no longer carried out. However, three of six tree species still showed significant differences between individuals grown in plots with previous crop-rotations, even 6 months after the last crop harvest (Table 4.6).

Table 4.6: P-values for fixed effects tested by a linear mixed model with the transformed dependent variables height (ln(h)), root collar diameter (ln(rcd) and slenderness (h/d) of target trees after 24 months (fixed factors: Treatment, covariable: microrelief, random intercept for plots, controlling for cluster- effect of trees nested in plots. Analysis was carried out separately for each tree species).

Tree species	Source	ln(h)	ln(rcd)	h/d
A. graveolens	Treatment	**0.026**	**0.013**	**0.003**
	Microrelief	0.495	0.251	0.080
C. odorata	Treatment	**0.018**	0.626	0.207
	Microrelief	0.192	**0.018**	0.159
D. retusa	Treatment	0.937	0.171	0.443
	Microrelief	0.323	0.368	0.152
H. alchorneoides	Treatment	0.118	**0.011**	0.259
	Microrelief	0.179	0.391	0.725
T. grandis	Treatment	0.068	0.130	0.804
	Microrelief	0.453	0.283	0.880
T. amazonia	Treatment	**0.031**	0.076	0.147
	Microrelief	0.809	0.431	0.399

The tree species *A. graveolens*, *C. odorata*, *T. amazonia* and *T. grandis* generally tended to be tallest in the G-P treatment (Figure 4.14 a). This difference was proven to be statistically significant with the exception of *T. grandis*. Despite the small differences in height increments between treatments during the period from 18 - 24 months, at the end of the observation period *T. amazonia* and *C. odorata* for instance, were – on average - still 150 cm (≙ 50%, p = 0.002) and 78 cm (≙ 24%, p = 0.036) taller in the former G-P treatment compared to the B-R-R treatment (p = 0.002 and p = 0.036, respectively). Differences between tree heights were also proven to be significant between the former G-P and FP treatment for both tree species (Figure 4.14 a). Moreover, in the case of *T. amazonia* and *A. graveolens,* trees showed a significantly better height growth performance over the entire observation period in the G-P treatment compared to the C-S treatment (p = 0.025 and p = 0.004, respectively). While trees in the C-S treatment showed a rather inferior height for most tree species, in the case of *C. odorata,* the C-S treatment showed significantly greater heights compared to the FP treatment (p = 0.006). This might be attributed to the lower infestation rates with *H. grandella* that will be presented in the following chapter. No statistically significant differences between treatments were detected for *D. retusa*, *H. alchorneoides* and *T. grandis*. Individuals of *D. retusa* and *H. alchorneoides* showed relatively small increases in height in association with the former G-P rotation and a comparatively good performance in the M-B-M-M rotation. Individuals of *H. alchorneoides* grown in the agroforestry treatments tended to be shorter after 24 months than those grown on the pure forest plantation plots.

Hence, intercropping with pigeon pea seemed to have a rather positive effect on height growth for the majority of the tree species, while none of the intercropping rotations had a significantly negative effect on tree growth.

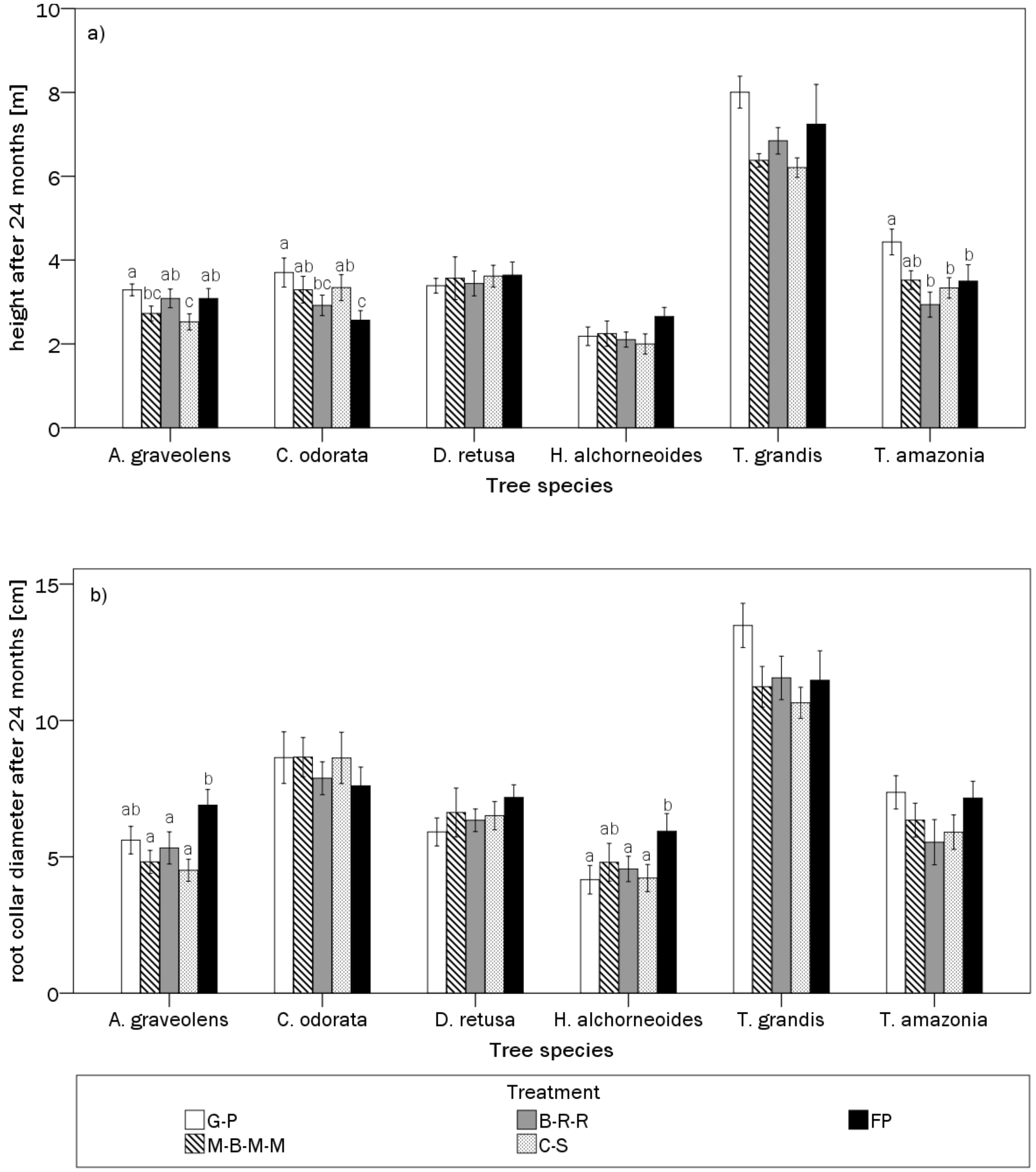

Figure 4.14: Height (a) and root collar diameter (b) of target trees after 24 months. Bars denote 95% confidence intervals. Different letters denote significant differences between treatments within tree species according to the LSD test ($p < 0.05$), if fixed effect “treatment” was significant (see Table 4.6)

With regard to diameter growth, *T. amazonia*, *C. odorata* and *T. grandis* trees in association with pigeon pea showed the largest mean diameters after 24 months. However, differences between treatments were not proven to be significant (see Table 4.6). The overall larger diameters in the former G-P treatment can be mainly attributed to the large increment gained after the harvest of the pigeon pea shrubs (18 - 24 months), as root collar diameters in this treatment tended to be small when measured at 18 months (see Table 4.4, Figure 4.13 d)). Despite the trend of large diameters in the former G-P treatment for these four species, the only significant treatment effects on root collar diameter after 24 months were detected for *H. alchorneoides* and *A. graveolens*. Both tree species had significantly higher root collar diameters without association of crops compared to those in the agroforestry treatments ($p \leq 0.021$). Two exceptions were the M-B-M-M rotation in the case of *H. alchorneoides* ($p = 0.062$) and the G-P rotation in the case of

A. graveolens (p = 0.067) (Figure 4.14 b). Hence, in the FP treatment, both tree species tended to grow more in diameter than in height compared to those in the agroforestry plots. This is illustrated by the slenderness value, which was significantly lower after 24 months for *A. graveolens* in the FP treatment compared to all intercropping rotations ($p \leq 0.003$, see Figure 4.15 and Table 4.6). As described above, it can be assumed that competition for light induced higher investment in height than in diameter growth in the intercropping treatments compared to the pure forest plantation. However this was not proven to lead to significant differences in the h/rcd values for the other tree species. The final height and diameter measurements furthermore show that with the exception of *A. graveolens* and *H. alchorneoides,* no negative effects of intercropping on tree performance during the first two years were found.

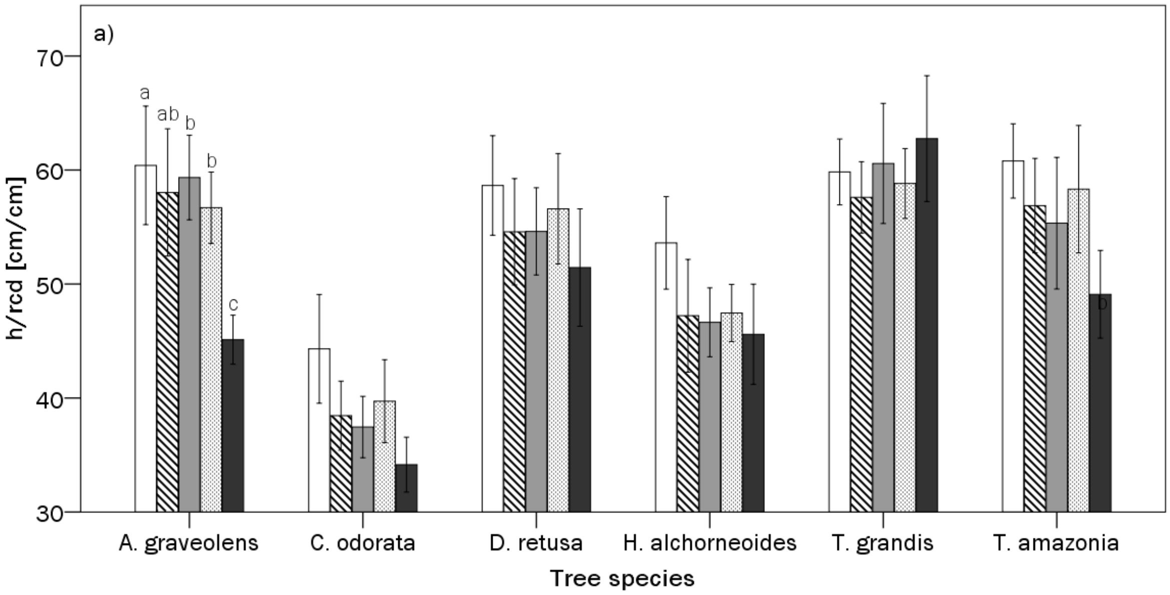

Figure 4.15: Slenderness (h/rcd) of target trees after 24 months. Bars denote 95% confidence intervals. Different letters denote significant differences between treatments within tree species according to the LSD test ($p < 0.05$), if fixed effect "treatment" was significant (see Table 4.6).

Surprisingly, **microrelief** did not have a significant effect on final height (Table 4.6). Final diameter was only significantly influenced by the microrelief in the case of *C. odorata*, where growing in a relative depression (coded as 1) was related to smaller diameters. (b = -0.1 p = 0.018 95% confidence interval -0.18 to -0-02). This is also true for the other tree species, even though the difference was not proven to be significant. However, as the model was improved by including the factor microrelief – shown by the smaller BIC value – it was not omitted from the model.

4.2.3.2 Tree survival

Figure 4.16 presents the mean survival rate of the different treatments and tree species. As already delineated in chapter 5.1.3, survival rate was highest for *A. graveolens* and *C. odorata* and lowest for *H. alchorneoides.* For this species a minimum survival rate of 6% - which means that only one out of 16 trees survived - was found in two plots, which were both assigned to the M-B-M-M treatment. This reflects the general observation regarding treatment-related differences: At the end of the observation period, the lowest survival rates for all tree species, except *T. grandis*, were observed in the M-B-M-M treatment. The difference is most striking for *D. retusa*. Mean survival rate of this tree species in the former maize fields was 55% (± 29%) after 2 years, while the survival rate of the other treatments ranged from 83% (± 6%) in the C-S treatment to 89% (± 3% and 11%) in the G-P and B-R-R treatment. Mortality in the M-B-M-M treatment mainly occurred between three and six months (Figure 4.16), indicating that trees encountered severe problems after the first maize harvest. The low survival rate in the M-B-M-M treatment might be explained by the sudden differences in the microclimate before and after the maize harvest. During the second and third months after establishment, trees in this treatment grew in the shadow of a dense maize field. By then, all trees were shorter than the maize. After the maize plants were cut, the trees had to cope with full sunlight while at the same time, precipitation decreased (due to the onset of the dry season). It is also possible that the maize consumed more water compared to other crops, thus leading to an early water deficit for trees in the former maize plots when the dry season started. High mortality might also be attributed to the process of maize harvesting. At the time of harvest, trees were between 30 and 90 cm tall, and hence, considerably smaller than the maize plants. Thus, it was necessary to pay attention during the maize harvest in order not to step on tree seedlings. The special planting design, which did not correspond to the regular grid of the maize rows, reinforced this problem. In a regular planting grid, lines with trees could have easily been avoided. Surprisingly, *T. grandis* did not show the tendency of low survival rates in the M-B-M-M plots. In contrast, the FP plots had a considerably lower mean survival rate of 64% after 24 months (± 36.9%) compared to the agroforestry treatments (81 (± 16.9) – 93% (± 8.8%)).

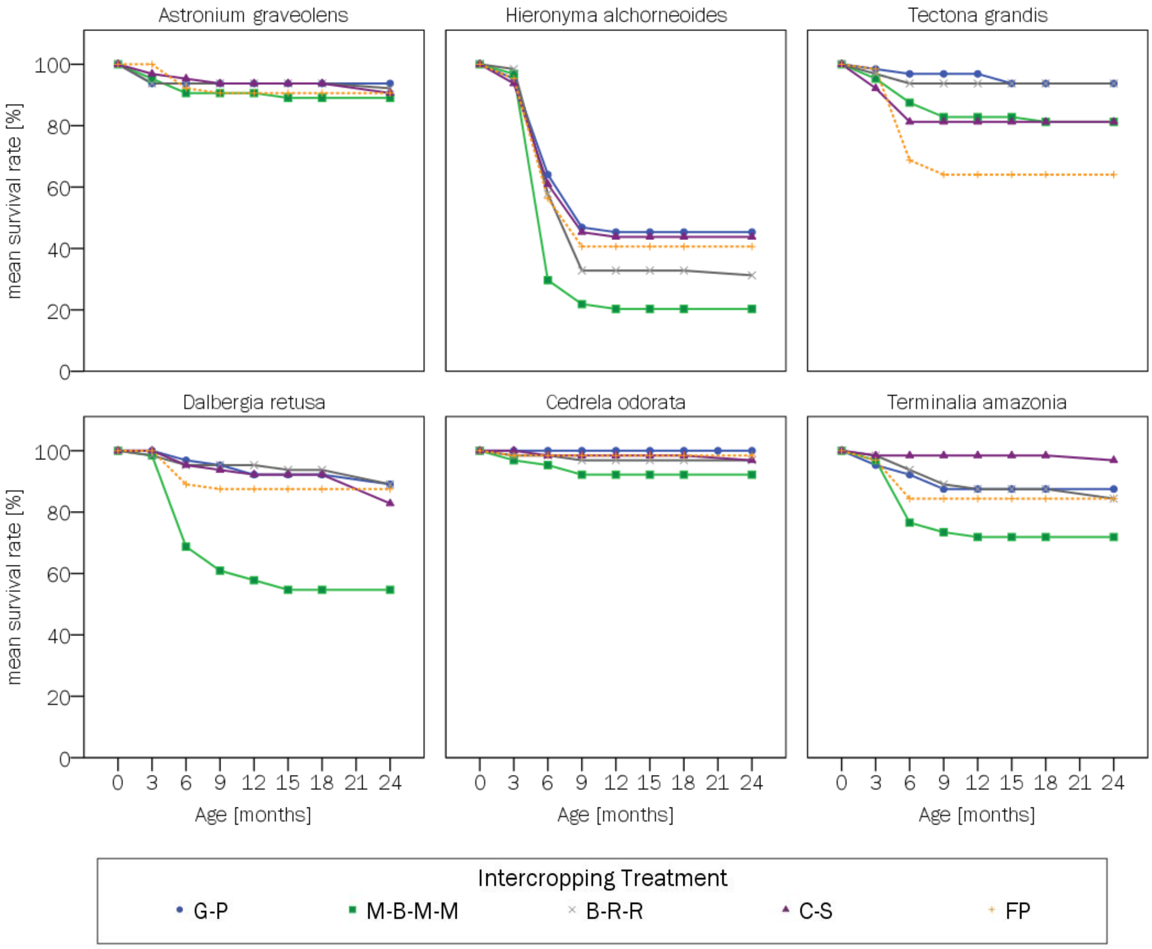

Figure 4.16: Mean tree survival per tree species and plot by treatment. (N = 4 plots - 16 trees each per tree species and treatment).

Figure 4.16 reveals that mortality was generally high between three and six months - a period corresponding to the end of the rainy season and the middle of the dry season. This result indicates that the first dry season is the most critical period for tree establishment. By the end of the dry season (at 9 months) very few trees had died. However, this graph shows the survival rate per planting position excluding replanting activities with subsequent mortality events. Accordingly,

Figure 4.17 illustrates that replanting success was particularly low in the M-B-M-M treatment (see dotted parts of the bar), indicating that the conditions for trees were not only difficult during the first dry season but also during subsequent maize rotations. For instance, in May 2009 (9 months after planting) the dead trees of *D. retusa* were replaced. Of 29 trees that had to be replaced in the M-B-M-M treatment 48% died again. *T. amazonia* and *H. alchorneoides* generally showed the lowest success of replanting activities.

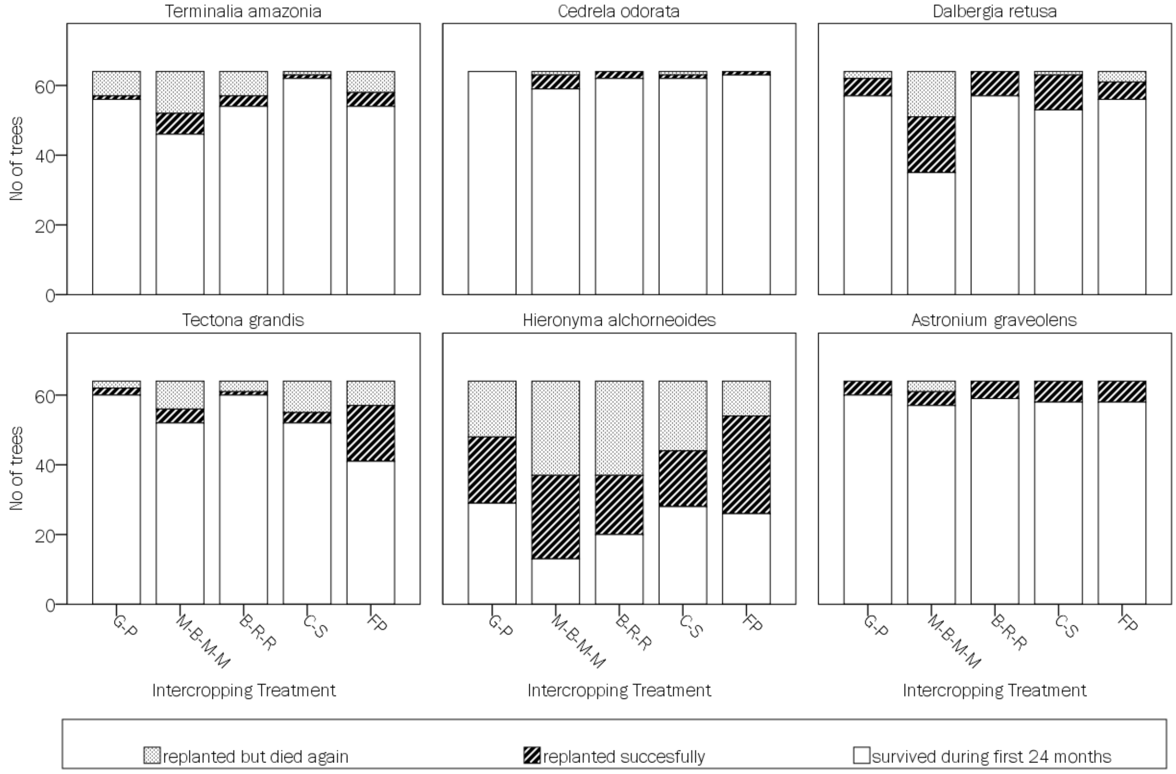

Figure 4.17: Mortality after 24 months and number of trees that died after replanting (Replanting was carried out after 3 and 9 months.

As differences in survival between tree species were proven to be significant (chapter 4.2.2), statistical comparisons between treatments were carried out separately for each tree species. The accuracy of the applied hazard function was significantly improved for all species when including the factors treatment and microrelief in the Cox model (-2-log-Likelihood statistic between models: $p < 0.01$). The hazard for mortality for trees in the M-B-M-M treatment was higher compared to all other treatments when controlling for the microrelief (Table 4.7) for all species except *T. grandis*. For *T. amazonia*, *C. odorata* and *D. retusa,* these differences were highly significant ($p < 0.01$). The highest hazard ratios ($= e^{\beta}$ see Equation (3.5)), and therefore, the greatest differences in survival probability between treatments, were found for *T. amazonia*: The hazard for mortality was 13 times higher during the first two years in the M-B-M-M treatment compared to the C-S treatment ($e^{\beta} = 13.7$, 95% confidence interval = 6.7 – 28.2, $p < 0.001$). When the M-B-M-M treatment was excluded, the agroforestry treatments tended to have a lower hazard for mortality compared to the pure forest plantation treatment. However, differences were only significant for *T. grandis*: Trees of this species had a significantly higher probability of death in the FP plots compared to all agroforestry treatments ($p < 0.001$). The small differences in predicted survival observed between treatments were proven not be significant for *A. graveolens*.

Controlling for treatment effects, all tree species had a significantly higher hazard of death when planted in a relative depression, compared to trees planted on a relatively higher planting position ($p < 0.001$) (Table 4.7). The magnitude of the hazard ratio was highest for *T. grandis* and

A. graveolens, with e^{β} equal to 3.3, indicating that the survival probability of these tree species was the most sensitive to microrelief. Though, due to the overall low mortality rate for *A. graveolens*, results for this tree species should be interpreted with caution. However, it can be concluded that the few deaths that occurred were on very humid planting positions and were most likely not because of treatment effects. In the case of *T. grandis*, a significant effect of microrelief was also proven for both height and diameter increment of this species (see previous chapter) – a further evidence of its sensitivity to planting positions in relative depressions in soils of high clay content.

Table 4.7: Hazard ratio (e^{β}) and p-values (p) of different pairs of treatments calculated by means of Cox regression (see Equation 3.5). Microrelief was included as covariable. Significant results with $p < 0.05$ are presented in bold.

Tree species	Treatment 1	vs. Treatment 2[1]									
		G-P		M-B-M-M		B-R-R		C-S		FP	
		p	e^{β}	p	e^{β}	p	e^{β}	p	e^{β}	p	e^{β}
Astronium graveolens	G-P	-	-	0.38	0.806	0.738	0.915	0.362	1.281	0.497	0.842
	M-B-M-M	0.38	1.241	-	-	0.604	1.135	0.06	1.589	0.85	1.044
	B-R-R	0.738	1.093	0.604	0.881	-	-	0.214	1.4	0.74	0.92
	C-S	0.362	0.781	0.06	0.629	0.214	0.714	-	-	0.103	0.657
	FP	0.497	1.188	0.85	0.957	0.74	1.087	0.103	1.522	-	-
	microrelief[2]	**< 0.001**	3.263	**< 0.001**	3.263	**< 0.001**	3.263	**< 0.001**	3.263	**< 0.001**	3.263
Cedrela odorata[3]	G-P	-	-	-	-	-	-	-	-	-	-
	M-B-M-M	-	-	-	-	**0.006**	2.535	**< 0.001**	4.891	**0.001**	4.104
	B-R-R	-	-	**0.006**	0.394	-	-	0.169	1.929	0.312	1.619
	C-S	-	-	**< 0.001**	0.204	0.169	0.518	-	-	0.745	0.839
	FP	-	-	**0.001**	0.244	0.312	0.618	0.745	1.192	-	-
	microrelief	-	-	**0.006**	2.127	**0.006**	2.127	**0.006**	2.127	**0.006**	2.127
Dalbergia retusa	G-P	-	-	**< 0.001**	0.184	0.713	1.108	0.53	0.85	**0.028**	0.589
	M-B-M-M	**< 0.001**	5.439	-	-	**< 0.001**	6.024	**< 0.001**	4.621	**< 0.001**	3.204
	B-R-R	0.713	0.903	**< 0.001**	0.166	-	-	0.317	0.767	**0.011**	0.532
	C-S	0.53	1.177	**< 0.001**	0.216	0.317	1.304	-	-	0.107	0.693
	FP	**0.028**	1.697	**< 0.001**	0.312	**0.011**	1.88	0.107	1.442	-	-
	microrelief	**< 0.001**	1.967	**< 0.001**	1.967	**< 0.001**	1.967	**< 0.001**	1.967	**< 0.001**	1.967
Hieronyma alchorneoides	G-P	-	-	**0.002**	0.747	0.132	0.866	0.711	1.038	0.135	0.864
	M-B-M-M	**0.002**	1.338	-	-	0.087	1.159	**< 0.001**	1.389	0.107	1.157
	B-R-R	0.132	1.155	0.087	0.863	-	-	0.055	1.198	0.982	0.998
	C-S	0.711	0.964	**< 0.001**	0.72	0.055	0.835	-	-	0.06	0.833
	FP	0.135	1.157	0.107	0.865	0.982	1.002	0.06	1.201	-	-
	microrelief	**< 0.001**	1.882	**< 0.001**	1.882	**< 0.001**	1.882	**< 0.001**	1.882	**< 0.001**	1.882
Tectona grandis	G-P	-	-	**< 0.001**	0.3	0.196	0.677	**< 0.001**	0.302	**< 0.001**	0.157
	M-B-M-M	**< 0.001**	3.333	-	-	**< 0.001**	2.256	0.973	1.006	**< 0.001**	0.523
	B-R-R	0.196	1.477	**< 0.001**	0.443	-	-	**< 0.001**	0.446	**< 0.001**	0.232
	C-S	**< 0.001**	3.314	0.973	0.994	**< 0.001**	2.243	-	-	**< 0.001**	0.52
	FP	**< 0.001**	6.374	**< 0.001**	1.912	**< 0.001**	4.314	**< 0.001**	1.923	-	-
	microrelief	**< 0.001**	3.314	**< 0.001**	3.314	**< 0.001**	3.314	**< 0.001**	3.314	**< 0.001**	3.314
Terminalia amazonia	G-P	-	-	**< 0.001**	0.44	0.767	1.063	**< 0.001**	6.056	0.183	0.774
	M-B-M-M	**< 0.001**	2.272	-	-	**< 0.001**	2.416	**< 0.001**	13.761	**< 0.001**	1.759
	B-R-R	0.767	0.941	**< 0.001**	0.414	-	-	**< 0.001**	5.697	0.103	0.728
	C-S	**< 0.001**	0.165	**< 0.001**	0.073	**< 0.001**	0.176	-	-	**< 0.001**	0.128
	FP	0.183	1.292	**< 0.001**	0.568	0.103	1.373	**< 0.001**	7.823	-	-
	microrelief	**< 0.001**	1.714	**< 0.001**	1.714	**< 0.001**	1.714	**< 0.001**	1.714	**< 0.001**	1.714

[1] Treatment coded 0 in the algorithm.

[2] As the covariable microrelief, is a binary variable (coded as 1 for a planting position in a relative depression and 0 for all other positions) it is only shown once in the matrix table

[3] No values are given for comparisons with G-P as none of the *C. odorata* tree seedling died in this treatment.

4.2.3.3 Tree quality and damages

4.2.3.3.1 Damages by Hypsipyla grandella

One major obstacle to reforestation with the valuable species, *C. odorata,* is its high susceptibility to damage by the moth, *H. grandella* (chapter 3.3.1). In this study, extent of infestation was evaluated every 3 months. When damages were detected, *H. grandella* management - namely cutting of the affected apical parts of the tree and removing, killing and burning of the larva – was carried out. In the following graph, the infestation rates per plot (i.e. per gradient of 16 trees of *C. odorata*) are presented for each 3 month interval. Hence, four samples were available for each treatment. It can be assumed that infestation was completely removed after each time period, due to intensive management.

The first damage from *H. grandella* was detected after six months, when tree height of *C. odorata* ranged between 31 and 144 cm (mean 72 cm ± 20.7 cm). Infestation rates increased during the first dry season (6-9 months) (Figure 4.18). Despite active control of *H. grandella,* infestation rates continued to increase during the 9 - 12 month period. At six months, 59% of all *C. odorata* trees in the trial were infected, and at 12 months, 70%. In the following time intervals, the abundance of *H. grandella* was generally reduced, due to the high amount of precipitation during the rainy season. Infestation rates decreased to 27.5% during the period from 12-15 months. After 24 months, when trees were measured and evaluated for the first time in 6 months, infestation was extremely high with 93%. This might be attributed to the less intensive pest management during this time period, which indicates the importance of a continuous monitoring interval of three months or less. Overall, there was only one tree (out of 320) that was not attacked by *H. grandella* at some point during the observation period. This tree, which grew in the M-B-M-M treatment, was also one of the tallest trees, reaching 450 cm after 24 months.

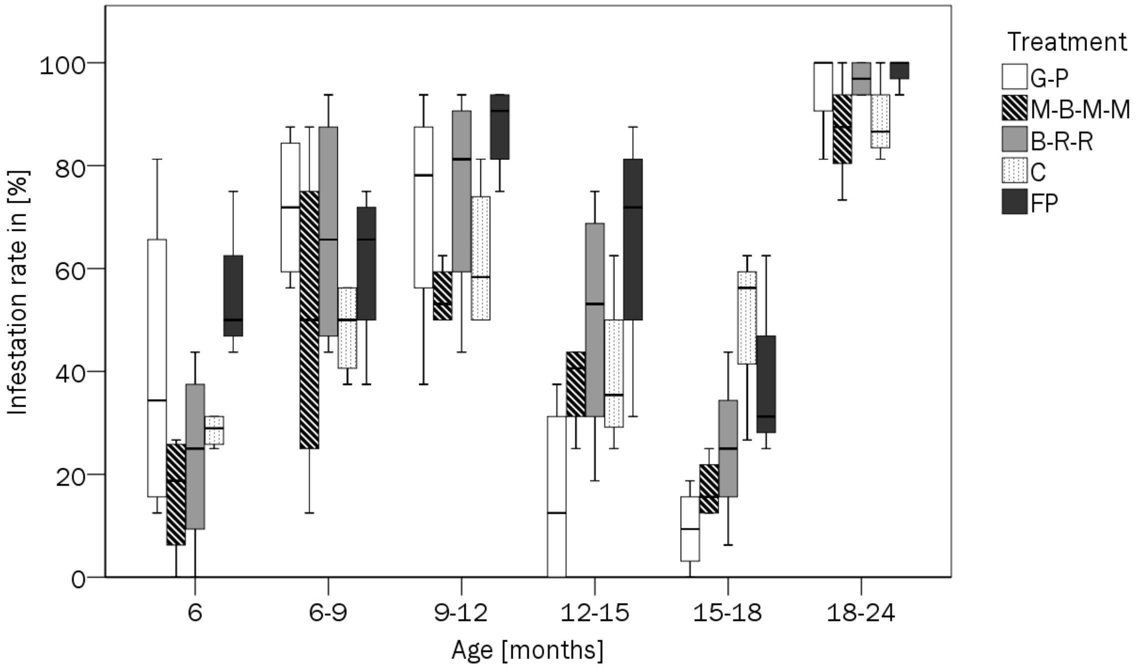

Figure 4.18: Infestation rate of *C. odorata* trees with *H. grandella* per plot by treatment and observation period (N per treatment = 4).

Prediction of infestation probability was significantly improved by the inclusion of treatment effects during all time periods (see Likelihood ratio test in Table 4.8).

Table 4.8: Likelihood ratio test and test of model effects (Type III, using Wald statistic) for the dependent variable infestation rate and the predictor treatment.

Time period	Source	Likelihood ratio test between intercept-only model and full model			Test of Model effects		
		Likelihood-Ratio-Chi-Square	df	p-value	Wald-Chi-Square	df	p-value
0-6	Intercept	27.163	4	**<0.001**	20.854	1	<0.001
	Treatment				24.651	4	**<0.001**
6-9	Intercept	11.454	4	**0.022**	5.499	1	0.019
	Treatment				9.915	4	**0.042**
9-12	Intercept	20.394	4	**<0.001**	29.114	1	<0.001
	Treatment				26.637	4	**<0.001**
12-15	Intercept	37.502	4	**<0.001**	4.363	1	0.037
	Treatment				10.785	4	**0.029**
15-18	Intercept	35.162	4	**<0.001**	58.944	1	<0.001
	Treatment				35.875	4	**<0.001**
18-24	Intercept	10.588	4	**0.032**	98.046	1	<0.001
	Treatment				10.457	4	**0.033**

Figure 4.18 reveals that infestation rates were particularly high in the G-P, B-R-R and FP treatments during the first 12 months. On plots of these three treatments either no crops (GP and FP) or only low-growing crops with less than 1 m in height (B-R-R) were planted during this time interval (see Figure 4.10 on page 65). In contrast, the mean infestation rate of plots with cultivation of maize and cassava tended to be lower. For instance, between 9 and 12 months an average of 87% (± 8%) of trees were attacked by *H. grandella* in the FP treatment but only 55% (± 6%) in the M-B-M-M treatment, and 62% (± 15%) in the C-S treatment. These differences were highly significant ($p \leq 0.001$) (Table 4.9). With increasing height of the pigeon pea shrubs, which were sown after 9 months, infestation rates decreased considerably. Between 12 and 18 months in two of the four plots assigned to this treatment, no single tree was infected by the larva. One of these plots (plot 10) still showed no damage from *H. grandella* after 18 months. Between 12 and 15 months, the odds or, in other words, the risk of a *C. odorata* tree being attacked by *H. grandella* was 10 times higher in the FP treatment compared to the GP Treatment ($e^{\beta} = 10.3$, 95% Wald confidence interval 2.27 – 47.6, $p = 0.002$) (Table 4.9). It can be assumed that tall shrubs or crops near trees might reduce the risk of severe calamities from *H. grandella*. This is also supported by the relatively high number of affected trees in the C-S treatment after the shrubs were cut at 12 months. The infestation rates in the former C-S treatment, as well as in the B-R-R and the FP treatment were significantly higher than in the G-P treatment during the period from 15-18 months ($p < 0.001$, $p = 0.033$ and 0.001, respectively). During the same time period, the odds of being attacked were also significantly lower in the M-B-M-M treatment compared to both the FP ($p = 0.03$) and C-S treatments ($p < 0.001$).

Table 4.9: P-values (p) estimated by the Wald-Chi-Test to test for differences between pairs of treatments in the fraction of infested trees per plot within each time period. Tests were carried out using simple contrasts. Significant results (p-values (p) > 0.05) are presented in bold. e^{β} is the ratio of odds for being infected by *H. grandella*, reported for each pair of treatments (see Equation 3.7) (N=4 per treatment and time period).

Age [months] Treatment 1 vs.	**Age [months]** Treatment $2^{1,2}$ vs.	**6**		**6-9**		**9-12**		**12-15**		**15-18**		**18-24**	
		p	e^{β}	p	e^{β}	p	e^{β}	p	e^{β}	p	e^{β}	p	e^{β}
FP	vs. G-P	0.36	1.76	0.26	0.61	0.11	2.74	**<0.01**	10.31	**<0.01**	5.80	0.37	3.10
C-S		0.35	0.58	**0.01**	0.37	0.44	0.64	0.06	3.55	**<0.01**	9.98	0.33	0.39
B-R-R		0.27	0.45	0.70	0.80	0.83	1.17	**0.02**	5.40	**0.03**	3.22	0.69	1.52
M-B-M-M		0.06	0.28	0.14	0.39	0.16	0.47	0.07	3.24	0.12	2.01	0.28	0.34
B-R-R	vs.M-B-M-M	0.42	1.62	0.33	2.05	0.08	2.49	0.26	1.67	0.23	1.61	**0.02**	4.51
C-S		0.07	2.12	0.91	0.94	0.32	1.35	0.79	1.10	**<0.01**	4.97	0.81	1.14
FP		**<0.01**	6.40	0.48	1.56	**<0.01**	5.80	**0.02**	3.18	**<0.01**	2.89	**0.02**	9.16
FP	vs. B-R-R	**0.01**	3.94	0.63	0.76	**0.17**	2.33	0.30	1.91	0.21	1.80	0.49	2.03
C-S		0.56	1.31	0.12	0.46	0.29	0.54	0.42	0.66	**<0.01**	3.10	**0.03**	0.25
FP	vs. C-S	**<0.01**	3.02	0.14	1.66	**<0.01**	4.31	**0.05**	2.90	0.19	0.58	**0.03**	8.02

[1] Treatment coded 0 in the algorithm

[2] Because of easier interpretation of odds > 1 control was not set as a reference category in this table. Comparison of treatments can be conversed using the reciprocal value of e^{β}

4.2.3.3.2 Tree quality

H. grandella attacks often result in severe quality losses of *C. odorata* trees, due to forked trees or multiple stems. This was also frequently observed in this trial. In addition to insect attacks, development of trees with bad growth forms can also occur due to genetic disposition, competition for space or other factors. The following section aims at answering the question whether sequential intercropping of trees leads to a lower tree quality. This question was investigated by calculating a “bad stem quality” rate, defined as the fraction of trees with forked or multiple stems per tree species and plot.

The boxplot diagrams in Figure 4.19 reveal that the effect of treatment on tree quality varied over tree species and time. Therefore no general pattern could be observed.

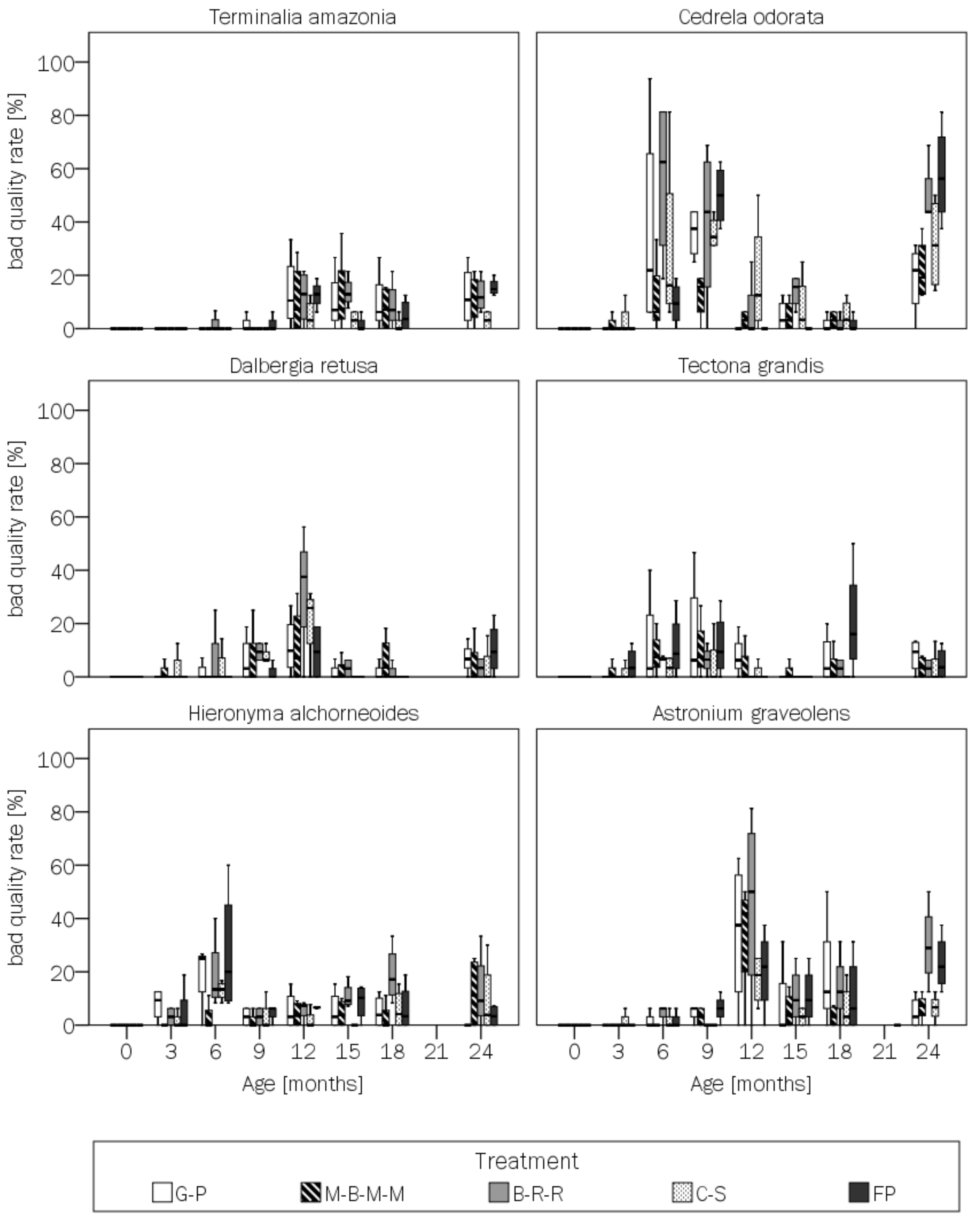

Figure 4.19: Rate of trees with badly shaped stems (bad quality rate) per plot by treatment, tree species and age. (N = 4 per tree species and treatment)

Differences in tree quality between different points in time might also be attributed to pruning activities and a potential variation in the repeated subjective assessment of quality. However, in this study the latter effect was minimized by evaluating specific quality indicators, such as the abundance of forked or multiple stems. Pruning was carried out shortly before the tree measurement after 15 months for all species except *T. amazonia*[62]. This explains the decreasing rates of badly shaped trees between 12 and 15 months in Figure 4.19. After two years, the

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[62] In the case of *T. amazonia* only very low branches were cut, as *T. amazonia* loses its branches naturally (Montero M. and Kanninen 2005).

percentage of trees with poor stem quality was below 11% for *T. amazonia*, *D. retusa* and *T. grandis*, with the latter showing the lowest percentage of bad quality trees with 5% (± 5%). However, this low rate is a consequence of the intensive management described above. In the case of *T. grandis,* the cutting of the sprouts at the bottom – the so called "deshija" - should be done as early as 12 months after planting. In this trial, 42% of *T. grandis* trees were singled after 15 months to improve stem quality (Figure 4.20).

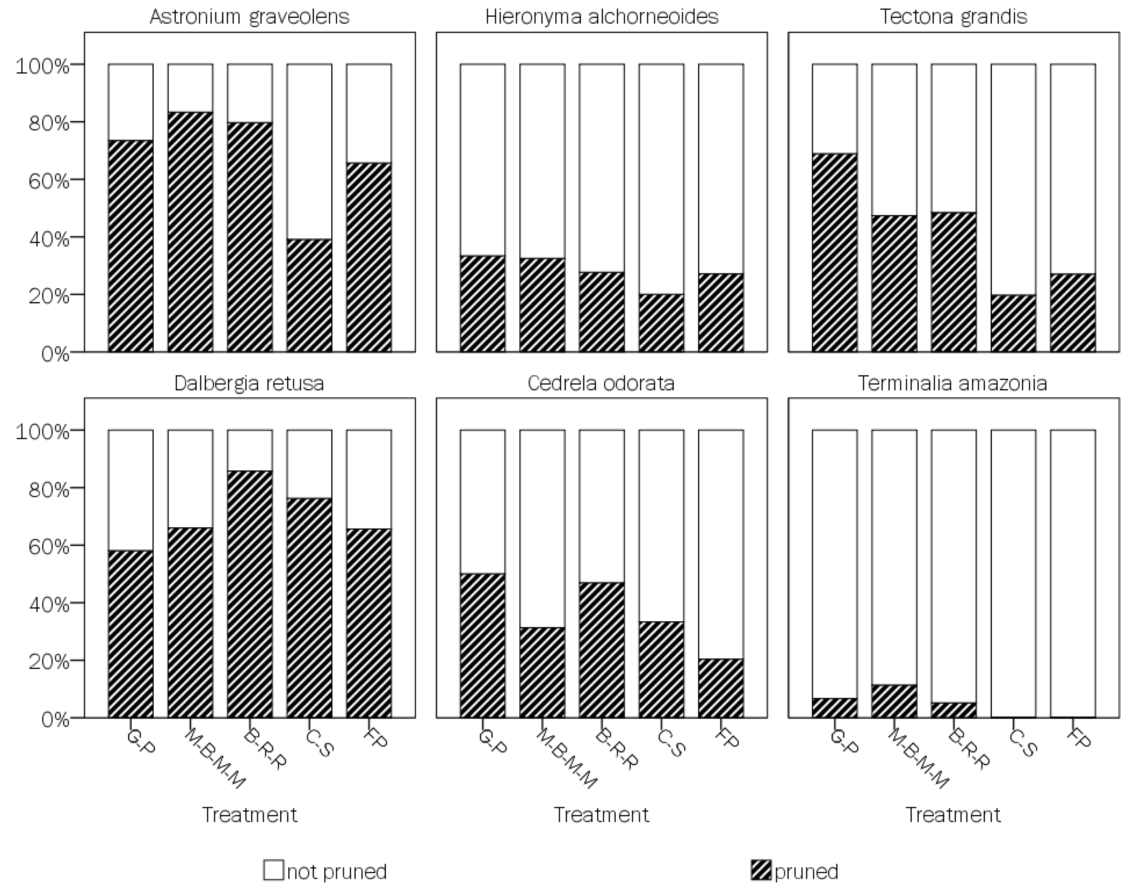

Figure 4.20: Percentage of trees pruned at age 15 months by tree species and treatment

Figure 4.19 reveals that the fraction of forked and multiple-stemmed trees of *C. odorata* tallies with the infestation rates in Figure 4.18. *A. graveolens*, *C. odorata* and *H. alchorneoides* in the B-R-R treatment tended to have higher numbers of poor quality stems compared to the C-S and M-B-M-M treatments. *T. amazonia* showed low numbers of forked trees in the C-S plots over the entire observation period. For instance, after 24 months, only 3% (± 3.6%) of *T. amazonia* trees in the latter treatment were badly shaped. However, at the end of the observation period, the logistic regression only revealed significant treatment effects for *C. odorata* (Wald Chi-Square = 24.67 p < 0.001) and *A. graveolens* (Wald Chi-Square = 134.74 p < 0.001) (see Table 4.11). In the case of *C. odorata,* the G-P treatment had the lowest percentage of badly shaped trees, with a mean of 19% (± 13%). On one plot in this treatment, none of the trees showed a forked trunk or multiple stems. As with the infestation rate with *H. grandella,* the highest percentage of trees with bad growth forms was found in one FP plot, with 80%, or 13 out of 16 trees being badly shaped. The odds for poor quality were significantly higher in the FP treatment compared to the G-P (e^{β} = 5.95, 95% Wald Confidence Interval = 2.2 - 16.1), M-B-M-M (e^{β} = 4.8, 95% Wald Confidence Interval = 2.0 - 11.5) and C-S treatments (e^{β} = 2.8, 95% Wald Confidence Interval = 1.11 – 7.4). In the B-R-R treatment, the probability of a tree having poor stem quality after two years was 3.4 times higher compared to the M-B-M-M treatment (95% Wald Confidence

Interval = 1.7 - 7.2) and 4.3 times higher compared to the G-P treatment (95% Wald Confidence Interval = 1.8 - 10.3). A similar pattern was observed for *A. graveolens:* The risk for bad quality was significantly higher in the FP and B-R-R treatment compared to all other agroforestry treatments, with p-values (based on Wald-Chi-Square) smaller than 0.004.

Table 4.10: Likelihood ratio test and test of model effects (Type III) for the dependent variable, rate of forked and multiple-stemmed trees per plot, and the predictor treatment by tree species at the end of the observation period. P-values that indicate significant treatment effects are presented in bold.

Age [months]	Source	Likelihood ratio test between intercept-only model and full model			Test of Model effects		
		Chi-Square	df	p-value	Wald-Chi-Square	df	p-value
A. graveolens	Intercept	27.647	4	**<0.001**	134.737	1	<0.001
	Treatment				28.920	4	**<0.001**
C. odorata	Intercept	32.908	4	**<0.001**	19.268	1	<0.001
	Treatment				24.667	4	**<0.001**
D. retusa	Intercept	3.228	4	0.520	91.219	1	<0.001
	Treatment				3.475	4	0,482
H. alchorneoides	Intercept	10.617	4	**0.031**	1017.740	1	<0.001
	Treatment				4.201	4	0,241
T. grandis	Intercept	2.134	4	0.711	135.715	1	<0.001
	Treatment				3.809	4	0,432
T. amazonia	Intercept	6.461	4	0.167	167.857	1	<0.001
	Treatment				11.817	4	0,019[1]

[1] The null hypothese was not rejected, because the Likelihood ratio test did not indicate a significant improvement of the model fit through inclusion of the predictor treatment.

The results reveal that the two treatments that were characterized by no crops or low-growing crops – FP and B-R-R - tended to show higher numbers of trees with symptoms that might lead to growth forms not adequate for high-quality wood products at the end of the rotation period. Accordingly, trees that grew in treatments with bushy crops or maize were, by trend of better quality. This was especially true for *C. odorata*. Certainly, future development cannot be derived from an observation period of only two years. However, results can be interpreted as a first indicator. The development of the percentage of poor quality stems over time also indicates that trees react very quickly to pruning activities. The clear increase in the fraction of badly shaped *C. odorata* trees between 18 and 24 months – when no management against *H. grandella* was carried out – show the severe consequences of reduced pest management on stem quality.

Another question in terms of tree quality in sequential intercropping systems is whether trees might potentially become bent over by competing crops. This was especially expected in combination with shrubby crops such as cassava and pigeon pea, which in this trial were grown in high densities and at short distances to the trees. However, less than 3% (2 out of 64 trees) were bent over in cassava fields. During the cultivation of pigeon pea one out of 64 trees was bent over in the case of *C. odorata*, *D. retusa*, *A. graveolens* and *T. grandis*. More trees were observed to be bent over by high grasses due to less intensive cutting of ground vegetation between 18 and 24 months when intercropping had stopped. For instance, 5 out of 64 *T. grandis* trees on the FP plots were bent over by grasses that were up to 2 m high when measurements were taken.

D. retusa trees growing in the M-B-M-M treatment were not observed to be bent over during the maize rotation – but instead during subsequent months. Four out of 64 trees in the M-B-M-M treatment fell over after the first dry season (9 months). Other trees had to be fixed on a pole. It is assumed that due to the induced height increment trees tended to invest less energy into root growth, resulting in very low stability. Therefore trees in the former maize fields seemed to be more likely to fall over because of strong winds that occur during the dry season. This effect might be reinforced by the presence of soils with a high clay content.

Growth form of D. retusa

In the case of *D. retusa,* the growth form was evaluated as an additional measure for quality. This tree species tends to develop a shrubby habitus, as described in chapter 3.2.1.1. No long term trials that have investigated management technologies to improve a straight growth form of this tree species in planted forests are known to the author. However, it has been observed in the northern hemisphere that intensive ramification of trees can be reduced by lateral shading. Therefore the following describes the investigation of whether the different intercropping rotations had an effect on the growth form of *D. retusa* in this trial. For this purpose, the percentage of *D. retusa* trees with crooked stems or shrubby growth forms per plot was calculated, in a manner similar to that used to calculate the infestation and percentage of poor quality stems in the previous chapters.

The overall fraction of undesired growth forms increased during the first 12 months from 50% (± 15%) to 87% (± 16%) and decreased in the subsequent observation period. This can be explained by pruning activities, which were carried out at age 15 months. Pruning can partly reduce shrubby growth forms. It has however no influence on crooked stems. Therefore the mean rate was only reduced by around 15% after pruning. Between 15 and 24 months, the overall mean rate of undesired growth forms remained relatively constant at around 70% (± 16% age 18 and 24).

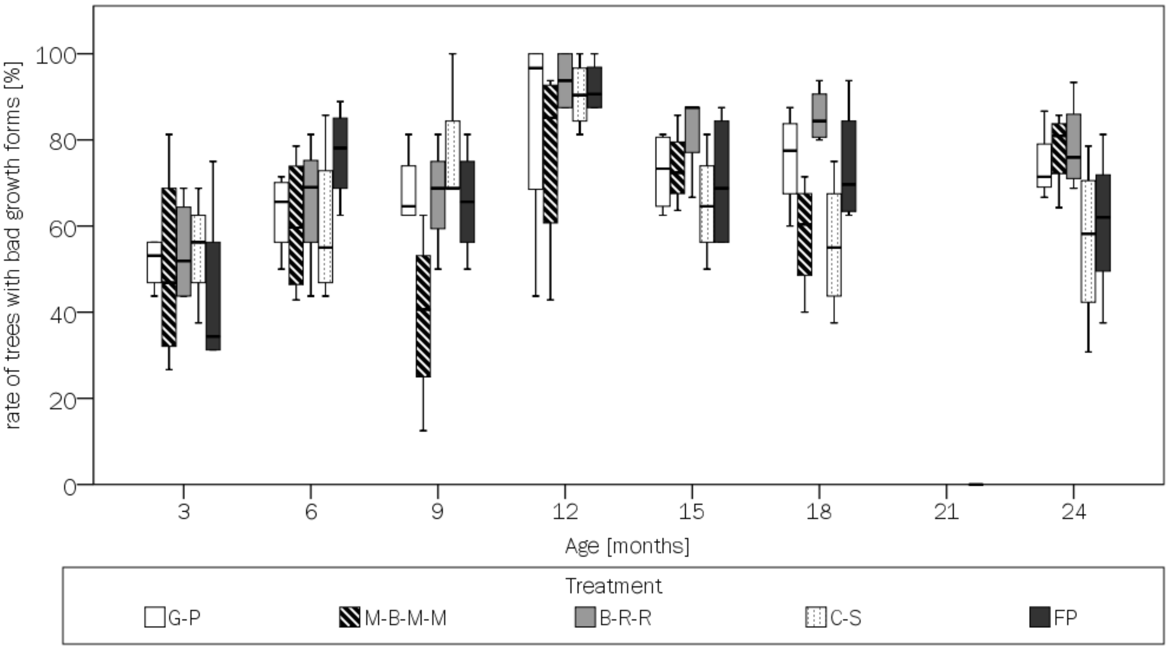

Figure 4.21: Rate of trees of *D. retusa* with crooked stems or shrubby growth forms at different points in time (N = 4 per treatment).

The only significant treatment effects on the growth form of *D. retusa* were found after 9 and 18 months (Table 4.11). However, the obviously low rate of poor growth forms in the M-B-M-M treatment after nine months (Figure 4.21) is attributed to the high number of trees that had to be replanted in this treatment after eight months. In the present analysis the proportion of trees with shrubby growth forms is based on the total number of trees alive at the time of measurement. Therefore replanted trees were evaluated as well. As the majority of replacement seedlings were classified as good growth forms, the rate of undesired growth forms decreased between six and nine months. Hence this cannot be interpreted as a treatment effect on quality.

However, after 18 months, the odds for bad growth forms were more than four times higher in the B-R-R treatment compared to the M-B-M-M (e^{β} = 4.4, 95% Wald confidence intervals: 2.2 – 9.1) and C-S treatments (e^{β} = 4.8, 95% Wald confidence intervals: 2.4-9.7). Even though 80% of the trees in the B-R-R treatment were pruned at age 15 months, the rate of bad growth forms remained high in this treatment until the age of 24 months. This is consistent with the overall high percentage of badly shaped trees in this treatment of *H. alchorneoides*, *A. graveolens* and *C. odorata*. The small difference in the percentage of bad growth forms of *D. retusa* in the B-R-R treatment before and after pruning might indicate that the growth form tended to be shrubby with multiple stems, which sprouted quickly again after cutting. This can be assumed as it was observed that trees with relatively straight growth forms but forked stems reacted positively to the cutting of the smaller stem, by not resprouting and growing relatively straight after pruning. Crooked trees with single stems tended to get straighter during the observation period.

Furthermore, the G-P treatment showed significantly higher percentages of bad growth forms compared to both the M-B-M-M (e^{β} = 2.3, 95% Wald confidence intervals: 1.1 - 5.1) and C-S treatments (e^{β} = 2.5, 95% Wald confidence intervals: 1.2 - 5.4). However, Figure 4.21 shows that the percentage of bad growth forms changed considerably between 18 and 24 months, therefore these differences to the M-B-M-M treatment should be interpreted with caution.

Table 4.11: Likelihood ratio test and test of model effects (Type III) for the dependent variable rate of bad growth forms for *D. retusa* per plot and the predictor treatment in different time periods. P-Values of significant treatment effects are presented in bold.

Time period	Source	Likelihood ratio test between intercept-only model and full model			Test of Model effects		
		Likelihood-Ratio-Chi-Square	df	p-value	Wald-Chi-Square	df	p-value
3	Intercept	1.928	4	0.749	0.087	1	0.768
	Treatment				1.201	4	0.878
6	Intercept	3.984	4	0.408	27.437	1	<0.001
	Treatment				5.129	4	0.274
9	Intercept	21.857	4	**<0.001**	18.595	1	<0.001
	Treatment				10.971	4	**0.027**
12	Intercept	10.376	4	**0.035**	61.853	1	<0.001
	Treatment				4.910	4	0.297
15	Intercept	5.370	4	0.251	71.168	1	<0.001
	Treatment				5.909	4	0.206
18	Intercept	19.213	4	**0.001**	51.447	1	<0.001
	Treatment				26.208	4	**<0.001**
24	Intercept	10.068	4	**0.039**	44.420	1	<0.001
	Treatment				8.805	4	0.066

The results show that no distinct pattern was found concerning the effect of treatment on growth forms of *D. retusa*. However, the results also show, that intercropping did not clearly impede stem quality. This finding indicates that for this species no opportunity costs have need to be calculated due to quality loss resulting from sequential intercropping.

4.3 Tree-crop interactions at the single-tree level

The previous chapter has dealt with the effect of treatments on tree growth at the stand level, or in other words, the overall effect of the crops grown in a plot on the growth performance of trees within this plot. The information provided on the performance of trees in different Taungya systems, as well as possible implications for management (as e.g. reduced efforts for weeding of trees) are of particular interest to forestry enterprises and farmers (see chapter 6). In contrast, the following section addresses interactions between single trees and crops, which has the potential to aid in the ecological evaluation of tree species for the use in agroforestry systems. The serious lack of studies on the tree species investigated here, in terms of shade tolerance and growth behavior under competition was discussed in chapter 3.2.1.1. Therefore this study also aimed to investigate single-tree performance under competition with different crops. For this purpose, competition was described by a competition index (see chapter 3.5.4). Replanted trees were excluded in order to investigate the biological growth performance of trees (see chapter 4.2.2).

4.3.1 Effects of tree-crop competition on single tree performance

This approach generally revealed only weak effects of competition on single-tree performance, which will be discussed in section 5.1. Therefore only examples of maize, cassava and pigeon pea will be presented in the following sections (see also appendix, Figure 11.1 ff).

4.3.1.1 Competition between trees and maize

Figure 4.22 shows the relationship between the modified hegyi index – hereafter referred to as the competition index (CI) - and the height increment of trees during the first maize rotation. The higher the index, the higher the height of the three maize plants in comparison to tree height, and the smaller the distance from the maize plants to the focal tree. During the first maize cultivation, all trees were smaller than the maize, which reached heights of up to 2.6 m (mean 2.2 m ± 0.2 m), while tree heights ranged between 9 and 173 cm (see also Figure 4.10). The distances between trees and maize were usually very small, ranging between 26 and 177 cm (mean 70 cm ± 17 cm), as maize was planted rather densely, at a distance of 30 cm within rows and 90 cm between rows, and germination rate was also high. The intent was not to plant any maize within a circle of 50 cm around each tree. However, some maize plants were found that germinated within this circle. The CI numbers found here were small compared to those reported for the hegyi index from studies in pure tree stands (e.g. Vanclay 2006, Ammer et al. 2005). This is also due to the fact that a fixed number of three plants was used instead of counting all plants within a circle with a fixed radius, as was the case in the studies using the hegyi index.

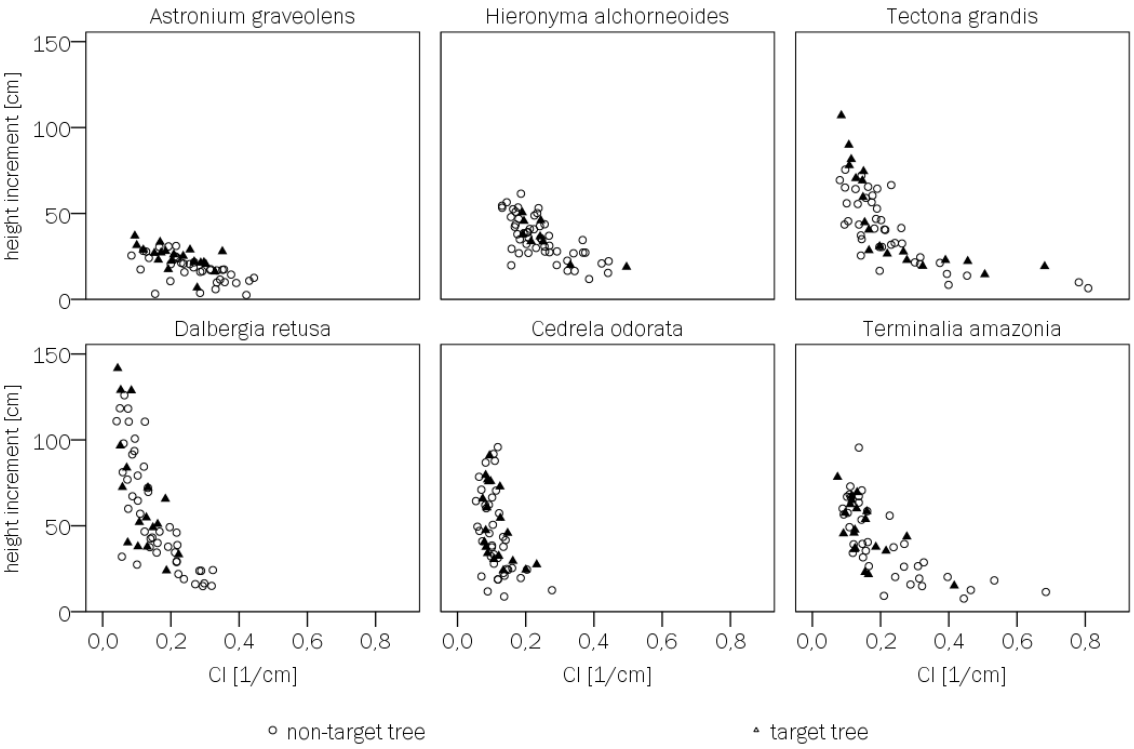

Figure 4.22: Height increment of trees in maize fields during the first 3 months plotted against the modified hegyi index (CI) at the end of the first maize rotation in the M-B-M-M treatment. Triangles denote the 5 tallest trees („target trees“) per plot after 24 months.

Figure 4.22 reveals that the increment tended to decrease when the sum of the distance-adjusted relative size of the three closest maize plants increased. The diagram also reveals an exponential relationship which was successfully linearized by using the natural log transformed CI. In some cases the dependent variable was also transformed in order to avoid heteroscedasticity. Table 4.12 presents the significant negative relationship (see b_1) between the CI and height increment in the maize fields during the first three months. More than half of the variation in height increment was explained by the CI for all species with the exception of *C. odorata* and *H. alchorneoides*.

Table 4.12: Results of regression analysis with dependent variable height increment between 0 and 3 months (h_0 - h_3) and independent variable $\ln(CI_{maize})$ during the first three months in the M-B-M-M treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$h_3 - h_0$	0.514	-0.247	(2.807)	-14.087	(1.862)	<0.001
C. odorata	$\ln(h_3 - h_0)$	0.217	1.856	(0.484)	-0.833	(0.215)	<0.001
D. retusa	$\ln(h_3 - h_0)$	0.669	2.110	(0.185)	-0.882	(0.085)	<0.001
H. alchorneoides	$h_3 - h_0$	0.456	-1.739	(5.967)	-25.897	(4.002)	<0.001
T. grandis	$\ln(h_3 - h_0)$	0.689	1.937	(0.169)	-1.020	(0.096)	<0.001
T. amazonia	$\ln(h_3 - h_0)$	0.639	1.911	(0.194)	-0.964	(0.104)	<0.001

In accordance to the height, the relationship between diameter increment and competition index was negative (Table 4.14) for all tree species. However, the CI did not predict a significant amount of variance for *H. alchorneoides* and *A. graveolens*. The other tree species showed a rather weak relationship, with *D. retusa* and *T. grandis* showing the highest R^2 values of 0.426 and 0.344, respectively.

Table 4.13: Results of regression analysis with dependent variable diameter increment between 0 and 3 months ($rcd_3–rcd_0$) and independent variable $\ln(CI_{maize})$ during the first three months in the M-B-M-M treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of the estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$rcd_3–rcd_0$	0.046	3.193	(0.871)	-0.928	(0.578)	0.114
C. odorata	$rcd_3–rcd_0$	0.138	0.369	(3.365)	-4.457	(1.504)	0.004
D. retusa	$rcd_3–rcd_0$	0.426	0.436	(1.447)	-4.182	(0.660)	<0.001
H. alchorneoides	$rcd_3–rcd_0$	0.032	3.339	(1.276)	-1.099	(0.856)	0.205
T. amazonia	$rcd_3–rcd_0$	0.198	1.333	(1.012)	-1.942	(0.547)	0.001
T. grandis	$\ln(rcd_3–rcd_0)$	0.344	1.562	(0.182)	-0.534	(0.103)	<0.001

As expected, both height and root collar diameter increment tended to decrease with increasing competition with maize for light and belowground resources. However, the exponential relationship shown in Figure 4.22 was mainly based on a few high values for CI associated with trees with small increments, while the variation in increment of trees with a competition index smaller than 0.2 was very high. This was true for both height and diameter increment (see appendix, Figure 11.1), and indicates that the negative influence of competition can be ignored if severe competition - represented by a CI of smaller than 0.2 is avoided. In order to illustrate this statement, Table 4.14 and Table 4.15 give the height increment and input variables of CI for the three trees with the highest and lowest CI respectively for each species (see also Equation (3.8).

Table 4.14: Characterization of neighborhood of the three trees of each tree species with the lowest CI values in the M-B-M-M treatment during the first three months: Given is the height increment of the focal tree ($h_3–h_0$), its total height after three months (h_3), the distances to the three closest maize plants ($dist_1$ to $dist_3$), and their heights before harvest (h_{m1} to h_{m3}).

	CI [1/cm]	$h_3–h_0$ [cm]	h_3 [cm]	$dist_1$ [cm]	$dist_2$ [cm]	$dist_3$ [cm]	h_{m1} [cm]	h_{m2} [cm]	h_{m3} [cm]
A. graveolens	0.08	26	50	87	85	100	140	120	120
	0.09	37	64	80	99	102	180	180	200
	0.1	32	58	83	115	124	160	240	220
C.odorata	0.05	64	101	78	88	100	140	180	160
	0.06	50	89	83	93	72	160	200	80
	0.06	79	120	90	112	77	240	200	240
D.retusa	0.04	111	140	70	101	114	180	160	180
	0.04	142	173	80	92	107	220	240	240
	0.05	118	157	76	73	108	220	220	220
H. alchorneoides	0.13	55	64	66	80	82	240	240	140
	0.13	53	68	55	88	97	240	180	240
	0.14	57	68	70	65	67	220	220	220
T.amazonia	0.07	78	104	93	76	91	220	220	220
	0.09	60	81	94	92	60	180	180	200
	0.09	46	63	90	111	116	200	200	200
T.grandis	0.08	69	79	66	120	132	200	200	220
	0.08	107	119	52	70	81	220	220	220
	0.09	44	52	110	138	95	180	160	200

Table 4.14 reveals that the “lowest competition” in the case of this trial is still characterized by distances around 1 m and a height relationship of up to 3. Height increments of the trees with these low CIs vary strongly. For instance, the height increment of the three trees of the species

T. amazonia with the lowest competition included one very high increment of 78 cm, but also a much lower increment of only 45 cm within the first 3 months.

The three highest CI values for each tree species (Table 4.15) characterize extreme crop/tree height relationships of up to 26 and very small distances of around 50 cm. This shows, combined with the previous table, that if the maize was not planted closer than 1 m to the tree, no clear negative relationship was observed. In most agroforestry projects distances between crops and trees are larger.

Table 4.15: Characterization of the neighborhood of the three trees with the highest CI values of each tree species in the M-B-M-M treatment during the first three months: Given is the height increment of the focal tree (h_3–h_0), its total height after three months (h_3), the distances to the three closest maize plants ($dist_1$ to $dist_3$), and their heights before harvest (h_{m1} to h_{m3}).

	CI [1/cm]	h_3–h_0 [cm]	h_3 [cm]	$dist_1$ [cm]	$dist_2$ [cm]	$dist_3$ [cm]	h_{m1} [cm]	h_{m2} [cm]	h_{m3} [cm]
A. graveolens	0.43	11	26	55	58	54	240	180	200
	0.44	13	31	36	45	80	220	220	220
	0.58	-3	21	51	50	52	220	220	180
C.odorata	0.20	24	53	54	59	69	200	220	220
	0.20	25	65	44	56	63	240	240	220
	0.23	28	64	45	49	52	240	240	240
D.retusa	0.29	24	52	26	60	134	240	240	240
	0.29	15	34	58	48	56	220	160	160
	0.30	17	38	67	52	77	240	240	240
H. alchorneoides	0.44	15	20	59	86	112	240	240	220
	0.44	22	32	47	51	55	240	240	240
	0.50	19	25	72	43	64	220	240	240
T.amazonia	0.51	15	25	61	45	65	220	240	240
	0.68	19	30	29	30	53	240	240	220
	0.78	10	17	45	54	62	240	220	240
T.grandis	0.53	18	25	64	55	46	240	240	240
	0.68	12	18	48	42	88	220	220	220
	1.28	1	10	52	55	62	240	240	240

A comparison of the lowest tree-maize competition values and the corresponding height increments (Table 4.14) as shown in Figure 4.22 reveals that the trees with the highest increments were not necessarily those with the lowest competition. This is also supported by the CI of the “target trees” (used for the analysis in chapter 4.2) which are also displayed in Figure 4.22. These were the tallest trees after 24 months. As they were equally distributed throughout the entire range of the CI, no direct influence due to competition during the first three months on later growth development was detected. Statistical analysis in chapter 4.2.3.1.1 showed that the overall growth of trees in the M-B-M-M treatment was better during the first three months compared to other treatments, which supports the assumption that if extreme competition situations with a distance of less than 1 m are avoided, no negative influences of direct competition need be expected.

The same competition analysis was carried out for the second rotation of maize in the M-B-M-M treatment (9 - 12 months) (Figure 4.23). Due to the greater heights of the trees, the height relation was generally smaller, resulting in CI values of smaller than 0.2 for all tree species.

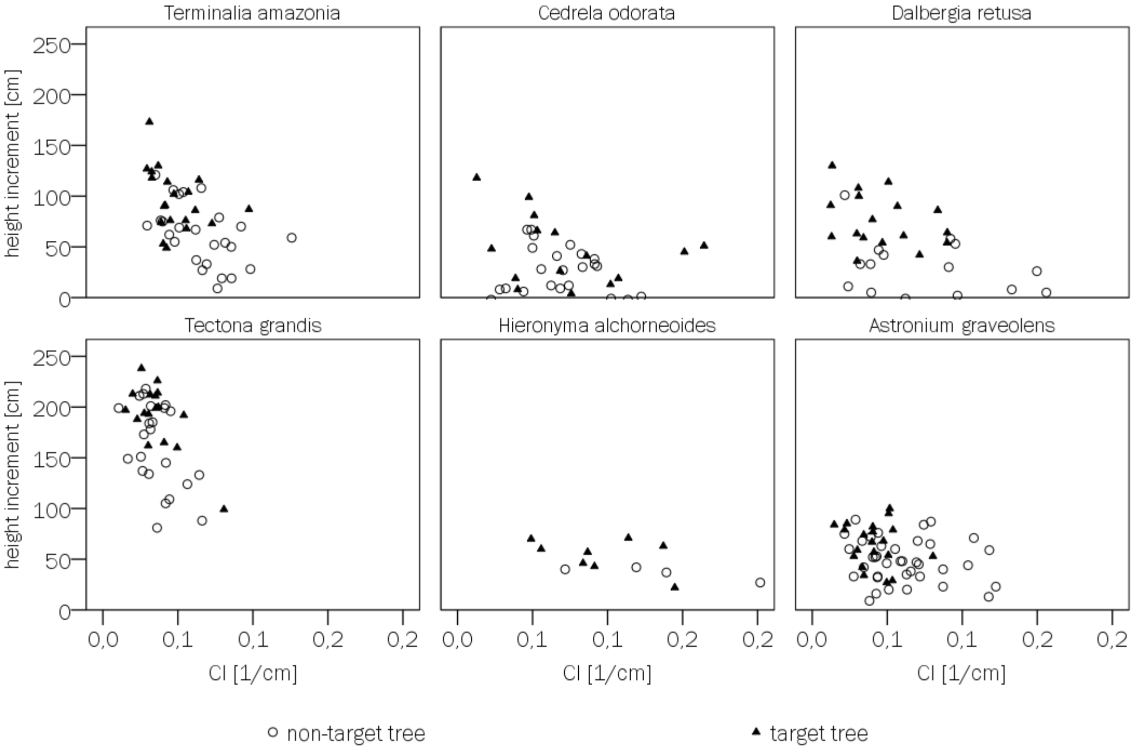

Figure 4.23: Height increment of trees in maize fields during the period from 9-12 months plotted against the modified hegyi index (CI) at the end of the second maize rotation (12 months) in the M-B-M-M treatment. Triangles denote the 5 tallest trees per plot after 24 months („target trees“).

Figure 4.23 already reveals a weak but negative relationship between single-tree competition and height increment. This was supported by the regression analysis, which showed that less than 40% of the variation in height increment was explained by direct competition (Table 4.16). However, for all tree species except *H. alchorneoides,* a significantly negative relationship was found. The few CI values greater than 0.1 in Figure 4.23 resulted from the relatively shorter trees in the case of *H. alchorneoides,* and from distances smaller than 1 m in the case of the other tree species. This again proves that if densities are kept larger than 1 m no severe reaction need be expected.

Table 4.16: Results of regression analysis with dependent variable height increment between 9 and 12 months (h_{12}–h_9) and independent variable ln(CI_{maize}) after 12 months in the M-B-M-M treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	h_{12}–h_9	.090	9.69	(19.04)	-14.72	(6.23)	0.022
C. odorata	h_{12}–h_9	0.15	-43.46	(20.45)	-23.34	(7.61)	0.003
D. retusa	h_{12}–h_9	0.29	-33.37	(24.20)	-28.31	(7.92)	0.001
H. alchorneoides	h_{12}–h_9	0.32	-2.37	(23.40)	-21.93	(10.01)	0.053
T. amazonia	h_{12}–h_9	0.35	-85.99	(34.53)	-56.04	(11.76)	<0.001
T. grandis	ln(h_{12}–h_9)	0.13	-96.20	(32.19)	-77.61	(9.84)	<0.001

In terms of diameter increment no clear reaction from competition was found (Table 4.17). Only for *T. amazonia* and *H. alchorneoides*, a significantly negative effect of distance-adjusted size of neighboring maize plants on diameter was proven.

Table 4.17: Results of regression analysis with dependent variable root collar diameter increment between 9 and 12 months ($rcd_{12}–rcd_9$) and independent variable $\ln(CI_{maize})$ after 12 months in the M-B-M-M treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$rcd_{12}–rcd_9$	0.01	9.09	(2.70)	-0.72	(0.89)	0.419
C. odorata	$rcd_{12}–rcd_9$	< 0.001	14.85	(4.85)	0.36	(1.79)	0.843
D. retusa	$rcd_{12}–rcd_9$	0.08	-1.75	(5.57)	-2.98	(1.80)	0.109
H. alchorneoides	$rcd_{12}–rcd_9$	0.36	-3.47	(5.36)	-5.41	(2.29)	**0.040**
T. amazonia	$rcd_{12}–rcd_9$	0.11	-0.75	(5.35)	-4.24	(1.82)	**0.025**
T. grandis	$rcd_{12}–rcd_9$	0.06	15.24	(10.59)	-4.90	(3.08)	0.120

During the last maize rotation (12-15 months) CIs for all tree species were smaller than 0.1, due to both the larger distances resulting from low germination rates and smaller height ratios. In accordance with the results from the second maize rotation, a weak but negative relationship between increment and CI ($R^2 < 0.4$) was found for both diameter and height growth. Best fit was achieved for *C. odorata* with R^2 equal to 0.377 (b = -410.02 p = 0.020)[63] for height and 0.263 (b = -216.89, p = 0.001)[64] for diameter respectively. The weakness of this relationship among the other tree species, with an $R^2 < 0.2$ is illustrated by Figure 4.24. Obviously during this phase, competition with maize did not seem to severely affect tree growth, allowing dense planting grids between trees.

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[63] No transformation was necessary for either dependent or independent variables of this regression model. Results are presented in the appendix (Table 11.7)

[64] No transformation was necessary for either dependent or independent variables of this regression model. Results are presented in the appendix (Table 11.8)

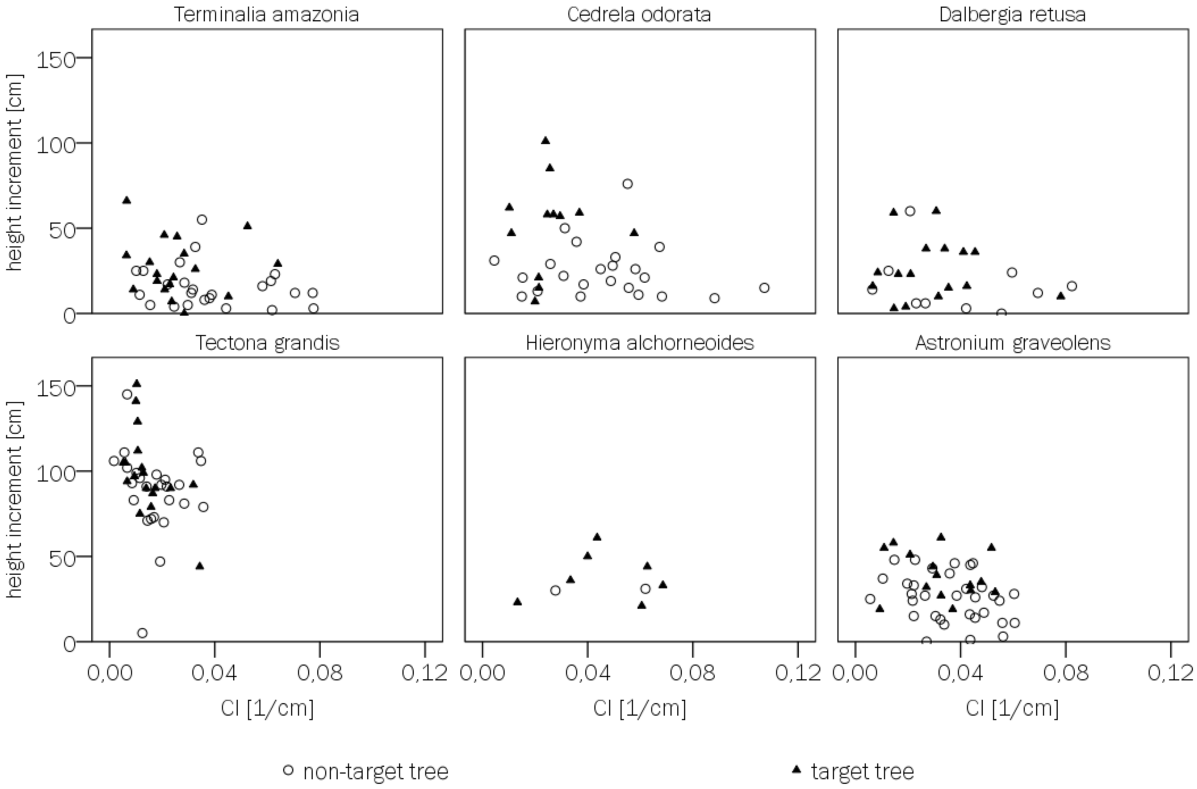

Figure 4.24: Height increment of trees in maize fields during the period from 12-15 months plotted against the modified hegyi index (CI) at the end of the third maize rotation (15 months) in the M-B-M-M treatment. Triangles denote the 5 tallest trees („target trees“)per plot after 24 months.

In chapter 4.2.3.2 it was mentioned that mortality during the first dry season was particularly high in the M-B-M-M treatment. Therefore, it was investigated whether direct competition for space, represented by the CI had an influence on survival. Surprisingly, no pattern was observed and hence no relationship between competition and survival was found (Figure 4.25). A logistic regression using CI as independent variable did not succeed in improving the prediction of survival during the first 6 months (-2 –Log-Likelihood test $p > 0.177$ for all tree species) or during the first 9 months (-2-Log-Likelihood test $p > 0.149$ for all tree species)[65].

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[65] A significant result of p O 0.045 was found for *T. amazonia*, however result of Type III Test of fixed effects was not significant at the $p > 0.5$ level.

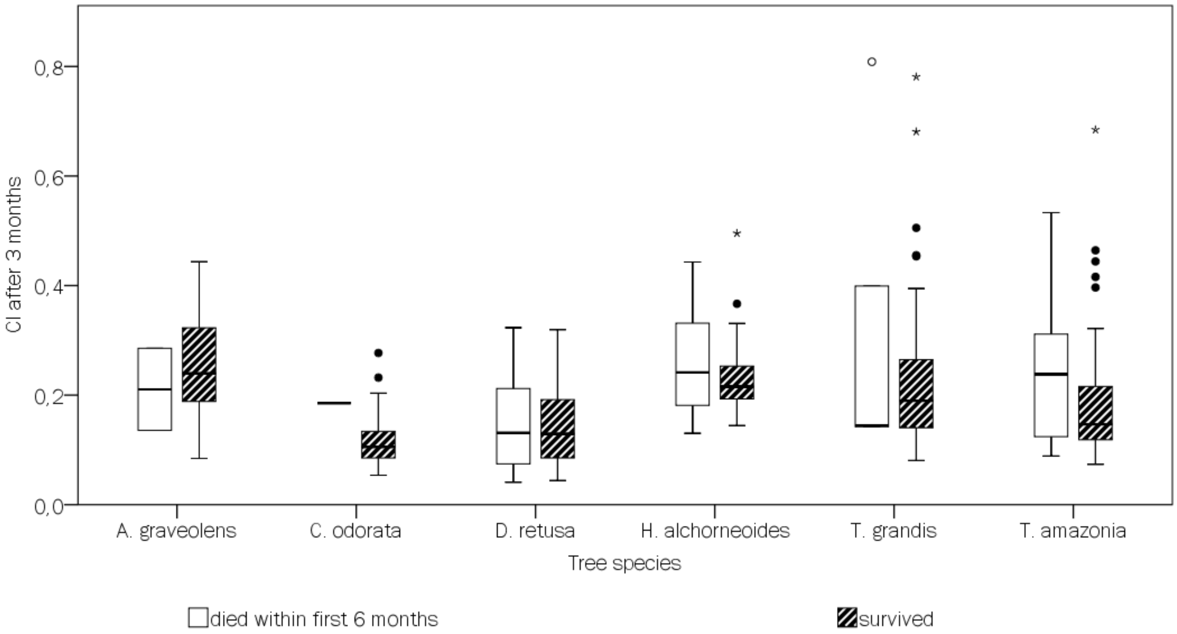

Figure 4.25: Range of competition index (CI) at the end of the first maize rotation for trees that died and those that survived in the M-B-M-M treatment during the first 6 months.

4.3.1.2 Competition between trees and cassava

In the following section the influence of competition on single-tree growth will be examined for each of the six tree species investigated in combination with cassava. In the C-S treatment two measurements of distance and height of the three closest cassava plants to each tree were taken, in order to calculate the CI both after the first half of the rotation period (6 months) and before the harvest (12 months) when the cassava plants had reached their final heights of up to 3 m. This was done, as it was assumed that the CI might change during the 12 month rotation period, due to mortality of cassava and faster growth of trees in relation to cassava. Also, the main growing periods for both cassava and trees were observed from 3-6 and from 9-12 months because of relatively lower growth immediately after establishment (0-3 months), and because of decrease in growth rate during the dry season (6-9 months). During the dry period mortality of cassava was high, therefore the situation after 12 months seemed to better describe the actual competition of trees with cassava than the situation after 6 months. This was also supported by the regression analysis, which showed that the results for the time period from 0-6 months corresponded well to those for the period from 3-6 months, and those for months 6-12 corresponded well with results from the period from 9-12 months, in contrast to other combinations. However, in order to display height and root collar diameter of trees during the whole observation period, the time periods from months 0-6 and from months 6-12 were used instead of the 3 months intervals.

After six months, the heights of cassava plants ranged from 32 to 360 cm (mean: 116 cm ± 43 cm), while distances between the focal tree and the three closest cassava plants ranged from 0.3 m to 13.2 m (2.2 m ± 2.0). Mean tree heights after 6 months ranged between 44 cm for *H. alchorneoides* and 91 cm for *D. retusa* (Table 4.4) and hence, trees were mostly smaller than cassava plants. Figure 4.26 plots the derived CI after 6 months and the height increment of trees in the period from 0-6 months.

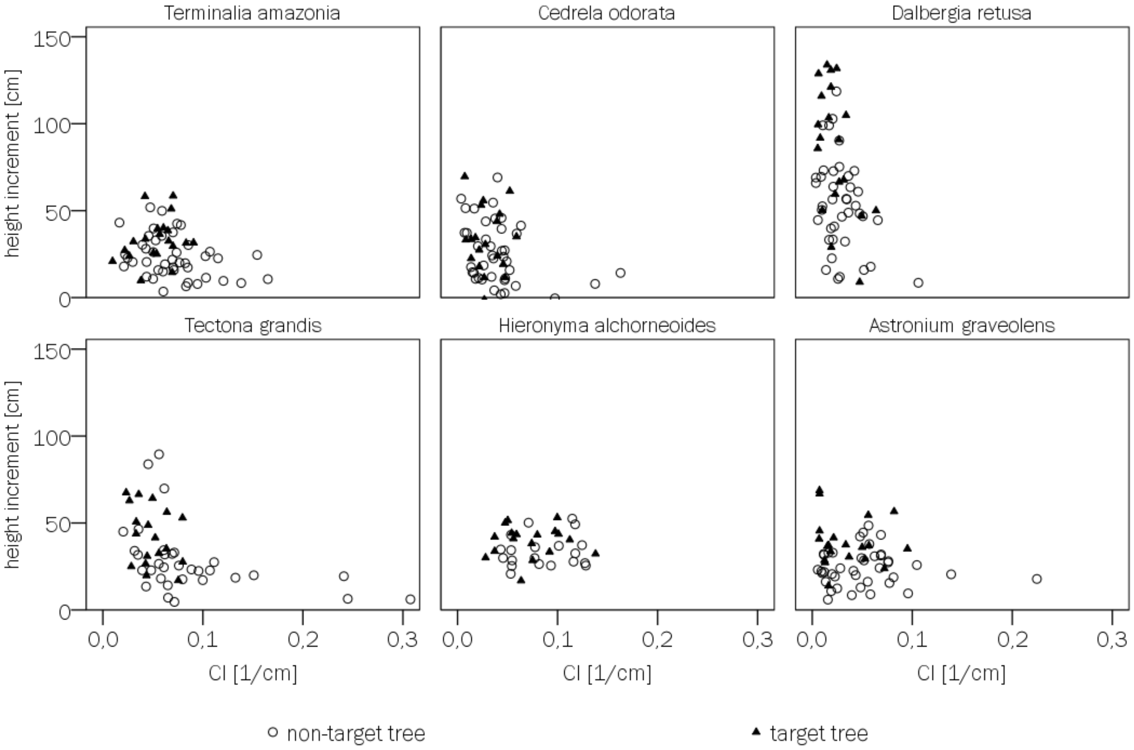

Figure 4.26: Height increment of trees in the first 6 months in the cassava fields (C-S treatment) plotted against CI after 6 months. Triangles denote the 5 highest trees per plot after 24 months („target trees").

The scatterplots reveal a by trend negative exponential relationship between height increment and CI, indicating that height increment decreased with increasing competition. The relationship was significant, yet small, for *C. odorata, D. retusa* and *T. grandis*, with $R^2 \leq 0.321$ (Table 4.18). None of the variance in height increment within the tree species *H. alchorneoides* was explained by the spatial competition situation. Figure 4.26 shows however, that the highest increments of *T. amazonia*, *T. grandis*, *D. retusa* and *H. alchorneoides* were found at medium CI indicating that in addition to competition, facilitation effects were present.

Table 4.18: Results of regression analysis with dependent variable height increment in the first six months (h_6–h_0) and independent variable $\ln(CI_{cassava})$ after six months in the C-S treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	h_6-h_0	0.05	17.08	(7.03)	-3.41	(2.00)	0.093
C. odorata	h_6-h_0	0.16	-10.23	(11.10)	-10.55	(3.12)	0.001
D. retusa	h_6-h_0	0.14	-1.22	(21.80)	-17.06	(5.56)	0.003
H. alchorneoides	h_6-h_0	<0.001	38.23	(10.06)	0.69	(3.80)	0.857
T. amazonia	h_6-h_0	0.03	14.38	(8.90)	-4.23	(3.07)	0.173
T. grandis	$\ln(h_6-h_0)$	0.32	9.58	(10.64)	-8.18	(3.56)	0.026

The results for the relationship between increment in root collar diameter and the CI are in accordance with that for the height increment, as illustrated in Table 4.19.

Table 4.19: Results of regression analysis with dependent variable root collar diameter increment in the first six months (rcd_6-rcd_0) and independent variable $\ln(CI_{cassava})$ after six months in the C-S treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	rcd_6-rcd_0	<0.001	7.94	(1.64)	0.14	(0.47)	0.769
C. odorata	$\ln(rcd_6-rcd_0)$	0.03	2.48	(0.30)	-0.11	(0.08)	0.175
D. retusa	rcd_6-rcd_0	0.08	7.01	(4.84)	-2.80	(1.24)	0.028
H. alchorneoides	rcd_6-rcd_0	0.02	5.97	(2.30)	-0.81	(0.87)	0.359
T. amazonia	$\ln(rcd_6-rcd_0)$	0.04	1.53	(0.30)	-0.17	(0.11)	0.118
T. grandis	rcd_6-rcd_0	0.26	-3.62	(5.28)	-7.54	(1.85)	0.000

The height of cassava plants after 12 months - shortly before harvest - ranged between 32 and 437 cm (mean 195 cm ± 56 cm), while mean tree heights ranged between 98 and 263 cm for *H. alchorneoides* and *T. grandis*, respectively (Table 4.4). This implies that most trees were dominated by the surrounding cassava plants. Distances were constant, with a mean of 2.2 m.

Figure 4.27 shows that during the period from 6 to 12 months, all tree species tended to have a negative relationship between height increment and CI. However, the fraction of explained variance was too small to prove an overall relationship (Table 4.20).

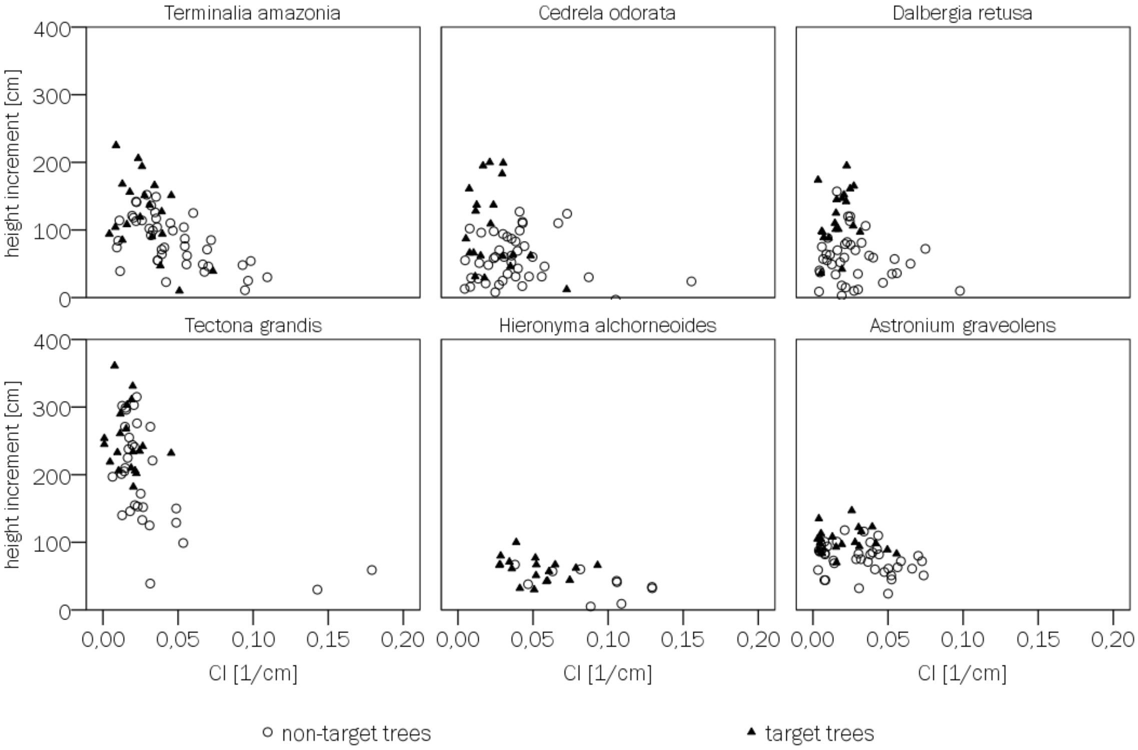

Figure 4.27: Height increment of trees between 6 and 12 months in the cassava fields (C-S treatment) plotted against CI after 12 months. Triangles denote the 5 tallest trees per plot after 24 months („target trees“).

Accordingly, the second largest height increment for *T. grandis* during the period from 6-12 months was found for a tree in a spatial situation of high competition: In this case, the distances to the closest cassava plants (after 12 months) were 74, 80 and 265 cm with all heights exceeding 265 cm. The crowns of the focal tree and cassava plants overlapped. The same pattern was observed for other tree species, both for height and root collar diameter increment.

Table 4.20: Results of regression analysis with dependent variable height increment for the period between 6 and 12 months (h_{12}–h_6) and independent variable ln($CI_{cassava}$) after 12 months in the C-S treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	h_{12}–h_6	0.07	59.10	(13.03)	-6.50	(3.21)	0.048
C. odorata	ln(h_{12}–h_6)	0.002	-10.23	(11.10)	-10.55	(3.12)	0.001
D. retusa	h_{12}–h_6	0.01	3.905	(0.49)	-0.040	(0.13)	0.468
H. alchorneoides	h_{12}–h_6	0.33	-21.51	(21.03)	-26.13	(7.33)	0.001
T. amazonia	h_{12}–h_6	0.23	-16.02	(27.01)	-33.15	(7.76)	0.000
T. grandis	h_{12}–h_6	0.23	57.85	(42.53)	-39.70	(10.37)	0.000

Surprisingly, the relationship between height increment and CI differed for some species between the two observation periods: *H. alchorneoides* showed the highest R^2 with 0.33 in the second time period even though none of the variance in height increment was explained by CI in the first period. Conversely, in the case of both *C. odorata* and *D. retusa* less than 1% of the variance in height increment was explained by the CI at the end of the rotation (after 12 months), while during the first six months, a fraction of more than 10% was explained by the CI for these tree species. This supports the observation already described for maize, that the height increment for *D. retusa* is greatly affected by competition during the first months after establishment, but is obviously not influenced in later stages of stand development. Other tree species, especially *T. amazonia*, and *H. alchorneoides,* only showed a significant reaction to competition during the second observation period.

All tree species except *H. alchorneoides* showed a highly significant negative relationship between root collar diameter increment and CI in the second observation period. However, R^2 suggests that other factors might have had more influence on tree growth than direct competition for growing space

Table 4.21: Results of regression analysis with dependent variable root collar diameter increment between 6 and 12 months (rcd_{12}–rcd_6) and independent variable ln($CI_{cassava}$) after 12 months in the C-S treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	rcd_{12}–rcd_6	0.24	2.79	(2.53)	-2.64	(0.62)	<0.001
C. odorata	rcd_{12}–rcd_6	0.11	-2.39	(6.25)	-4.64	(1.68)	0.007
D. retusa	rcd_{12}–rcd_6	0.22	-5.63	(4.32)	-4.20	(1.06)	<0.001
H. alchorneoides	rcd_{12}–rcd_6	0.07	-1.87	(6.41)	-3.02	(2.24)	0.188
T. amazonia	rcd_{12}–rcd_6	0.19	-2.39	(2.84)	-3.08	(0.82)	<0.001
T. grandis	rcd_{12}–rcd_6	0.39	5.00	(5.13)	-7.07	(1.25)	<0.001

Even though the investigation of the CI of the three closest cassava plants around each tree did not reveal any clear relationships, the results suggest that tree growth - both in terms of height and root collar diameter - was negatively influenced by direct competition. Even though the R^2 was small, significant effects were observed. It should furthermore be considered that CI was included as a sole predictor in interpreting the results, while other factors influencing tree growth, such as site factors were deliberately excluded from the model (which will be discussed in section 5.1). Hence, an explained relationship of more than 20% might be considered meaningful. However, results also suggest, that no severe negative effects in terms of increment need be expected when growing cassava in the neighborhood of trees, which is also supported by the wide range of CI values of the target trees, all of which showed the best height performance after 24 months (Figure 4.26 and Figure 4.27).

Regarding mortality, it can be observed in Figure 4.28 that trees that died during the first 12 months tended to have a higher CI compared to those that survived.

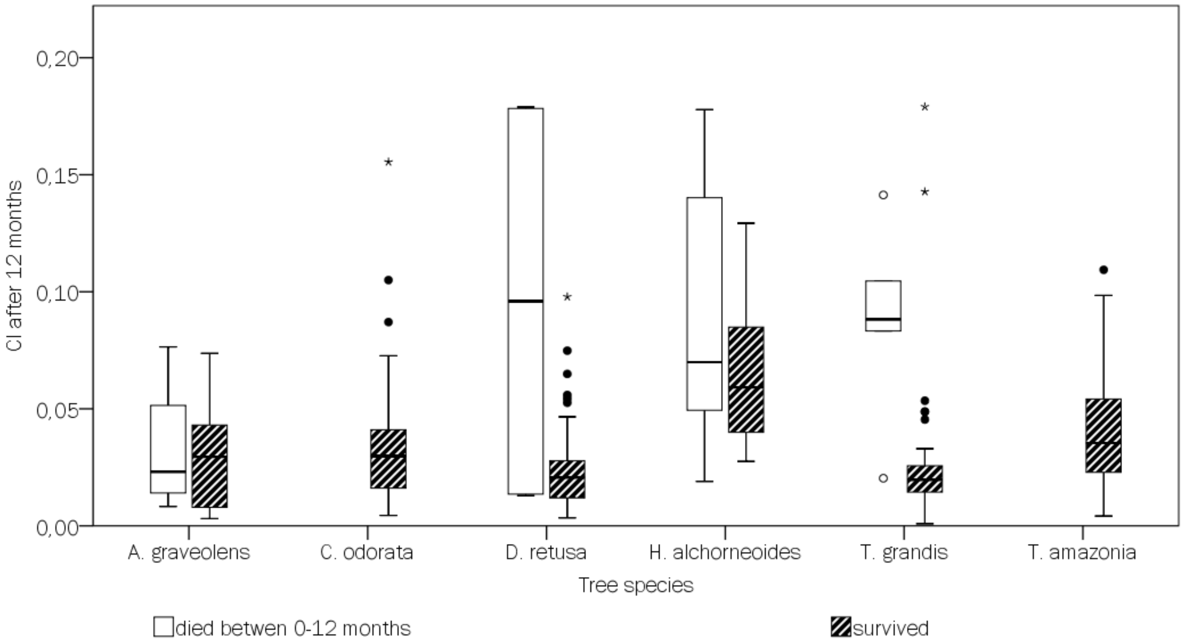

Figure 4.28: Range of competition index (CI) values at the end of the cassava rotation for trees that died and those that survived in the C-S treatment during the first 12 months.

The logistic regression proved that the prediction of survival during this time period was significantly improved by the CI for *D. retusa*, *T. grandis* and *H. alchorneoides* (Table 4.22). However, the overall explained variation (computed by Nagelkerkes R^2) was less than 36 % for *D. retusa* and *T. grandis*, respectively and only 9% for *H. alchorneoides*. Variability of the CI among trees that died was high (Figure 4.28). The comparison of survival rates between the different treatments in chapter 4.2.3.2 has shown that trees in the C-S treatment showed a surprisingly high survival rate, which can also be observed in Figure 4.28, as no single tree of *T. amazonia* and *C. odorata* died in the cassava treatment before 12 months. Therefore the results can be summed up as follows: Survival of *D. retusa*, *T. grandis* and *H. alchorneoides* seems to be negatively influenced by strong competition with cassava. Other tree species do not seem to react to competition in terms of survival.

Table 4.22: Likelihood ratio test and test of model effects (Type III) for the prediction of mortality by the competition index (CI) at the end of the cassava rotation.

Time period	Source	Likelihood ratio test between intercept-only model and full model			Test of Model effects		
		Likelihood-Ratio-Chi-Square	df	p-value	Wald-Chi-Square	df	p-value
A. graveolens	Intercept	0.161	1	0.688	0.164		0.001
	CI				10.406		0.685
D. retusa	Intercept	9.206	1	0.002	20.849		0.000
	CI				6.842		**0.009**
H. alchorneoides	Intercept	4.24	1	**0.039**	3.299		0.069
	CI				3.826		0.050
T. grandis	Intercept	8.618	1	0.003	19.999		0.000
	CI				7.591		**0.006**

4.3.1.3 Competition between trees and pigeon pea

Similar to the competition analysis in cassava fields, two measurements were also carried out in the pigeon pea treatment. As germination of pigeon pea was better than expected, some pigeon pea shrubs had to be cut after 12 months in order to avoid damage to the trees. Therefore the lateral competition changed slightly, and two measurements were carried out - after 12 and after 18 months. Thus, the length of the time periods differed. Shrub heights ranged from 60 to 300 cm ($\overline{x}$ = 138 cm ± 91 cm) after 12 months and 10 to 400 cm ($\overline{x}$ = 240 ± 50) after 18 months. Distances between trees and the three closest pigeon pea shrubs ranged from 0.3 to 8 m ($\overline{x}$ = 1.6 ± 0.8). In accordance with the previous analyses, the final height of the focal tree at the end of each observation period was used to calculate the CI[66].

Figure 4.29 reveals a negative trend in growth increment with rising CI. *T. amazonia* and *C. odorata* showed a similar pattern as was found for these species in association with cassava: They tended to reach the highest increments at medium CIs. The scatterplots of *A. graveolens* and *T. grandis* also show that these species did not react to lateral competition with pigeon pea, as proven by the regression analyses (Table 4.23).

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[66] As already described in the previous chapters, CI was also calculated based on height at beginning of the observation period. However, as results did not differ, and for reasons of consistency, CI was calculated based on final tree height for all tree-crop combinations.

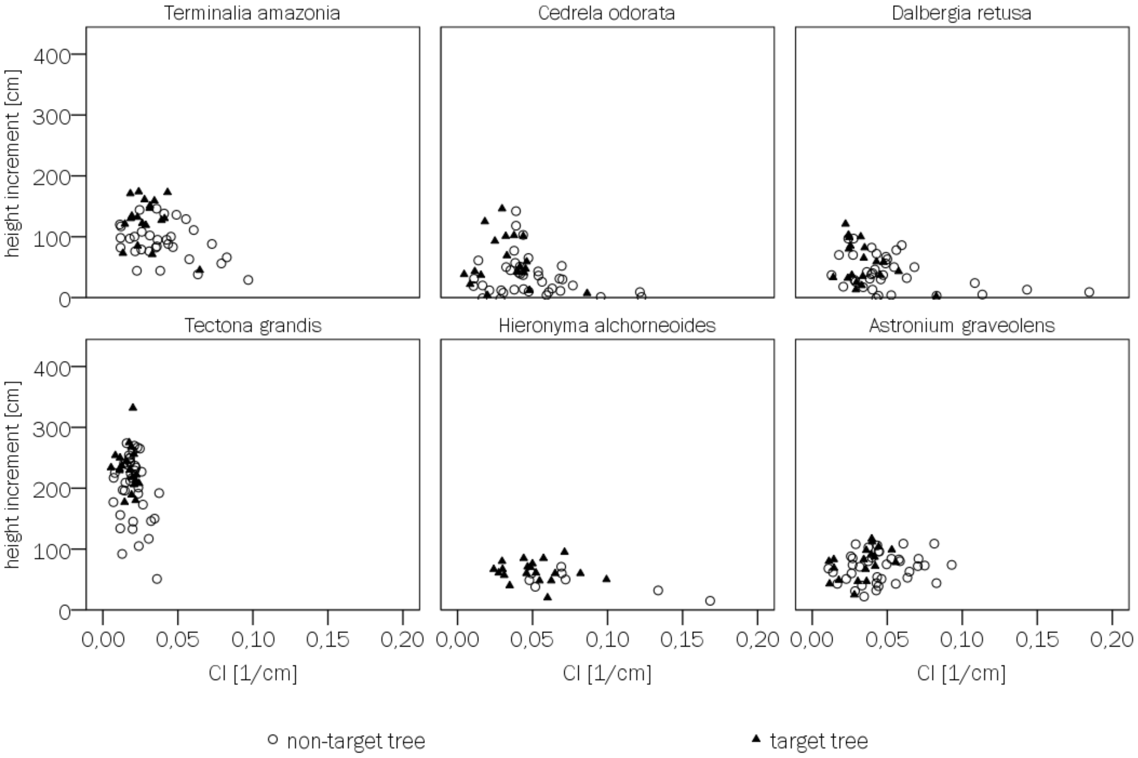

Figure 4.29: Height increment of trees for the period between 9 and 12 months in the pigeon pea fields (G-P treatment) plotted against CI after 12 months. Triangles denote the 5 tallest trees per plot after 24 months („target trees“).

Table 4.23: Results of regression analysis with dependent variable height increment between 9 and 12 months ($h_{12}-h_9$) and independent variable $\ln(CI_{pigeon\ pea})$ after 12 months in the G-P treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$h_{12}-h_9$	0.04	103.94	(20.73)	9.67	(6.21)	0.125
C. odorata	$\ln(h_{12}-h_9)$	0.09	1.652	(0.747)	-0.515	(0.22)	0.024
D. retusa	$h_{12}-h_9$	0.11	-20.57	(25.54)	-19.98	(7.90)	0.015
H. alchorneoides	$h_{12}-h_9$	0.20	10.39	(20.14)	-16.92	(6.81)	0.020
T. amazonia	$\ln(h_{12}-h_9)$	0.07	3.633	(0.329)	-0.273	(0.096)	0.006
T. grandis	$h_{12}-h_9$	0.04	105.04	(67.57)	-26.43	(16.64)	0.118

Surprisingly, *T. amazonia* reacted with a clearly decreasing diameter increment to competition with pigeon pea shrubs. This might also be attributed to an increased height growth which was already demonstrated in chapter 4.2.3.1. Even though heights also tended to decrease with rising competition, the R^2 was only 0.07 for height but 0.6 for diameter (Table 4.24). For the other tree species, the amount of explained variance was rather small, but a significant decrease in diameter increment with rising CI was also shown for *D. retusa* and *H. alchorneoides*.

Table 4.24: Results of regression analysis with dependent variable root collar diameter increment for the period between 9 and 12 months ($rcd_{12}–rcd_9$) and independent variable $\ln(CI_{pigeon\ pea})$ after 12 months in the G-P treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$rcd_{12}–rcd_9$	0.21	0.15	(2.79)	-3.14	(0.83)	<0.001
C. odorata	$rcd_{12}–rcd_9$	0.03	12.06	(6.32)	2.36	(1.85)	0.206
D. retusa	$\ln(rcd_{12}–rcd_9)$	0.14	-0.04	(0.66)	-0.54	(0.20)	0.011
H. alchorneoides	$\ln(rcd_{12}–rcd_9)$	0.20	0.06	(0.89)	-0.70	(0.30)	0.027
T. amazonia	$\ln(rcd_{12}–rcd_9)$	0.66	-1.32	(0.38)	-1.00	(0.11)	<0.001
T. grandis	$rcd_{12}–rcd_9$	0.01	25.10	(9.66)	-1.77	(2.38)	0.461

In accordance with the results presented in the previous chapter, reaction to competition was more distinct in the second half of the observation period (Figure 4.30). All tree species showed a significant reduction of height increment with increasing CI (Table 4.25).

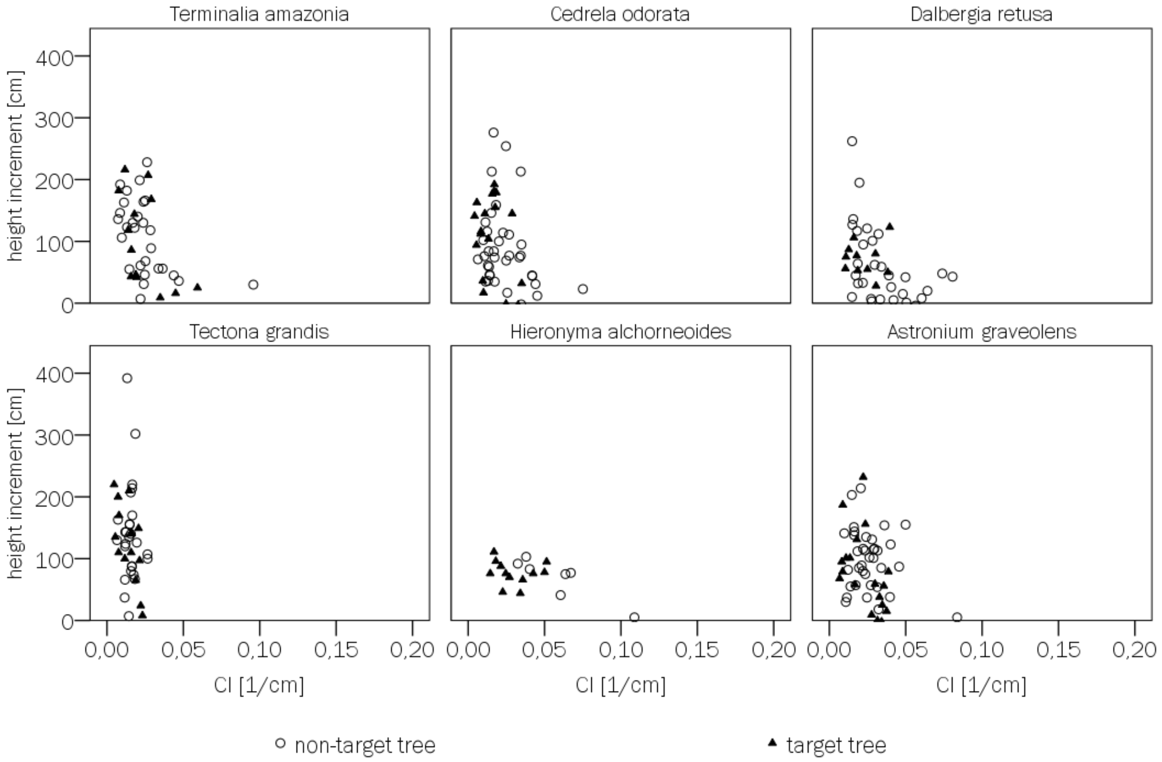

Figure 4.30: Height increment of trees in the period between 12 and 18 months in the pigeon pea fields (G-P treatment) plotted against the CI after 18 months. Triangles denote the 5 tallest trees per plot after 24 months („target trees“).

Table 4.25: Results of regression analysis with dependent variable height increment for the period between 12 and 18 months ($h_{18}-h_{12}$) and independent variable ln($CI_{pigeon\ pea}$) after 18 months in the G-P treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$h_{18}-h_{12}$	0.17	-94.68	(53.19)	-47.25	(14.06)	0.001
C. odorata[1]	$h_{18}-h_{12}$	0.15	-112.56	(57.41)	-48.06	(14.40)	0.001
D. retusa	$h_{18}-h_{12}$	0.26	-204.69	(55.26)	-68.44	(15.63)	<0.001
H. alchorneoides	$h_{18}-h_{12}$	0.41	-191.33	(55.21)	-72.04	(17.28)	<0.001
T. amazonia	$h_{18}-h_{12}$	0.52	-359.07	(57.37)	-114.33	(15.39)	<0.001
T. grandis	$h_{18}-h_{12}$	0.45	-671.22	(111.35)	-180.17	(27.03)	<0.001

[1] Residuals of this model were not normally distributed according to the K-S and Shapiro-Wilks-Test either with or without transformation. Therefore the untransformed dependent variable was used. Visual estimation of residuals using Q-Q plots did not show a severe violation of the assumption of normally distributed residuals. Furthermore, no patterns were observed in residuals ploted against predicted values and hence the model was accepted. Nevertheless this result should be interpreted with caution.

With the exception of *A. graveolens,* all tree species also tended to react negatively in terms of diameter increment when planted close to pigeon peas (Table 4.26).

Table 4.26: Results of regression analysis with dependent variable root collar diameter increment for the period between 12 and 18 months ($rcd_{18}-rcd_{12}$) and independent variable ln($CI_{pigeon\ pea}$) after 18 months in the G-P treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	ln($rcd_{18}-rcd_{12}$)	0.03	4.08	(0.19)	-0.06	(0.05)	0.212
C. odorata	$rcd_{18}-rcd_{12}$	0.06	-12.84	(12.81)	-6.65	(3.21)	0.043
D. retusa	$rcd_{18}-rcd_{12}$	0.09	-22.86	(12.47)	-8.12	(3.53)	0.025
H. alchorneoides	$rcd_{18}-rcd_{12}$	0.35	-33.44	(9.76)	-11.09	(3.05)	0.001
T. amazonia	ln($rcd_{18}-rcd_{12}$)	0.15	3.74	(0.15)	-0.12	(0.04)	0.004
T. grandis	$rcd_{18}-rcd_{12}$	0.34	-132.52	(25.30)	-32.48	(6.14)	<0.001

However, despite the negative relationship between distance-adjusted height of neighbors and height and diameter increment, results suggest again, that the influence on tree performance is rather small as long as extreme competition situations are avoided. This is illustrated by Table 4.27, which characterizes the competition situation of the three trees of each tree species with the greatest height increment during the period from 12 to 18 months. Even though the CI of these trees is at the lower end (cf Figure 4.30), the distance to the closest neighbor is, in most cases. less than one meter. This shows that the high CI values resulted from extremely small distances – often combined with rather small trees - while the distances that are usually applied in agrisilvicultural systems of 1 m or more obviously do not seem to cause severe reductions in height and diameter increment.

Table 4.27: Characterization of the neighborhood of the three trees of each tree species with the largest height increment during the period from 12-18 months in the G-P treatment: Given is the height increment of the focal tree (h_{18}–h_{12}), its total height after 18 months (h_{18}), the calculated competition index (CI), the distances to the three closest pigeon pea shrubs ($dist_1$ to $dist_3$), and their heights before harvesting (h_{p1} to h_{p3}).

	h_{18}–h_{12} [cm]	h_{18} [cm]	CI [1/cm]	$dist_1$ [cm]	$dist_2$ [cm]	$dist_3$ [cm]	h_{p1} [cm]	h_{p2} [cm]	h_{p3} [cm]
A. graveolens	232	390	0,02	78	70	170	320	210	260
	214	310	0,02	122	116	160	290	320	200
	203	350	0,01	126	163	220	320	210	290
C.odorata	276	370	0,02	145	142	117	260	280	280
	254	360	0,02	130	70	170	330	280	400
	213	300	0,03	116	62	124	310	330	290
D.retusa	262	400	0,01	72	152	160	200	200	300
	195	295	0,02	205	178	68	240	250	220
	136	290	0,02	76	140	218	150	190	260
H. alchorneoides	111	265	0,02	175	128	142	190	280	170
	103	190	0,04	88	125	162	280	280	290
	96	195	0,02	200	90	250	170	190	140
T.amazonia	228	340	0,03	86	120	120	330	270	340
	216	420	0,01	183	175	212	340	230	370
	207	390	0,03	63	145	118	360	300	320
T.grandis	392	540	0,01	102	177	210	370	370	300
	302	540	0,02	50	170	255	370	240	310
	220	580	0,02	57	130	113	300	220	300

4.3.2 Effect of competition for light on single tree performance

The competition for growing space investigated in the previous chapters already served to characterize below and aboveground competition. To quantify the actual aboveground competition, or in other words, the light regime, PAR measurements were carried out. The relative shading of each tree was calculated as a percentage of PAR of open condition and PAR radiation above each tree. Results will be presented for cassava and pigeon pea as an example.

As not many trees were shaded by cassava during the first 6 months it was not possible to make any inferences about possible effects of shading on tree performance. Nevertheless, data is presented in the appendix (Figure 11.2). Figure 4.31 shows the height increment during the period between 6 and 12 months in relation to shading by cassava measured after 12 months. The graphs reveal that due to the high mortality of cassava, the majority of trees were not directly shaded by cassava.

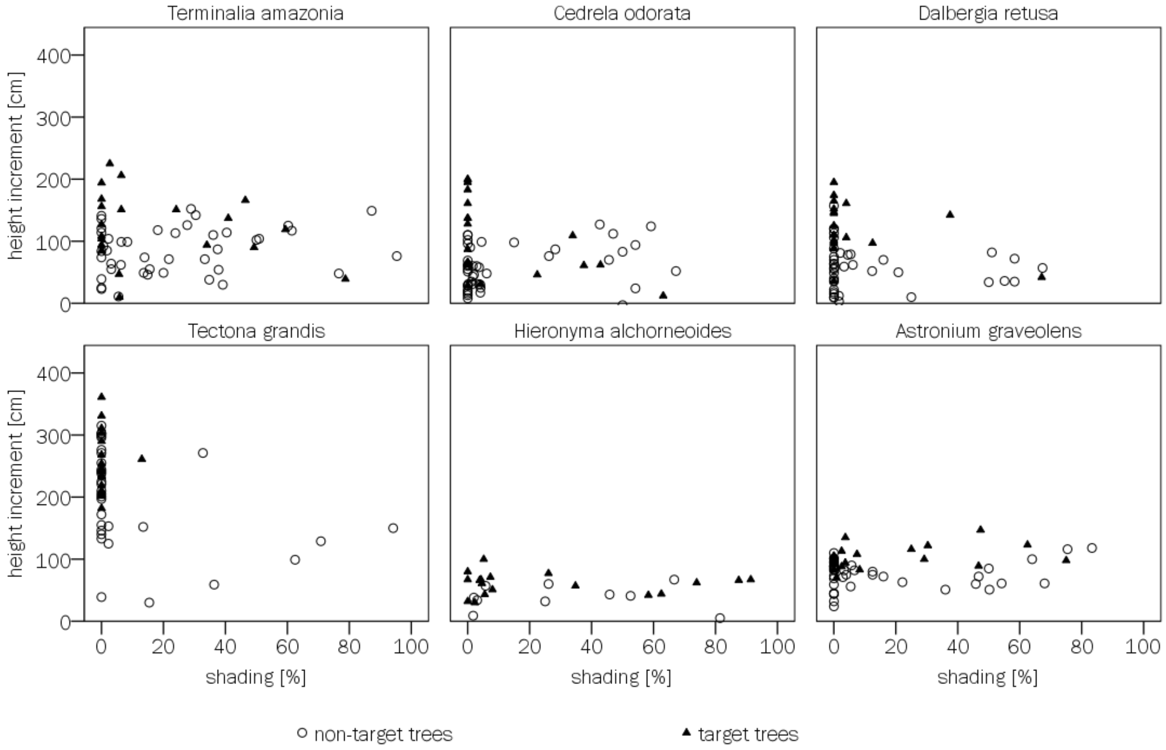

Figure 4.31: Relationship between the height increment of trees during the period from 6 to 12 months in the C-S treatment and the relative shading by cassava, based on PAR measurements. The 20 tallest trees (out of 64) after 24 months ("target trees") are displayed as triangles.

The linear regression of the data did not reveal any significant relationship between shading and height increment (Table 4.28), while model fit was generally low. In the regression model presented in Table 4.28, trees that were not shaded by cassava (shading = 0%) were excluded from the analysis to avoid heteroscedasticity. However, results including and excluding unshaded trees hardly differed. Only *T. grandis* showed a significantly negative relationship between height increment and shading (b_1 = -13.77, SE = 3.88, p = 0.001) when including the increment of unshaded trees. As residuals of this model showed strong signs of heteroscedasticity, unshaded trees were excluded.

Table 4.28: Results of regression analysis with dependent variable height increment between 6 and 12 months (h_{12}–h_6) and independent variable (shading [%])$^{0.5}$ after 12 months in the C-S treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets. (Shading < 0% was excluded)

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	h_{12}–h_6	0.01	83.14	(8.53)	1.10	(1.59)	0.494
C. odorata	h_{12}–h_6	0.10	43.16	(10.71)	4.00	(2.19)	0.078
D. retusa	h_{12}–h_6	0.02	61.94	(11.78)	-1.40	(2.36)	0.561
H. alchorneoides	h_{12}–h_6	0.00	51.39	(8.32)	0.04	(1.48)	0.977
T. amazonia	h_{12}–h_6	0.06	66.93	(14.24)	4.28	(2.56)	0.103
T. grandis	h_{12}–h_6	0.01	154.59	(55.55)	-2.25	(9.49)	0.819

Interestingly, Figure 4.31 reveals a slightly positive relationship between shading and height increment for *A. graveolens*, which was also observed during the first observation period (see appendix, Figure 11.2). This relationship was however not proven to be significant. Yet, the root collar diameter increment was found to decrease significantly with increasing shade caused by cassava shrubs (Table 4.29). This supports the observation mentioned in chapter 4.2.3.1, that height increment of *A. graveolens* was stimulated by the interplanted shrubs at the expense of diameter increment.

Table 4.29: Results of regression analysis with dependent variable root collar diameter increment for the period between 6 and 12 months ($rcd_{12}-rcd_6$) and independent variable (shading [%])$^{0.5}$ after 12 months in the C-S treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets. (Shading < 0% was excluded)

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$\ln(rcd_{12}-rcd_6)$	0.16	2.76	(0.13)	-0.06	(0.02)	0.016
C. odorata	$(rcd_{12}-rcd_6)$	0.02	14.71	(3.28)	-0.55	(0.67)	0.423
D. retusa	$\ln(rcd_{12}-rcd_6)$	0.03	2.27	(0.32)	-0.05	(0.07)	0.433
H. alchorneoides	$\ln(rcd_{12}-rcd_6)$	0.01	1.88	(0.19)	0.02	(0.04)	0.663
T. amazonia	$\ln(rcd_{12}-rcd_6)$	<0.01	1.93	(0.23)	-0.01	(0.04)	0.745
T. grandis	$\ln(rcd_{12}-rcd_6)$	0.30	3.48	(0.27)	-0.09	(0.05)	0.098

Measurements to assess shading of trees by pigeon pea shrubs were only carried out once - at the end of the pigeon pea rotation. *T. grandis* was excluded from further analysis, as most *T. grandis* trees already towered over the pigeon pea shrubs, and hence, received full light (Figure 4.32).

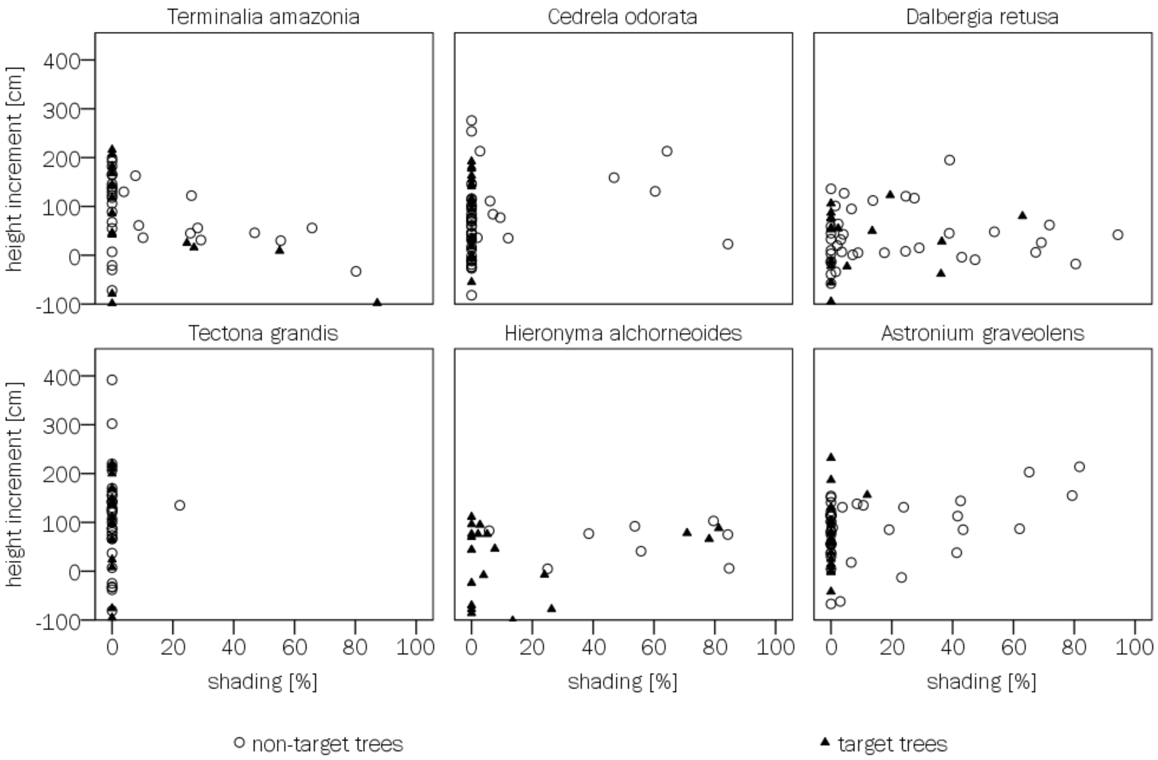

Figure 4.32: Relationship between the height increment of trees during the period between 12 and 18 months in the G-P treatment and relative shading by pigeon pea shrubs based on PAR measurements. The 20 tallest trees ("target trees") out of 64 after 24 months are displayed as triangles.

A significant relationship between shading and height growth was found only for *T. amazonia* (Table 4.30). However, Figure 4.32 reveals that the negative trend was mainly caused by two trees with high shading and low height increment. These cases were not identified as significantly affecting the regression model when examining Cook's distance and the DFBeta[67] values. However, when excluding them, no significantly negative relationship was observed. In accordance with the results found in the cassava treatment, *A. graveolens* also showed a slightly positive relationship between height increment and shading, which was however, not proven to be significant.

Table 4.30: Results of regression analysis with dependent variable height increment for the period between 12 and 18 months (h_{18}–h_{12}) and independent variable (shading [%])$^{0.5}$ after 18 months in the G-P treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets. (Shading < 0% was excluded)

Tree species	dependent variable	R^2	b_0		b_1		p-value
T. amazonia	h_{18}–h_{12}	0.33	129.45	(36.89)	-16.79	(6.24)	0.017
C. odorata	h_{18}–h_{12}	0.02	93.31	(45.25)	3.20	(8.33)	0.711
D. retusa	h_{18}–h_{12}	<0.001	49.39	(19.64)	-1.09	(3.69)	0.770
T. grandis[1]	h_{18}–h_{12}	-	-	-	-	-	-
H. alchorneoides	h_{18}–h_{12}	0.04	21.12	(29.84)	3.89	(4.77)	0.426
A. graveolens	h_{18}–h_{12}	0.20	39.96	(34.80)	12.45	(6.19)	0.062

[1] There were not enough cases of shading available for this tree species to carry out a regression analysis

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[67] Difference between a parameter estimated using all cases and estimated when one case is excluded (Field 2009).

Results from examining the relationship between the diameter increment and shading were consistent to those obtained when examining the height increment. None of the tree species showed a significant reaction in diameter increment due to shading by pigeon pea shrubs.

Table 4.31: Results of regression analysis with dependent variable root collar diameter increment for the time period between 12 and 18 months ($rcd_{18}–rcd_{12}$) and independent variable (shading [%])$^{0.5}$ after 18 months in the G-P treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets. (Shading < 0% was excluded)

Tree species	dependent variable	R^2	b_0		b_1		p-value
T. amazonia	$rcd_{18}–rcd_{12}$	0.09	17.08	(7.35)	-1.55	(1.20)	0.213
C. odorata	$rcd_{18}–rcd_{12}$	0.02	14.21	(8.19)	0.64	(1.51)	0.121
D. retusa	$rcd_{18}–rcd_{12}$	0.01	7.87	(3.59)	-0.09	(0.63)	0.884
T. grandis[1]	$rcd_{18}–rcd_{12}$	-	-	-	-	-	-
H. alchorneoides	$rcd_{18}–rcd_{12}$	0.01	1.59	(2.73)	0.27	(0.39)	0.496
A. graveolens	$rcd_{18}–rcd_{12}$	0.07	8.69	(11.17)	2.18	(1.99)	0.289

[1] There were not enough cases of shading available for this tree species to carry out a regression analysis

Results from light measurements in cassava and pigeon pea plots showed that shading did not influence individual tree growth and thus suggest that no negative reactions of trees to short-term shading by intercrops need be expected.

4.4 Crop production

4.4.1 Overall yields and biomass production of crops

Table 4.32 presents the yields and biomass harvested in the trial on a per hectare basis. The data were extrapolated from the total yield and biomass harvested and weighed on an area of 0.5 ha for each crop. As it represents the sum of a complete inventory, the table does not contain deviations.

With the exception of the first maize and pigeon pea rotation, yields were generally low compared to the average yields for Panama reported by the FAO (2013b) (see chapter 5.2.3 for details). This is not surprising considering the physical soil conditions at the study site (see chapter 3.1.1), extreme weather conditions due to the El Niño phenomenon and the avoidance of the use of insecticides or fungicides. Accordingly, fertilizer was only used during the first and third maize cultivation and only a minimal application of herbicides was done compared to common agricultural practices. These low input management practices were necessary to reduce fertilizer effects in the trial and in order to meet the regulations of FSC certification. Hence, overall yield should not be compared to industrial crop cultivation. Furthermore, the waterlogged site, together with bad seed quality led to a total loss of ginger. Soy beans were also unsuccessful in the trial, because of an unexpectedly high amount of precipitation from November through January, which impeded the germination and flowering of plants.

Table 4.32: Total marketable yield and aboveground biomass of harvested and remaining plant parts in each of the four crop rotations. Data are based on a total harvest on 0.5 ha (see text for details). (CF = factor for conversion of fresh weight into dry weight, obtained by drying samples at 60°C for more than 72 hours see chapter 3.4.2)

Crop	Harvested plant parts					Remaining aboveground biomass			Total biomass
	plant part	yield [kg/ha]	total weight[1] [kg/ha]	CF	dry weight [kg atro/ha]	total weight [kg/ha]	CF	dry weight [kg atro/ha]	dry weight [kg atro/ha]
Crop rotation G-P									
Ginger	tubers	-	-	-	-	-	-	-	-
Pigeon Pea	dry seeds[2]	626	1038	0.81	841	19126	0.47[3]	8989	9830
Crop rotation M-B-M-M									
Maize 1	cobs	4613	7243	0.44	3187	12756	0.23	2934	6121
Beans	dry seeds[2]	406	596	0.88	525	3107	0.19	590	1115
Maize 2	cobs	2697	4019	0.44	1768	3804	0.23	875	2643
Maize 3	cobs	560	920	0.44	405	3798	0.23	873	1278
Crop rotation B-R-R									
Beans	dry seeds[2]	596	872	0.88	768	2437	0.19	463	1231
Rice 1	dry seeds	-	-	-	-	-	-	-	-
Rice 2	dry seeds[4]	202	227	0.75	170	534	0.39	208	378
Crop rotation C-S									
Cassava	tubers	3614	3834	0.53	2035	9620	0.53	5108	7143[5]
Soy beans	dry seeds	42	61	0.91	55	177	0.26	46	101

[1] Refers to non-marketable harvested plant parts such as the husks of bean pods. For maize this value refers to damaged or for other reasons non-marketable maize.
[2] Both green and dried pods were harvested. Green pods were converted into dried pods (see text and footnote No. 70 for details)
[3] Conversion factor was weighted by different plant fractions (see Table 11.9 in the appendix and Kreuzer (2013)
[4] In husk
[5] Contains belowground biomass, as roots were also harvested and weighed.

The high clay content also led to low yields and a low survival for cassava of only 53 %. As dry rice is generally more suitable for such waterlogged sites this crop was included in the trial, but also presented marginal yields, due to high losses from birds[68] - which led to a total loss in the first rotation - fungal attacks and high levels of competition with grasses due to the reduced use of herbicides[69]. The low yields highlight the high dependence of this exotic crop on synthetic pesticides. It therefore seems to be less adequate for use in forest plantations if a certified wood production is planned. As yields were negligible for rice, ginger and soy beans, these data will be excluded from further statistical analysis.

Maize yields showed a linear decline in weight of harvested corn cobs from the first to the third rotation. However, yields in the third rotation should be interpreted with caution, as extreme rainfalls during November impeded the growth and flowering of maize plants. This can be illustrated by the high germination rate of the third maize rotation (88%), while the total fresh weight of corn cobs and total number of cobs reached only 12% and 15% respectively of that of the first maize rotation. Fresh weight of corn cobs decreased by 42% between the first and the second maize rotation as no fertilizer was used. However, the number of corn cobs only decreased by 30%, representing a lower individual cob weight. It should be noted that the fresh and dry weights of yields in Table 4.32 include the whole maize cobs, whereas data in the

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[68] In the region of Tortí a range of toxic substances (some of them lethal to birds) is usually applied to the seeds and again onto plants after flowering to avoid damages by birds. These toxins are not allowed in FSC forest plantations and are not advisable in forest plantations if the function of biodiversity is to be restored.
[69] Pre- and post-emergent herbicides, including the active components Paraquat or Molinate, are locally used in rice fields, but are not allowed in FSC plantations, and their use is even restricted in the European Union.

literature usually refer to yields of dried maize seeds only. In order to convert the number of corn cobs into yield of threshed and dried maize seeds (in kg) the conversion factor of 0.092 reported by INEC (2006) can be used. Yield of maize seeds would then account for 2.2 t/ha in the first maize rotation.

Beans showed a higher yield when no previous cultivation of maize was carried out (B-R-R rotation in Table 4.32). In the case of all leguminous plants, the “marketable fresh weight” refers to the yield of threshed dried seeds. Nonmarketable parts represent the weight of the empty pods and non-marketable green pods which were converted into weight of dried pods[70]. Even though pigeon peas were harvested in green pods - as higher prices can be obtained for the green peas compared to dry threshed seeds – the weights of all pods were converted to dried pod weights to facilitate an easier comparison with the literature. Data on the plant parts actually sold and the prices obtained will be given in Table 4.57 in chapter 4.5.3.2. The total yield of pigeon pea in this trial was within the range of yields reported for Panama by the FAO (2013b). An average of 186 g of dried seeds were produced per shrub when both dried and green pods were pooled together, and actually, an average of 331 g green pods and 8 g seeds were harvested per shrub.

Aboveground biomass – excluding harvested plant parts - was by far greatest for pigeon pea, which produced 9 t/ha of dry matter excluding the harvested pods[71]. Around half of this amount was produced by the cassava shrubs. Cassava was the only crop for which belowground biomass was also evaluated, as the tuber crops were harvested[72].

4.4.2 Comparison of yields between pure agriculture and agroforestry

The following section will give an overview of differences in yields between pure agricultural and agroforestry plots. Crop yields are inherently lower on agroforestry plots due to trees occupying some of the area which would otherwise be available for crop production. This difference will be taken into account in the economic evaluation in chapter 4.5. In this section, however, yield will be evaluated on the basis of the actual area that is available for crop planting to assess the overall effect of trees on crop production.

Table 4.33 shows the mean yield and biomass production in the four agroforestry plots and the corresponding pure agricultural plots of each crop within each crop rotation. Yield did not differ significantly between any of the sampling types. Among plots planted solely with pigeon pea, plot VIII was identified as an outlier with a yield of dried threshed beans of 0.24 kg/m^2. To achieve a normal distribution and homogeneity of variances, this case was omitted, and the control plots then showed a 40% higher yield compared to the agroforestry plots ($T(5) = 2.879$, $p = 0.035$)[73]. Accordingly, total biomass was by trend higher, yet not significantly higher ($T(5) = 2.191$, $p = 0.08$) in the pure agricultural plots compared to the agroforestry plots.

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[70] To calculate this conversion factor, 10 samples each of 50 dried and 50 green pods were weighed. The resulting factors for conversion of green pods into dried pods were 0.47 for common beans, 0.52 for pigeon pea and 0.38 for soy beans. These samples were also used to calculate the fraction of whole pods comprised of seeds by separating seeds and husks and weighing each separately. The portion of total weight of a whole dried pod weight from seeds was 68.1% for common beans, 60.3% for pigeon pea and 73.0% for soy beans.

[71] See Table 11.9 (appendix) for obtained dry matter fraction of different plant parts for pigeon pea shrubs

[72] In the case of pigeon pea, samples of belowground biomass suggested a below to aboveground biomass ratio of 9 (Kreuzer 2013). Due to the small sample size of this study, only aboveground biomass will be considered.

[73] The result was also confirmed by applying the rank-based non-parametric Mann-Whitney Test to all 8 samples that showed a standardized test statistic of -2.309 and exact p (two-sided) of 0.029.

Table 4.33: Yield per m^2 [kg atro/m^2] and remaining aboveground biomass per m^2 [kg atro/m^2] by sampling type (AF = Agroforestry, CP = Pure crop plantation). The table shows number of samples (N), arithmetic means ($\bar{x}$), 95% confidence intervals (in brackets) and results of T-Test between sampling types for each dependent variable (t = t-value, df = degrees of freedom, p = p-value).

		AF			CP			T-Test		
Crop	Dependent	N	$\bar{x}_{AF}$	(confidence interval)	N	$\bar{x}_{CP}$	(confidence interval)	t	df[1]	p
Crop rotation G-P										
Pigeon pea	Yield	4	0.05	(0.0 - 0.07)	4	0.11	(0.0 - 0.24)	1.490	3.1	0.23
Pigeon pea	Biomass	4	0.89	(0.5 - 1.29)	3	1.28	(0.8 - 1.77)	2.191	5.0	0.08
Crop rotation M-B-M-M										
Maize 1	Yield	4	0.31	(0.2 - 0.37)	4	0.38	(0.3 - 0.47)	1.990	6.0	0.094
Maize 1	Biomass	4	0.28	(0.2 - 0.39)	4	0.36	(0.0 - 0.67)	0.739	6.0	0.488
Beans	Yield	4	0.04	(0.0 - 0.05)	4	0.05	(0.0 - 0.07)	0.319	4.0	0.766
Beans	Biomass	4	0.06	(0.0 - 0.09)	4	0.07	(0.0 - 0.13)	0.722	6.0	0.498
Maize 2	Yield	4	0.18	(0.1 - 0.25)	4	0.18	(0.1 - 0.31)	0.103	6.0	0.921
Maize 2	Biomass	4	0.21	(0.1 - 0.36)	4	0.04	(0.0 - 0.09)	-3.230	6.0	**0.018**
Maize 3	Yield	4	0.04	(0.0 - 0.08)	4	0.03	(0.0 - 0.06)	-1.202	6.0	0.275
Maize 3	Biomass	4	0.09	(0.0 - 0.16)	4	0.07	(0.0 - 0.11)	-.657	6.0	0.535
Crop rotation B-R-R										
Beans	Yield	4	0.07	(0.0 - 0.1)	4	0.04	(0.0 - 0.07)	-2.141	6.0	0.076
Beans	Biomass	4	0.06	(0.0 - 0.09)	4	0.01	(0.0 - 0.02)	-4.109	6.0	**0.006**
Crop rotation C-S										
Cassava	Yield	4	0.18	(0.1 - 0.28)	4	0.16	(0.0 - 0.35)	-.223	6.0	0.831
Cassava	Biomass	4	0.43	(0.2 - 0.70)	4	0.44	(0.0 - 0.99)	0.075	6.0	0.943

[1] Degrees of freedom lower than 6 (or 5 in the case of pigeon pea biomass) indicate that the separate variance T-Test was applied.

In contrast to the results for pigeon pea, beans and the second maize rotation showed significantly higher biomass production in the agroforestry plots compared to the pure agricultural plots (Table 4.33). However, in the case of beans, this pattern was not consistent between the M-B-M-M and B-R-R treatments. Accordingly, the different maize rotations did not show a consistently higher biomass production in the agroforestry plots. Hence, these observed patterns might be attributed to other effects. However, a trend towards higher yields in the agroforestry plots compared to the pure agricultural plots was also observed for cassava, beans, the second and third maize rotations and soy beans.

The results of this analysis are important for the further economic analysis, as the experiment showed that no severe overall reduction of agricultural yields due to the presence of trees is to be expected during the first year, and hence, the same yield per unit area can be assumed for both agroforestry and pure agriculture. The following analysis will focus on differences in crop production between different planting densities and tree species, without considering pure agricultural plots.

4.4.3 Effect of tree species and planting distance on crop yields and biomass

In order to investigate the effect of the tree species combination on crop yield and biomass production, a simple ANOVA was carried out for each planting distance. Table 4.34 reveals that – with few exceptions - no effect of tree species identity on crop production was detected. Only plant biomass of the second maize rotation was significantly higher for maize planted between *C. odorata* trees (CoCo gradient[74]) compared to the mixture of *T. grandis* and *T. amazonia* (TgTa) (p = 0.021, based on Tukey Test). Surprisingly, all of the four samples taken between *C. odorata* at a distance of 2 m revealed a higher plant biomass production of maize compared to those taken between other tree species (Figure 4.33). However, at greater distances this effect was no more evident. Additionally, maize yield per plant was not proven to significantly differ between tree species combinations. Yield per plant was included into the statistical analyses, as it presents a good indicator for plant vitality. Furthermore this parameter is not area dependent and is less influenced by possible biases that might result from the potential and actually planted – and measured - crop area that will be discussed in detail in chapter 5.1.

Table 4.34: p-Values of ANOVA to test for differences in dependent variables yield/m^2 [kg atro/m^2], yield per plant [kg atro/m^2] and aboveground biomass excluding harvested parts [kg atro/m^2] between tree gradients for each tree planting distance (N = 4). All dependent variables were square root transformed prior to analysis. Significant results are presented in bold.

dependent variable	planting distance of trees [m]							
	2.0	2.7	3.4	4.1	4.9	5.6	6.3	7.0
Maize 2[1]								
$(\text{yield/m}^2)^{0.5}$	**0.055**[2]	0.100	0.982	0.956	0.944	0.980	0.844	0.080
$(\text{yield/plant})^{0.5}$	0.897	0.911	0.752	0.924	0.853	0.805	0.665	0.073
$(\text{biomass})^{0.5}$	**0.021**	0.809	0.976	0.987	0.799	0.577	0.986	0.268
Maize 3[5]								
$(\text{yield/m}^2)^{0.5}$	0.779	0.759	0.372	0.543	0.984	0.905	0.143	0.755
$(\text{yield/plant})^{0.5}$	0.964	0.862	0.768	0.699	0.818	0.822	0.107	0.907
$(\text{biomass})^{0.5}$	0.504	0.698	0.329	0.703	0.993	0.995	0.934	0.798
Cassava								
$(\text{yield/m}^2)^{0.5}$	**0.003**	0.367	0.141	0.485	0.683	0.124	0.873	0.058
$(\text{yield/plant})^{0.5}$	0.108	0.431	0.516	0.549	0.688	0.105	0.894	0.337
$(\text{biomass})^{0.5}$	0.208	0.301	0.096	0.627	0.947	0.572	0.816	0.073
Pigeon pea								
$(\text{yield/m}^2)^{0.5}$	0.494	0.354	0.639	0.279	0.969	0.835	0.346	0.966
$(\text{yield/plant})^{0.5}$	0.330	0.755	0.290	0.300	0.959	0.673	0.129	0.865
$(\text{biomass})^{0.5}$	0.175	0.879	0.599	0.685	0.634	0.794	0.804	0.870
Beans[3] [4]								
$(\text{yield/m}^2)^{0.5}$	0.124	0.635	0.153	0.081	0.063	**0.008**	0.074	0.707
$(\text{biomass})^{0.5}$	**0.028**	0.228	0.550	0.842	0.751	0.391	0.199	0.087

[1] Refers to the second maize rotation in the M-B-M-M treatment
[2] TaHa was excluded as only one sample was available
[3] Data from bean harvest with and without previous maize harvest (M-B-M-M and B-R-R treatment) were pooled together
[4] Number of plants was not counted for beans
[5] Refers to the third maize rotation in the M-B-M-M treatment

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[74] See Table 3.8, page 28 for abbreviations

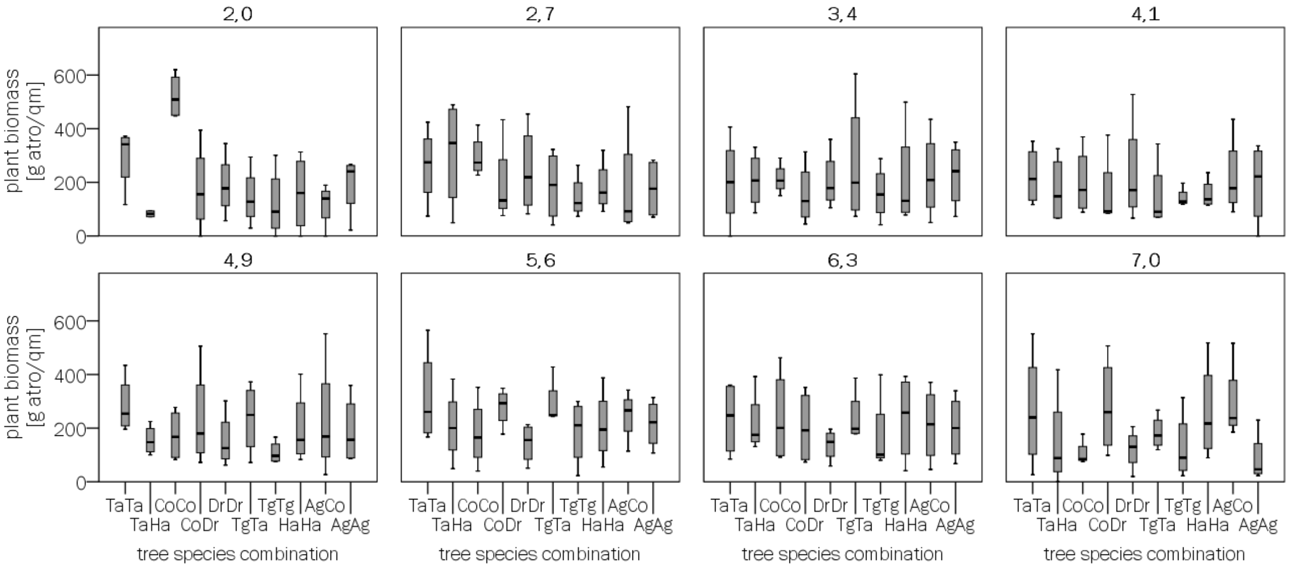

Figure 4.33: Aboveground plant biomass of the second maize rotation (excluding harvested cops) by tree species combination at each planting distance [m] (see Table 3.8, page 29 for abbreviations).

A significant effect of tree species at a planting distance of 2 m was also detected on cassava yields/m² (Table 4.34). Tuber yields in the TaTa gradients were significantly higher compared to the TaHa ($p = 0.014$) and CoDr gradients ($p = 0.007$). Yields for the HaHa gradients were furthermore significantly higher than for both the TaHa ($p = 0.05$) and CoDr ($p = 0.021$) gradients. In the CoDr gradients, cassava yields were also significantly lower compared to those in the AgCo gradients ($p = 0.033$). However, due to the low germination rate of cassava mentioned earlier, the gradients CoDr, AgAg, DrDr, CoCo, AgCo only consisted of 2 samples at the 2 m distance, while no samples were available for TgTg. This difference in sample size might have affected results and is illustrated in the following scatterplot (Figure 4.34).

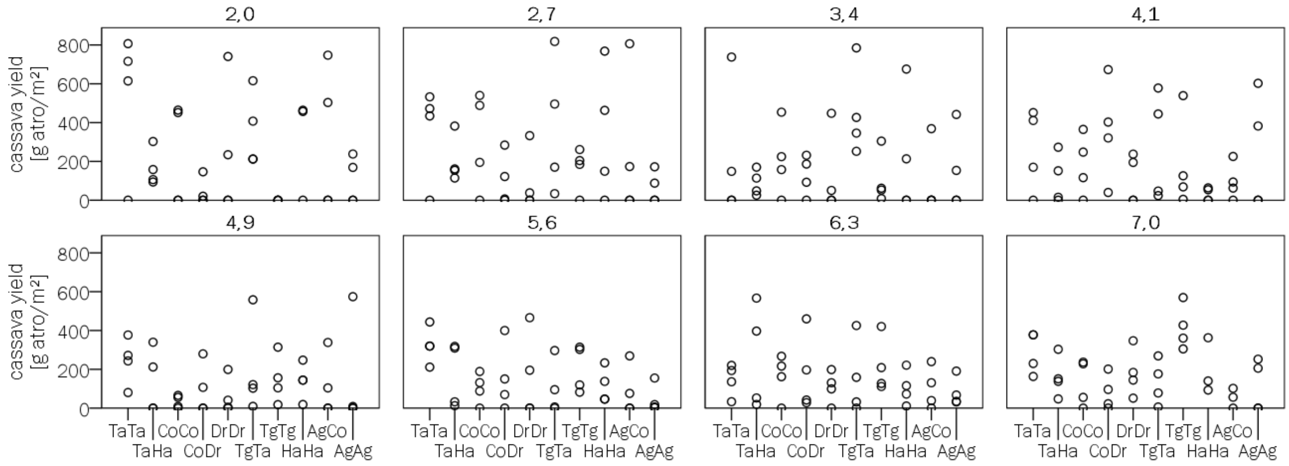

Figure 4.34: Scatterplots of observed cassava yields within different light gradients at different planting distances [m] (see Table 3.8, page 29 for abbreviations). Please note: Plots in which no single crop plant was present were omitted from the model, but are however shown in this graph to illustrate the entire data set.

Due to this low sample size at the 2 m distance the effects measured are rather unreliable. It seems, however, plausible that yields between *H. alchorneoides* trees were higher, as mortality among these tree species was high and trees were generally smaller than those of other tree species (see chapter 4.2). In contrast to cassava, bean yields were found to be significantly lower in the HaHa gradients than in both the AgCo and CoDr gradients at a distance of 5.6 m ($p = 0.021$ and $p = 0.046$, respectively). At a distance of 2 m, biomass of beans was higher in the CoCo than in the AgCo gradients ($p = 0.019$) (see Figure 11.3, appendix).

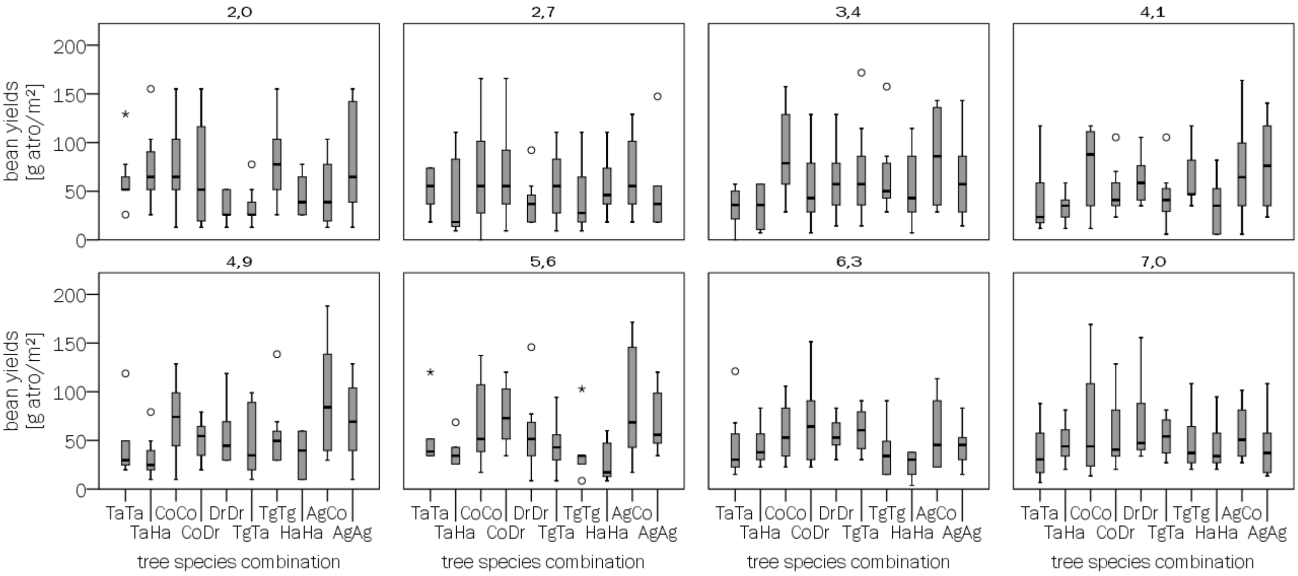

Figure 4.35: Bean yields by tree species combination at each planting distance [m] (see Table 3.8, page 29 for abbreviations). Yields in the M-B-M-M and B-R-R treatment were pooled together.

Overall, the species identity of neighboring trees did not to have a significant effect on crop yields during the first year of stand establishment. The high variance in crop production revealed by Figure 4.33 to Figure 4.35 shows that factors other than tree species affected crop production, while the ANOVA analysis did not reveal any plausible and consistent patterns.

It was however also hypothesized that the distance between trees might have a significant effect on mean yields and biomass production of subsamples. In a first step it was tested whether the regression slopes significantly differed between tree species, or in other words whether the effect of planting distance differed between tree species. For this purpose a weighted covariance analyses with factor tree species and covariable planting distance was carried out. The effect of differing slopes was analyzed by adding the interaction term. This interaction term was significant for all parameters for cassava[75]. Furthermore the effect of the planting distance on biomass production of the second maize rotation and both bean rotations was found to significantly differ between tree species[76]. For the other crops, none of the independent variables or the interaction term were significant[77]. However, due to significant interaction terms for some of the dependent variables the effect of planting density was analyzed separately for each tree-species combination.

Table 4.35 shows the results of the weighted regression calculated separately for each tree species combination to identify the effects of planting distance on the dependent variables yield/m^2, yield per plant and aboveground biomass/m^2. It reveals that planting distance generally explained a variance proportion of less than 30% for all parameters. It furthermore shows that the

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[75] Results of interaction of tree species (factor) and planting distance (covariable) with independent variable yield/m^2 was $F(9) = 3.196$; $p = 0.001$, with yield/plant result was $F(9) = 2.069$, $p = 0.033$ and with biomass/m^2 result was $F(9) = 2.899$, $p = 0.003$.

[76] Results of interaction of tree species (factor) and planting distance (covariable) with independent variable maize yield/m^2 was $F(9) = 3.618$, $p < 0.001$ and with independent variable beans yield/m^2 result was $F(9) = 4.339$, $p < 0.001$

[77] This was true in both models including or excluding the interaction term.

effect of planting distance was not significant for any parameters for pigeon pea. This seems plausible, as pigeon pea shrubs were taller than trees during most of the development and flowering periods of the shrubs. In contrast to the previous chapter, these results suggest that pigeon pea does not seem to be overly sensitive to competition with trees during the first months. Accordingly, further analyses by Kreuzer (2013) found that the germination rate of pigeon pea was also not significantly affected by tree species identity or planting distance.

Table 4.35: Results of the weighted regressions of independent variables yield Y [kg atro/m^2], yield per plant (Y/pl) [kg atro/m^2], and aboveground biomass (B) (excluding harvested plant parts) [kg atro/m^2] by planting distance, presented separately for each tree species combination (TSC). Results show model fit (R^2), estimated value of slope (b) and p-value (p) of predictor planting distance for each crop. All independent variables were square root transformed prior to analysis.

TSC		Maize 2			Maize 3			Cassava			Pigeon Pea			Beans[1]		
		Y	Y/pl	B	Y	Y/pl	B	Y	Y/pl	B	Y	Y/pl	B	Y	Y/pl	B
AgAg	R^2	0.07	0.09	0.06	0.06	0.07	0.05	0.09	0.00	0.21	0.07	0.03	0.01	0.05		0.00
	b	-0.02	-0.01	-0.02	-0.01	-0.01	-0.01	-0.04	0.01	-0.09	0.02	0.56	0.03	-0.01		0.00
	p	0.16	0.11	0.19	0.19	0.16	0.27	0.21	0.82	**0.05**	0.16	0.35	0.29	**0.07**		0.62
AgCo	R^2	0.00	0.04	0.05	0.20	0.10	0.01	0.45	0.26	0.49	0.04	0.04	-0.02	0.00		0.03
	b	0.00	-0.01	0.02	-0.02	-0.01	-0.01	-0.08	-0.08	-0.14	-0.02	-0.87	-0.02	0.00		0.01
	p	0.76	0.31	0.21	0.05	0.12	0.65	**<0.01**	**0.04**	**<0.01**	0.32	0.32	0.47	0.74		0.16
CoCo	R^2	0.34	0.22	0.31	0.11	0.00	0.08	0.22	0.03	0.22	0.00	0.07	0.06	0.02		0.09
	b	-0.05	-0.01	-0.05	-0.02	0.00	-0.02	-0.05	-0.02	-0.08	0.00	0.84	-0.04	-0.01		-0.01
	p	**<0.01**	**0.01**	**<0.01**	0.12	0.99	0.19	**0.03**	0.48	**0.03**	0.79	0.21	0.23	0.22		**0.02**
CoDr	R^2	0.00	0.03	0.04	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.02	0.03		0.08
	b	0.01	0.01	0.02	0.00	0.00	0.01	-0.01	0.03	-0.01	0.01	-0.04	0.02	-0.01		-0.01
	p	0.74	0.34	0.27	0.64	0.92	0.62	0.77	0.65	0.87	0.70	0.96	0.50	0.19		**0.03**
DrDr	R^2	0.30	0.05	0.11	0.04	0.10	0.18	0.04	0.08	0.22	0.06	0.02	0.11	0.00		0.00
	b	-0.05	-0.01	-0.03	-0.01	0.00	-0.03	-0.02	0.04	-0.07	-0.02	-0.43	-0.06	0.00		0.00
	p	**0.01**	0.22	**0.07**	0.32	0.62	**0.04**	0.41	0.22	0.04	0.21	0.50	**0.07**	0.87		0.75
HaHa	R^2	0.00	0.02	0.02	0.05	0.05	0.01	0.31	0.19	0.29	0.01	0.02	0.01	0.02		0.28
	b	0.00	0.00	0.01	-0.01	-0.01	-0.01	-0.08	-0.09	-0.11	0.01	0.52	-0.01	0.00		-0.03
	p	0.80	0.43	0.46	0.25	0.27	0.61	**<0.01**	**0.03**	**0.01**	0.69	0.40	0.60	0.23		**<0.01**
TaHa	R^2	0.02	0.06	0.00	0.15	0.12	0.09	0.00	0.00	0.00	0.00	0.03	0.02	0.00		0.13
	b	-0.01	-0.01	0.00	-0.02	-0.01	-0.21	0.01	-0.01	0.00	0.00	0.67	-0.02	0.01		0.01
	p	0.44	0.21	0.98	0.04	0.07	0.12	0.80	0.81	0.93	0.75	0.35	0.42	0.67		0.00
TaTa	R^2	0.00	0.00	0.01	0.03	0.02	0.08	0.33	0.11	0.09	0.06	0.02	0.01	0.05		0.12
	b	0.00	0.00	-0.01	0.01	0.00	0.02	-0.06	-0.06	-0.05	-0.02	-0.64	-0.02	0.00		-0.01
	p	0.76	0.99	0.68	0.39	0.49	0.16	**<0.01**	0.10	0.13	0.20	0.45	0.58	**0.07**		**<0.01**
TgTa	R^2	0.23	0.05	0.04	0.23	0.08	0.16	0.17	0.11	0.11	0.01	0.09	0.03	0.01		0.01
	b	0.04	0.01	0.02	-0.03	-0.01	-0.02	-0.06	-0.08	-0.09	0.01	1.02	-0.02	-0.01		0.00
	p	**0.01**	0.22	0.28	**0.02**	0.16	0.75	**0.02**	**0.07**	**0.08**	0.60	0.11	0.41	0.41		0.54
TgTg	R^2	0.01	0.40	0.00	0.18	0.03	0.04	0.20	0.15	0.15	0.02	0.02	0.18	0.07		0.08
	b	0.00	0.01	-0.01	-0.01	-0.01	-0.01	0.06	0.08	0.09	-0.01	0.48	-0.07	-0.01		-0.01
	p	0.72	0.30	0.73	0.50	0.37	0.35	**0.02**	**0.04**	**0.04**	0.50	0.49	**0.02**	**0.05**		**0.03**

[1] Bean harvests from M-B-M-M and B-R-R were pooled together

The only consistent effect found across most crops was the negative correlation between crop production and planting distance in the CoCo gradient. *C. odorata* has already shown higher maize yields and biomass compared to other tree species at the 2 m distance (Figure 4.33). This negative trend is, however, not only caused by high yields at 2 m, as can be observed in the following figures. A negative correlation between both yield and biomass and planting distance was also found for other tree species and crops (Table 4.35). The possible reasons for this negative correlation might also be related to trial design and management and will be discussed in detail in chapters 5.1 and 5.2.3. One possible explanation might be the weeding regime. Especially during the first months, weeding was carried out more intensively around trees and might therefore have induced a higher crop growth in direct competition to trees i.e. at a small subsample size. As an example, Figure 4.36 demonstrates the high variability of biomass production for beans at various planting distances. As beans were sown and harvested during the first 6 months of tree development, it seems rather unlikely that the effects apparent in Figure 4.36 can be attributed to tree growth itself but rather to differences in weeding regimes. Similar patterns were also found for bean yields which were however not significant.

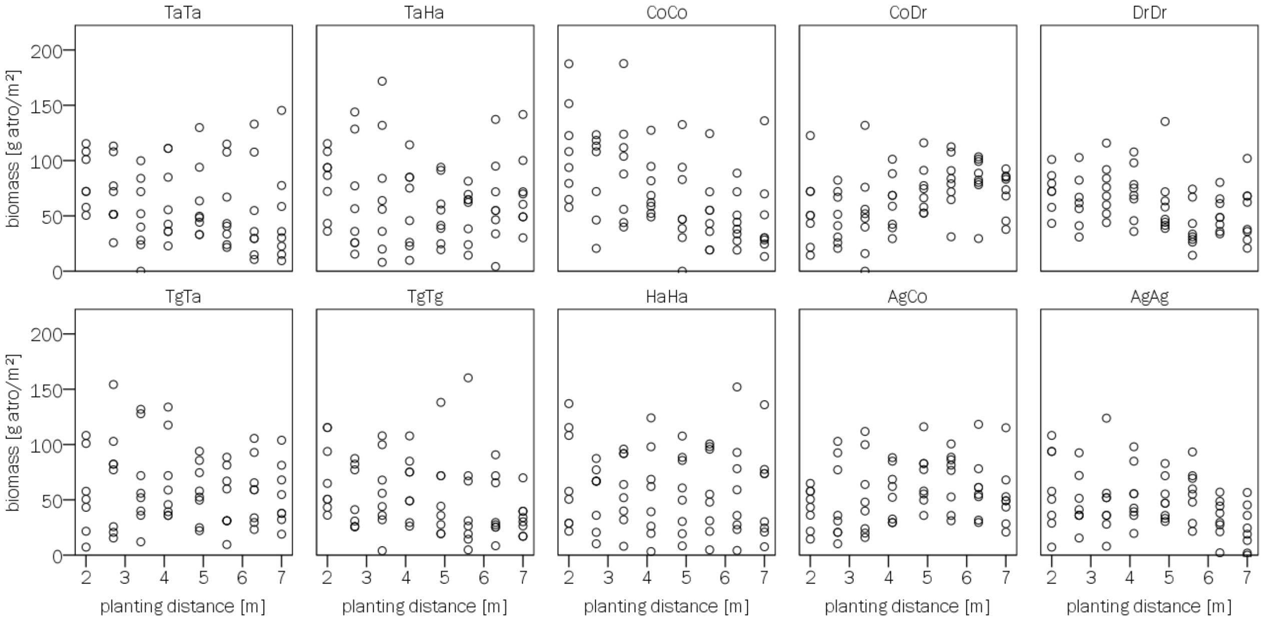

Figure 4.36: Aboveground biomass production of beans (excluding pods) by planting distance of trees. Results are shown separately for each tree species combination (see Table 3.8, page 29 for abbreviations). Data from bean harvests in the M-B-M-M and B-R-R rotation were pooled together.

In contrast to these mostly negative correlations, planting distance of *T. grandis* was positively related to both cassava yield and biomass production. Accordingly maize production in the second rotation was positively related to planting distance within the TgTa gradient. This is plausible, as *T. grandis* was the tallest tree species during both maize and cassava rotations. Figure 4.37 illustrates the effect of planting distance on cassava yield per plant. The significant positive correlation of this parameter with planting distance shows that competition of cassava with *T. grandis* trees influenced plant vitality and hence, tuber production. As mentioned earlier results of cassava yields only show trends, due to the small sample size.

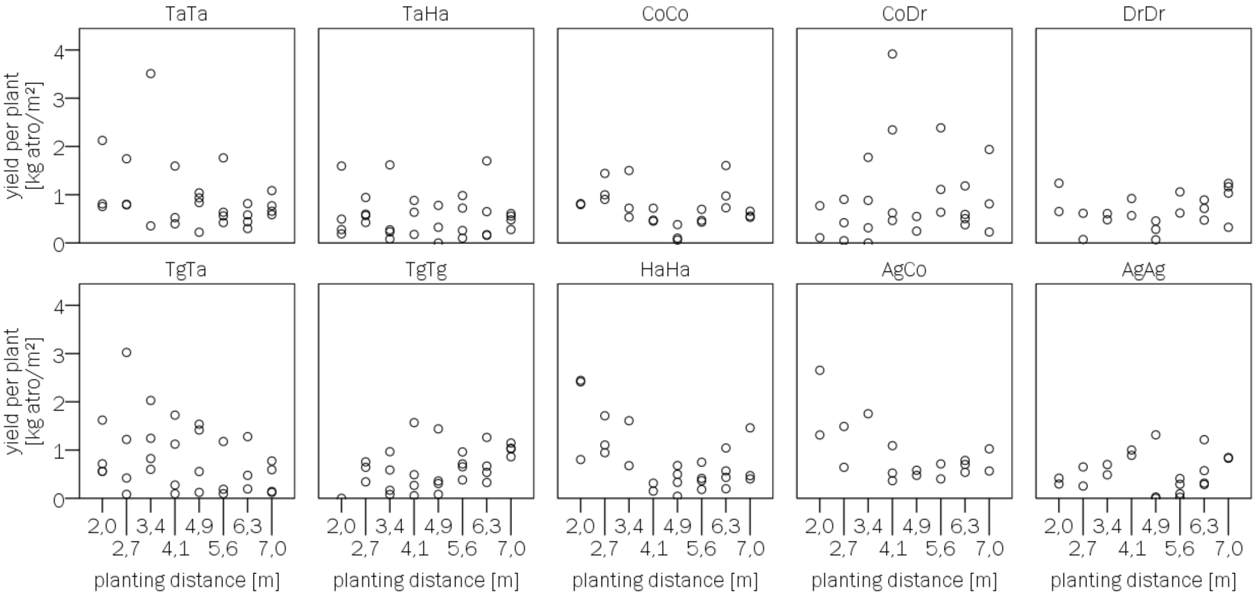

Figure 4.37: Cassava yield per plant by planting distance of trees. Results are shown separately for each tree species combination (see Table 3.8, page 29 for abbreviations).

The small R² values of the weighted regressions (Table 4.35) suggest that other factors, especially site differences, might have had a greater influence on crop production during the first years than factors related to the presence of trees. Hence, no clear reduction in yields or biomass attributable to tree spacing was found. Furthermore, the effect of planting density differed between tree species in the maize, beans and cassava rotation. The observed difference in both the magnitude and direction of the effect might mainly be driven by individual tree heights during the observation period. As tree height was strongly correlated with tree species identity (see chapter 4.2), tree height was not included as a further covariable. However to test the effect of single tree height – independent from tree species identity - an additional regression model was tested which included the independent variables, planting distance and tree heights of the adjacent southern and northern tree of each subsample. In accordance to the data presented in Table 4.34, this analysis did not reveal significant effects of tree heights on maize, pigeon pea or bean yields, while the total model did not explain a significant amount of variance[78] and R² was below 0.2 for all parameters and crops. A significant relationship was only found for cassava (Table 4.36). In accordance to the findings presented in Table 4.34, planting density was negatively correlated with yield[79]. Even though this analysis does not account for tree species identity, it is more reliable with respect to the effect of planting distance, as more samples were available for each planting density. In accordance to the effect of planting distance, yields were also positively correlated with the heights of the northern and southern trees[80]. The results of this supplementary multiple regression analysis show that it seems rather unlikely that trees have a clear negative effect on crop yields during the first two years of tree development. The positive effect of trees in the cassava treatment should however be interpreted with caution, as total model fit was still low ($R^2 = 0.131$).

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[78] This was true for all parameters of the three crops, e.g. square root transformed pigeon pea yields/m² F-Test of total model $F(3) = 0.444$, $p = 0.722$. As results are similar to those shown in Table 4.34, they are not reported in detail.

[79] This was also true for yield/plant ($p = 0.024$) and biomass/m² ($p < 0.001$).

[80] This was also true for yield/plant and biomass/m²

Table 4.36: Results of multiple regression of dependent variable (cassava yield [kg atro/m^2])$^{0.5}$ and independent variables planting distance [m], height of southern adjacent tree of subplot [cm] (HeightS) and northern adjacent tree [cm] of subplot (HeightN). (b = unstandardized coefficient, SE = standard error, T = T-value, p = p-value)

Predictor variable	b	SE	T	p
Constant	0.482	0.049	9.940	**<0.001**
Planting distance	-0.034	0.008	-4.367	**<0.001**
HeightS	$3.6*10^4$	$1.5*10^4$	2.382	**0.018**
HeightN	$4.1*10^4$	$1.6*10^4$	2.540	**0.012**

4.5 Economic evaluation

The research questions to be answered in this chapter are:

- Does the agroforestry approach generate income during the first years after forest plantation establishment and thus improve the economic profitability of reforestation?
- Which tree-crop combination yields the highest economic profitability?
- Can forestry and agroforestry compete with other prevalent land uses in the region in terms of profitability?
- How sensitive are the different land use systems to possible price (and yield) changes in the future?

In order to answer these questions data collected on the trial was analyzed using financial measures (see chapter 3.5.6, page 48). All costs and revenues from management of the forest plantation, agroforestry system and pure crop cultivation during the first two years are real data from the trial. Predictions on future cash flows were mainly derived from measurements taken in the trial and in other plantations during the course of this research project. Therefore these data are presented as results in the scope of the following chapter.

4.5.1 Investigated land use options

All tree-crop combinations presented in chapter 3.2 will be considered in the economic analysis, with the exception of the B-R-R rotation. It has been demonstrated in 4.4.1 that rice yields were very low in this trial, due to the avoidance of the use of pesticides and toxic additives, in order to meet the requirements of FSC certification (see chapter 4.4.1). Yields might therefore not be representative. However, due to the high dependence of rice on pesticides that are not permitted in sustainable forest management (following the FSC standard) and its very specific site requirements, the use of rice for intercropping of forest plantations in Panama is rather restricted. Therefore no further assumptions on yields were made and the B-R-R rotation was omitted from the economic analysis. Data on soy beans and ginger were also not considered because of no or very low yields (see chapter 4.4.1). Accordingly, only the first two maize rotations were used as representative data.

Tree density and tree growth measurements for the six tree species investigated were taken for both, pure forest plantations and intercropped forest plantations from the monitoring plots with the common tree spacing of 3 x 3 m (sampling type FP 3 x 3 see chapter 3.2.3). Thus, an initial stocking of 1111 trees/ha was used to investigate a commonly used tree planting scenario. Only *D. retusa* was planted in a spacing of 2 x 3 m, equaling an initial stocking of 1667 trees/ha. Costs for tree management observed in the agroforestry trial with an originally lower tree density, due to the experimental design, were adjusted accordingly.

Pure agriculture and cattle farming are presented as alternative land use options to forestry and agroforestry. Interviews in the area surrounding Tortí, carried out in the course of this project showed that the cultivation of cassava, beans, maize and pigeon pea, along with cattle farming are the most prevalent land uses in the region, with 76% of the surveyed land area being devoted to cattle farming (Schuchmann 2011). Maize-beans, pigeon pea and cassava farming is so far not carried out on an industrial scale, but rather on smaller plots of farms for household consumption and selling of small amounts (see detailed information in chapter 3.1.2, page 20). Therefore the traditional planting methods applied in the trial (see chapter 3.3.2), along with the prices obtained on the local market seem to be a more realistic land use alternative to consider in this analysis compared to highly mechanized agriculture. Additionally, the soils of the study area tend to be waterlogged during most of the year, hindering the use of heavy machinery, and the high clay content makes tilling or other intensive soil preparation methods difficult. Given these site conditions, the trial data used for economic evaluation of pure crop production were based on marginal agriculture. This is also in accordance with the assumption that reforestation should only be carried out on marginal sites.

Management practices for livestock ranching in Panama vary strongly depending on size of farm, road access, household income, cultural background of the farmer[81] and the landowner's education and access to consultation services from local institutions (Coomes et al. 2008, Schuchmann 2011). Many farmers in the region of Tortí, especially those with indigenous backgrounds traditionally burn their pastures during the dry season to improve growth of desired grass-species (Fischer and Vasseur 2000, Love and Spaner 2005, Schuchmann 2011) (see also chapter 3.1.2). In order to reduce the use of slash and burn practices and the on-going conversion of forest to grass land for livestock ranching, state organizations promote the use of improved pasture grasses to increase per ha cattle production (see also Table 3.2, page 21). Using improved pasture grasses can more than double milk or meat production (e.g. Hänsela et al. 2009, Castro 2011). In this study the calculated costs and revenues from cattle farming are based on the following management practices: Cattle is grown for meat production on a farm using improved pasture grasses. Herbicides are used for pasture improvement but no burning is carried out. The farm is divided into different plots which are separated by fences. Cattle rotate between different plots, allowing the pasture to regenerate and sustain grass production. By applying these frequently used measures a relatively high stocking of four cows per ha can be achieved. For meat production, the "Ceba" (span. for mast) system is applied, in which young cows are bought on the market, fattened on the farm and resold within the same year. The management techniques applied in this land use alternative are based on the interviews of Schuchmann (2011) and information was refined with the help of experienced cattle farmers serving as key informants (pers. communication of Rivera 2010 and Lopez 2010 among others) and local institutions such as the Ministry for Agricultural Development (MIDA) in Chepo and the Institute of Agricultural Research (Idiap) in Santa Fé. The calculated scenario includes relatively advanced techniques. These were however, considered to be adequate for comparison, as for all land uses, it was assumed that technical advice by a local institution is available (discussed later on in this chapter). Moreover, this scenario avoids the underestimation of profitability of cattle farming when traditional, less labor-intensive but also less productive systems are compared to the highly labor-intensive production of high-value timber products.

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[81] indigenous roots or descendants of Spanish settlers, the so called "colones")

4.5.2 Cash Outflows

Costs of purchase of land were omitted from all calculations as they are the same for all land use options. Labor costs were based on a $14.42 per day wage (d), which was the salary paid on the trial, including social security. This salary corresponds to the minimum wage of $1.24 per hour for workers in agriculture and fishery, as defined in executive decree No. 263 from December 2009 (Gaceta official 26, 431-B). We also consider this salary to represent the opportunity costs for the efforts of subsistence farmers, as they would receive this salary (including social security) if they would devote their time to working for an agricultural company instead of working on their own land. All costs are presented on a per ha basis. All costs are given in US$/ha, shortened to $/ha from here onward.

4.5.2.1 Establishment costs

As described in chapter 3.1.1, the trial was established on an abandoned pasture with the first signs of succession already apparent, characterized by an abundance of shrubby species. In Panama this stage is called “rastrojo”. The initial land preparation costs were the same for agroforestry, forest plantation and pure agriculture, accounting for $189/ha, including manual and chemical clearing of weeds. It was assumed that the same initial costs would apply to cattle farming before sowing improved pasture grasses.

The costs for forest plantation establishment were considered to be the same for all tree species in both the pure forest plantation and the agroforestry system. Only the costs for the establishment of *D. retusa* differed from other tree species, due to higher initial stand density. Therefore total establishment costs for this species were higher, amounting to $2073 instead of $1638. The relatively high establishment costs compared to e.g. Griess and Knoke (2011) can be attributed to increased labor costs and relatively high costs for tree seedlings due to elaborate efforts to collect seed from nearby natural forests in order to ensure the use of local provenances (see Table 3.11, page 32).

Table 4.37: Establishment costs for trees in the agroforestry and pure forest plantation scenario. Costs of *D. retusa* differ due to the higher planting density of 1667 trees/ha, and amount to $2073 (d = day wage, l = liter, qq = quintal, lb = pound).

Activity or input	Unit	amount	Cost $/unit	Total costs $/ha
Manual field preparation (machete)	d	10	14.42	144
Application of herbicide	d	2	14.42	29
Herbicide	l	4	4.00	16
Transportation (seedlings & other inputs)	d	4	14.42	58
Seedlings	piece	1111	0.70	778
Marking and staking	d	6	14.42	86
Digging holes	d	10	14.42	144
Planting	d	11	14.42	159
Application of fertilizer	d	2	14.42	29
Fertilizer	qq[1]	1.2	42.00	50
Poles for fencing	piece	14	2.00	42
Staples, wire for fencing	lb	100	0.45	45
Fencing (labor)	d	4	14.42	58
Total				***1638***

[1] 1 qq equals 100 lb and 46 kg

For cattle farming, the following costs were derived from interviews with farmers practicing this land use method.

Table 4.38: Establishment costs for cattle farming assuming the use of improved pasture grasses (d = day wage)

Activity or input	unit	price $ per unit	amount	total price $/ha
Field preparation (machete)	d	14.42	10	144
Chemical field preparation	d	14.42	2	29
Herbicide	l	4	4	16
Seeds	kg	12.00	7	84
Sowing of improved fodder grass	d	14.42	1	14
Wire for fencing (rolls)	piece	35.00	2	70
Staples for fencing	box	1.66	12	20
Poles for fencing	piece	4.00	63.5	254
Fencing (labour)	d	14.42	20	200
Total				***832***

All costs for crops will be considered management costs and are presented in the next section.

4.5.2.2 Management costs

Costs for tree management

As described in chapter 3.3.1, dead trees were replaced during the first 12 months. The results presented in chapter 4.2.2 showed that mortality differed significantly between trees species. Therefore differences in mortality between tree species were considered in the financial analysis. These were derived from all measured trees in both the AF and FP sampling types (Table 3.10) (N = 320 per tree species). As mortality did not differ significantly between all treatments within each tree species (chapter 4.2.3.2) and in order to simplify data interpretation, the same mortality rates were considered for pure forest plantations and all tree-crop combinations. Table 4.39 reveals the high costs due to tree mortality for *D. retusa* and *H. alchorneoides* stands.

Table 4.39: Percentage of trees replanted within the first 12 months and costs for replanting (including planting costs and costs for seedlings) (see also Figure 4.7).

Tree species	Percentage of trees replanted	Total costs for replanting $/ha
Astronium graveolens	8%	20
Cedrela odorata	7%	17
Dalbergia retusa	20%	156
Hieronyma alchorneoides	65%	162
Tectona grandis	30%	75
Terminalia amazonia	19%	47

In Table 4.40, the costs of pure forest plantation management are presented. Weeding in the agroforestry treatments was carried out in the course of crop management and will therefore be presented in the next section. However costs for pruning were observed to be the same in the pure forest plantation and agroforestry systems.

Table 4.40: Management costs of pure forest plantation by year and tree species. Amount of day wages (d) necessary for each activity per ha and year ([d/ha/year]) and resulting total costs per ha and year (yr) ([$/ha/yr]) are displayed. (See text for explanation)

Year	Activity or input	*T. grandis*		*T. amazonia*		*C. odorata*		Other species[1]	
		d [d/ha/yr]	Costs [$/ha/yr]	d [d/ha/yr]	Costs [$/ha/yr]	d [d/ha/year]	Costs [$/ha/yr]	d [d/ha/yr]	Costs [$/ha/yr]
0	Spot-ringed weeding	22	317	22	317	22	317	22	317
1	Spot-ringed weeding	5.5	79	5.5	79	5.5	79	5.5	79
	Manual weeding	12	173	12	173	12	173	12	173
	Herbicide[2]	16	64	16	64	16	64	16	64
	Application of herbicide	8	115	8	115	8	115	8	115
	Pruning	12	173	0	0	0	0	6	87
	Pest control	0	0	0	0	36	519	0	0
	Total		*605*		*432*		*951*		*518*
2	Manual weeding	16	231	16	231	16	231	16	231
	Herbicide[2]	16	64	16	64	16	64	16	64
	Application of herbicide	8	115	8	115	8	115	8	115
	Pruning	6	87	0	0	0	0	6	87
	Pest control	0	0	0	0	36	519	0	0
	Total		*497*		*410*		*929*		*497*
3	Manual weeding	8	115	12	173	12	173	12	173
	Herbicide[2]	8	32	12	48	12	48	12	48
	Application of herbicide	4	58	6	87	6	87	6	87
	Pruning	6	87	0	0	0	0	0	0
	Pest control	0	0	0	0	36	519	0	0
	Total		*292*		*308*		*827*		*308*
4	Manual weeding	8	115	12	173	12	173	12	173
	Herbicide[2]	8	32	12	48	12	48	12	48
	Application of herbicide	4	58	6	87	6	87	6	87
	Pruning	3	43	6	87	3	43	3	43
	Pest control	0	0	0	0	0	0	0	0
	Total		*248*		*394*		*351*		*351*
5	Manual weeding	4	58	8	115	8	115	8	115
	Herbicide[2]	0	0	8	32	8	32	8	32
	Application of herbicide	0	0	4	58	4	58	4	58
	Pruning	3	43	3	43	3	43	3	43
	Pest control	0	0	0	0	0	0	0	0
	Total		*101*		*248*		*248*		*248*
6	Manual weeding	4	58	8	115	8	115	8	115
	Herbicide[2]	0	0	8	32	8	32	8	32
	Application of herbicide	0	0	4	58	4	58	4	58
	Pruning	3	43	3	43	3	43	3	43
	Pest control	0	0	0	0	0	0	0	0
	Total		*101*		*248*		*248*		*248*
7	Manual weeding	4	58	4	58	4	58	4	58
	Herbicide[2]	0	0	0	0	0	0	0	0
	Application of herbicide	0	0	0	0	0	0	0	0
	Pruning	3	43	3	43	3	43	3	43
	Pest control	0	0	0	0	0	0	0	0
	Total		*101*		*101*		*101*		*101*
8-25	Manual weeding	4	58	4	58	4	58	4	58

[1] *A. graveolens*, *D. retusa*, *H. alchorneoides*

[2] Unit for herbicide is liter (4 liter at $4/liter were used per application)

Weeding costs were the same for all tree species during the first 2 years. As described in chapter 3.3.1, intensive spot-ringed weeding, combined with chemical weed control was applied in the year of establishment. In years one and two after establishment, less intensive manual weeding, combined with two applications of herbicide was carried out. In the following years, weeding costs for *T. grandis* stands were assumed to differ from those in stands of native species, due to the high initial growth rate of *T. grandis* described in chapter 4.2.2. Competing grasses were assumed to be shaded out starting in year four, hence significantly reducing maintenance costs. This is supported by the measured light transmission of less than 10% which was observed in a three-year-old *T. grandis* plantation in the same planting design, situated in Mundito, approximately 50 km east of the study site[82] (Table 4.41).

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[82] Situated at 9°75’60’’ N, 80° 42’ 00’’ W, managed by the Forest Finance Group

Table 4.41: Shading [% of intercepted light] of different tree species in plantations of different ages at an initial planting distance of 3 x 3 m taken from Waltenberger (2013). Values correspond to the mean of three different estimation methods for shading (PAR measurement, Densiometer measurement and visual estimation in steps of 5%). See Waltenberger (2013) for detailed information. Given are sample size (N), arithmetic mean ($\bar{x}$) and standard deviation (SD).

Age	Site[1]	*T. amazonia*			*D. retusa*			*T. grandis*			*H. alchorneoides*			*A. graveolens*			*C. odorata*		
		N	$\bar{x}$	SD	N	$\bar{x}$	SD	N	$\bar{x}$	SD	N	$\bar{x}$	SD	N	$\bar{x}$	SD	N	$\bar{x}$	SD
2	Tortí	28	19.4	(21.0)	18	4.2[3]	8.6	28	36.4	(19.9)	28	5.4	(9.9)	20	4.5[3]	(6.8)	20	4.8[3]	(7.8)
3	Mundito	40	16.2	(21.9)	40	0.7[2]	(0.3)	40	91.7	(9.3)	40	48.5	(29.6)	-	-	-	-	-	-
6	Las Lajas	28	94.3	(3.5)	-	-	-	28	90.3	(6.2)	28	82.0	(12.1)	-	-	-	-	-	-
10	Las Lajas	28	87.7	(3.7)	-	-	-	28	87.8	(3.2)	28	86.8	(5.6)	-	-	-	-	-	-
16	Las Lajas	28	91.0	(5.3)	-	-	-	28	78.9	(14.3)	28	84.7	(6.7)	-	-	-	-	-	-

[1] Data labeled "Tortí" were gathered in the FP 3 x 3 m plots of the present study. Mundito is situated in the province of Daríen (8°47'44'' N, 80°42 00'' W). The oldest plantations are situated around the town of Las Lajas (8°15' N, 81°53' W) in the province of Chiriquí. All plantations are managed by the Forest Finance Group.

[2] planting distance 2 x 3 m

[3] planting distance 3 x 3.5 m

For the native tree species it was assumed that weed clearing was reduced stepwise between year two and six after establishment (Table 4.40). This assumption was based on personal experience, information from ANAM (2010) and personal communications with Camacho (pers. comm., 2011) and Herrera (pers. comm. 2011). From year five in *T. grandis* stands and year seven in native species stands, costs of $58/ha (2 day wages) were calculated. Observations in older plantations have shown that growth of herbaceous vegetation is reduced significantly by this age (Waltenberger 2013). The costs for weed control after seven years of $58/ha/yr for all species mainly include the clearing of lines within tree rows to enable access to trees for monitoring and marking previous to thinning activities. The space between tree rows was left unmanged, as studies have shown that trees of this age can support a biodiverse understory vegetation, which might also include valuable native tree species (e.g. Cusack and Montagnini 2004, Paul 2008). However, a more intense cutting of understory vegetation was necessary before thinning, which is included in the costs for thinning activities (to be presented in Table 4.42).

The costs for pruning of *T. grandis* and *T. amazonia* differed from the other native tree species: *T. grandis* tends to sprout very early and therefore, the so called "deshija" - the cutting of the mostly thick sprouts - must be carried out starting in year one. This was usually done in the course of pruning activities, but was more time consuming compared to the pruning of the native tree species (Table 4.40). The native tree species selected, with the exception of *T. amazonia,* have a strong tendency to develop forked trunks and low branches during the first years, which reduces wood quality (see chapter 3.2.1.1). Straight growth of *D. retusa* can be enhanced by pruning activities (4.2.3.3.2, page 83). Therefore the cutting of branches must be carried out for all tree species, except *T. amazonia*, starting in year one. *T. amazonia* is the only species investigated that naturally loses its branches during the first years. Montero M. and Kanninen (2005) suggested leaving the branches during the first years to suppress grasses. However, Nichols (1994) stressed that branches should be cut after three to four years to improve wood quality. Therefore, pruning of *T. amazonia* was assumed to be carried out starting at age four. During years eight to 25 (not displayed in Table 4.40), pruning was carried out again at age nine and age 13 in all stands, at a cost of $43/ha each. Pruning costs for all species did not differ between agroforestry and pure forestry plots.

In this trial, the only tree species that had to be protected against disease was *C. odorata*. Though attacks from leaf-cutting ants were observed in *T. grandis* and other smaller insect or fungal infestations were detected in individuals of *A. graveolens* and *D. retusa,* no measures had to be taken. However, in the case of *C. odorata,* three day wages were necessary four times a year in order to control infestation with *H. grandella* during the first two years. Pest management included cutting the apical parts as well as the sprouts that are frequently attacked by the larvae and lead to low wood quality as described in chapter 4.2.3.3.1 (page 78). As delineated in chapter 4.2.3.3.1, infestation was significantly reduced when trees were planted in association with maize, cassava and pigeon pea. Therefore costs for pest management were assumed to be only half of those of the pure forest plantation treatment. Pest management was assumed to be carried out until year four as studies have shown that infestation decreases considerably when trees reach a height of 4 m (Lamprecht 1986, Ohashi et al. 2011).

As no real data for thinning activities could be collected in the trial, thinning and harvesting costs were derived from ANAM (2010), and checked for plausibility by interviewing local forest management companies. In accordance with this data costs for infrastructure maintenance, tools, equipment and transport were added (Table 4.42). For each thinning, a fixed amount of $219 was used as a base cost for the preparation of thinnings, tools and equipment, and volume determination, which was assumed to be the same for each thinning according to ANAM (2010).

Table 4.42: Base costs calculated for each thinning (d = day wage)

Activity or input	d/ha	Costs per d [$]	Total costs [$/ha]
Cutting of understory to access trees	1	14	14
Tree selection and marking	3	14	43
Classification and volume determination	5	14	72
Infrastructure maintentance	1	14	14
Protective clothing			25
Chainsaw, oil and maintenance			40
Other tools and equipment			10
Total			***218***

Stem- and diameter- dependent costs were added according to Table 4.43. These include felling, cutting of branches, manual and mechanized skidding (depending on diameter class) and transport to timber yard by tractor. These estimated costs were assumed to be the same for all tree species, according to Griess and Knoke (2011).

Table 4.43: Harvesting costs per stem depending on diameter class (recalculated and extended based on ANAM 2010)

	dbh-class [cm]	Costs per tree [$]
First thinning	0-14	0.82
Second thinning	15-20	2.95
Final harvest	>20	4.57

Total thinning costs for each tree species are presented in Table 11.10 (appendix).

Costs for crop management in agroforestry systems

In the agroforestry systems tested, weeding of trees was carried out in the course of crop management and therefore differed from pure forest plantation management. However, one additional spot ringed weeding (5.5 day wages) was undertaken 3-4 weeks after planting because crops did not yet shade out grasses. These costs were not considered in the pure agricultural scenario (presented in the next section). In the year of plantation establishment, no field preparation for crops had to be carried out, as this had already been done in the scope of tree planting. During the dry season, when no crops were grown (see Figure 3.7, page 33) weeding was not necessary, due to the reduced growth of herbaceous vegetation.

As described in chapter 3.2.2, the M-B-M-M rotation started with a maize rotation using fertilizer, followed by beans (during the dry season) and a maize rotation without fertilizer. This rotation cycle was chosen in order to sustain natural soil productivity by replacing mineral fertilizer with leguminous crops[83]. This approach had the further advantage that soil was covered by beans during the dry season reducing wind erosion. Hence, maize was sown and harvested twice – once with and once without fertilizer[84]. Due to smaller yields in the second maize rotation (see Table 4.32)[85] harvesting and transportation costs were also reduced (Table 4.44). The observed day wages for crop production in the trial are slightly higher compared to MIDA (2010b) and hence, underestimation is rather unlikely. Transportation costs were derived from MIDA (2010b).

In eastern Panama both beans and pigeon pea are usually harvested in February during the dry season. As the calendar year is used for the estimation of the yearly cash flow, costs for sowing and harvesting in some cases do not appear in the same year (see Table 4.44 and Table 4.45). The decision as to how long crop cultivation in tree stands could be carried out was based on tree growth, as described later on in this section. Therefore the general categories “intermediate years” and “last year of cultivation” are used in the following tables.

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[83] As an alternative, organic fertilizer could have been used (as e.g. bocachi). However, in order to ensure the same doseage of nutrients in all sampling units, this approach was not appropriate in this trial. Moreover, mineral fertilizer is more frequently used by local farmers Schuchmann (2011)

[84] Data from the third maize rotation presented in Table 4.32 were not considered in the economic analysis due to unrepresentatively small yields for reasons described in chapter 4.4.1.

[85] Detailed data on sold yields will be given in chapter 4.5.3.2.

Table 4.44: Production costs of maize and beans in the agroforestry system (d = day wage, l = liter, lb = pound, qq = quintal (= 100 lb)

			year 0			Intermediate years			Last year of cultivation		
	Activity or input	Unit	Amount	Costs per Unit [$]	Costs per yr [$/ha/yr]	Amount	Costs per Unit [$]	Costs per yr [$/ha/yr]	Amount	Costs per Unit [$]	Costs per yr [$/ha/yr]
Maize rotation without fertilizer (Mai-August)	Manual weeding	d			-	5	14.42	72			-
	Application of herbicide	d			-	2	14.42	29			-
	Herbicide	l			-	4	4.00	16			-
	Seeds	kg			-	27	4.72	127			-
	Sowing	d			-	11	14.42	159			-
	Harvest	d			-	8	14.42	115			-
	Bags	piece			-	136	0.50	68			-
	Transportation to market[1]	lb			-	136	0.50	68			-
	Total							***654***			
Maize rotation with fertilizer (August-November)	Manual weeding	d	5.5	14.42	79	5	14.42	72			-
	Application of herbicide	d			-	2	14.42	29			-
	Herbicide	l			-	4	4.00	16			-
	Seeds	kg	27	4.72	127	27	4.72	127			-
	Sowing	d	11	14.42	159	11	14.42	159			-
	Fertilizer	qq	4	35.00	140	4	35.00	140			-
	Fertilizer application	d	6	14.42	87	6	14.42	87			-
	Harvest	d	11	14.42	159	11	14.42	159			-
	Bags	piece	191	0.50	96	136	0.50	68			-
	Transportation to market[1]	lb	191	0.50	96	136	0.50	68			-
	Total				***942***			***924***			
Beans (November – February)	Manual weeding	d	5	14.42	72	5	14.42	72			-
	Application of herbicide	d	2	14.42	29	2	14.42	29			-
	Herbicide	l	4	4.00	16	4	4.00	16			-
	Seeds	kg	10.4	1.70	18	10.4	1.70	18			-
	Sowing	d	15	14.42	216	15	14.42	216			-
	Harvest	d			-	**23**	14.42	332	**23**	14.42	332
	Bags	d			-	21	0.50	11	21	0.50	11
	Podding	piece			-	7	14.42	101	7	14.42	101
	Transportation to market[1]	lb			-	21	0.50	11	21	0.50	11
	Total				***351***			***805***			***453***

[1]Transportation within a distance of 50 km assumed

Sowing of pigeon pea started 9 months after tree establishment (year one, see Table 4.45). Therefore weed clearing costs for year zero equaled weed clearing costs for the pure forest plantation. Consequently, for better comparison, an additional land use option was investigated which assumed the sowing of pigeon pea between tree rows starting in year zero. In this scenario, the first spot-ringed weeding was added to the costs in accordance to the maize-beans-maize rotation. In order to test these assumptions, an additional trial was established in September 2011 approx. 35 km east of Tortí. Trees on this site were planted at a density of 1111 trees per ha. Pigeon pea was sown four weeks after tree planting. The results suggest that young trees were not negatively influenced by pigeon pea in terms of mortality and growth performance (Eichhorn 2013). It was furthermore observed that the calculated costs for weeding also seemed realistic for tree seedlings in year 0, as pigeon pea rapidly shaded out weeds. In order to avoid bending down of trees due to competition with pigeon pea, some branches of pigeon pea were cut six months after sowing in both scenarios (shown as “clearance cutting of trees” in the following table).

Table 4.45: Production costs for pigeon pea in the agroforestry system (d = day wage, l = liter, lb=pound)

Activity or input	Unit	year 1			Intermediate years			last year of cultivation		
		Amount	Costs per Unit [US$]	Costs [$/ha/yr]	Amount	Costs per Unit [US$]	Costs [$/ha/yr]	Amount	Costs per Unit [US$]	Costs [$/ha/yr]
Manual weeding	d	5	14.42	72	5	14.42	72			-
Application of herbicide	d	2	14.42	29	2	14.42	29			-
Herbicide	l	4	4.00	16	4	4.00	16			-
Seeds	lb	30	0.50	15	30	0.50	15			-
Sowing	d	12	14.42	173	12	14.42	173			-
Weeding (after 2 months)	d	5	14.42	72	5	14.42	72			-
Clearance cutting of trees	d	2	14.42	29	2	14.42	29			-
Harvest	d			-	8	14.42	115	8	14.42	115
Bags	piece			-	136	0.50	68	136	0.50	68
Podding	d			-	0	14.42	0	0	14.42	0
Transportation to market[1]	lb			-	136	0.50	68	136	0.50	68
Cutting of remnant pigeon Pea	d			-	3	14.42	43	3	14.42	43
Total				*406*			*701*			*295*

[1] transportation costs were taken from MIDA (2010a)

Table 4.46 reveals that the same weeding costs as in the pure forest plantation were necessary in in the agroforestry system with cassava during year zero, as cassava did not reduce growth of competing vegetation. It only began to shade out grasses – yet still not efficiently – towards the end of the cassava rotation, due to its open canopy (see also chapter 4.3.2). In the last year of cultivation, the same cleaning costs as in the pure forest plantation management were calculated, which are not included in the table, as they differ between tree species.

Table 4.46: Production costs for cassava in the agroforestry system (d = day wage, l = liter, lb=pound)

Activity or input	Unit	year 0			Intermediate years			last year of cultivation		
		Amount	Costs per Unit [US$]	Costs [$/ha/yr]	Amount	Costs per Unit [US$]	Costs [$/ha/yr]	Amount	Costs per Unit [US$]	Costs [$/ha/yr]
Manual initial weeding	d			-	5	14,42	72			-
Application of herbicide	d			-	2	14,42	29			-
Herbicide	l			-	4	4,00	16			-
Seeds				35			35			-
Sowing	d	10	14,42	144	10	14,42	144			-
Weeding	d	22	14,42	317	14	14,42	202			-
Harvest	d			-	10	14,42	144	10	14,42	144
Bags	piece			-	33	0,50	17	33	0,50	17
Transportation to market[1]	lb			-	33	0,50	17	33	0,50	17
Total				*258*			*676*			*178*

[1] transportation costs were taken from MIDA (2010c)

Costs of pure agricultural management

Costs of pure cultivation of maize, pigeon pea and cassava were calculated assuming the same labor costs. Given that no area was occupied by trees in the pure agricultural scenario, cultivation was carried out on 1 ha instead of only an area of 0.91 ha in the agroforestry system[86]. This means, that the same labor costs apply to a 10% larger area. Personal experience proves this assumption, as care has to be taken not to damage trees, making all agricultural activities such as sowing and weeding more expensive in the agroforestry treatments. However, inputs such as seeds and fertilizer were also increased by 10%. Costs associated with trees such as spot-ringed weeding around trees in year zero within maize fields, or cutting of pigeon pea shrubs to decrease competition with trees were omitted in the pure agricultural scenario. Manual cleaning costs in the pure cassava were set at $86 (equals 6 d/ha) in year zero, based on experiences on the pure cassava plots in the trials.

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[86] Assuming that a circle of 50 cm around each tree is not planted with crops, as applied in the trial.

Yearly costs for cattle farming amounted to $1718 per ha and year (Table 4.47). These costs included buying of calves, weeding, replanting of improved fodder grasses and maintenance of fences. Costs also include labor and input costs for caring for cattle, such as vaccinations, monitoring of health status and labor and transportation costs for selling or buying of livestock. In this scenario, four calves per ha at an estimated price of $350 each must be bought annually for masting.

Table 4.47: Production costs for cattle (d = day wage)

Activity or input	unit	Costs per unit [$]	amount	Total costs [US$/ha/yr]
Animal maintenance (cow monitoring, application of vaccination, transport, selling, buying)	d	14	4	58
Weeding + replanting of improved fodder grasses	d	14	2	58
Seeds for replanting (every year from the second year after establishment)	kg	12	2	24
Maintentance of fence	d	14	2	58
Vaccination + food supplements				40
Purchase of livestock	calve	350	4	1400
Transport of cows (rental for cow trailer + fuel)	Piece	40	2	80
Total				*1718*

Administration costs

Average annual fixed costs including administration, technical assistance, construction and maintenance of infrastructure as well as tools and equipment were added. These costs were calculated based on personal experience and interviews of forest plantation companies and verified with the information on average fixed costs of farmers, published annually by the Statistical Authority of Panama (Instituto Nacional de Estadística y Censo, INEC) (INEC 2011).

The Ministry of Agricultural Development of Panama (MIDA) usually calculates costs for technical assistance instead of administration costs (e.g. MIDA 2010b). This approach was adapted for this study. The costs for technical and legal assistance in Table 4.48 therefore include the costs for administration and technical support by an agricultural or forest engineer for activities such as yearly planning and training of workers. Using this approach, assistance costs per ha can be considered constant for different farm sizes. Other costs, such as, land insurances, other administrative costs or taxes are omitted, as they are more area-dependent than land-use dependent. Table 4.48 reveals that for pure plantation forestry and agroforestry 50% higher costs were calculated for technical assistance than for pure agriculture. This difference takes into account that forestry activities usually require more elaborate planning compared to agricultural activities which merely change over time. Moreover, in order to improve timing of management activities such as thinning, a yearly monitoring of trees with costs of $25 per ha was considered.

Table 4.48: Annual fixed costs [$/ha/yr] of land use options including trees compared to those for pure crop and cattle farming

Activity or input	Forestry and agroforestry	Pure agriculture
Technical and legal assistance	70	50
Supervision by owner or foreman	35	35
Construction and maintenance of general infrastructure[1]	15	15
Tools, equipment + fuel[1]	30	10
Monitoring costs[1]	25	-
Total	***170***	***110***

[1] These costs are, by definition variable (Thommen and Achleitner 2003), are however considered to be dependent only on the size of farmland, and to be annually constant.

Cost comparison

As shown in Table 4.40, costs during the first years only slightly differ between tree species, with exception of *C. odorata*. Therefore, costs of the different land use options during the first 5 years – the phase of plantation intercropping - are exemplarily shown for *T. amazonia* in Figure 4.38 . The decrease in costs in the agroforestry systems correlates with the decrease in yields, which will be explained in the following chapter.

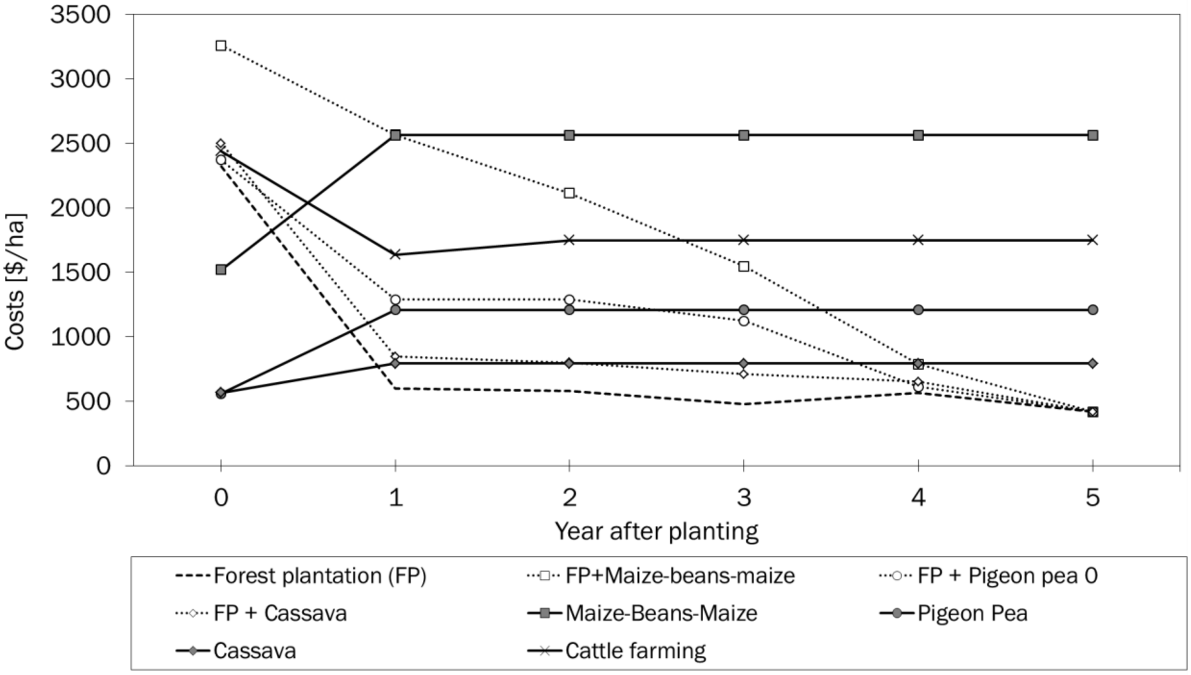

Figure 4.38: Comparison of costs for pure agriculture (solid lines) with those for agroforestry systems (dotted lines) and pure forest plantations (dashed line) during the initial phase. Data for agroforestry systems and pure forest plantations are based on *T. amazonia* as an example. Pigeon pea 0 refers to pigeon pea cultivation starting in year zero (see chapter 4.5.1).

4.5.3 Cash Inflows

4.5.3.1 Cash Inflows from tree harvests

In order to calculate potential incomes from thinnings and final harvest of trees, yield projections were carried out. The status of trees in the FP 3x3 sampling type after two years was used as a basis for yield projections. These data refer to the “commercial status” of all measured trees described in chapter 4.2.2 (Table 4.4). Due to the lack of approved growth models for the tree species investigated, growth rates derived from the literature were used (Table 4.49). In the following table only those sources from literature are shown, that investigated growth in pure forest plantations with comparable densities and stand age of more than five years in order to avoid overestimation of growth rates. As studies from the lowland humid tropics across Central America are cited, site quality may differ considerably between the trials. Therefore, unpublished inventory data from older plantations in Panama, provided by the Forest Finance Group (ForestFinance 2012) are also displayed in the table. The plantations selected for comparison were the closest to the trial site and were all established by the same company assuring a comparable stand history. Yet, plantations older than 5 years with comparable management regimes and representative sample size were only available in the region of Chiriquí in the western part of Panama. This data has already been analyzed extensively by Griess and Knoke (2011).

Table 4.49: Literature review on growth data of tree species investigated on comparable sites in the lowland humid tropical climate of Central America (Initial S/ha = stem number at time of planting per ha, dbh = diameter at breast height, h = height, MAI dbh = Mean annual increment in dbh, MAI height = Mean annual increment in height, uk = unknown). (See also Table 4.50 for detailed information on growth data in FP 3x3 plots).

Source	Age	location	Initial S/ha	dbh [cm]	h [m]	MAI dbh [cm/yr]	MAI h [m/yr]
A. graveolens							
on-trial data	2	Tortí	1111	2.0	2.1	1.0	1.0
ForestFinance (2012)	4	Darien	1111	4.1	3.2	1.0	0.8
Piotto et al. (2004)	5.5	Peninsula of Nicoya, Costa Rica	1111	6.48	4.71	1.2	0.9
Cordero and Boshier (2003)	8	Honduras	2500	-	-	1.0	0.5
Cordero and Boshier (2003)	13	Costa Rica	2500	-	-	0.8-1	0.6-0.8
Cordero and Boshier (2003)	31	Honduras	278	17.7	22.1	0.6	0.7
C. odorata							
on-trial data	2	Tortí	1111	2.9	2.4	1.5	1.2
ForestFinance (2012)	4	Darien	1111	4.8	4.6	1.2	1.2
Cordero and Boshier (2003)	<5	Nicaragua and Honduras	uk	-	-	1.3-1.6	1.3-1.6
Piotto et al. (2004)	5.7	Peninsula of Nicoya, Costa Rica	2500	3.0	1.7	0.5	0.3
Condit and Sautu (2001)	8	Costa Rica		15-22	12-15	2.3	1.7
Whitmore (1978)	8	Puerto Rico	1736	4.4	4.5	0.5	0.5
Whitmore (1978)	8	Virgin Islands, USA	1736	5.9	4.5	0.7	0.6
Wadsworth (1960)	8	Mexico	1111	11	6	1.4	0.7
Wadsworth (1960)	12	Mexico	10000	8	6	0.7	0.7
Wadsworth (1960)	12	Panama	2222	24	21	2.0	1.7
Wadsworth (1960)	13	Honduras	2222	28	15	2.1	1.1
Wadsworth (1960)	18-20	Ecuador	1111	50	25	2.5	1.2
Lamb (1968)	25	Sapoba, Nigeria	1550	40	32	1.6	1.3
Lamb (1968)	32	Sapoba, Nigeria	1550	45	37	1.4	1.2
D. retusa							
on-trial data	2	Tortí	1111	2.9	2.4	1.5	1.2
ForestFinance (2012)	4	Darien	1111	4.8	4.6	1.2	1.2
ForestFinance (2012)	7	Chiriqui	1111	7.2	9.11	1.0	1.3
Piotto et al. (2004)	5.7	Peninsula of Nicoya, Costa Rica	1111	6.99	5.4	1.2	0.9
Hazlett (1980)	31	Honduras	uk	-	-	0.8	-
Cordero and Boshier (2003)	11	Costa rica	2500	-	-	1.0	0.6
H. alchorneoides							
on-trial data	2	Tortí	1111	1.5	1.7	0.8	0.9
ForestFinance (2012)	4	Darien	1111	4.2	3.7	1.1	0.9
ForestFinance (2012)	15	Las Lajas	1111	22.5	22	1.5	1.5
Montagnini et al. (2003)	6	Northeast of Costa Rica^{1,2}	2500	10.3	11.9	1.8	2.0
Griess and Knoke (2011)	10	Las Lajas	400	13.4	15.3	1.3	1.5
Griess and Knoke (2011)	25	Las Lajas projected	400	34	40.3	1.4	1.6
Piotto et al. (2010)	16.5	Northeast of Costa Rica^{1}	2500	18.2	23.2	1.1	1.4
Piotto et al. (2003b)	8 to 13^{3}	Northeast of Costa Rica	1111-2500^{3}	-	-	1.9	1.7
Redondo-Brenes and Montagnini (2006)	13	Northeast of Costa Rica^{1}	2500	15.5	21	1.4	1.7
Cordero and Boshier (2003)	> 9	Costa Rica	1111	-	-	1.7	1.8
Cordero and Boshier (2003)	<6	Costa Rica	1111	-	-	2.2-2.5	2.3-2.5

Table 4.49 (continued): Literature review on growth data of tree species investigated on comparable sites in the lowland humid tropical climate of Central America (Initial S/ha = stem number at time of planting per ha, dbh = diameter at breast height, h = height, MAI dbh = Mean annual increment in dbh, MAI height = Mean annual increment in height, uk = unknown). (See also Table 4.50 for detailed information on growth data in FP 3x3 plots).

Source	Age	location	Initial S/ha	dbh [cm]	h [m]	MAI dbh [cm/yr]	MAI h [m/yr]
T. amazonia							
on-trial data	2	Tortí	1111	3.3	3.0	1.6	1.5
ForestFinance (2012)	3	Panama	1111	3.0	3.0	1.0	1.0
ForestFinance (2012)	4	Darien	1111	3.2	6.3	0.8	1.6
ForestFinance (2012)	5	Darien	1111	6.0	6.3	1.2	1.3
ForestFinance (2012)	15	Las Lajas	1111	28.0	27.4	1.9	1.8
Griess and Knoke (2011)	10	Las Lajas	1111	18.8	20.0	1.9	2.0
Griess and Knoke (2011)	25	Las Lajas projected	1111	43.8	43.4	1.8	1.7
Haggar et al. (2003)	6	Northeast of Costa Rica[1]	1111	15.4	13.9	2.5	2.3
Montagnini et al. (2003)	7	Northeast of Costa Rica[1,2]	2500	10.3	11.9	1.8	2.0
Piotto et al. (2003b)	8 - 13[3]	Northeast of Costa Rica	1111-2500[3]	-	-	2.4	2.0
Redondo-Brenes and Montagnini (2006)	13	Northeast of Costa Rica[1]	2500	22.3	21.0	1.7	1.6
Piotto et al. (2010)	16.5	Northeast of Costa Rica[1]	2500	24.8	24.9	1.5	1.5
Montero M. and Kanninen (2005)	30	Costa Rica, superior sites	625-2500	-	-	2.4	2.4
Montero M. and Kanninen (2005)	30	Costa Rica, medium sites	625-2500	-	-	1.6	1.3
Montero M. and Kanninen (2005)	30	Costa Rica, bad sites	625-2500	-	-	1.0	0.7
T. grandis							
on-trial data	2	Tortí	1111	6.5	6.4	3.2	3.2
ForestFinance (2012)	3	Panama	1111	7.6	7.8	2.5	2.6
ForestFinance (2012)	4	Darien	1111	10.5	10.1	2.6	2.5
ForestFinance (2012)	15	Las Lajas	1111	19.6	17.9	1.3	1.2
Griess and Knoke (2011)	10	Las Lajas	714	18.3	17.1	1.8	1.7
Griess and Knoke (2011)	25	Las Lajas projected	714	37	25.4	1.5	1.0
Redondo-Brenes and Montagnini (2006)	13	Northeast of Costa Rica[1]					0.0
Pérez and Kanninen (2005)	30	Costa Rica, medium site quality maximum volume	1111	36.6	32.4	1.2	1.1
Pérez and Kanninen (2005)	30	Costa Rica, medium site quality maximum dbh	1111	38.9	25.9	1.3	0.9
Pérez and Kanninen (2005)	30	Costa Rica, high site quality maximum volume	1111	45.3	32.4	1.5	1.1
Pérez and Kanninen (2005)	30	Costa Rica, high site quality maximum dbh	1111	47.8	32.4	1.6	1.1
Piotto et al. (2004)	5.7	Peninsula of Nicoya, Costa Rica		14.0	10.7	2.5	1.9
Piotto et al. (2003b)	8 to 13[3]	Northeast of Costa Rica	1111-2500[3]			2.4	1.9
FAO (2002)	25-30	Panama	-	-	-	1.1-2.0	1.1-2.0

[1] La Selva Research Station

[2] Data of unthinned stands are cited

[3] On-farm research on plantations with different ages and initial densities

For *T. grandis* and *T. amazonia,* growth tables from Costa Rica were available at the time of preparing this thesis. As these growth tables distinguish between poor, medium and good site conditions, these growth data seems to be adaptable for Panama, as site variety can be assumed to be similar to that of Costa Rica. For *T. grandis,* the growth table elaborated by Pérez and Kanninen (2005) for medium quality sites and a management aimed at maximizing diameter increment was chosen (see Table 4.49). A mean annual increment of 1.3 cm in diameter and 0.9 m in height seems a careful estimation considering the range of increments between 1.1 - 2.0 cm/year in diameter and 1.1 – 2.0 m/year in height reported by FAO 2002 in Teak plantations on medium sites in Panama. Extensive research on the native tree species *T. amazonia* has been carried out by Montero M. and Kanninen (2005) and their data has been used for growth prediction. They published a mean diameter and height increment of 1.3 cm/year and 1.6 m/year, respectively on medium quality sites in Costa Rica during the first 30 years. *H. alchorneoides* has already been investigated for Panama by Griess and Knoke (2011). In accordance to this study, growth data from Redondo-Brenes and Montagnini (2006) were used for growth prediction, which represents a rather conservative assumption compared to other studies (Table 4.49).

Representative studies on growth data for other native tree species remain scarce. *A. graveolens* is so far – despite its high timber quality - rarely grown in plantations (see also Waltenberger

2010). One reason might be the low growth rates reported in the few trials available. Accordingly, a comparably low future increment of 0.9 cm/year and 0.7 m/year in diameter and height respectively as described by Cordero and Boshier (2003) was assumed. Growth information for *C. odorata* can be found in a range of publications from Central America. However, this data has seldom been gathered on individuals in forest plantations but rather on those occurring in natural forests (Lamprecht 1986), as shade trees in agroforestry systems alongside coffee (Beer et al. 1997) or cocoa (Villarreal et al. 2006), in silvopastoral systems (Love and Spaner 2005a) or in living fences (León and Harvey 2006). Data from plantations in Panama is not available. Therefore the longest time line known to the author of 30 years by Lamb (1968) was used, assuming a height growth of 1.2 m/year and a diameter growth of 1.4 cm/year during the first 25 years. Compared to other data presented in Table 4.49 this assumption too is rather conservative. *D. retusa* (rosewood) has been excessively exploited in natural forests in Central America (ANAM 2011). But, despite the high demand for rosewood on the national market, it has rarely been grown in plantations and hence, little is known about growth rates (Waltenberger 2010). All comparable studies considered, reported similarly low growth rates as those for *A. graveolens*. This is not surprising given the high wood density of *D. retusa*, which ranges from 0.99 to 1.22 kg/m³ (Jiménez-Madrigal and Rodríguez 2010). The longest time line of growth data for *D. retusa* in planted forests was reported by both Hazlett (1980) and Cordero and Boshier (2003). According to the latter study, an annual increment of 1 cm/year in diameter and 0.6 m/year in height were assumed.

The same tree growth rates were assumed for both pure forest plantations, and for the agroforestry systems, though it has been shown in chapter 4.2.3.1 that tree growth of some tree species was positively influenced by intercropping. For all tree species, a yearly mortality rate of 2% was assumed within the first 10 years and 1% in the period from 10-25 years.

All growth tables used are attached in Table 11.10 (see appendix). Figure 4.39 illustrates the high total volume production of *T. amazonia* and *H. alchorneoides* which even offset the growth of *T. grandis* after the first ten years based on the present assumptions. *C. odorata* has a similar total volume production after 25 years as compared to *T. grandis* with 466 m³/ha. The slow growing species *D. retusa* and *A. graveolens* showed a total increment of only 202 and 180 m³/ha, respectively at the end of the rotation period.

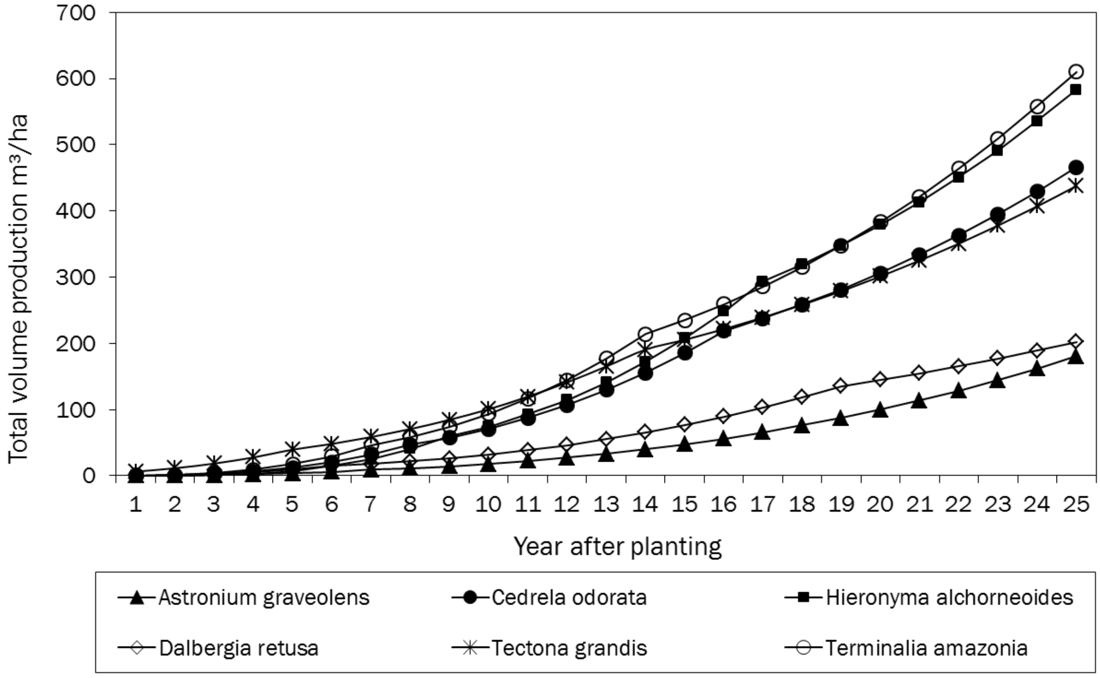

Figure 4.39: Predicted total volume production [m³/ha] of investigated tree species

In order to derive future revenues from wood products, appropriate thinning regimes had to be defined. The overall objective of thinning in this trial was to produce high value sawn timber and hence, to maximize the diameter growth of single trees, instead of maximizing stand growth and stand volume. The goal was a final stem count of approximately 200 stems per ha. For this purpose, a heavy low thinning concept as traditionally known from Europe – as e.g. for spruce, described by Gerhardt (1925) - and also frequently used in lowland tropical hardwood plantations (Evans and Turnbull 2004) was applied. In Central America, trials to optimize the intensity and timing of thinning in wood plantations have been carried out only for *T. grandis,* as for instance by Kanninen et al. (2004) and Bermejo et al. (2004). Hardly any experiences are available for thinning concepts of the slower-growing native tree species. In the following section, the frequency, thinning and timing of thinning activities used to predict the cash inflows from the six timber tree species will be presented.

Frequency of thinning was reduced to two cuttings compared to other suggested thinning models which apply three to five thinnings during a 25 year rotation, (FAO 2002, Kanninen et al. 2004, Bermejo et al. 2004). Only two thinning operations were applied in order to reduce costs as recommended by Evans and Turnbull 2004 and Cordero and Boshier 2003 and applied by Griess and Knoke (2011). In the course of the first precommercial thinning, trees with bad quality were removed. The consecutive commercial thinning are aimed at improving the quality and diameter increment of trees.

In accordance with the thinning concept for *T. grandis* reported by Kanninen et al. (2004) and Bermejo et al. (2004) **thinning intensity** was designed to produce a stem number reduction of 40% in the first thinning and 50% in the second thinning. Stem number control is frequently used in tropical plantations (Lamprecht 1986, Onyekwelu et al. 2011). For the sake of simplicity, the same intensity was applied to all of the tree species investigated, with the exception of *D. retusa*: For this species, stem reduction in the first thinning was set to 50% due to the higher initial stem number.

In order to define the **timing of the first thinning,** different authors have used parameters such as medium height (for example 7 - 9 m in *T. grandis* plantations) (Keogh 1982), basal area (Kanninen et al. 2004, Piotto et al. 2010) or live crown ratio, which is the ratio between crown length and tree height (Evans and Turnbull 2004). However, the latter information was not available for stands of the tree species investigated with more than 3 years growth. In this study, crown closure was used to define the timing of the first non-commercial thinning (Geoff et al. 2006, Onyekwelu et al. 2011). The underlying assumption of this approach is that diameter growth declines after crown closure because of competition, which leads to mortality of lower branches and smaller crowns resulting in smaller diameter increments (Zadnik Stirn 1990, Geoff et al. 2006, Pretzsch 2009). In an attempt to predict the time of crown closure in the future, a regression analysis of crown diameter and dbh measurements was carried out using data obtained from both the monitoring plots around the trial (FP 3x3 treatment) two years after planting with a density of 1111 trees per ha, and from older plantations measured by Paul (2012 unpublished) and Waltenberger (2013). The older plantations are situated in the Region of Darien (Mundito) and Chiriquí (Las Lajas),[87] and were established at the same planting distance as in the trial. This data was however, not available for all tree species (Table 4.50, next page). After two years, many of the measured trees did not yet exceed 1.3 m of height and therefore no dbh was recorded. Sample size (N) therefore differs between mean height (N_h) and diameter (N_{dbh}) measurements at ages one and two (Table 4.50). Crown radius was predicted based on both height and diameter.

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[87] See Table 4.41 for exact location

Table 4.50: Height (h) [m], diameter at breast height (dbh) [cm] and crown radius (cr) [m] in plantations of different ages based on sample size of height (N_h) and dbh (N_{dbh}). Standard deviations are given in brackets. Data from the trial (Location = Tortí) is based on the commercial status of FP 3 x 3m sampling type.

Age	Location	N_h	h	N_{dbh}	dbh	cr(N_h)	cr(N_{dbh})
Astronium graveolens							
1	Tortí	183	1.1 (0.4)	9	1.0 (0.3)	0.39 (0.14)	0.51 (0.13)
2	Tortí	177	1.9 (0.9)	112	2.2 (1.1)	0.64 (0.35)	0.81 (0.33)
Cedrela odorata							
1	Tortí[2]	319	1.2 (0.5)	59	1.3 (4.5)	0.64 (0.12)	0.41 (19.82)
2	Tortí[2]	325	2.4 (0.8)	281	2.9 (5.6)	0.84 (0.18)	0.81 (19.31)
Dalbergia retusa							
1	Tortí	228	1.0 (0.8)	44	1.9 (0.7)	0.36 (0.29)	0.82 (0.24)
2	Tortí	206	2.5 (1.2)	155	2.9 (1.3)	1.21 (0.55)	1.41 (0.46)
3	Mundito	37	4.8 (1.5)	37	4.9 (1.6)	1.50 (0.41)	1.50 (0.41)
Hieronyma alchorneoides							
1	Tortí	130	0.7 (0.4)	1	1.1 (0.0)	0.23 (0.15)	0.72 (0.00)
2	Tortí	105	1.7 (0.8)	55	2.5 (1.0)	0.54 (0.30)	0.77 (0.21)
3	Mundito	29	4.2 (1.2)	29	4.6 (1.6)	1.21 (0.31)	1.21 (0.31)
6	Las Lajas	35	11.2 (3.2)	35	9.7 (3.7)	1.67 (0.49)	1.67 (0.49)
10	Las Lajas	32	13.2 (4.2)	32	12.3 (5.4)	1.76 (0.56)	1.76 (0.56)
16	Las Lajas	32	21.3 (4.0)	32	20.4 (5.3)	2.85 (0.66)	2.85 (0.66)
Terminalia amazonia							
1[1]	Tortí	187	1.0 (0.6)	20	1.4 (0.7)	0.41 (0.27)	0.80 (0.14)
2	Tortí	132	3.0 (1.5)	109	3.3 (1.9)	1.03 (0.44)	1.15 (0.37)
3	Mundito	31	5.2 (1.4)	31	4.5 (1.5)	1.28 (0.32)	1.28 (0.32)
6	Las Lajas	32	19.8 (2.2)	32	19.1 (1.9)	2.92 (0.58)	2.92 (0.58)
10	Las Lajas	32	21.1 (1.8)	32	18.8 (2.2)	2.77 (0.56)	2.77 (0.56)
16	Las Lajas	32	24.2 (4.7)	32	24.4 (5.5)	3.81 (0.79)	3.81 (0.79)
Tectona grandis							
1	Tortí	167	1.9 (1.4)	93	3.3 (1.1)	0.45 (0.23)	0.61 (0.08)
2	Tortí	89	6.5 (2.8)	79	6.6 (2.0)	0.93 (0.49)	0.99 (0.48)
3	Mundito	36	10.7 (2.7)	36	10.7 (3.0)	1.83 (0.49)	1.83 (0.49)
6	Las Lajas	32	13.2 (1.9)	32	13.8 (1.8)	2.05 (0.29)	2.05 (0.29)
10	Las Lajas	32	16.0 (1.9)	32	16.6 (3.2)	2.89 (0.49)	2.89 (0.49)
16	Las Lajas	32	19.1 (3.6)	32	20.8 (5.4)	3.42 (0.76)	3.42 (0.76)

[1] Data from year 1 measured in the trial was not included in the regression analysis. It is however displayed here, as these data will be discussed in the following section

[2] No plots of *C. odorata* with a density of 1111 trees/ha were established at the trial site. Therefore data from the trial with differing planting densities were used (sampling type AF and FP).

Figure 4.40 shows the linear relationship between crown radius and diameter for the species investigated. From a biological point of view a linear regression might not seem appropriate. It is to be expected that crown radius reaches an asymptote at a certain dbh, while diameter growth continues to rise. A logistic regression model might therefore seem more appropriate. However, during the rather short observation period of up to 16 years, linear regression models showed the best R^2 for all species and were therefore chosen (see below).

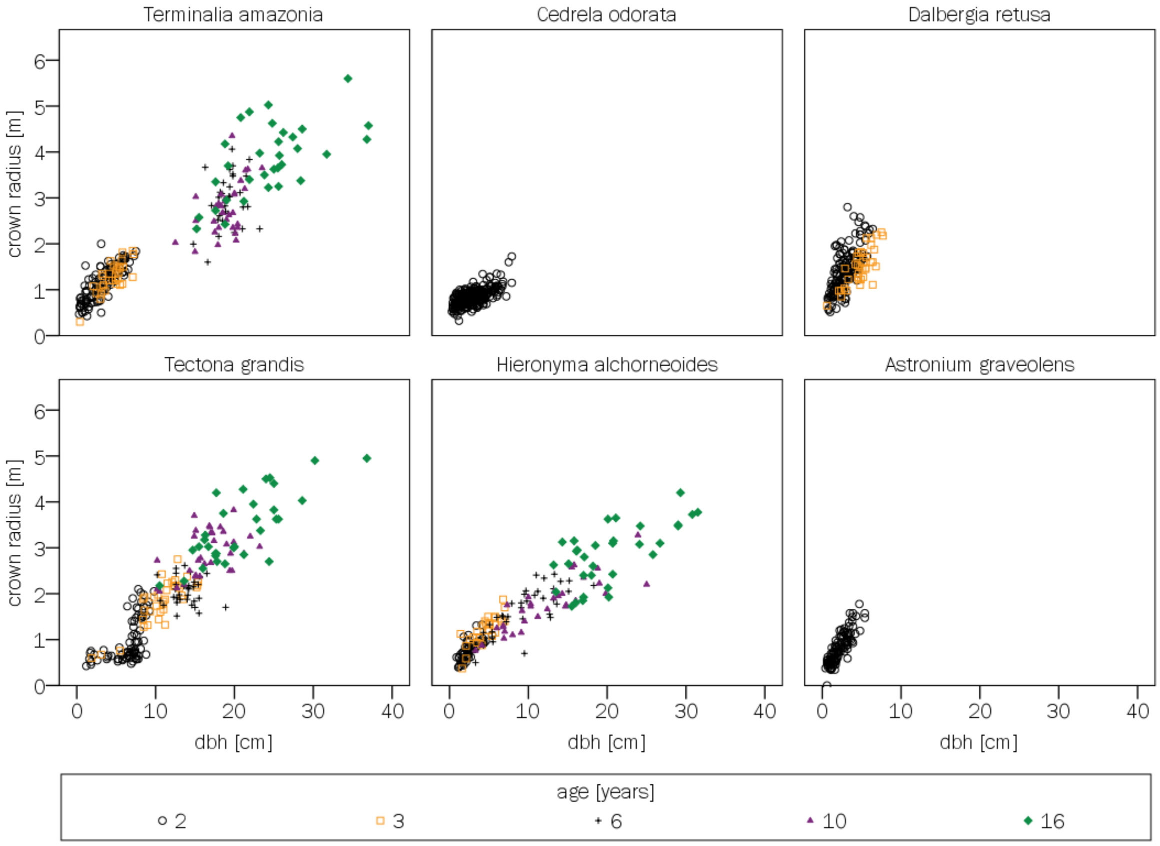

Figure 4.40: Relationship between crown radius and dbh by tree species, based on data set described in Table 4.50.

Figure 4.40 reveals the relatively slow growth of native tree species during the first 3 years, as the data for years two and three hardly differ. *T. grandis* shows a nonlinear pattern for diameters at breast height between 0 and 10 cm: The relationship between height and crown radius seems to be illustrated by a line parallel to the x-axis with an intercept of 0.5 to 1 m of crown radius. In fact, *T. grandis* is known to show a straight, monopodial growth during the first years, with very little branching (Leroy et al. 2009). If branches do develop, they are cut early in the course of pruning as they tend to droop down, causing a loss in quality. Therefore, the crown usually consists of numerous leaf whorls along the stem with an individual leaf length of 30 - 60 cm and width of 20 - 35 cm. At around age three, trees develop a sympodial ramification (Schütt 2004, p. 637). This growth characteristic explains the homogenous crown radius at young stand ages. To avoid nonlinear patterns of residuals, data for *T. grandis* in plantations younger than three years was excluded from the regression model.

Dbh significantly predicted crown radius for all tree species ($p < 0.001$) (see Table 4.51). More than 65% of the variation in crown radius was explained by the dbh (see R^2 in Table 4.51) with the exception of *D. retusa* ($R^2 = 0.414$). Due to the lack of data for plantations older than three years for *A. graveolens*, *C. odorata* and *D. retusa,* the amount of variation explained by the model was rather low and hence results for these tree species should be interpreted with caution.

Table 4.51: Results of the linear regression with predictor breast height diameter [cm] (dbh) and outcome crown radius (cr) (in [m]) by tree species. The linear regression model applied was $cr = b_0 + b_1 * dbh$. Standard errors of estimated coefficients are given in brackets.

Tree species	R^2	b_0		b_1		p-value
A. graveolens	0.743	0.271	(0.034)	0.250	(0.014)	<0.001
C. odorata[1]	0.651	0.633	(0.017)	0.071	(0.005)	<0.001
D. retusa	0.414	0.809	(0.059)	0.187	(0.016)	<0.001
H. alchorneoides	0.856	0.586	(0.038)	0.106	(0.003)	<0.001
T. grandis[2]	0.842	0.429	(0.124)	0.137	(0.008)	<0.001
T. amazonia	0.870	0.747	(0.041)	0.117	(0.003)	<0.001

[1] Data from sampling type AF and FP in the trial were used

[2] Data < 3 years were excluded to avoid non-linear patterns in residual plots. When data of 2 year old stands from the FP 3 x 3 sampling type in the trial were included, R^2 was 0.817, intercept = 0.069 and b = 0.156

The R^2 value was relatively high when predicting crown radius by height (Table 4.52). More than 80% of the variance in crown radius was explained by height for *A. graveolens*, *H. alchorneoides*, *T. grandis* and *T. amazonia*. For these four tree species, crown closure could be adequately predicted, while the results for *D. retusa* and *C. odorata* should be considered cautiously. In the case of *C. odorata,* predictions were difficult to make as they depended strongly on the severity of attacks of *H. grandella,* and hence increment losses due to the necessary cutting of branches (chapter 4.2.3.3.1). In the case of *D. retusa,* the bushy growing habit made predictions more difficult and resulted in a high tree-to-tree variation.

Table 4.52: Results of the linear regression with predictor, height (h) in [m], and outcome, crown radius (in [m]), by tree species. The linear regression model applied was $cr = b_0 + b_2 * h$. Standard errors of estimated coefficients are given in brackets.

Tree species	R^2	b_0		b_2		p-value
A. graveolens[1]	0.822	-0.063	0.027	0.364	0.013	<0.001
C. odorata[2]	0.523	0.402	0.023	0.171	0.009	<0.001
D. retusa	0.536	0.479	0.052	0.267	0.016	<0.001
H. alchorneoides	0.859	0.407	0.032	0.113	0.003	<0.001
T. grandis[3]	0.815	0.096	0.158	0.166	0.01	<0.001
T. amazonia	0.826	0.675	0.045	0.115	0.003	<0.001

1 *A. graveolens* showed signs of heteroscedasticity. However, as the calculated time of crown closure (Table 4.53) is in accordance to the prediction based on dbh (Table 4.51), no further attempts to meet model assumptions (e.g. transformation) were made.

[2] Data of sampling type AF and FP in the trial were used

[3] Data from stands of less than 3 years growth was excluded to avoid non-linear patterns in residual plots. When data from 2 year-old stands from the FP 3x3 sampling type in the trial were included, R^2 was 0.793 intercept = -0.103 and b = 0.175

Using the results from the regression models above, the dbh and height at the time of crown closure (dbh_{cc} and h_{cc}, respectively) were calculated (Table 4.53). For this purpose, crown closure was assumed to take place when crowns overlapped by more than 30%. At the present density of 3 x 3 m, crown radius cr_{cc} must be larger than 1.95 m to achieve crown closure, assuming a concentric crown. The calculated dbh_{cc} and h_{cc}[88] were then compared to the predicted dbh and height from the growth model (Table 11.10, see appendix) to estimate stand age at the time of crown closure. In the case of *A. graveolens*, *C. odorata* and *D. retusa,* height was used as the predictor, as it seems to be more reliable in young stands, whereas in older stands, dbh can usually be estimated more accurately than height. The last column in Table 4.53 shows the age for the precommercial thinning which was used in the prediction model.

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[88] For this purpose regression models from Table 4.51 and Table 4.52 were rearranged as $dbh_{cc} = (cr_{cc} - b_0)/b_1$ and $h_{cc} = (cr_{cc} - b_0)/b_2$, respectively, where $cr_{cc} = 1.95$ m

Table 4.53: Diameter at breast height (dbh_{cc}) and height (h_{cc}) at the time of crown closure as calculated by the regression model. For this purpose, the regression models shown in Table 4.51 and Table 4.52 were rearranged as $dbh_{cc} = (cr_{cc} - b_0)/b_1$ and $h_{cc} = (cr_{cc} - b_0)/b_2$, respectively, where cr_{cc}= 1.95 m. Derived age at the time of crown closure is displayed based on both the regression model with predictor height (Age_{cc} (h_{cc}), and the model with predictor dbh (Age_{cc} (dbh_{cc}).

Tree species	dbh_{cc} [cm]	h_{cc} [m]	Age_{cc} (dbh_{cc}) [years]	Age_{cc} (h_{cc}) [years]	Age at precommercial thinning [years after planting]
A. graveolens	6.7	5.5	7	7	7
C. odorata	18.6	9.1	13	8	8
D. retusa	6.1	5.5	5	6	6
H. alchorneoides	12.9	13.7	10	9	9
T. grandis	11.1	11.2	5	6	5
T. amazonia	10.3	11.1	7	8	7

In the case of *T. grandis,* the calculated time corresponded to recommendations by Kanninen et al. (2004) and Bermejo et al. (2004). Similarly, the results for *T. amazonia* were in agreement with those published in the study by Montero and Kanninen (2005). In the case of *H. alchorneoides,* the time calculated by the model for the first thinning was slightly later then that reached using the top height approach of Cordero and Boshier (2003) and ANAM (2010), both of whom recommend a thinning at a height of 7 - 9 m (in the present prediction achieved at age 6). *H. alchorneoides* has been shown not to react to early thinning with induced diameter growth (Piotto et al. 2003a). As this species has a slow initial growth and tends toward heavy bifurcation if thinned too early, the delayed thinning in comparison to that done for other species seems appropriate. The same is true for *C. odorata*. Lateral competition of trees might induce fast height growth, which is desirable in order to reduce damages by *H. grandella*. *D. retusa* is also thinned relatively early due to its higher planting densities. Thinning before crown closure is generally not considered in order to ensure suppression of grass, as also supported by Evans and Turnbull (2004).

Consecutive thinnings are frequently carried out based on the basal area (e.g. Onyekwelu et al. 2011 and references therein). For *T. grandis* and *Swietenia macrophylla* respectively, Kanninen et al. (2004) and Mayhew and Newton (1998) suggested, thinning when basal area reaches 20 m²/ha. This approach was adopted here for the **timing of the second thinning**. As shown in Figure 4.41, a basal area of 20 m²/ha was achieved between ages 13 and 19 under the present growth prediction. *A. graveolens* did not reach this size until year 25, due to its naturally slow diameter growth. The second thinning of *T. grandis* was slightly delayed based on suggestions from ANAM (2010), Keogh (1987) and Zanin (2005), who supported a consecutive thinning between years 11 and 12. However, these studies both assumed a rotation period of 20 years. With the exception of *D. retusa,* all species recovered a basal area of more than 20 m²/ha after the second thinning. However, in order to simplify assumptions and facilitate interpretation of data, no further thinnings were considered (Figure 4.42). The derived standing volume using the present growth prediction and a form factor of 0.5 for all species (as proposed by Piotto et al. (2010) and Wishnie et al. (2007) among others) is displayed in Figure 4.42.

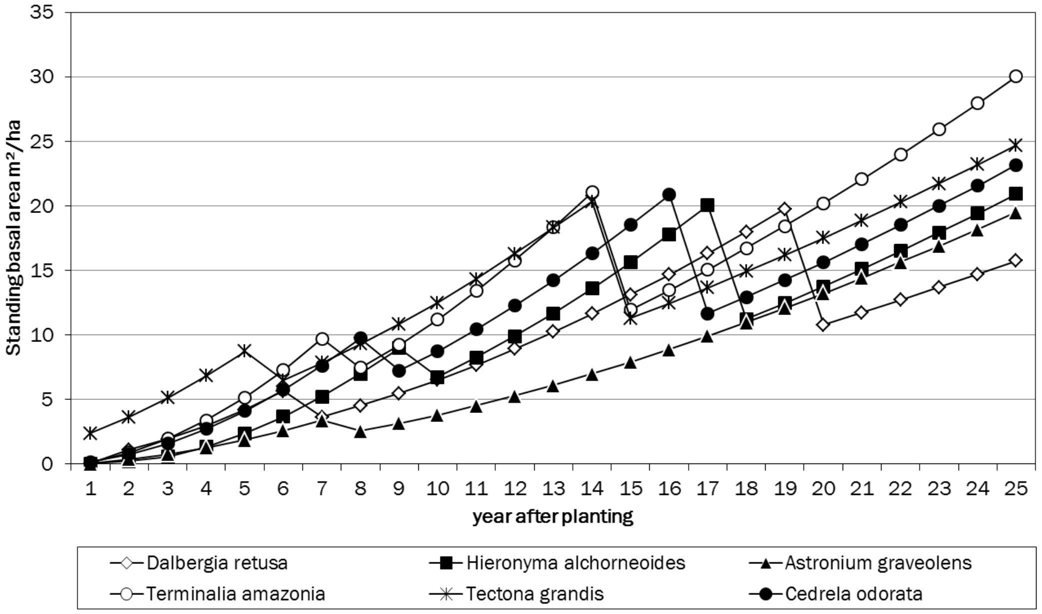

Figure 4.41: Basal area [m²/ha] of the six tree species investigated under the growth prediction and thinning concepts applied.

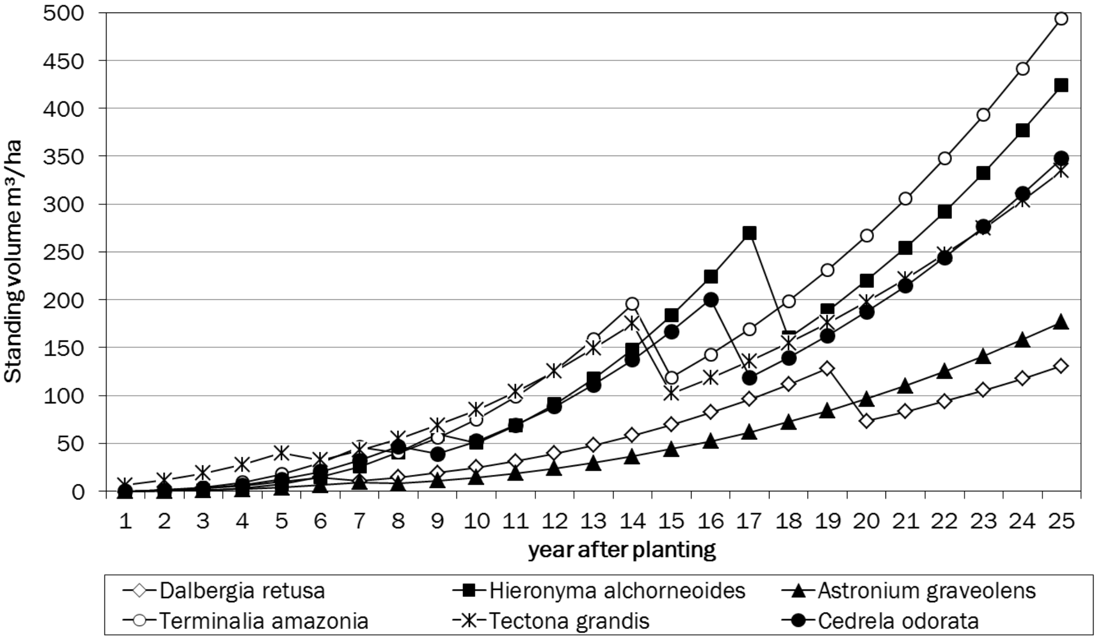

Figure 4.42: Standing volume [m³/ha] of the six tree species investigated under the growth prediction and thinning concepts applied.

Table 4.54 gives an overview of the derived thinning regime, which is displayed in more detail in Table 11.10 (see appendix). Stem numbers in this table do not sum up to 1111 as a yearly mortality of 2% during the first 10 years and 1% between year 11 and 25 was assumed for all tree species according to the experiences of Evans and Turnbull (2004), Camacho (2012, pers. communication) and Herrera (2012, pers. communication).

Table 4.54: Overview of thinning concept (I = Intensity of thinning in % of stem number, S = harvested stem number per ha, V = total harvested volume [m^3/ha])

	First Thinning				Second thinning				Final harvest (Age 25)	
Tree species	Age	I	S	V	Age	I	S	V	S	V
Astronium graveolens	7	40	394	4	>25	50	0	0	478	177
Cedrela odorata	8	40	386	19	16	50	262	100	239	347
Dalbergia retusa	6	50	753	7	19	50	317	64	299	131
Hieronyma alchorneoides	9	40	378	24	17	50	259	135	239	424
Tectona grandis	5	40	410	16	14	50	267	88	239	337
Terminalia amazonia	7	40	394	18	14	50	267	98	239	494

According to Griess and Knoke (2011) and FAO (2002), a harvest loss of 20% is assumed. Of the remaining wood volume, 80% is considered to be stem wood, as also proposed by Griess and Knoke (2011) and hence, only 64% of harvested wood volume is actually sold as stem wood. This is also in accordance with Piotto et al. (2010), who assumed 67% of standing volume to be marketable material. Heartwood proportion was not considered for wood price calculations, as its variation between sites, tree species and management regimes remains unclear, and wood prices usually present an average over all stems.

Wood prices were derived from the National Forest Office of Costa Rica (Oficina Nacional Forestal) (ONF 2012) as no official information on wood prices for native timbers were available in Panama. Prices for teak logs were used as a base price. Wood prices for native tree species were then calculated in relation to teak prices. These relations were derived from ONF (2012), ANARAP (2011) and interviews with local wood sellers and sawmills. This approach was chosen, as the most detailed information considering different assortments and exact selling conditions (off wood yard, in container etc.) was only available for *T. grandis*, and information on wood prices of native tree species was scarce. Furthermore, absolute wood prices can differ strongly depending on the volume determination method[89], region, amount and quality of wood being sold (ONF 2012, Zanin 2005), making a direct comparison of wood prices derived from different sources or interviews difficult. The prices for *T. grandis* timber reported by ONF (2012)[90] (Table 4.55) were based on the largest inventory available for Central America. Due to the rather recent development of the timber plantation sector in Panama, wood prices from plantations are mainly based on small diameters of logs originating from thinning operations, whereas the inventories for Costa Rica include wood prices reported from mature plantations. Prices for *T. grandis* reported in Table 4.55 are also in accordance with the prices estimated by the ITTO (2011). The table furthermore shows that the price for *T. amazonia* was the lowest, at only 50% of that for *T. grandis*. Lower wood quality (see chapter 3.2.1.1) and its yellow color generally lead to lower wood prices. The ONF and ANARAP consider *T. amazonia* to be a “medium hardwood“ with prices similar to those for *Acacia mangium, Eucalyptus ssp., Pinus caribeae* and *Gmelina arborea*. Interviews with local wood-selling companies, sawmills as well as data on current wood prices in the first trimester of 2012 from ONF 2012 support this assumption. *H. alchorneoides* -also sold as a medium hardwood - obtains however, higher prices, according to ONF (2012). This might mainly be due to its higher workability and durability compared to *T. amazonia* (Cordero and

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[89] In Central America, both the Hoppus and Brereton formulas are used to determine the wood volume of each log. The Hoppus scale uses the circumference (c) and length (L) of the trunk to determine the wood volume ($V_{Hoppus} = ((c^2\text{-}10)(L\text{-}5)/16)$, while the Brereton scale uses the quadratic mean of the diameters at both ends (D^2) multiplied by the length of the log and the constant, 0.7854. In Panama, the Hoppus formula is more widely used (Zanin 2005, Camacho 2012, Chavez 2012, pers. communication). One reason for this might be that the Brereton formula gives significantly fewer cubic meters to the seller than the Hoppus measurement (Zanin 2005). For this study, volume was calculated according to Pretzsch (2009) by $V = dbh^2*(\pi/40000)*h*f$, with dbh measured in [cm] and height in [m], and using a form factor f of 0.5 (Table 11.10 see appendix)

[90] Original prices were given in „pulgada maderera tipica (pmt)” which equals a board of 2.54 cm*2.54 cm*3.36 m. Therefore one m^3 equals 326 pmt. Five hundred Costa Rican Colones were considered to be equal to 1$.

Boshier 2003). *C. odorata* is sold as hardwood in Costa Rica, and under the name “Spanish Cedar” on international markets. It does not, however, fetch the same prices as *T. grandis*. No price information was available for *D. retusa* and *A. graveolens*. *A. graveolens* is widely used for furniture and floors in Panama (Carrasquilla 2006). Due to its high timber quality “excellent options on the international market” have been purported by Cordero and Boshier (2003). Based on the experiences of local forest engineers and interviews with sawmills, the same wood price as that used for *T. grandis* was assumed (Chavez, 2011, pers. communication, Schnall, 2011, pers. communication). Even though *D. retusa* (rosewood) is listed as vulnerable by the IUCN due to its overexploitation in natural forests, it is rarely planted in forest plantations. Processed rosewood can reach a price of up to $0.90 per square foot of sawn timber in the local sawmills of Tortí (personal interviews). Due to its high wood quality, and hence its demand along with its scarcity, wood prices were assumed to be the same as those used for *T. grandis*.

Table 4.55: Round wood prices in $/m^3 in container. To account for the transport costs to harbor, in accordance with Camacho (pers. communication, 2011), $10/m^3 were subtracted from the original wood price reported by ONF (2012). Costs apply for logs with lengths from 4 to 7.95 m, which corresponds to the medium price for logs between 2.2 m and 8 m long.

dbh [cm]	Prices according to ONF 2012	*T. grandis*	*A. graveolens*	*C. odorata*	*D. retusa*	*H. alchorneoides*	*T. amazonia*
Species factor[1]		*1*	*1*	*0.75*	*1*	*0.75*	*0.5*
< 13	0	0	0	0	0	0	0
13-14.9	134	124	124	93	124	93	62
15-16.9	145	135	135	101	135	101	68
17-18.9	156	146	146	110	146	110	73
19-20.9	168	158	158	119	158	119	79
12-22.9	179	169	169	127	169	127	85
23-24.9	197	187	187	140	187	140	94
25-26.9	218	208	208	156	208	156	104
27-28.9	237	227	227	170	227	170	114
29-30.9	273	263	263	197	263	197	132
31-35	313	303	303	227	303	227	152
>35	385	375	375	281	375	281	188

[1] Species- specific prices were calculated by multiplying the price according to ONF (2012) by a species factor

As harvesting costs are dependent on the number of stems and their diameters, they are displayed at this point together with the predicted revenues:

Table 4.56: Costs, revenues and profits in $/ha from thinnings and final harvest.

Tree species	Costs			Revenues			Profit		
	First Thinning	Second Thinning	Final harvest	First Thinning	Second Thinning	Final harvest	First Thinning	Second Thinning	Final harvest
A. graveolens	542	0	2404	0	0	19103	-542	0	16699
C. odorata	536	1415	1312	0	8123	62547	-536	6708	61235
D. retusa	838	1156	1585	0	6489	17396	-838	5333	15811
H. alchorneoides	530	1403	1312	0	10939	61672	-530	9536	60360
T. grandis	556	1439	1312	0	9525	80880	-556	8086	79568
T. amazonia	542	1439	1312	0	5291	59286	-542	3852	57974

Table 4.56 reveals that, despite the high total increment of *T. amazonia* (see Figure 4.39), revenues are considerably lower compared to those for *T. grandis*, due to the lower wood prices. Because of their slow growth rates, *A. graveolens* and *D. retusa* reached final felling values of less than 17,000 $/ha after 25 years.

4.5.3.2 Cash Inflows from crops

As described in chapter 3.3.2, maize was sold as fresh corn cobs. The usual selling unit is a sack containing 100 cobs. Good quality cobs were sold for human consumption, while cobs of poor quality (for example, cobs that were already too hard, were damaged by insects and birds or were too small) were sold for a lower price as livestock fodder, especially for pigs. The price achieved at the local market in Tortí, presented in Table 4.57, is in keeping with prices reported from the Central Market in Panama (IMA 2009-2011). Beans were harvested and sold as dried beans, while pigeon pea was sold both as dried and threshed seeds and in green pods. This was because, although a higher price could be obtained for fresh green pods compared to the dried seeds, some pods had already dried out at the time of harvest and therefore had to be processed as dried seeds.

Table 4.57: Revenues from crops in Agroforestry (AF) and pure Agriculture (CP)

Crop	Unit	Yield/ha		Price per unit [$]	Revenue [$/ha]	
		AF	CP		AF	CP
Maize rotation with fertilizer – high quality cobs	No. of corn cobs[1]	19112	21023	0.07	1338	1472
Maize with fertilizer – low quality cobs	No. of corn cobs	4788	5267	0.03	144	158
Maize with fertilizer - total					*1482*	*1630*
Beans[3]	Quintal[2] (qq)	6.9	7.6	55.00	380	418
Maize rotation without fertilizer – high quality cobs	No. of corn cobs	13560	14916	0.07	949	1044
Maize rotation without fertilizer – low quality cobs	No. of corn cobs	3390	3729	0.03	102	112
Total maize without fertilizer					*1051*	*1156*
Pigeon Pea – green pods	Quintal (qq)	24.5	27.0	60.00	1471	1620
Pigeon Pea – dried seeds	Quintal (qq)	5.9	6.5	55.00	326	357
Pigeon Pea total					*1797*	*1977*
Cassava	Quintal (qq)	78.5	86.4	10.00	785	864

[1] Corn cobs were sold per sack of 100 fresh corn cobs
[2] 1 qq equals 100 lb or around 46 kg
[3] Bean yields slightly differed from those presented in Table 4.32 due to losses through processing and sorting of damaged seeds. Yields of both rotations which included beans (B-R-R and M-B-M-M) were pooled together.

Cassava tubers were sold locally, mainly to restaurants, by the quintal (qq), which is equal to 46 kg. However, a part of the harvest was sold for a lower price because of inferior quality. Therefore a relatively low mean price of $10 was achieved. Cassava yields were low due to the waterlogged site. However, for marginal agricultural land on which reforestation is usually carried out, these yields seem realistic for cassava, which requires well drained and ventilated soils. Table 4.57 shows the revenues for crops in both the agroforestry system and in the pure agricultural plots (see also chapter 4.4). As no space was occupied by trees[91], 10% higher crop yields and revenues were derived for the pure crop plantations (CP).

In chapter 4.4, it was shown that no differences in crop yields between tree species were found. Therefore the same crop yields were assumed for all tree species in the first year. In Table 4.50, it was also shown that all tree species had a crown radius smaller than 0.5 m at the end of year one, which corresponds to the radius around each tree that was not planted with crops. Trees were also smaller than cassava, pigeon pea and maize plants (see Figure 4.10, pp. 65) until the

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[91] 1 ha instead of 0.91 ha is available for cultivation of crops

end of year one. Therefore it can be assumed that crops were not shaded by trees and hence, yields were not reduced in the first year. However, in the following years differences in canopy traits and growth rates between tree species might be expected to lead to different yields. Due to time limitations, crop yields were, however, only investigated during the first 18 months after tree planting. Hence, potential yields during the subsequent years had to be predicted based on tree growth, canopy traits and light transmission:

At the end of year two, *T. grandis*, *T. amazonia* and *D. retusa* had the highest mean crown radius, with 0.93, 1.03 and 1.2 m, respectively (Table 4.50). Assuming that the area covered by a tree crown cannot be planted with a crop, this would lead to a reduction of area available for crop planting, and thus of yield by 24%, 31% and 53% respectively. Light is also a crucial factor for most, particularly annual, crop species (see chapter 2.2.1). At the end of year two, light transmission was reduced through tree canopy by 36% and 19% in stands with spacing of 3 x 3 m of *T. grandis* and *T. amazonia*, respectively, compared to areas planted solely with crops. For *D. retusa* shading accounted for 20% at a spacing of 3 x 2 m after two years (Table 4.41 and Waltenberger 2013). For C4 plants such as maize, studies in agroforestry systems have shown that yield is reduced at the same magnitude as light transmission (Friday and Fownes 2002, Ding and Su 2010). However, predicting yield reduction by availability of area or by availability of light leads to different results, which might be mainly attributed to differences in canopy structure. For instance, as described earlier, *T. grandis* initially has a very small conical crown but a very fast monopodial growth, leading to a small reduction of area available for crops but to a relatively high level of shading. In contrast, the flat-topped spreading crown and small leaves of *D. retusa* lead to a high projection area but relatively low level of shading. Hence, the higher level of light transmission in stands of *D. retusa* suggests that more crop plants might potentially be grown under the calculated mean projected area of the crown. Leroy et al. (2009) also demonstrated in tropical plantations that the area below the tree crown might receive more radiation than a position between tree rows, especially during morning and evening hours. However, in order to prevent yield predictions from becoming too optimistic, the more conservative approach of reduced area was chosen as a basis for predicting future yield reduction. As the crowns of young trees develop quickly throughout the year, thus allowing a higher crop yield at the beginning of the year and a lower yield at the end of the year, simplified categories for yield reduction were defined for each crop in order to not overcomplicate assumptions (Table 4.58).

Table 4.58: Categories for yield reduction based on crown radius (applied to data in Table 4.50)

Crown radius [cm]	% of area available for crop cultivation[1]	Yield reduction factor
50 – 80	100 – 85 %	1
81 - 110	84 – 65 %	0.75
110 – 130	64 – 45 %	0.50
> 130	< 45 %	0

[1] Based on a total area of 0.91 ha and hence, the circle with a radius of 0.5 m around each tree is not considered as potential area for crop planting

The assumption of no yield reduction up to a tree crown radius of 80 cm seems realistic, as a regression analysis of height and crown radius showed that trees with this crown radius were still shorter than 3 m, and hence, shorter than most of the crops (Table 4.50). Moreover, light transmission in stands with a mean crown radius smaller than 80 cm was more than 80% (Waltenberger 2013). When crown radius reached 1.3 m, no crop harvest was expected, as light transmission was assumed to be too low. In the following section, the detailed assumptions made will be presented by crop species.

Being a C4 plant, **maize** is a highly light-demanding plant species (e.g. Lieberei and Reisdorff 2012). In agroforestry systems it is therefore only recommended for use in the very early stages of a Taungya system (Kapp and Beer 1995, Heineman et al. 1997, Martin and van Noordwijk 2009). For the native tree species, the categories from Table 4.58 were used to assess yield reduction based on the reduced cropping area. For fast growing *T. grandis,* light measurements were also taken into account, due to its fast height growth and constant crown radius (Table 4.41):

Table 4.59: Yield reduction scenario for maize in the agroforestry system. Factors multiplied by yield in year zero.

Tree species	Year 0	Year 1	Year 2	Year 3	Year 4
A. graveolens	1	1	1	0.75	0
C. odorata	1	1	1	0.75	0
D. retusa	1	1	0.75	0.5	0
H. alchorneoides	1	1	1	0.75	0.5
T. grandis	1	1	0.5	0	0
T. amazonia	1	1	0.75	0.5	0

A yield reduction of 50% was assumed for *T. grandis* in year two, due to the low level of light transmission in these stands, as displayed in Table 4.41. For *A. graveolens*, *C. odorata* and *H. alchorneoides,* constant yields were assumed up to year two, given their small crown diameters and heights. At the end of year two, these tree species were still smaller than the maize plants, thus not affecting maize yields. For these initially slow-growing tree species, a yield reduction of 25% was assumed in year three, while *D. retusa* and *T. amazonia* only allowed a fraction of 50% of initial yield. *T. grandis* did not allow for any maize growth due to intensive shading of more than 90 % from year three onward.

These assumptions were supported by an additional trial which was carried out in a three-year-old plantation in Mundito in which maize was still being grown in stands of *T. grandis*, *H. alchorneoides*, *T. amazonia*, *D. retusa* and *Bombacopsis quinatum*[92] (Paul 2012, unpublished data). Trees and crops were planted in the same density as in the present scenario[93]. The results of this trial (not presented here in detail) showed that maize was still able to germinate between native tree species, while shading was too intense in *T. grandis* stands. Maize yields were low in all stands, as no fertilizer was used in this trial, and tall vegetation was not cut as intensively to the ground prior to the application of glyphosate as in the agroforestry trial. Due to low yields, biomass production was used as a measure for relative yield instead of marketable corn cops (Figure 4.43).

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[92] Not planted in the agroforestry trial in Tortí

[93] Four plots of 144 m^2 each were located randomly within stands of each tree species. The size of the total forest plantation in which the plots were located was 38 ha.

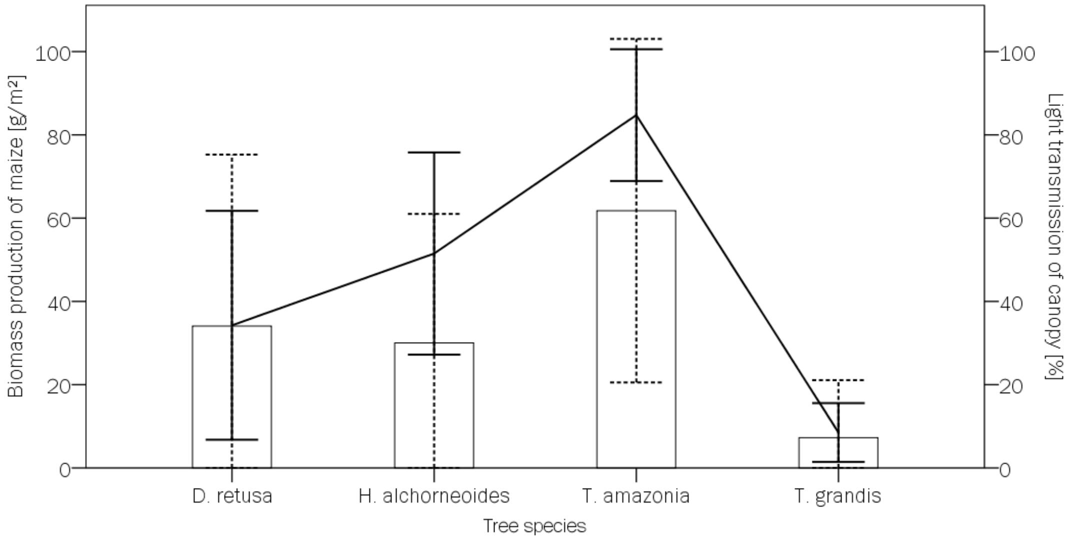

Figure 4.43: Total dry weight of biomass including cobs (bars, left axis) and light transmission level (solid line, right axis) [%] under canopy compared to an open field by tree species. Fresh weight was converted to dry weight using the same factors presented in Table 4.32. Data were based on total plant biomass per plot (N = 4 per tree species) and mean transmission of 10 light measurements per plot (N = 4 per tree species). Dashed error bars denote the 95% confidence interval for biomass, and continuous error bars denote the 95% confidence interval for light transmission. Data were taken from Paul (2012, unpublished data).

Results showed that biomass production of maize was surprisingly high in the *T. amazonia* stands, despite the relatively wide and dense canopy characteristic of this species, along with its good initial height growth. However, the experiment also showed that no economically viable maize production was possible by year four, even though higher yields might be possible with more intensive management. Only for *H. alchorneoides,* were yields of 50% still assumed in this year due to its slow growth[94].

Yield reduction of **beans** was assumed to be the same as that of maize. Even though common bean is a C3 plant, and therefore does not require as much light as maize, the plant itself is smaller and hence, yields might be expected to be similarly affected.

As **cassava** needs sufficient light for producing starch (Lieberei and Reisdorff 2012) the yield reduction scenario for maize was also applied to cassava (Table 4.59).

The yield reduction scenario for **pigeon pea** slightly differed from that for maize and beans. The reason for this was that pigeon pea was planted in a dense planting grid of 1 x 1 m in the agroforestry trial, as the primary aim of using this plant was shading out of grasses. Yield data from the first pigeon pea rotation revealed that low densities showed by trend the highest yield per shrub, while yield per shrub stayed rather constant under a moderate increase in density between 0.3 to 1 shrub/m² (Figure 4.44) (Kreuzer 2013).

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[94] The high rates of shading in Figure 4.43 and in Table 4.41 at age three might be misleading, as *H. alchorneoides* was planted under remnant trees in Mundito, due to its shade tolerance. Therefore shading in these stands cannot be attributed only to shading by *H. alchorneoides*.

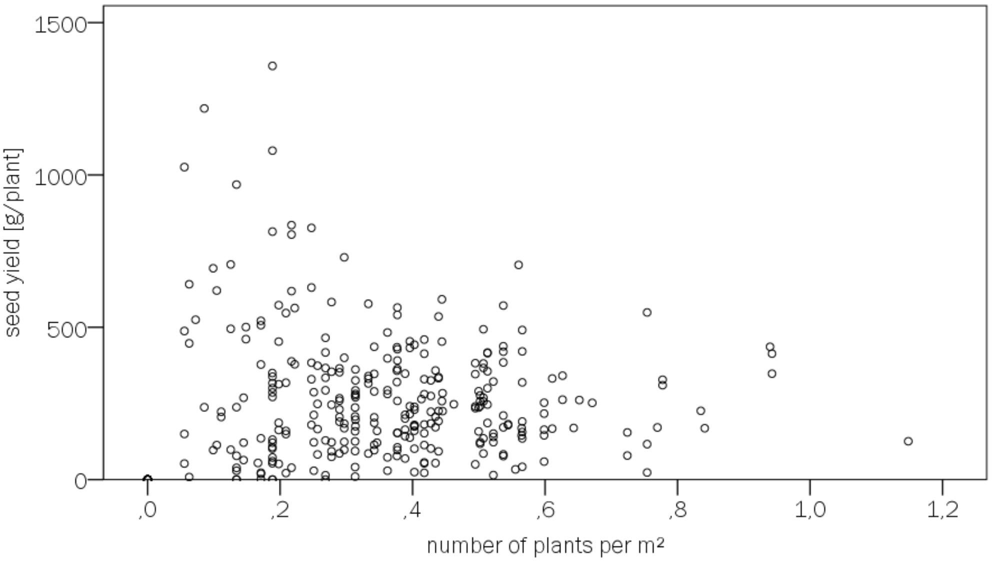

Figure 4.44: Relationship between number of pigeon pea shrubs per m² and yield (transformed to dry seed yields). Data was provided by Kreuzer (2013).

Therefore, the same yield could be assumed, even when shrubs are planted in a wider grid of 1.5 x 1 m or 1.5 x 1.5. Furthermore, pigeon pea is slightly shade tolerant, which was proven by the data presented in chapter 4.4, as no significant differences in yield were found between different tree densities and resulting light regimes. In year three, the same yield reductions as those assumed for maize, based on reduced cropping area were assumed. The high level of shading in *T. grandis* plantations and the added affect from the dropping of its large leaves, which quickly cover soil, were assumed to prevent germination of seeds. This was proven by personal observation in an additional trial (not presented in this thesis) which was carried out in the monitoring plots surrounding the agroforestry trial after 21 months. In this additional trial, none of the sown pigeon pea germinated in the *T. grandis* plots, while germination was successful in both *T. amazonia* and *H. alchorneoides* stands.

Table 4.60: Yield reduction scenario for pigeon pea in the agroforestry system. Factors were multiplied by yield in year zero

	Year 0	Year 1	Year 2	Year 3	Year 4
A. graveolens	1	1	1	0,75	0
C. odorata	1	1	1	0,75	0
D. retusa	1	1	1	0,5	0
H.alchorneoides	1	1	1	0,75	0.5
T. grandis	1	1	1	0	0
T. amazonia	1	1	1	0,5	0

With decreasing crop yields, **costs for harvesting, transport and inputs** (Table 4.44 to Table 4.46) were accordingly adjusted using the same reduction factor. Yields in the pure agricultural option were assumed to stay constant over time. In the cattle farming option, it was assumed that the four cows per ha raised were sold in the same year at a livestock price of $550 each. This assumption is in accordance with the mean cattle prices for 2011 at the market of Chepo - the closest cattle market in the region (IMA 2011). Revenues gained from crops in the different scenarios are illustrated in Figure 4.45 (next page). This figure reveals the high cash inflows obtained from the maize-beans-maize rotation, due to the two yearly maize harvests with relatively high revenues compared to other crops. All other crop rotations showed yearly revenues below those of cattle farming.

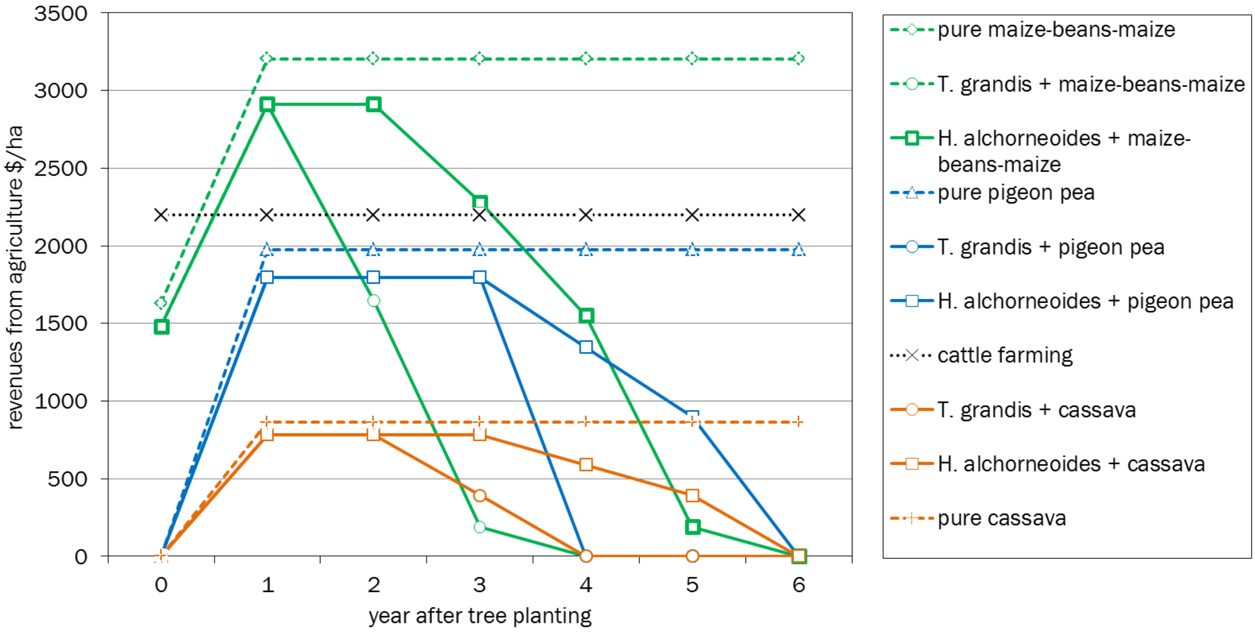

Figure 4.45: Cash inflows from maize (green lines), pigeon pea (blue lines), cassava (orange lines) and cattle farming (black line) in monoculture (dashed lines) and mixed with trees (solid lines). Revenues in agroforestry systems are shown for *T. grandis* and *H. alchorneoides only,* as revenues from crops planted with other tree species lie between these curves (see Table 4.59 and Table 4.60).

4.5.4 Net Cash Flow

The previous chapter has shown that through the agroforestry approach early cash inflows can be achieved from agricultural crops planted in forest plantations, though they are low compared to those obtained from pure agricultural crop cultivation and, with the exception of the maize-beans-maize rotation, also low compared to revenues from cattle farming. In the next step, the question of whether a positive Net Cash Flow (NCF) - i.e. the difference of cash inflow minus cash outflow - can be obtained during the first years of plantation establishment by cultivating crops between trees will be explored. Figure 4.46 compares the NCF from the different agroforestry options and the pure forest plantations for each of the six different tree species. Only the first five years after tree planting are displayed, as crop cultivation can only be expected to be feasible until year four, and thus, values would only differ within this time period. Revenues in year five are calculated exclusively for *H. alchorneoides,* due to the harvest of the last crops that were planted in year four.

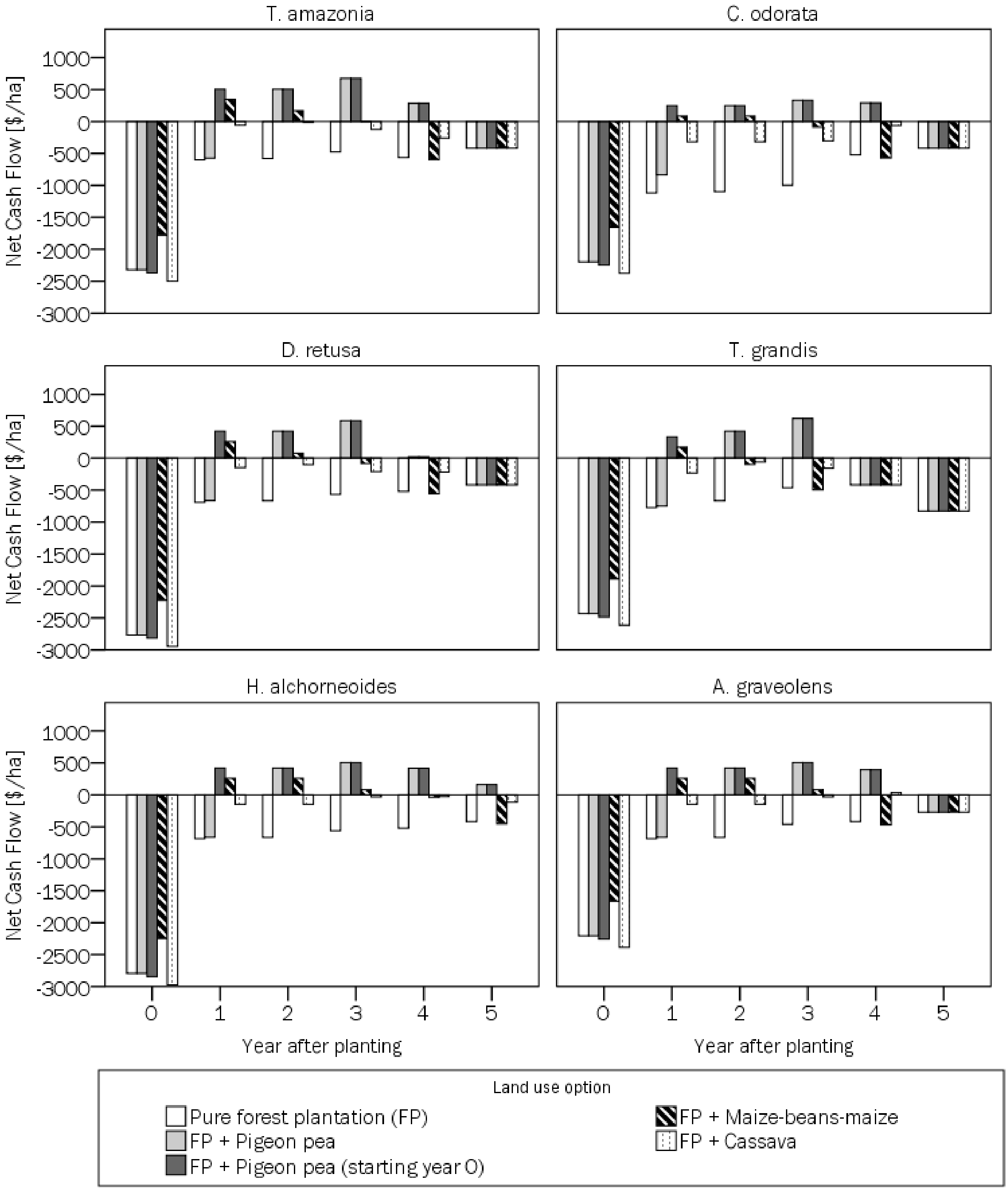

Figure 4.46: Comparison of Net Cash Flow between different tree-crop combinations.

Figure 4.46 reveals that the financial burden of stand establishment in year zero was reduced by planting maize between trees, as the first cash inflow from the harvest of maize was received in the same year. In the other intercropping systems, however, the NCF in the year of tree establishment was the same or even more strongly negative compared to that for the pure forest plantation, as there were additional planting costs for crops, while revenues from crops were sometimes first realized in year one, due to longer rotation periods. Finally, in the case of cassava, management costs for trees and crops were not completely offset by revenues from cassava harvest leading to a negative NCF during the entire period of its cultivation. This might be explained by the high weeding costs for trees which were the same as those for the pure forest plantations as this crop did not suppress grasses during its cultivation. Thus the high management and establishment costs of cassava were subtracted from the comparably low revenues achieved by this crop, which led to an overall negative final NCF. However, by selling cassava tubers, planting and management costs were still partly offset, resulting in an overall better NCF for tree stands intercropped with cassava compared to that for pure tree stands (Figure 4.46).

In contrast to the agroforestry system with cassava, establishment and management costs of trees combined with pigeon pea (starting in year zero) were only marginally higher compared to those for the establishment and management of pure forest plantations. This was due to the considerable reduction in weeding costs for trees achieved by planting pigeon pea, due to its fast growth and fast crown closure. The same was true for maize. Hence, early positive NCF can be achieved at year one of a forest plantation when intercropping trees with maize-beans-maize and pigeon pea (when starting in year zero).

Under the present assumptions, the NCFs among the different tree-crop combinations in the first five years were found to be highest for *T. amazonia* when intercropped with pigeon pea ($ 674/ha, year three) and second highest when combining the same tree species with maize ($ 346/ha, year one). The NCF for *T. amazonia* grown in pure plantation was $ -602/ha in year one and $ -478/ha in year three, thus demonstrating the positive financial effects of intercropping. NCFs during the first five years were generally lowest for those land use options which included *C. odorata* and *T. grandis*, due to their higher initial pruning costs (Table 4.40). Differences between pure tree plantations and the agroforestry systems decreased with time due to declining crop yields. According to the prediction of light and spatial competition between trees and crops, intercropping of *T. grandis* stands could only be carried out up to two to three years after planting, whereas native tree species could still be intercropped until four years after planting. During the last year of maize and bean cultivation, total costs in this agroforestry system were higher than those for pure forest management, due to the high costs for the labor intensive harvesting of beans combined with the relatively low revenues from this crop.

Figure 4.46 has demonstrated that the financial burden for tree management can be partly offset by intercropping trees with annual crops. The next question to be answered is: How large are the differences in NCF between forestry and agroforestry and other prevalent land uses during the first years after stand establishment. To answer this question, the data for pure and intercropped *D. retusa* stands was used for a comparison to the pure agricultural options (Figure 4.47), as the NCF for *D. retusa* represented an average among the six tree species. All NCFs are displayed in Table 11.11 (see appendix).

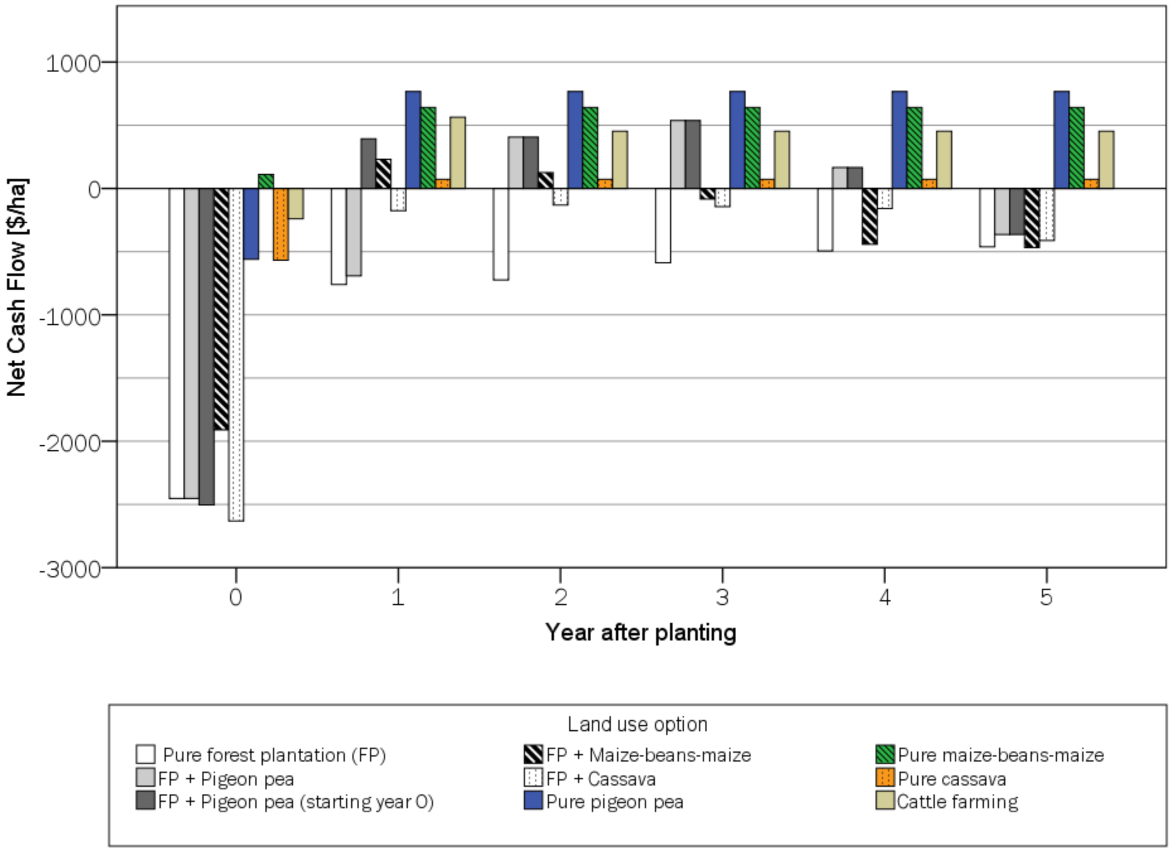

Figure 4.47: Net Cash Flow of *D. retusa* in pure plantation and in combination with crops compared to that for pure agriculture

The NCF for pure crop cultivation was per se higher compared to the agroforestry systems as in the latter, 1) costs of tree management were added to those for crop management and 2) lower yields on the same area could be assumed for the same management costs as those for pure crops. Nevertheless, tree intercropping with pigeon pea was competitive in terms of NCF with cattle farming in year three, as in this year the reduced sowing costs for pigeon pea were offset by the high incoming payments from the harvest of the pigeon pea planted in the previous year. Overall, the results of this comparison show that the difference in terms of NCF between forestry and agriculture can be reduced by intercropping trees with crops during the establishment phase. For instance, in year one, the NCF for intercropping of *D. retusa* compared to the corresponding pure agricultural option was 59% lower for maize, 45% lower for pigeon pea and 105% lower for cassava, while the NCF for pure forestry was 110 - 207% lower than that for pure crop cultivation and 222% than that for cattle farming.

The short-term perspective of the yearly NCF in the first years after establishment might be of high interest for farmers who usually have scant financial resources. However, as described in the previous chapter high future cash inflows can be gained by commercial thinning in plantation forests compared to the rather low revenues from agricultural commodities. Thus, the long term view will be presented in the following chapter, using the Net Present Value method.

4.5.5 Net Present Value and Internal Rate of Return

The comparison of land use systems in terms of Net Present Value (NPV) will be carried out based on an interest rate of 6%. Figure 4.48 reveals that the highest NPV of $17,836/ha over a rotation of 25 years under the present assumptions was obtained by the tree-crop combination *T. grandis* and pigeon pea, where pigeon pea was planted from year zero to year two. The next highest NPV was obtained by *T. grandis* associated with maize-beans-maize during the establishment phase.

All native tree species had a lower NPV than the exotic *T. grandis,* due to lower wood prices. The NPV of *D. retusa* and *A. graveolens* were – when not associated with pigeon pea (planted in year zero) – negative, reflecting that the investment in this land use system was not profitable at a 6% interest rate. This is due to the low growth rates of these tree species, which can be accounted for by extending the rotation period as will be demonstrated in the chapter to follow. For all of the tree species investigated, the NPV was higher when combining trees with crops than for pure forest plantations. This was true even for cassava, despite its low yields: When combining trees with cassava the NPV was between 8% (*T. grandis*) and 26% (*C. odorata*) higher than that for pure tree plantations. The same was true when trees were combined with a maize-beans-maize rotation (NPVs of 13% (*T. grandis*) to 40% (*C. odorata*) higher), or with pigeon pea (planted in year zero, resulting in NPVs 19% to 49% higher for *T. grandis* and *C. odorata,* respectively).

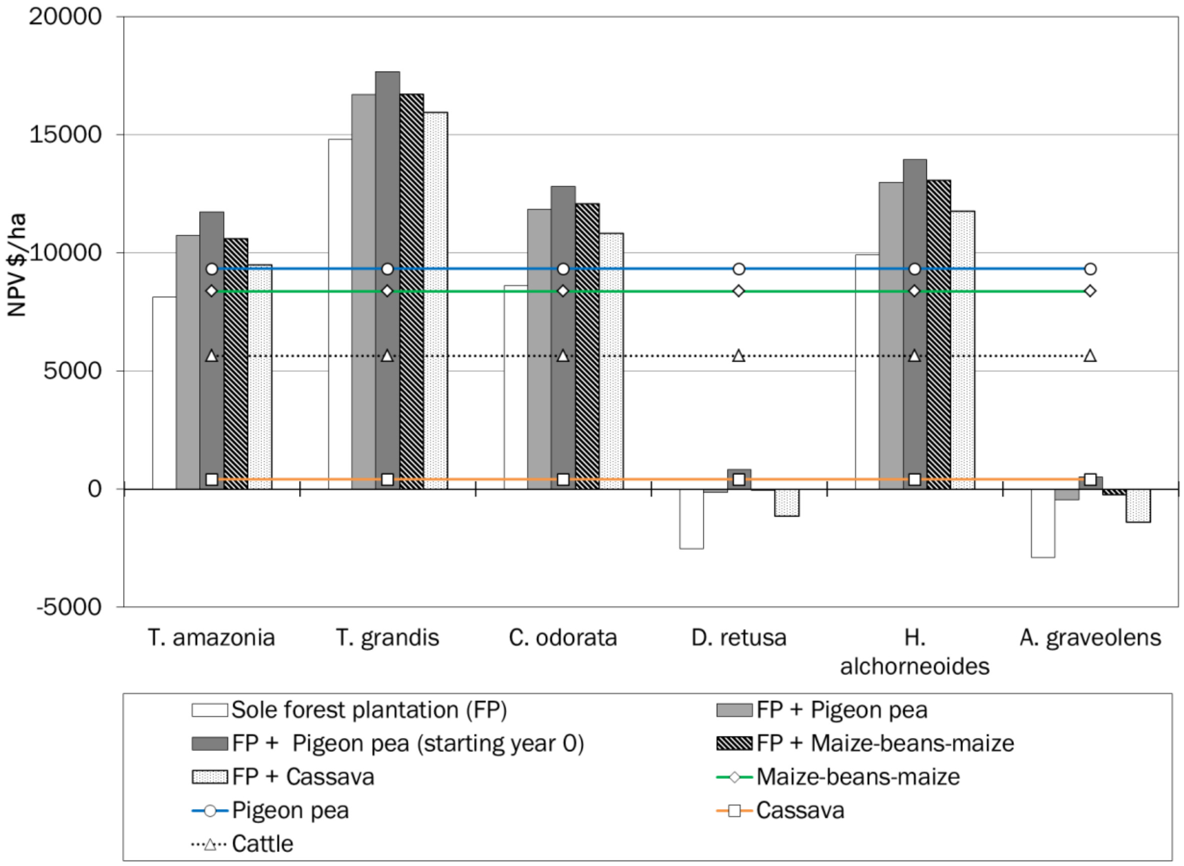

Figure 4.48: Net Present Value (NPV) of different pure forest stands (white bars) and agroforestry systems (patterned bars) compared to pure cropping systems (solid lines) and cattle farming (dashed line) at a interest rate of 6%.

It is notable that the highest differences in terms of NPV between pure forest plantations and agroforestry systems were calculated for *C. odorata,* due to the reduction of costs for pest management in the agroforestry systems. All land use systems involving *T. grandis* and *H. alchorneoides* were more profitable compared to pure agriculture (see bars compared to solid lines in Figure 4.48). Planting *T. amazonia* and *C. odorata* was only more cost effective than pure agriculture when planted in association with crops. However, all land use systems including trees were, with the exception of *D. retusa* and *A. graveolens*, more profitable than cattle farming (see dashed line in Figure 4.48). Among the pure agricultural land use options maize-beans-maize and pigeon pea cultivation had the highest NPVs of $8379 and $9336 per ha respectively, while pure cassava cultivation only had a NPV of $416/ha at an interest rate of 6%. This low NPV could be attributed to the low yields in the trial. Under these site conditions, a farmer might not decide to grow pure cassava, which will be discussed in chapter 5.2.5.

As mentioned above, the current low wood prices for native timber trees led to the lower NPVs for the native tree species compared to that for the exotic *T. grandis*. However, the literature review has shown that growth rates of native species can compete with that of *T. grandis* (see Figure 4.39). Consequently, if the same timber prices were calculated for all tree species, which was also assumed by Griess and Knoke (2011), the results would change considerably (Figure 4.49). To facilitate comparison with Figure 4.48, an interest rate of 6% was assumed at a rotation length of 25 years.

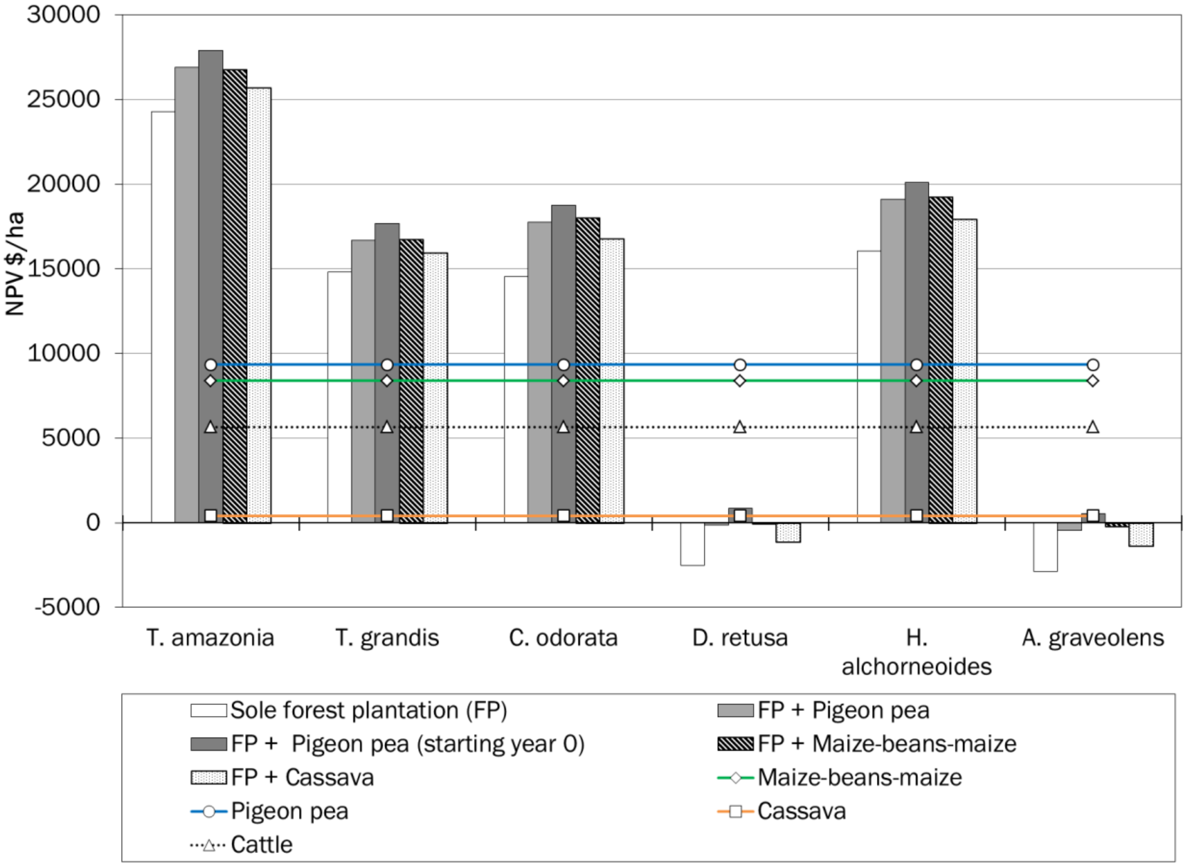

Figure 4.49: Net Present Value (NPV) of different pure forest stands (white bars) and agroforestry systems (patterned bars) compared to pure cropping systems (solid lines) and cattle farming (dashed line) at a interest rate of 6%, under the assumption of equal wood prices for all species (wood price for *T. grandis* see Table 4.55).

The NPVs for *D. retusa* and *A. graveolens* do not differ between Figure 4.48 and Figure 4.49, as for both species the same wood prices as for *T. grandis* were assumed in both figures (see also Table 4.55). In contrast, the NPVs for the pure forest plantations of *T. amazonia* and *H. alchorneoides* were both higher - by 62 and 7%, respectively – than that for *T. grandis* under the assumption of equal wood prices. *C. odorata* stands still had an NPV 3% lower than that for *T. grandis* when grown in pure forest plantations, whereas all tree-crop combinations which included *T. amazonia*, *C. odorata* and *H. alchorneoides* performed better in terms of NPV compared to the corresponding combinations with *T. grandis*.

The previous figures have shown the NPV at a selected interest rate of 6%. Results can however, considerably change depending on the underlying interest rate. Figure 4.50 and Figure 4.51 therefore illustrate the NPV of all land use options under a rotation period of 25 years at varying interest rates of up to 20%. All of the agroforestry systems investigated had a higher NPV than the corresponding pure forest plantation (see dashed line in Figure 4.51 (next page) under all interest rates. The differences between pure forest plantations and the agroforestry systems increased with increasing interest rate, as the positive effect of early returns from crop harvests is given more weight. For instance, *T. grandis* intercropped with maize-beans-maize had a 3% higher NPV than pure *T. grandis* stands at a 6% interest rate. However, at an interest rate of 10% this difference increased to 55%.

Figure 4.50 and Figure 4.51 also give information on the Internal Rate of Return (IRR) of the land use options studied: The IRRs of pure forest plantations range between 2 and 12%, with *A. graveolens* showing the lowest and *T. grandis* the highest IRR (Figure 4.51). At these interest rates the NPV was zero (where the curves in Figure 4.49 intersect the solid line) and thus the investment was economically beneficial up to this requested rate of return. *C. odorata*, *H. alchorneoides* and *T. amazonia* all had an IRR of 10% in pure forest plantations. The IRRs for the agroforestry systems - ranging between 5 and 15%- were higher than those for the pure forest plantations. With the exception of *A. graveolens* and *D. retusa*, the IRRs for all agroforestry systems exceeded 10% under the present assumptions, and are similar for *C. odorata*, *H. alchorneoides* and *T. amazonia*. For these three native species and *T. grandis*, the IRRs for cassava intercropping ranged between 11 and 12%, for intercropping with maize-beans-maize and pigeon pea from 13 to 14%, and for intercropping with pigeon pea (when planted in year zero) from 14-15%. Pure agriculture with pigeon pea, maize-beans-maize and cattle had IRRs greater than 20% (Figure 4.50), due to their yearly and constant profits, representing their attractiveness for small-scale farmers compared to the long-term investment required to grow trees.

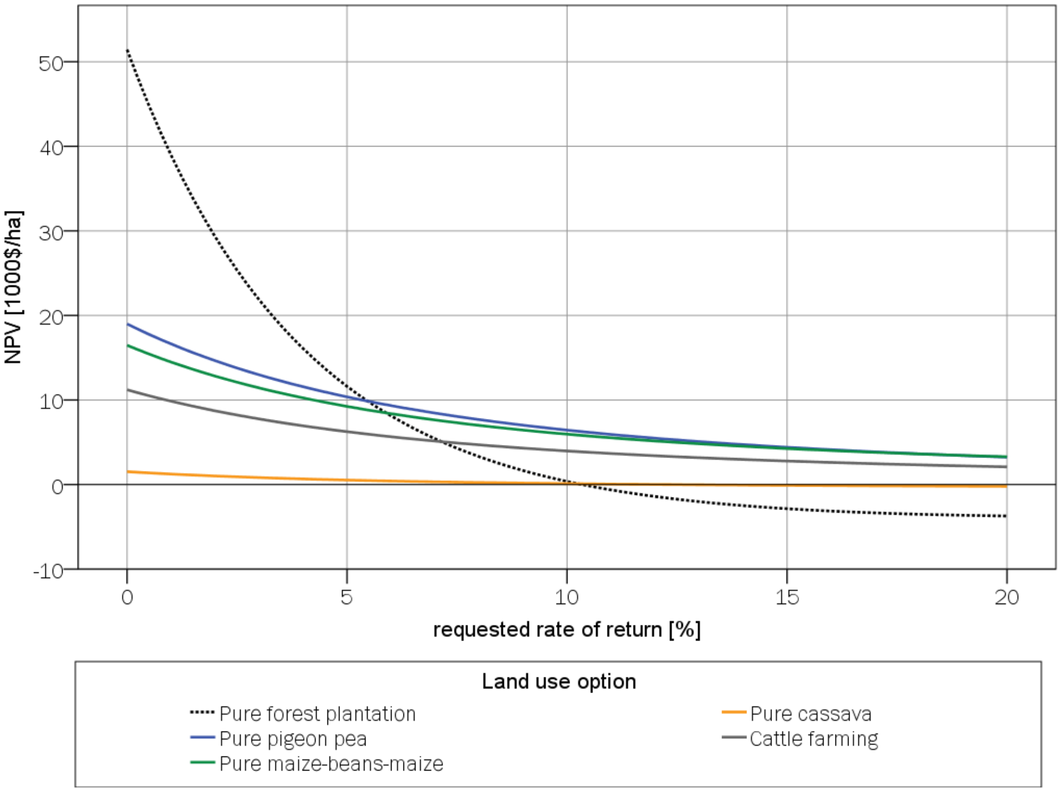

Figure 4.50: Net Present Value (NPV) for pure agricultural land use options (colored solid lines) by interest rate. For comparison, the NPV for a pure forest plantation of *T. amazonia* is displayed (dashed line). NPV for all tree species are shown in Figure 4.51

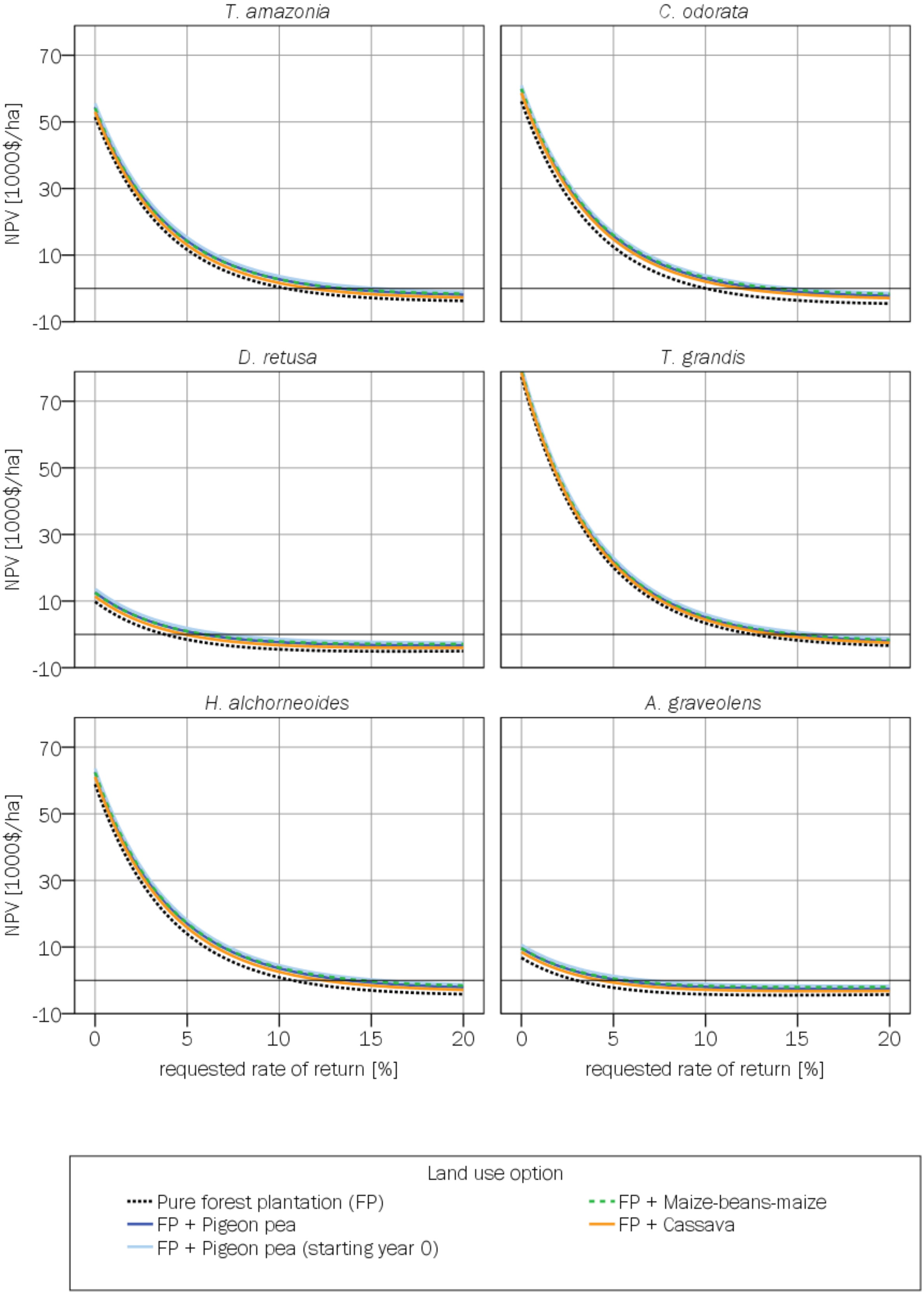

Figure 4.51: Net present values (NPV) of pure forestry (FP) and different tree crop combinations at varying interest rates. Rotation period is 25 years.

4.5.6 Land Expectation Value

An important factor influencing financial performance of tree plantations or agroforestry systems is the rotation length of trees. In this study, we used a 25-year rotation, as it is commonly used by forest plantation companies in Panama (Schnall 2011, Herrera 2010, personal communication). In order to assess the most beneficial production time – under the given assumptions - the Land Expectation Value (LEV) was estimated for different rotation lengths. For rotation lengths below 25 years, the same timing and intensity of thinnings as used for the 25 year rotation were assumed. However, if less than one year lay between thinning and final harvest, no thinning was carried out. For rotations longer than 25 years, the first and second thinning were carried out in accordance to the 25 year scenario – namely, the precommercial thinning of 40% of stems done at the time of crown closure and the second thinning of 50% of stems undertaken when basal area exceeded 20 m^2/ha. In addition, a third thinning with an intensity of 40% of stem number was done when more than 20 m^2/ha were recovered. However, no additional thinning was carried out if less than 4 years lay between the third thinning and the final harvest.

Figure 4.52 (next page) reveals that the LEVs were higher for the agroforestry systems than for the pure forest plantations, which is in accordance with the results of the analysis of NPV. The LEVs for *C. odorata*, *T. grandis* and *T. amazonia* culminated at a rotation length of 25 years, proving that this is the optimal rotation length under the present interest rate of 6%. The LEV of *H. alchorneoides*, however, culminated at a rotation length of 30 years, implying that extending the rotation length by 5 years would result in a 36% higher LEV. This effect is mainly due to the slower diameter growth of *H. alchorneoides*. The prediction table presented in the appendix (Table 11.10) shows that after 25 years *H. alchorneoides* does not yet reach the diameter class of >35 cm which gives the highest wood price (Table 4.55). This demonstrates that the graduation of prices significantly influences the optimization of rotation length.[95]

The slow growing species, *A. graveolens* and *D. retusa,* do not culminate within the predicted 35 years. Nevertheless, LEVs were not calculated for higher rotations lengths, as the underlying growth rate, which is based on a mean annual increment rate measured in rather young stands, might considerably overestimate the growth in stands exceeding an age of 35 years. Therefore, the trend of slightly increasing LEVs of *T. amazonia* and *C. odorata* after a rotation length of 30 years should also be interpreted with caution. However, rotation lengths of at least 30 years seem appropriate for these valuable tree species under the present assumptions. The LEV increased by approximately 210% for both species when the rotation period was extended from 25 to 30 years. The NPV, however, was less than $6000/ha for both species, even when intercropped with pigeon pea. Even at a rotation length of 35 years, the LEVs for *A. graveolens* and *D. retusa* were lower than those for the other tree species.

It was hypothesized that initial intercropping of forest plantations might shorten rotation lengths of trees, due to early cash-inflows. In fact, for *D. retusa*, a positive LEV was achieved at a rotation length of 30 years for all agroforestry systems while pure forest plantations still had a negative LEV. The same was true for a rotation length of 35 years for *A. graveolens* and a rotation length of 10-15 years for the faster-growing tree species. Yet, the estimation of a LEV > 0 only implies that buying bare land with the intention of carrying out one of the investigated land use option does not result in a financial loss. However, the more important question to answer - using the LEV-method - is whether the culmination of the LEV curve, representing the optimal point in time for harvesting, is shifted to a shorter rotation length due to intercropping.

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[95] The reader might wonder how the slow diameter growth of *H. alchorneoides* fits to its predicted high total volume production (Figure 4.39) which was shown to be even higher than that of *T. grandis*. This is attributed to the superior height growth development of *H. alchorneoides* which leads to higher volumes, even though the diameter class of >35 cm is only reached after 27 years under the present assumptions.

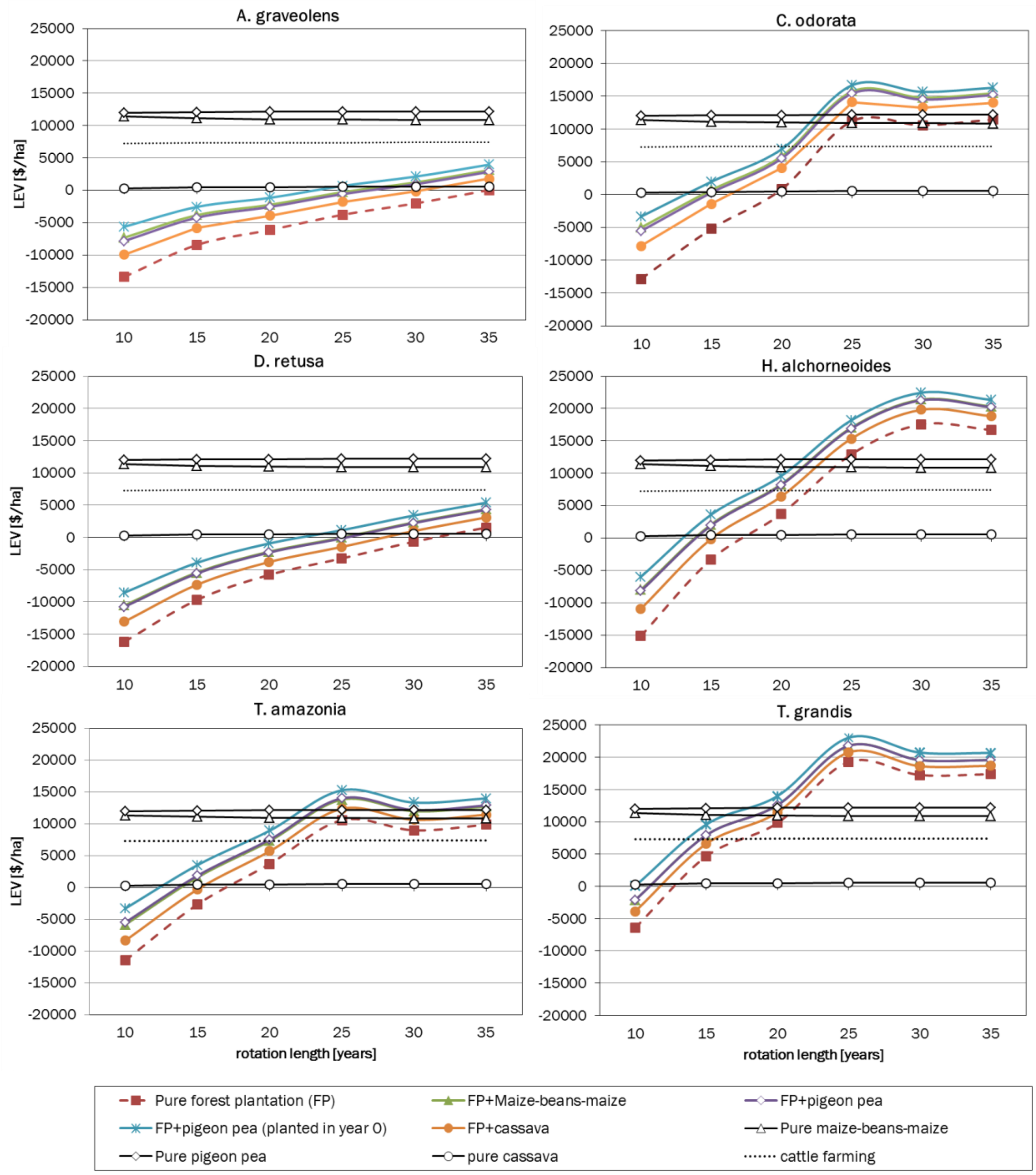

Figure 4.52: Land Expectation Value (LEV) at different rotation lengths at an interest rate of 6%. The colored lines denote pure forest plantations (dashed red lines) and different tree-crop combinations (solid colored lines) for each tree species. Pure agricultural alternatives are given for comparison within each tree species (black lines).

However, the lines representing the different tree-related land uses in Figure 4.52 are rather parallel, and those representing the agroforestry systems do not – as expected - intersect with that for the pure forest plantation. This can be attributed to the rather short period of intercropping and the rather low revenues from crops that decline with time. For instance, at an internal rate of 6%, revenues from maize in the maize-beans-maize rotation would need to be 5-6 times as high in order to shorten the rotation length of native tree species and more than 10 times as high to shorten that of *T. grandis*. Rotation lengths furthermore decrease with increasing interest rate. However, even at a requested rate of return of 20%, the optimal rotation length for pure forest plantations was still estimated to be 25 years for all tree species, thus only implying a reduction of rotation length for *A. graveolens*, *D. retusa* and *H. alchorneoides*. Yet, differences between rotation lengths were very small for all tree species. However, in contrast to pure forest stands, the optimal rotation length for *T. grandis* and *T. amazonia* in all agroforestry systems was reduced to 20 years under an interest rate of 20% and 19% respectively. This illustrates that under normal conditions a rotation period of 25 years seems to be adequate for both agroforestry and pure plantations of *T. grandis*, *T. amazonia* and *C. odorata*, and a rotation of 30 years is recommended for the other species.

The LEVs were accordingly calculated for pure annual crops (see solid black lines in Figure 4.52) and cattle farming (dotted line). Figure 4.52 reveals that growing *A. graveolens* and *D. retusa* can only compete with pure cassava production when grown in the agroforestry systems. However, cultivation of these tree species could not compete with other pure agricultural alternatives – neither when grown in pure stands nor when associated with crops. In contrast to *A. graveolens* and *D. retusa*, the LEVs for the agroforestry systems which included the other native tree species exceeded those for the agricultural alternatives at a rotation length of 25 years, while pure forestry only achieved values similar to those for pure maize-beans-maize and pigeon pea cultivation. Yet, even pure plantation forestry with *C. odorata*, *H. alchorneoides* and *T. amazonia* exceeded the LEV values for cattle farming at a rotation length of 25 years. *T. grandis* intercropped with pigeon pea and maize-beans-maize was even able to compete with the corresponding pure cropping systems at a rotation length of only 20 years. When compared to cattle farming, even pure forestry of *T. grandis* showed a higher financial performance under the 20-year rotation length. This illustrates the advantage of the exotic tree species over the native tree species, as financial performance is comparable to that of other prevalent land uses even if the rotation length has to be shortened due to financial needs or other unforeseen reasons. Financial performance can furthermore be improved by initial intercropping, which is in accordance with the results presented in chapter 4.5.5.

4.5.7 Effect of varying Cash In- and Outflows

Investments in forestry and agriculture are underlying various uncertainties: Cash in- and outflows are subject to changes because of volatile timber markets, natural hazards or rising costs for inputs and labor, among others. By allowing expected costs and revenues to change, the sensitivity of the investment towards the change of different variables can be tested (Alavalapati and Mercer 2005, Griess and Knoke 2011).

Outgoing payments might rise, due to rising costs for input and labor. According to the National Statistics Division of Panama (INEC 2006), costs for agricultural inputs rose between 1998 and 2007: For instance, costs for maize seeds during this period rose by 50%, costs for fertilizer (15-30-8) by 48% and costs for fuel by 78%. However, the largest portion of production costs, in both forestry and agriculture is represented by labor costs. The minimum wage in agricultural enterprises was raised from $0.94 per hour in 2006 (Gaceta official No 25.501 13.03.2006) to $1.24 in 2009 (Gaceta official 26, 431-B, 12.2009), corresponding to an increase of 30%. Due to the rapid economic development of Panama it is likely that this increase will continue.

Revenues from crops and timber face even more severe uncertainties, as growth rates of trees and yields from crops might vary widely due to natural hazards such as pests and extreme weather conditions which might be caused by climate change and the El Niño phenomenon. Additionally, site variability can lead to considerable departures from the assumed mean growth rates and yields. Another input variable which can influence revenues from crops and timber is the expected price received for the produced commodity. As timber and agricultural markets are known to be highly volatile, price fluctuations can severely affect revenues. Figure 4.53 shows price and yield fluctuations for maize and beans in Panama during the last ten years.

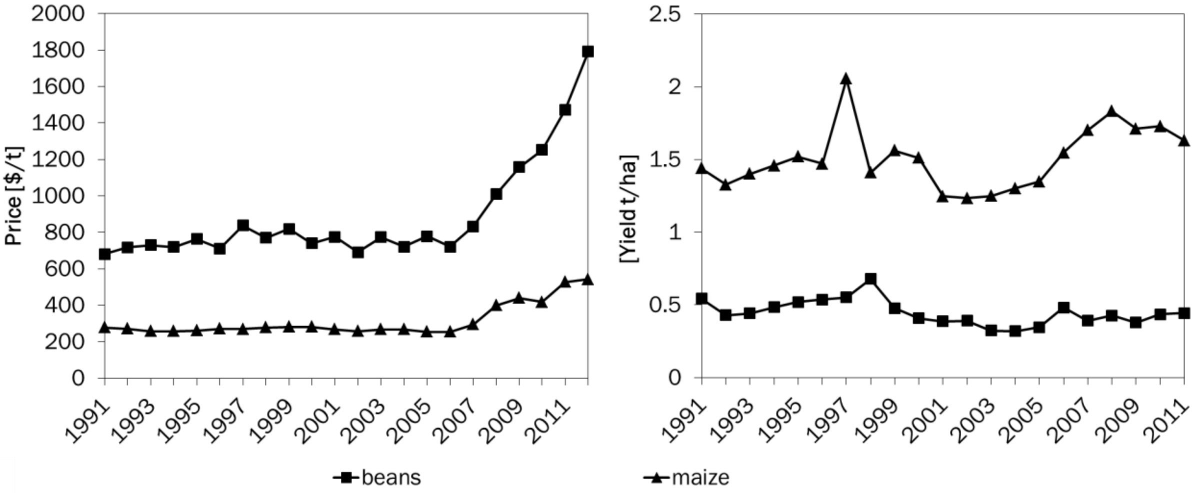

Figure 4.53: Price (corresponding to mean price at the central market) and yield fluctuation of maize (dried seeds) and beans (dried red beans "frijol chiriquano") in Panama from 1991-2012 (Prices were taken from INEC (2011) and IMA (2009-2011), yield was taken from FAO (2013b).

Data from price fluctuations for wood in Panama is scarce. On the world market *T. grandis* wood has shown a price volatility of 22% during the period between 1998 and 2010 (ITTO 2011) and all of the main tropical timbers observed by the ITTO showed a volatility of 25%. However, prices at the national level might underlie even higher price fluctuations. Between 1998 and 2010, wood prices of *T. grandis* rose annually by 4.8% (Zimmermann and Glauner 2011), and all other tropical timbers an average of 3.9%. However, there is some controversy about the future development of tropical timber prices (Hallett et al. 2011, Zimmermann and Glauner 2011). Based on the retrospective data given above, a change of 50% in costs (all costs including input and labor) and revenues for both crops and timber was chosen in order to illustrate the change in NPV under extreme situations. To increase readability, Figure 4.54 only presents the pessimistic scenario for each parameter - namely a 50% increase in costs and a 50% decrease in revenues. However, the percentage change in the NPV calculated for the pessimistic scenario compared to the standard scenario equally applies to the optimistic scenario. The data given in Figure 4.54 (next page) furthermore refer to a discount rate of 6%.

Figure 4.54 (next page) reveals that, despite the range of negative situations tested, the NPVs of all tree-crop combinations remained positive, with the exception of those for the slow-growing species, *A. graveolens* and *D. retusa*. *C. odorata* would furthermore not achieve an IRR of 6% under the assumption of a 50% decrease in revenues from wood if planted in pure forest plantation. Results furthermore show that rising costs can effectively be buffered by adding an agricultural component during forest plantation establishment.

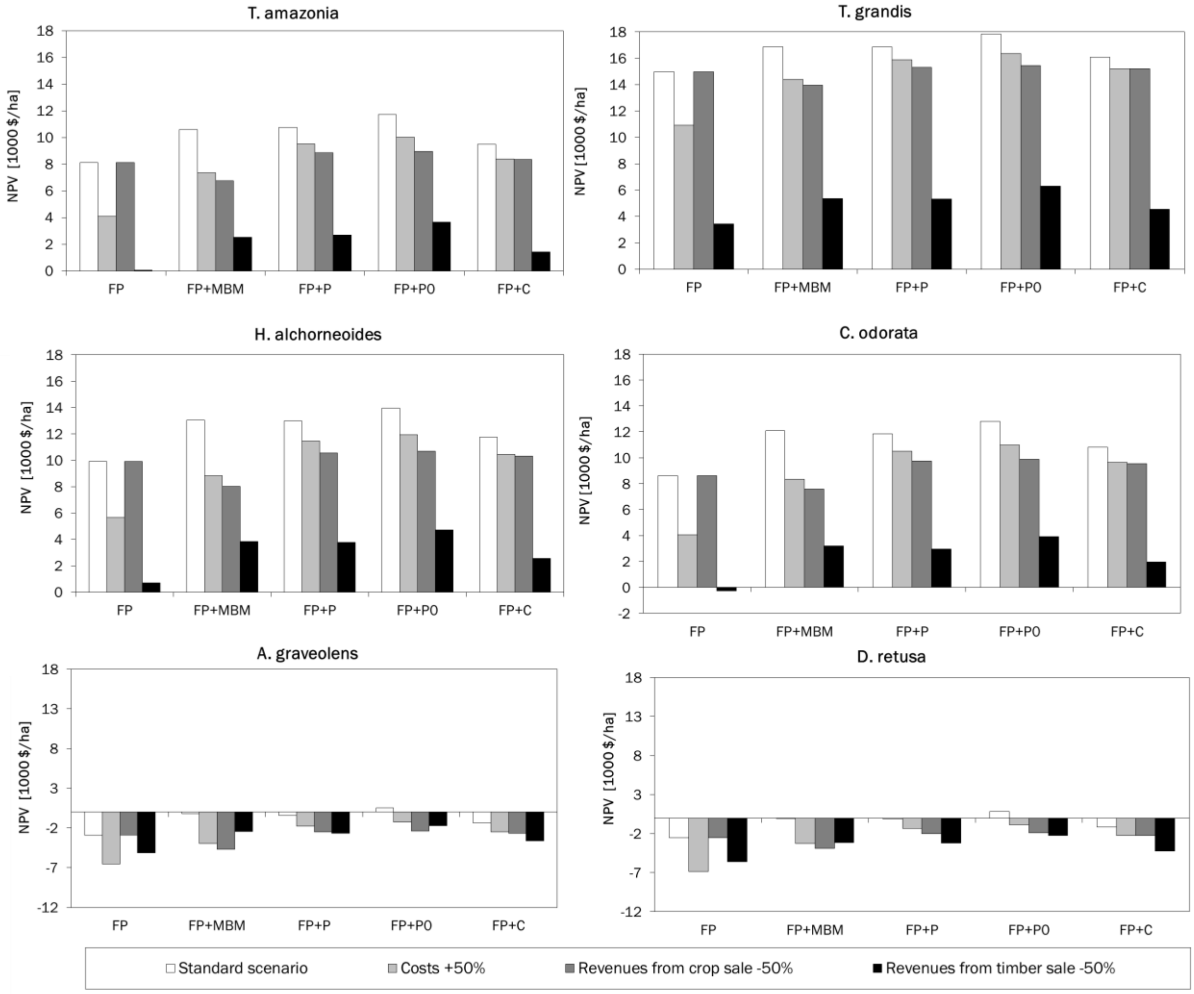

Figure 4.54: Net Present Values of different tree-crop combinations at an interest rate of 6% under changing input variables and a rotation length of 25 years. (FP = Forest plantation, FP+MBM = Trees intercropped with maize-beans-maize, FP+P = Trees intercropped with pigeon pea, FP+P0 = Trees intercropped with pigeon pea planted in year 0, FP+C = Trees intercropped with cassava).

For instance if costs are raised by 50%, the NPV of *T. amazonia* would decrease by 49% in the pure forest plantation but only by 31% when planted in combination with maize-beans-maize, by 11% when combined with pigeon pea (planted in year 1) and by 12% when combined with cassava. As sowing and harvesting is carried out three times a year in the maize-beans-maize rotation this treatment is more labor-intensive than the other agroforestry treatments and is thus more sensitive towards cost changes, especially concerning labor costs. Even though the management of crops is generally labor-intensive, combining trees with crops reduces the sensitivity of the NPV towards changes in costs compared to pure forest plantations, as the cash-outflows are (partly) offset by cash-inflows from crops (see chapter 4.5.4). Therefore an increase in costs does not negate the superiority of the agroforestry systems compared to pure forest plantation at a up to 50% change in costs. This pattern was observed for all tree species (Figure 4.54). The slow-growing tree species, *D. retusa* and *A. graveolens,* would require a cost reduction of 30 and 40% in order to achieve an IRR of 6% when grown in pure forest plantation. However, when grown in combination with maize-beans-maize and pigeon pea (planted in year 1) a cost reduction of 5 and 10%, respectively would be sufficient to achieve an IRR of 6%.

Figure 4.54 furthermore reveals that a change in revenues from the sale of crops has a slightly greater influence on the NPV of the agroforestry system than a change in costs. If revenues from crops decreased by 50%, the NPV of growing *T. amazonia* at a 6% interest rate would decrease by 36% when combined with maize and beans, 18% when combined with pigeon pea and 12% when combined with cassava. The NPV of *T. amazonia* associated with maize-beans-maize would be 17% lower than *T. amazonia* in pure forest plantation, while all other agroforestry treatments would still be superior.

Yet, tree plantations with or without initial intercropping seem to be most susceptible towards changes in revenues from timber sale. However, while a 50% decline in revenues from timber sales led to a decline in the NPV of up to 100%[96] in pure forest plantations, the declines in the agroforestry treatments were smaller, yet still high – from 65% (*T. grandis* + pigeon pea planted in year zero) to 85% (*T. amazonia* + cassava). This illustrates the high dependence of the NPV of forest plantations and timber-based agroforestry systems on timber revenues, while the prediction of future changes in wood prices remains difficult.

However, by calculating the felling values at an NPV of zero, the minimum final value of the forest plantation can be estimated and hence, an interval of possible roundwood prices that would still lead to the rate of return requested by the farmer can be determined[97]. In Figure 4.55 (next page), felling values exceeding $150,000 were considered to be unrealistic, as for instance, prices for *T. grandis* would have to double to reach this figure under the assumed harvested stem wood volume. The graphs reveal that for interest rates below 10%, moderate felling values of less than $65,000 are required for the pure forest plantations to reach a NPV greater than zero. For pure *T. grandis* stands, roundwood prices could decline by 30% compared to the prices given in Table 4.55 (see the black line in Figure 4.55) to reach the felling value of $57,188, even at a 10% interest rate and the present growth prediction. At the same interest rate, *T. amazonia* and *H. alchorneoides* wood prices could decline by 7 and 30%, respectively, compared to the wood prices calculated for this study. For *C. odorata,* wood prices would have to stay constant, while wood prices of *A. graveolens* and *D. retusa* would need to increase by 52 and 108% to reach an NPV of zero at an interest rate of 10%. At the moderate interest rate of 6% used in the previous figures, NPVs would still be greater than zero for pure forest stands, even if felling values for *T. amazonia*, *C. odorata* and *H. alchorneoides* decreased by 59 (*T. amazonia*) to 74% (*T. grandis*). This decrease could be due either to lower growth rates or lower wood prices. However, felling values for *D. retusa* and *A. graveolens* would need to increase by 38 and 39% to achieve an IRR of 6%.

Figure 4.55 also demonstrates that the initial enrichment of forest plantations with crops can considerably reduce the required felling value of trees at the end of the rotation: For instance, at a 6% interest rate a felling value of $24,193 would be necessary in a pure *T. amazonia* stand to achieve a positive NPV. However, when combined with pigeon pea or maize-beans-maize rotations, the requested felling values account for only $12,894 and $13,554, respectively. When planting pigeon pea in the year of tree establishment, the required felling value would be even lower, with $8,725. In the latter land use option, the felling value could be 85% smaller than the assumed felling value presented in Table 4.55 and still result in a NPV greater than zero. Differences between felling values for pure forest plantations and trees in agroforestry systems increase with increasing discount rates, due to the earlier returns from the sale of crops in the agroforestry options. Reducing the necessary felling value through the initial intercropping of trees, might improve the financial attractiveness of reforestation for farmers, as wood prices for small-scale reforestation are likely to be low due to small quantities, lack of market knowledge and low timber quality. Hence, enriching forest plantations effectively reduces the dependence of economic profitability on the final felling value.

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[96] Even up to 1000% for *D. retusa* and *A. graveolens* because of very small and negative values, not considered in this figure.

[97] Unlike the data given in Figure 4.54, this analysis does not consider revenues from thinnings.

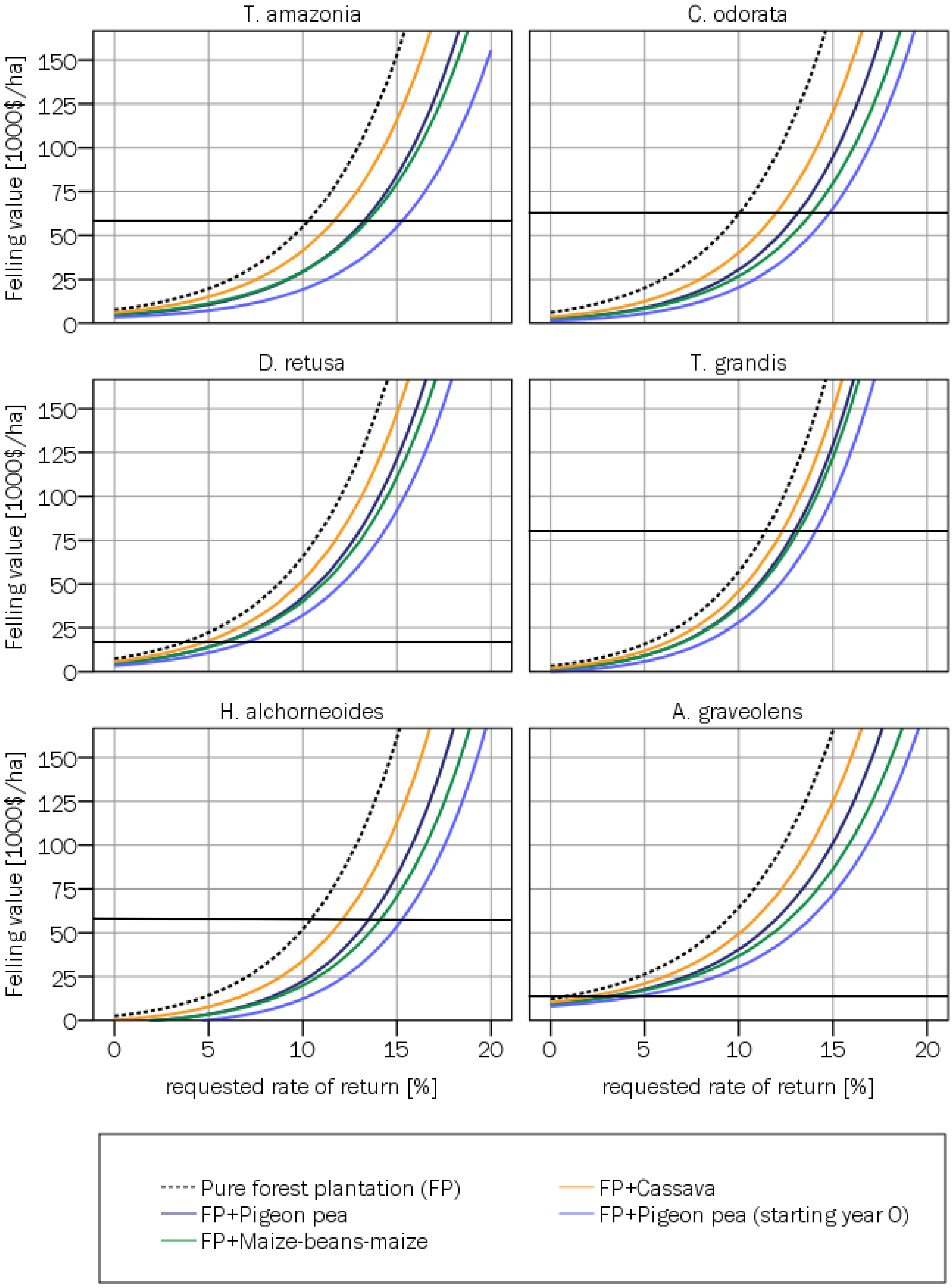

Figure 4.55: Felling value at which the NPV equals zero by interest rate for the different tree-crop combinations at a rotation length of 25 years. The solid black line represents the calculated felling value after 25 years under the present assumptions (see Table 4.55).

Differences in underlying wood prices also affect the sensitivity of the NPV of the various tree species to changes in costs and revenues: In Figure 4.54 the sensitivity of the NPV of *T. grandis* to all three parameters appears to be the lowest among all of the species investigated. For instance, when assuming an increase of 50% in costs for pure forest plantations, the NPV of the native tree species decreases by between 43 and 53% (excluding *A. graveolens* and *D. retusa*) whereas the NPV of *T. grandis* only decreases by 27%. This low level of sensitivity can be explained by the relatively high final felling value and revenues from thinnings of *T. grandis* compared to the native species, which are due to both the higher growth rates and the higher underlying timber prices of *T. grandis*. When setting the wood price of all tree species equal to the price for *T. grandis* (see Table 4.55, page 138), *T. amazonia* and *H. alchorneoides* are revealed to be less sensitive towards changes in costs than *T. grandis*. This effect can be attributed to the fact that interplanting of trees with crops can be carried out during a longer time period between native tree species. Thus, management costs can be (partly) covered by revenues from agricultural products over a longer time frame. This difference between species under the assumption of the same wood prices is displayed in Figure 4.56 for the native species *C. odorata* and *T. amazonia*, as these species show the highest and lowest sensitivities, respectively towards cost changes. The reason for the large change in NPV under rising costs for *C. odorata* can be explained by the labor-intensive pest control required to combat *H. grandella*. The change in NPV under the assumption of an increase in costs by 50% is displayed for pure forest plantations and for trees intercropped with pigeon pea (planted in year 1) as an example for the agroforestry systems. It should be noted that this agroforestry option generally shows the lowest sensitivity towards changes in costs (see Figure 4.54).

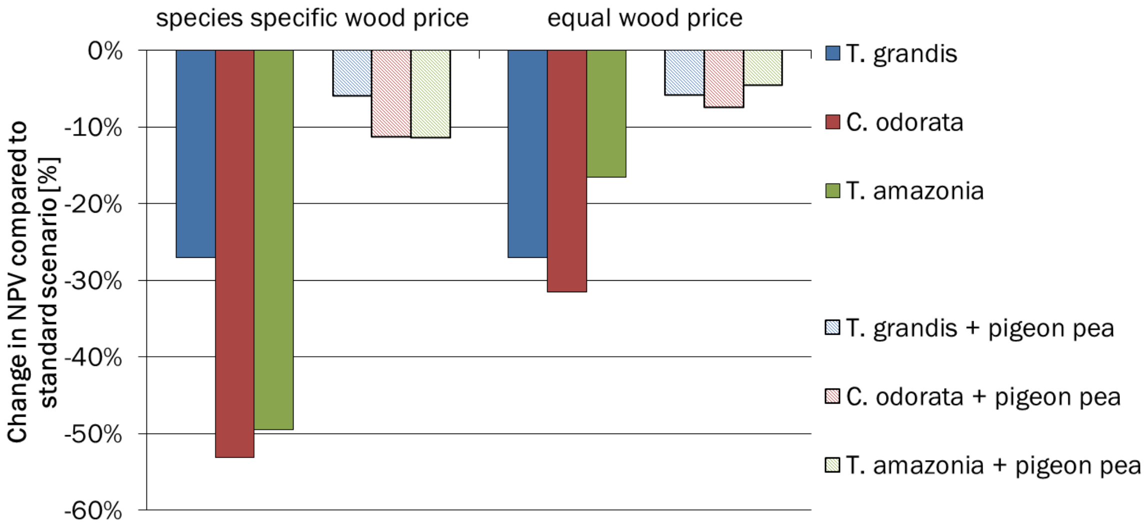

Figure 4.56: Change in NPV in % when assuming an increase in costs by 50% at a 6% interest rate for pure forest plantations (solid bars) and agroforestry (hatched bars) under the assumption of species specific wood prices (s. Table 4.55 page 138) (left bars) and equal wood prices for all three species (corresponding to the price of *T. grandis* in Table 4.55, right bars).

This comparison shows that the observed difference in sensitivity of the NPV between tree species (Figure 4.54) can be mainly attributed to differences in the assumed wood prices in the standard scenario. If equal wood prices are assumed for all tree species, the sensitivity of the NPV is lower for both *T. amazonia* and *H. alchorneoides* than for *T. grandis*. This is true for these two tree species both when grown in pure forest plantation and in the studied agroforestry systems.

A comparison of the results of the tree-related land use options (Figure 4.54) with those of the pure agricultural alternatives (Figure 4.57) shows that pure agriculture has a considerably higher sensitivity towards changes in costs than both agroforestry and pure forest plantations. While a 50% rise in costs results in a decrease in NPV by less than 53%[98] in pure forest plantations and less than 32% in the agroforestry systems, the NPV of the different pure agricultural land uses decreases by 85 – 1269%, with pigeon pea showing the lowest and cassava the highest susceptibility towards price changes, calculated for a time frame of 25 years. However, Figure 4.57 reveals that the lowest absolute values of NPV with -8379 $/ha and -12917 $/ha under the assumption of a 50% increase in costs and decrease in revenues, respectively, were calculated for the pure maize-beans-maize rotation, while the high relative change in NPV of cassava cultivation is mainly due to a small positive absolute value of the standard scenario. None of the pure agricultural land-use options achieved a positive NPV at a 6% interest rate under the assumption of a 50% decrease in revenues from crops. This high sensitivity of agriculture to rising costs and decreasing revenues is due to the high annual cash-outflows (during the modeled period of 25 years). In contrast to agriculture, in both forest plantations and agroforestry, the highest costs were incurred during the first years after establishment, while yearly cash outflows between year eight and year 25 were relatively low, at $228/ha in years in which no thinning operations were carried out (see Table 11.11, in the appendix).

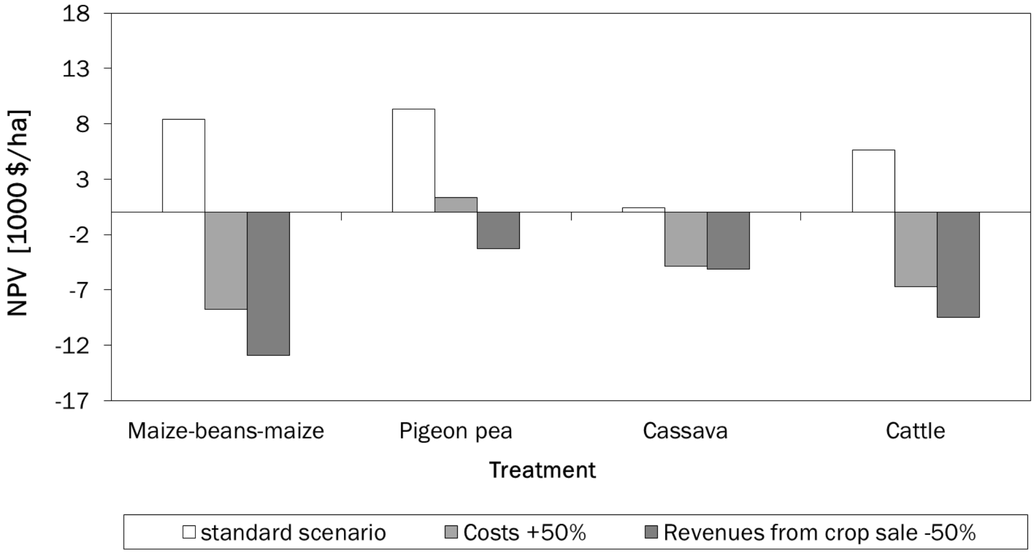

Figure 4.57: Net Present Values (NPV) of different agricultural land use options at an interest rate of 6% under changing costs and revenues.

In addition to the fact that agriculture is only carried out during the first years in the agroforestry system, the effect of product diversification also leads to a lower susceptibility towards changes in revenues. While the pure agricultural land-use options depend on the market price of one or in the case of the maize-beans-maize rotation, two – food commodities, in the agroforestry systems, the risk of price changes for agricultural products is buffered by the revenue received from selling timber.

So far, a sensitivity analysis has only been carried out for a moderate interest rate of 6%. The remaining question is therefore, how financial sensitivity of different land use options changes with interest rates. As the observed high sensitivity of the NPV of pure agriculture can – aside from the dependence on the price of a single product - be attributed mainly to high yearly cash-

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[98] This figure excludes *A. graveolens* and *D. retusa* and would amount to less than 173% if these tree species with negative NPVs were included.

outflows over a period of 25 years, this sensitivity is relatively independent of the interest rate. For instance, a decrease of 50% in revenues from pure maize and beans would lead to a relative decrease in the NPV of 250% in the maize-beans-maize treatment at an interest rate of 1%, and 266% at an interest rate of 20%. In contrast, in the agroforestry systems, agriculture is only carried out in the first years after tree establishment and hence, the effect of changing revenues from crops increases in importance for the NPV with rising interest rate. For instance, if *T. amazonia* stands were intercropped with maize-beans-maize, the NPV would only decrease by 8% under the assumption of a decrease in crop revenues by 50% and an interest rate of 1%. However, at a 10% interest rate, a decrease in cash inflows from crops would lead to a reduction of the NPV by 134%. However, the absolute NPV would still be positive, which is also true for the other tree crop combinations: Even under a decrease of revenues from crops by 50%, the IRR of all tree-crop-combinations, with the exception of those including *D. retusa* and *A. graveolens* would still be between 9 and 13%. Above these interest rates, the NPV of the agroforestry system would be negative and similar to that of the pure agricultural options, ranging between approximately -3000 and -5000 $/ha. The same pattern can be observed for changes in costs, as the highest costs in the agroforestry systems and forestry accrue during the first years after establishment, whereas they stay constant over time in the pure agricultural alternatives. In accordance with Figure 4.55 the percentage change in NPV under a 50% change in revenues from timber also strongly increases with increasing interest rates. For instance, under the assumption of a 50% change in revenues from wood harvest, the NPV of pure *T. amazonia* stands changes by 65% at a 1% interest rate and by 158% at a 9% interest rate. Under the same assumption, NPV of *T. amazonia* stands intercropped with pigeon pea changes by 61% at a 1% interest rate and by 90% at 9% interest rate.

Referring to the initial question of how key parameters affect financial performance, it can be summed up that among the land use options studied, agroforestry is the most robust in the face of changes in cash in- and outflows under moderate interest rates. Comparing agroforestry and forest plantations, agroforestry has been shown to buffer the risk of uncertain wood prices. This effect is most distinct when combining trees with pigeon pea, as this crop is less labor-intensive than others, while relatively high prices can be obtained for it.

5 Discussion

5.1 Critical appraisal of methodology

Agroforestry is a rather young field of research which combines a range of disciplines, such as forestry, agriculture, ecology and socio-economy. Hence, methods for the comprehensive evaluation of agroforestry practices or systems are still under development (see review in chapter 2). To address this issue, this study applied a new research design that combined commonly recognized methods from different disciplines to assess the intercropping of young tree plantations. This section discusses the observed potentials and pitfalls of the applied methods and gives recommendations for future agroforestry studies.

Trial design and establishment

The challenge of this study was to design an experimental layout that would allow

- investigation of different tree densities and their effects on crop production
- conventional crop cultivation and hence, economic evaluation of the overall system
- inclusion of one exotic and at least 3 native tree species to broaden knowledge on the use of native tree species for reforestation and intercropping
- testing of four different crop rotations
- empirical observation of different management methods by farmers on a small area
- establishment of the whole trial on an area smaller than 4 ha.

The trial as designed fulfilled the above mentioned requirements, however the above-stated goals were accomplished with varying degrees of success, which shall be discussed in this chapter.

Agroforestry research projects often aim at the investigation of a number of different tree-crop combinations under varying densities while they mostly face severe limitations of land and labor (Huxley 1985a, Schlönvoigt 1993a). In an attempt to solve this common problem, a simplified fan design based on Nelder (1962) was developed (see chapter 3.2.2 and chapter 2.2.2). The first difficulty of such a systematic design was encountered during establishment: The plan was to arrange the individual plots within a fully randomized block design. However, most of the land available to the trial was characterized by slopes of more than 5% which would have resulted in an environmental gradient within one plot, compromising the systematic gradient. However, homogenous within-plot conditions could only be assured on a small strip of the available land, which resulted in directly adjacent "blocks". The individual plot size of more than 1000 m² therefore seems to have been too large to ensure homogenous within-plot environmental conditions. Thus, in order to reduce the size requirements for individual plots, a reduction of the number of tree-species combinations within one plot should be considered in further studies.

However, compared to more complex designs that often demand advanced measurement techniques, this design was relatively easy to establish using marked ropes on sticks, a 50 m measuring tape and a compass. Furthermore, management and cultivation of the trial area was easy. However, tree survival might be underestimated in this trial, compared to common spacing designs, as trees were often damaged during weeding and crop harvest due to the unfamiliar planting design.

The control plots were deliberately not included in the randomized agroforestry design: In order to fully exclude any effects from crops, control plots were established within the surrounding forest plantation, close but not in direct proximity to the agroforestry trial. Still, differences in site conditions can certainly not be fully excluded, even though soil samples did not reveal severe differences.

Experiences with this trial furthermore support the value of systematic designs as demonstration plots, as they allow for empirical observation of the growth performance of a wide range of tree-crop combinations at differing planting densities on a small area (Huxley 1985a, Detlefsen and Somarriba 2012). Individual farmers, associations and representatives from governmental institutions visiting the trial gave positive feedback on the high variety of options that were presented and investigated. Presenting a set of options rather than only one optimized design has been found to improve the chances for adoption of agroforestry by farmers (Current et al. 1995a, Fischer and Vasseur 2002, see also chapter 5.2.5). The assessment of tree and crop performance within the agroforestry trial will be discussed in more detail in the following sections.

Assessment of tree growth and survival

Data on growth performance was gathered for each tree over a 24 month period at an interval of three months. However, for the statistical analysis of intercropping (= treatment) effects, only the data from target trees – defined as the tallest trees after 24 months (chapter 4.2.2) – were considered. This approach reduced sample size but also avoided the overestimation of tree growth due to high mortality in particular treatments. For instance, due to the high mortality of *D. retusa* seedlings in the M-B-M-M treatment, it can be assumed that only the most vital trees with the best genetic characteristics survived. Thus, comparing the mean growth performance in the M-B-M-M treatment with that of a treatment with a high survival rate (e.g. C-S treatment) might lead to the false inference that seedlings in the M-B-M-M treatment showed a superior growth performance when in fact this difference could mainly be due to the survival of less vital and competitive trees. A similar approach has been applied in other studies which have investigated tree seedling development under different treatments (Aguirre 2007 and references therin). However, in this study there was no difference in the effects of treatments on tree growth found between the different populations.

As described in chapter 3.5.1, statistical analyses of treatment effects on tree growth performance were carried out separately for each tree species, as strong differences among species were found in the development of height, root collar diameter and slenderness. In addition, it was expected that tree species would strongly differ in their reaction to intercropping, as has been described by many authors (Chamshama et al. 1992, Schlönvoigt and Beer 2001, Haggar et al. 2003, see also chapter 2.1.4). When including both, tree species and treatments in one model, this effect can be investigated using the interaction between these fixed factors. However, given the obvious differences in growth development between tree species, this interaction swamped the main treatment effect. Interpretation of such interactions is furthermore not intuitive, while even subjective when interaction plots are used for their interpretation (Doncaster and Davey 2007, Brosius 2011 p. 637). To more thoroughly analyze these interaction effects, treatment-contrast and contrast-contrast interactions have often been used (Quinn and Keough 2002), which are even more complex to interpret and thus often result in erroneous inferences (Preacher et al. 2006). Instead, analyzing treatment effects separately by tree species facilitated their direct and easy interpretation. For similar reasons, a longitudinal linear mixed model was not used, as it would have further violated the model assumptions, due to the nonlinear growth trajectories of the tree species (see chapter 3.5.1). Instead the increment of height and root collar diameter during different time periods was compared, as suggested by Piepho et al. (2003).

Another statistical approach used in this study that should be discussed is the integration of the plot as a random factor within the multilevel analysis. As already described, the establishment of a fully randomized block design which included all intercropping treatments and control treatments was not possible due to the limited size and spatial arrangement of suitable land available for the trial. It is out of question that a randomized block design should be favored, if homogenous site conditions within blocks can be assumed (Cochran and Cox 1992). However, in the case of this trial, the adjacency of plots prohibited any block building to include site effects in the model. In order to account for the dependence of observations of trees of one species within one plot, the plot number was included as subject in the hierarchical analysis to avoid pseudo replication (cf. Hurlbert 1984). Another possible approach would have been to use the mean of the dependent variable within one tree species and plot. This would, however, have inherently resulted in a loss of information. The effect of clustered trees (of one species) within plots, and hence the difference in sites was however rather small, as shown by the Intraclass Correlation (ICC). The ICC is the proportion of the variance explained by the grouping structure in the population (Heck et al. 2010)[99] and is therefore a measure for the importance of a grouping variable - in this case the plot. According to Heck et al. (2010) the grouping – and therefore a multilevel analysis - can be considered unnecessary if the ICC is smaller than 5%. In this study the ICC was above 5% in all analyses – supporting the use of a multilevel model. The ICC was highest for the final height status of *A. graveolens,* with 14% - while the random site effect was not significant for any dependent variable (p based on Wald-z-Test > 0.1). This finding is in accordance to the soil samples (chapter 4.1), which showed rather homogenous conditions across plots and high variation among planting positions.

The grouping of trees of one tree species within one plot could however not be taken into account for the statistical analyses of survival using the Cox Proportional Hazard Model, as SPSS 20 does not have an option for multilevel analyses using the COXREG command. An alternative approach would have been to assess survival at the end of the observation period using a Generalized Linear Mixed Model (GLMM). A GLMM however, does not take into account the temporal dynamics of mortality events and the fact that this data is usually censored as described in chapter 3.5.2. In contrast, given the low values of ICC for tree growth[100] and the evident effect of the microrelief on tree survival, it can be assumed that the microrelief of an individual tree, included as a covariable had a stronger effect on tree survival than between-plot variation. In addition, the Cox Regression is rather robust towards the violation of independence of observations due to spatial clustering (Ankerst pers. comm.).

Assessment of the competitive situation of individual trees and its effect on growth performance

The additional analysis of individual tree growth in relation to competition with surrounding crops for space, belowground and aboveground resources (chapter 4.3) might appear redundant to the analysis of treatment, i.e. crop effects on tree performance (chapter 4.2). However, it could also be argued that the most vital trees investigated in chapter 4.2 might have been those with the lowest individual degree of competition with crops, and hence, the potentially negative effect of intercropping on tree growth might not be sufficiently represented. For this reason, a competition index was calculated, which was defined as the sum of the distance adjusted relative size of the three closest crops in relation to the focal tree. The application of this index to agricultural crops, based on the methods described by Hegyi (1975) - which were actually developed for competition analyses in forest stands - seems rather uncommon. The index calculated in this study strongly differs from the original idea, as a fixed number of crops were measured, in order to reduce measuring effort. However, in contrast to less complex parameters commonly used to describe growing space, such as mean or minimum distance or height/distance ratios (Holmes and Reed 1991), this index also takes into account size asymmetry (Thomas and Weiner 1989, Schwinning and Weiner 1998). It it is also easier to measure than other indices, which have been reviewed for their use in studies in ecology (Weigelt and Jolliffe 2003), intercropping (Connolly et al. 2001a) and forestry research (Pretzsch 1997, Ammer et al. 2005). Ammer et al. (2005), Holmes and Reed (1991) and Vanclay (2006) also found that the index showed a good correlation with increment. Indeed, also in this study, the competition index CI showed the best correlation with height and diameter increment of all parameters tested (see above). However, R^2 of the regression model was generally rather low, with exception of the first maize rotation. This might

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[99] It is defined as $ICC = \sigma^2_j / (\sigma^2_j + \sigma)$ where σ^2_j is the between group variance (in this case j = plot nr.) and σ the within group (= plot) variance

[100] Accordingly, the ICC for the GLMM with dependent variable survival after 24 months was below 5% for most tree species.

be attributed to the fact that the competitive situation was rather homogenous as compared to forest stands, which led to very similar values of CI with a high variation in height and diameter increment due to other influential factors. Additionally, site conditions might be correlated with the competition index. Accordingly, a low germination rate of crops and hence, low CI values for trees (because of high distances to crops) might be attributed to difficult site conditions, which might also lead to less growth in tree height and mask potential competition and facilitation effects.

It could furthermore be argued that the relative increment, instead of the total increment, should have been used; as small trees usually have a small CI value and often lower total increments, while their reaction to the competitive situation might result in a high relative increase or decrease in height growth. However, the results of the regression model using either the relative or the total increment as the dependent variable were in agreement with each other and thus, the latter was used to facilitate the application of standard statistical methods.

Overall, this method presents an easy option for characterizing competitive situations of tree seedlings in crop fields, especially when distances and height relationships strongly differ. The results of the analysis will be discussed in the following chapter.

In addition to the characterization of each tree's growing space, the availability of light resources was estimated as an additional parameter for tree-crop competition. For this purpose, PAR measurements were carried out when crops had reached their final height, i.e. shortly before harvesting. This approach could potentially lead to a misinterpretation of the effect of light competition on tree growth, due to the temporal dynamics of shading. Accordingly, a low shading value at the end of the rotation might characterize a tree, which had at the time of measurement overtowered neighboring crops. This value, however, gives no information as to whether the tree had been previously shaded - which might have stimulated height growth - or weather low competition with crops for light resources allowed high growth performance. For this reason, two light measurements were carried out in the cassava rotation and additional parameters to characterize aboveground competition, such as shaded crown area, were estimated at the end of the pigeon pea rotation. However, data from the first light measurement agreed with the second measurement in the cassava rotation (see Figure 4.31 and Figure 11.2). Accordingly, Kreuzer (2013) showed that similar results were achieved using a range of different parameters to characterize aboveground competition between pigeon pea and trees. Nevertheless, the combined interpretation of such light measurements with the characterization of growing space is advisable. The thesis of Waltenberger (2013) furthermore assessed the suitability of three different measurement techniques for quantifying light transmission - a PAR sensor, a spherical densiometer and subjective visual estimates – and concluded that results from all three methods showed a high correlation with each other. Additionally, Waltenberger (2013) concluded that the visual estimates might even provide a better characterization (if always done by the same person), as they take into account the overall environmental conditions, are easy to apply and do not require an expensive device or particular weather conditions or solar angles.

Assessment of crop production

Estimation of crop production was carried out in relation to tree species combination (light gradient) and planting distance. Given the systematic design, the resulting subunits for crop-related measurements were trapezoidal subplots of varying surface area (see chapter 3.4.2). Sample units of differing size are common in systematic intercropping designs (Mead and Stern 1980, Mead and Riley 1981, Willey and Rao 1981), but are however problematic because of differing sampling errors. This problem was taken into account by use of a weighted regression, which did not, however, change statistical inference in any of the separately analyzed tree species combinations as compared to the standard regression. Differences in sample error might therefore present a less severe problem than measurement error. As described above, the trial was designed to allow conventional management of the crop component, while focusing on its effect on tree growth at the stand level. However, in order to ensure a regular grid of crops between trees, marked ropes were used during sowing – a practice that does not comply with common agricultural practices. Nevertheless, the margin of error in the accuracy of the actual planting design to the planned pattern was – despite high efforts – certainly above 10 cm. The estimated crop production per m² was, however, based on the area of the trapezoidal subplot minus the area occupied by the tree. Hence, only the area that was potentially available for crop planting was considered. However, inaccurate marking of the sample area and inaccurate planting pattern, e.g. the inexactness of the circle with a radius of 0.5 m around each tree, which should not be planted with crops, might have biased the estimates of yield/m². Due to the use of common crop densities, the number of crop rows was not always exactly equal between subplots. Particularly for crops with a planting grid of 1 x 1 m, single plants were often located exactly on the border of two subplots. These effects were minimized by always using the same marked ropes and a very time-consuming marking of subplots, which might not be practical in large trials[101]. Furthermore, due to testing of 8 different planting distances, small deviations from potential crop areas or number of crops in single trapezoidal units do not considerably influence the trend among planting distances. However, the small sample size of four repetitions for each tree-species-planting-distance combination led to a high variation in yields, and seems not adequate for statistical inferences, considering the high potential for measurement errors in such an on-farm systematic trial. Therefore parameters which are not area-dependent, such as the yield per plant, were also included in the analysis and the results appeared to be more reliable. The yield per plant is furthermore often used as it is a good indicator of plant vitality (cf. Gliessman 2007).

However, comparing crop yield/m² between the pure crop plantation plots and the agroforestry plot is – despite the high differences in plot size (factor 5) - justifiable due to large individual sampling units of more than 225 m² and a comparably low sampling error. However, due to the extremely high differences in sample unit area between the pure crop plots and the individual trapezoidal sample units– by a factor of up to 38 - the agricultural control plots were not included in the statistical analysis which investigated tree species effects.

In contrast to this simplified design, more complex systematic designs that apply exact relative positions of trees and crops (Freeman 1964, Willey and Rao 1981, Huxley 1985a, Schlönvoigt 1993a, Huxley et al. 1994, Kohli and Saini 2003) allow for more detailed inferences on effects of competition and the optimization of tree-crop distances. However, focusing on the optimization of tree-crop distances at the single crop plant level might not be of relevance for farmers as they are likely to fully exploit available space, even if the per plant yield might not be optimal at some positions. Furthermore, such designs provide no information on economic performance and possible management restrictions[102]. In accordance with statements from Martin and van Noordwijk (2009) and Dupraz (1998) (see also chapter 2.2.1), this study has also shown that differences in management due to the presence of trees had a greater influence on crop yields than the potential ecological influence of tree species or planting distance (discussed in the following chapter). This supports the further refinement of designs that combine the systematic optimization of tree planting designs under a practical arrangement and management of the crop component in agrisilvicultural practices. Another design, that allows conventional crop harvest between different tree layouts on a comparably small area was proposed by Lin and Morse (1975) (and applied by e.g. Jama and Getahun 1991). It was, however, only designed for one tree species. In the present study, 0.5 ha of each crop were harvested and measured manually. A reduction in the number of tree species investigated to three is therefore recommended if less land and labor is available.

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[101] In addition, these errors could further be reduced by permanent marking of subplots and spared area around trees. However, experience shows that such markings are expensive and unlikely to remain permanent, especially when intensive agricultural management is carried out.

[102] Rao and Coe (1991) suggest a minimum of 1000 m² for economic analysis in agroforestry trials

Economic analysis

For the economic assessment of the different land use options, standard ranking methods used in financial mathematics were used. Predicting stand development over 25 years based on information from only two years is, however, subject to high levels of uncertainty. However, an intensive literature review and interviews with key informants and farmers were carried out to obtain reliable data on future management, alternative land use options and potential for up-scaling of data, as already discussed in chapter 4.5. Assumptions are furthermore reported in detail in chapter 4.5 (and discussed in chapter 5.2.4), both to make data transparent and allow for adjustment or refinement in future studies. The lack of knowledge about tree growth performance makes predictions of future revenues from forestry particularly difficult. Therefore conservative growth rates and carefully recorded initial heights and diameters were used to lower the chances of overestimation of yields. Predicted wood volume (and therefore revenues from harvests) furthermore depends on the form factors applied. We assumed equal form factors as suggested by Wishnie et al. (2007) and Piotto et al. (2010), due to the lack of species-specific form factors. In order to analyze how differences in obtained prices have the potential to change financial results, a sensitivity analysis, which will be further discussed in chapter 5.2.4, was carried out.

5.2 Discussion of results

5.2.1 Comparative assessment of initial growth performance between tree species

One objective of this study was to extend the level of knowledge about initial growth behavior and survival of native tree species, and hence, their suitability for use in reforestation in eastern Panama. Observed growth performance will therefore be discussed in the following section, with a focus on the question of whether native tree species were able to compete with the exotic, *T. grandis*, in terms of initial growth and survival rate.

Of the six tree species tested, *T. grandis* reached the greatest heights and diameters after 2 years - 7 m and 11 cm[103], respectively. The native species could by far not compete with this exotic tree species and reached only half of these values. This superior initial performance of *T. grandis* over native timber species has also been reported by other authors (e.g. Piotto et al. 2004, van Breugel et al. 2011). Despite the difficult physical soil conditions, mean tree height of *T. grandis* exceeded the means measured in Panama by van Breugel et al. (2011) and Wishnie et al. (2007) by more than 1 m, compared to the commercial status of the plantation and by 1.5 m compared to the biological status. Only the mean height in Soberania, a region close to the Panama Canal, was comparable to that measured in the trial, with 6 m (van Breugel et al. 2011). This site was characterized by wet climate and fertile, clayey soil like the trial site. This is also in accordance with Park et al. (2010), who showed that basal area of *T. grandis* was low on sites with excessive drainage and coarse-textured soils. However, they also reported a negative influence of clay loams and loams on the growth of *T. grandis*, which was obviously not the case on the trial site. When comparing growth and survival rates of *T. grandis* with those of the native tree species it should furthermore be taken into account that the planting material for *T. grandis* obtained from CATIE was grown from improved and selected seeds, while seeds of the native tree species were collected locally from only a limited number of mother trees.

The native species with the best initial growth performance were *T. amazonia* and *D. retusa*, while the one with the lowest was *H. alchorneoides*. However, native species were relatively homogenous in growth performance ranging between 2 – 3 m in height and 2 – 5 cm in root

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[103] Data corresponds to target trees

collar diameter, based on biological performance. Comparable data on initial tree growth of these species is scarce. These values are, however, in accordance with data from Butterfield and Mariano (1995), Vozzo (2002), Cordero and Boshier (2003), Wishnie et al. (2007), van Breugel et al. (2011), Plath et al. (2011a) and Plath et al. (2011b) (see also Table 3.5). *C. odorata* showed comparably high root collar diameters, with an average of 7 cm, which can however mainly be attributed to damages by *H. grandella* which resulted in the development of a thick buttress. Therefore these relatively high basal diameters should not be interpreted as a sign of superior diameter growth of *C. odorata,* but rather as an indicator of minor stem quality.

In terms of survival, *T. amazonia*, *C. odorata* and *A. graveolens* performed better than *T. grandis* (82% survival), for which high survival rates of more than 90% were reported during the first 2-3 years by Piotto et al. (2004) and van Breugel et al. (2011) in Costa Rica and Panama, respectively. This is especially surprising for *C. odorata* as for this species low initial survival rates of 11 and 47% were reported by Piotto et al. (2004) and Plath et al. (2011b), while van Breugel et al. (2011) found survival rates of 61 to 94% on different sites in Panama within the first two years. Plath et al. (2011b) suggested that *C. odorata* should only be planted on well-drained soils, due to the low survival rates. This cannot be supported by the findings of this study, as survival was high in spite of the temporarily waterlogged site. In accordance with this study, survival rates above 80% have been reported for *T. amazonia* and *A. graveolens* among different sites in Panama (van Breugel et al. 2011). *D. retusa* had a slightly lower survival rate than *T. grandis*, but still 80%. This figure is, however, small in comparison to the high initial survival rates of 90% reported by other authors (Tilki and Fisher 1998, Piotto et al. 2003b, Piotto et al. 2004, van Breugel et al. 2011). This tree species might have had greater difficulties coping with heavy soils and dry weather conditions during planting. This was also true for *H. alchorneoides*, which showed a particularly low mean survival of only 36%, while survival rates of 70-80% were observed in Costa Rica (Butterfield and Mariano 1995, Flores 2002a, Piotto et al. 2003b). Due to the high mortality and resulting small sample size, the growth performance of *H. alchorneoides* and associated treatment effects should generally be interpreted carefully (see next chapter).

Small-scale environmental heterogeneity was found to strongly influence growth performance and survival of all species. In terms of height and diameter growth *T. amazonia*, *A. graveolens* and *H. alchorneoides* did not show a significant influence for microrelief, suggesting that these species were more robust towards waterlogging than the other species. However, all species showed a significant influence of the microrelief on tree survival. This effect was particularly high for *H. alchorneoides*, *T. grandis* and *D. retusa*, while rather small for *T. amazonia*, *A. graveolens* and *C. odorata*. Considering their overall high survival rates, the latter tree species might be better adapted to heavy soils with seasonally waterlogged soils, while *H. alchorneoides* and *D. retusa* seem to be less adequate for these sites (while this was highly dependent on relative planting positions). In accordance with these findings Park et al. (2010) found that *C. odorata* was a within-site generalist, responding to regional differences in site but not local environmental variation, while *T. grandis* was found to be an environmentally sensitive tree species. In order to improve growth performance and save costs for replacing dead trees, the local environmental variation, especially the microrelief should be carefully taken into account during planting.

5.2.2 Effect of intercropping on growth performance, survival and quality of trees

The question to be answered in this study was: does sequential intercropping impede tree growth performance and stem quality? These two aspects will be discussed separately, beginning with growth performance and including survival.

Effect on growth performance and survival

From this study, inferences can only be made from an intercropping phase of 18 months and an observation period of 24 months. This corresponds to the intercropping time often used in the traditional Taungya System (Schlönvoigt and Beer 2001), even though intercropping might be possible for more than three years as shown in chapter 4.5.3.2.

Table 5.1 reveals that at the end of the observation period only two species - *A. graveolens* and *H. alchorneoides* - showed a negative effect of intercropping on final height and diameter.

Table 5.1: Summary of differences in final height (h), diameter (d) and survival (s) between pure forest plantations (FP-Treatment) and different intercropping systems (G-P = Ginger-pigeon pea rotation, M-B-M-M = Maize-beans-maize-maize rotation, B-R-R = Beans-rice-rice rotation, C-S = Cassava-soy beans rotation) within each tree species after 24 months, based on the LSD-pairwise comparison for significant treatment effects proven by the mixed model for h and d, and results of the Cox Regression for s (see chapter 4.2.3.1.2 and 4.2.3.2). Arrows denote significant positive (⬆), negative (⬇) effects or no effect (⇨) of intercropping on growth parameters. Differences among all treatments are reported in chapter 4.2.3.1.2. See Table 3.4, page 23 for abbreviations of tree species.

Treatment	Ag			Co			Dr			Ha			Tg			Ta		
	h	d	s	h	d	s	h	d	s	h	d	s	h	d	s	h	d	s
G-P	⇨	⇨	⇨	⬆	⇨	⇨	⇨	⇨	⬆	⇨	⬇	⇨	⇨	⇨	⬆	⬆	⇨	⇨
M-B-M-M	⇨	⬇	⇨	⬆	⇨	⬇	⇨	⇨	⬇	⇨	⇨	⇨	⇨	⇨	⬆	⇨	⇨	⬇
C-S	⬇	⬇	⇨	⬆	⇨	⇨	⇨	⇨	⇨	⇨	⬇	⇨	⇨	⇨	⬆	⇨	⇨	⬆
B-R-R	⇨	⬇	⇨	⇨	⇨	⇨	⇨	⇨	⬆	⇨	⬇	⇨	⇨	⇨	⬆	⇨	⇨	⇨

However, *H. alchorneoides* did not show any negative crop specific reactions during different cultivation periods (Table 5.2). But, due to the very low initial growth of *H. alchorneoides*, which only reached 2 m (± 0.6 m)[104] after two years, tree seedlings were overgrown by crops with tall growth forms, and were hence often overlooked during harvesting and tending operations, even though they were marked with painted sticks. This might be another possible explanation for the high mortality rate of this species.

A. graveolens showed a lower growth performance than in pure stands when associated with beans-rice-rice (B-R-R), cassava-soy beans (C-S) and maize-beans-maize-maize (M-B-M-M) rotations. However, these negative effects might – in the case of this species - also be attributed to site differences. This is supported by the fact that the ginger-pigeon pea (G-P) treatment showed a significantly lower height and diameter increment during the first 9 months than the pure forest plantation (FP) plots even though the same management was applied in both treatments. This site specific effect was however, only observed for *A. graveolens* and might be attributed in part to differences in soil moisture (Table 4.2) and other soil characteristics that were not measured in the trial. All other tree species showed consistent results between the G-P and FP treatments during the first 9 months indicating no site-specific effects on tree growth.

Apart from *A. graveolens* and *H. alchorneoides,* the native tree species showed either no effect or rather a positive effect of intercropping on the final growth status after two years. This was also

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[104] biological status of all sampling types

true for *T. grandis*, which has been reported to react negatively to interplanting in traditional Taungya systems (Coster and Hardjowasono 1935, Aguirre 1963). Even six months after the last crop harvest, the positive effect of pigeon pea on height growth was still observed for *T. amazonia* and *C. odorata*. The latter species also showed considerably greater heights on former maize and cassava fields as compared to that reached in pure forest plantations. The superior height growth of *C. odorata* in these three treatments is mainly due to the observed lower infestation rates with *H. grandella* that will be discussed in the second part of this chapter. However, the magnitude of induced height increment cannot be attributed to reduced pest infestation alone. This is supported by the diameter growth rates observed that also tended to be higher in the agroforestry treatments compared to the control plots, even though this effect was not proven to be significant.

C. odorata, *D. retusa* and *T. amazonia* had significantly higher survival rates in pure forest plantations than they had in association with maize. As mortality mainly occurred during the first 6 months, this effect can be attributed to the first maize rotation.

Given these results hypothesis H1 –

“Intercropping tree seedlings with crops does not negatively influence growth, quality and survival of timber species” -

could be accepted in terms of growth and survival for the tree species *C. odorata*, *D. retusa*, *T. grandis* and *T. amazonia*. *A. graveolens* and *H. alchorneoides*, however, should be used with caution in agroforestry systems, even though the negative effect of intercropping on *A. graveolens* seems to be site-related in this study. The low survival rate in maize fields further suggests that planting maize before the first dry season after tree establishment is not recommended. The sudden change in the microclimate after the harvest of the maize has the potential to deliver a solar shock to young tree seedlings, especially when maize is harvested shortly before the dry season, as it was the case in this experiment. *D. retusa* showed the highest mortality after the first maize harvest. This is not surprising, as this species has been described as sensitive to exposure to direct sunlight (Marin and Flores 2002b). However, mortality might also have occurred due to damages during the harvesting process. This effect might be reduced if standard tree planting densities were used.

Overall, tree seedlings in young tree plantations seem not to suffer from intercropping in the long run. Nevertheless some significant short-term effects of intercropping on seedling performance were observed that shall be discussed in the following sections. Table 5.2 sums up the proven significant differences in height and diameter increment between pure forest plantations and different intercropping systems. As far as was possible, effects were assigned to specific crops of the four rotations. It is assumed that effects were most prominent during and shortly after the cultivation period of the crop, which is supported by the growth curves shown in Figure 4.9. However, it should be kept in mind that growth rates measured within one cultivation phase might also be influenced by the previous cropping phase of the same treatment.

Table 5.2: Short-term effects of intercropping systems on height (h) and diameter (d) increment as compared to pure forest plantation (FP). Differences were tested for significance using LSD pairwise comparison when overall treatment effect was proven to be significant by the linear mixed model. Arrows denote significant positive (⬆), negative (⬇) effects or no effect (⇨) of intercropping on growth parameters. See Table 3.4, page 23 for abbreviations of tree species. In the C-S treatment ⇩ denotes negative effects that were proven to be significant during 9-18 but not between 0-9 months. Differences among all intercropping systems are reported in chapter 4.2.3.1.1

Crop	Rotation	Time period	Ag		Co		Dr		Ha		Tg		Ta	
			h	d	h	d	h	d	h	d	h	d	h	d
Maize	M-B-M-M	0 - 3	⇨	⇨	⬆	⬇	⬆	⇨	⬆	⇨	⇨	⇨	⬆	⇨
Maize-Beans	M-B-M-M	0 - 9	⬇	⬇	⇨	⇨	⇨	⇨	⇨	⇨	⇨	⇨	⇨	⬇
Beans	B-R-R	0 - 9	⬇	⬇	⇨	⇨	⇨	⇨	⇨	⇨	⇨	⇨	⬇	⬇
Cassava	C-S	0 - 9/9 - 18	⇩	⬇	⬆	⇨	⇨	⇩	⇨	⇨	⇩	⇨	⇨	⇩
Pigeon pea	G-P	9 - 18	⬆	⇨	⬆	⇨	⇨	⬇	⇨	⇨	⇨	⇨	⬆	⇨
Maize-Maize	M-B-M-M	9 - 18	⇨	⬇	⇨	⇨	⇨	⬇	⇨	⇨	⇨	⇨	⇨	⇨
Rice-Rice	B-R-R	9 - 18	⬆	⇨	⇨	⇨	⇨	⬇	⇨	⇨	⇨	⇨	⇨	⇨

Effects that were consistent over all tree species were the positive effects of both the first maize rotation and of pigeon pea, as well as the negative effect of cassava on height growth. The diameter growth of *D. retusa* was negatively influenced by intercropping with pigeon pea, maize and rice. However, Table 5.1 shows that after two years no significant effects of intercropping on final height and diameter were observed.

It could be argued that the growth-inducing effect of maize during the first three months was due to crop fertilization. This is, however, unlikely in this experiment, as fertilization of trees was carried out only two weeks earlier using the same fertilizer. Furthermore the small rooting systems of tree seedlings suggest that the distance of more than 50 cm to the tree which was used when applying fertilizer to plants was sufficient to avoid the additional fertilization of trees. By placing the fertilizer into holes, displacement of nutrients was prevented. Moreover, when maize was fertilized after 12 months, this additional nutrient input did not have a growth-inducing effect on trees. It can therefore be concluded that other factors, particularly competition for light, led to the superior height increment. This effect could also be an explanation for the increased height growth in the G-P treatment. It is known that shaded tree seedlings in the understory seek light by increased height growth (Coomes and Allen 2007, Imo 2009). The allocation of resources into height growth is usually realized at the expense of diameter growth. This effect was also observed for trees associated with pigeon pea and maize leading to a high h/d value. In terms of wood production - which is the primary aim of many forest plantations – reduced diameter growth is unfavorable. However, Evans and Turnbull (2004) and Potvin and Dutilleul (2009), among others argue that induced height growth of tree seedlings – even if it is at the expense of diameter growth will eventually lead to an induced accumulation of wood, as height growth also leads to a larger crown and thus higher photosynthesis rate. Accordingly, in this trial, diameter growth increased for *T. amazonia* and *A. graveolens* after cutting of the pigeon pea shrubs, with the effect only being significant for *T. amazonia*. *T. grandis* also showed an increased diameter growth after the cutting these shrubs, but did not show increased height increment during the period from 15-18 months. This might be explained by the fact that *T. grandis* already towered over most crops during the last cropping phase, and thus below-ground effects of pigeon pea – to be discussed later in this section - might have improved tree growth. However, it should be noted that increased height growth can also have negative effects on plant growth. In the case of *D. retusa,* the increased height growth in the M-B-M-M treatment during the first three months occurred at the expense of root development, which can lead to reduced stability and might also be a reason for the high mortality rate for this tree species in the M-B-M-M treatment.

A direct influence of shading on height increment could, however, not be identified by means of PAR measurements, which might partly be attributed to the measurement technique (see chapter 5.1). However, the results show that no negative effect of shading was found, and in the case of *A. graveolens* even a positive trend of shading by cassava and pigeon pea shrubs on height and diameter increment was observed. This finding is in accordance with the pioneer character of this tree species described by Griscom and Ashton (2011). Particularly the seedlings of *A. graveolens* have been reported to be strongly light-demanding (Marin and Flores 2002a), which explains the apparent reaction to shading by crops.

The weak relationship between shading and growth performance at the single-tree level in contrast to the clearly superior height increment in the pigeon pea plots shows that not direct competition effects, but rather the overall change in conditions arising due to a dense stand of shrubs might have influenced seedling performance. Improved growth conditions might include the suppression of grasses that was observed within pigeon pea fields, due to a light transmission level of less than 90% on the ground. Competition with grasses - especially exotic grasses which were also abundant on the trial site – has been shown to be a major factor reducing or even impeding tree growth on abandoned pastures (Griscom et al. 2009, Palomeque 2012). Other factors already described in chapter 2.2.1 include the improved microclimate under the shrub canopy and the protection against solar radiation. Changes in microclimate, such as humidity, were, however, not directly measured and the possible influence is speculative. However, the importance of these factors was supported by the observed negative effect of cassava on tree growth. Even though this shrub also grows up to three meters in height the high transmission of light by the open crown of cassava (highest measured shading was below 80%) allows grasses to grow in its understory and consequently does not change microclimate in the way dense maize or pigeon pea fields do. This effect was augmented in this trial by the low germination rate of cassava due to the waterlogged site. However, a negative effect of cassava on hardwood seedling growth has also been observed by Coster and Hardjowasono (1935) and Schlönvoigt and Beer (2001), while a positive effect of pigeon pea has been observed by Beltrame and Rodrigues (2007).

Figure 5.1: Ground vegetation in cassava (left) and pigeon pea (right) fields. Plots are situated exactly next to each other and hence, same initial ground vegetation and seed bank can be assumed. (Trees in the left picture are *H. alchorneoides* seedlings at age 12 months) (Pictures taken by the author).

The potential of the nurse effect of pigeon pea - and to a lesser extent also of maize - due to reduced competition with grasses and improved microclimate was further supported by the observation that the rather low-growing crops like beans and rice did not show any effect on tree growth. As rice showed a very low germination rate, competition with grasses was similarly high as that in the pure forest plantation plots. Another factor that was hypothesized in chapter 2.2.1 to potentially influence tree growth was the nitrogen fixation ability of leguminous crop species. However, while pigeon pea showed a height-inducing effect on *A. graveolens*, *C. odorata* and *T. amazonia*, beans did not. None of the tree species showed a significant positive effect from intercropping with beans. This shows that the effect of nitrogen fixation of pigeon pea might not be as important as the effect of reduced competition with grasses. *T. amazonia* even reacted negatively to beans as an intercrop. This species has been shown not to react significantly to fertilization but to the intercropping with leguminous trees like *Inga edulis* and *Gliridia sepium* (Carpenter et al. 2004), which is in accordance with the findings of this study.

Apart from the suppression of weeds, other positive effects of pigeon pea on tree growth might be the reduction of soil compaction due to root penetration (Young 1997) and improved nutrient input from the nutrient-rich foliage of pigeon pea (e.g. Loss et al. 2009, Nair et al. 1999). It was furthermore observed that pigeon pea helped to drain the waterlogged site, even during the heavy rainfalls in November and December 2010. Despite the known positive effects of pigeon pea, it was also expected that competition for nutrients and especially for water from the fast-growing shrubs, which can grow up to 4 m high, with tree seedlings at the end of the rainy season could potentially impede tree growth more intensively than smaller crops with less water and nitrogen consumption, such as beans and rice. However the opposite was the case. This might be attributed to the shallow root systems of trees during the first year, and hence the fact that competition with grasses is higher than competition with shrubs that take up nutrients and water from deeper soil layers. However, sampling of the roots of *C. cajan* showed that the majority of the root system was allocated superficially within the first 30 cm of soil but did not spread in a radius of more than 50 cm (Kreuzer 2013). This is surprising, considering that the rooting system of *C. cajan* is reported to reach a depth of 60 cm (Reddy 1990). The shallow rooting system in this trial might be attributed to the heavy clay soils which impeded normal root development. Hence, belowground competition between trees and pigeon pea occurred in the same soil layer but was spatially separated. The same was observed for maize roots. However, using the methods of this study, effects of below and aboveground competition cannot be separated. Nevertheless, the analysis of the influence of neighboring crops on tree growth showed that competition generally only occurred in extreme situations with a distance of less than one meter and a considerable difference in height between trees and crops. It was furthermore observed that those trees with the greatest heights after 24 months were exposed to all levels of competition, without revealing any patterns. This was true for all tree-crop combinations. These findings are in contrast with other studies that revealed the importance of direct competition on plant growth (Silander and Pacala 1985, Potvin and Dutilleul 2009). For instance, Hickman (1979) found that the mean distance to the four neighboring plants (different species of *Polygonum spp.*) accounted for 48 to 73% of the variation in dry weight biomass. This was true for both intra- and interspecific combinations. However, Martin and van Noordwijk (2009), Watanabe (1992) and Dupraz (1998) also observed that the effects of overall crop management might be more important than tree-crop interactions at the single tree level. The results also confirm the observation of Imo (2009) that competition was higher with grasses than with planted crops. In accordance with Verinumbe and Okali (1985), Nair (1993) and Rao et al. (1997) competition for light generally seemed to play a more important role for tree growth than belowground competition, if extreme proximity was avoided.

Effect on quality and damages

In the case of *C. odorata* height growth performance and damage by *H. grandella* were strongly connected, as the infested, mostly apical branches were either cut to control the pest or died off. With the exception of one, all 320 *C. odorata* trees were attacked at least once by *H. grandella* during the two-year observation period. This demonstrates the high susceptibility of *C. odorata* to damages by *H. grandella* in commercial reforestation projects, as also reported by other authors (Newton et al. 1998, Pérez-Salicrup and Esquivel 2008, Ramírez et al. 2008). However, the results also showed that infestation rates were significantly reduced when young tree seedlings were intercropped with pigeon pea, cassava and maize. Both height growth performance and quality was significantly lower in pure forest plantations than in these intercropping treatments. Hence, intercropping of *C. odorata* with agricultural crops - especially those that reach the same height as tree seedlings or tower above them - can effectively reduce damages by *H. grandella*. It was also proven, that these damages did not cause the death of the trees, as *C. odorata* showed a survival rate of more than 90%, but led to a significant reduction in growth performance and timber quality, as was also found in earlier studies (Newton et al. 1993, Mayhew and Newton 1998, Wylie and Speight 2012). This positive effect of tall or shrubby crops is supported by similar experiences from other agroforestry systems such as coffee (Beer et al. 1997, Viera and Pineda 2004) and cacao (Villarreal et al. 2006), and has been shown to increase with lateral competition (Navarro et al. 2004). The infestation reducing effect of intercropping was highest in maize fields during the first six months after plantation establishment and in the pigeon pea fields when the shrubs had reached their final height and crown radius. Even though no height-inducing effect was observed in the cassava fields, infestation rates with *H. grandella* were significantly reduced. Accordingly, height performance and infestation rate in the B-R-R rotation, where crops were smaller than trees during the entire observation period was very similar to that observed in the control plots. In contrast to the findings of this study, leguminous companion trees in silvopastoral systems in Panama did not have an effect on the growth performance of *C. odorata* within the first two years (Plath et al. 2011a). One possible explanation for the differing results might be that the shrub species used in this study - *C. cajan* – is relatively fast-growing - reaching up to 3 m after 4 months - compared to the leguminous trees used in the cited study.

It is generally known that taller *C. odorata* trees with multiple shoots are affected less by shoot borers (Ward et al. 2008, Mo et al. 1997) and that infestation of *C. odorata* with *H. grandella* generally decreases when the trees reach a height of around 6 m (e.g. Ohashi et al. 2011 and references therein). Inducing rapid early growth by intercropping while at the same time “hiding” trees within agricultural fields therefore is an effective silvicultural measure to help reduce damages by *H. grandella.* This might not only have a clear economic advantage through improved quality but also through reduced costs for the frequent monitoring and manual cutting of infested parts required. The clear increase of infestation between 18 and 24 months when monitoring frequency was reduced seems to indicate the necessity for a three-month monitoring interval during the first two years. Therefore, if the time period in which *H. grandella* can cause serious damage to the tree can be shortened by encouraging faster initial growth, costs can be reduced considerably.

Apart from *C. odorata,* only *A. graveolens* showed significant differences in tree quality among treatments. The pattern was similar to that for *C. odorata,* with the B-R-R and F-P plots having significantly lower stem qualities than other intercropping treatments. This shows that stem quality was not impeded by planting crops, but in contrast was even improved.

The potential improvement in the growth form of *D. retusa*, which tends to develop crooked stems, through the interplanting with crops could not be confirmed in this study. Even though significantly higher numbers of badly shaped trees were found in the B-R-R treatment after 18 months, this pattern was not consistent over time and suggests either differences in the subjective assessment of quality or a rapid change in growth form that might not be related to treatment effects. Kapp and Beer (1995) also showed that increased branching in *T. grandis* stands can be reduced by lateral shade, as prolific formation of sprouts as a reaction to light is impeded.

Taken together, these results suggest no reduction in tree quality through intercropping and hence, hypothesis H1 - *“Intercropping tree seedlings with crops does not negatively influence growth, quality and survival of timber species”* - could be fully confirmed for all tree.

5.2.3 Crop production

Comparative assessment of yields and biomass production

Table 5.3 demonstrates that the yields of maize, beans and pigeon peas were comparable to mean yields recorded for Panama (MIDA 2011, FAO 2013b). Yields of cassava and rice were particularly low in the trial due to unsuitable site conditions and limited use of pesticides, as already described in chapter 4.4.1.

Table 5.3: Yield [t/ha] recorded in the trial compared to statistical data for Panama provided by FAO (2013b) and mean yields reported for traditional agricultural farming systems MIDA (2011).

	Trial	FAO (2013b)	MIDA (2011)
Maize, grain only (first rotation)	2.1	1.6	1.6
Maize, grain only (second rotation)	1.6	1.6	1.6
Maize, grain only (third rotation)	0.4	1.6	1.6
Beans[2], dry	0.4	0.4	0.7
Pigeon peas, dry	0.6	0.5	0.9
Cassava, tubers	3.6	17.1	23.0
Rice, grain only	0.2	3.0[1]	1.8

[1] data for paddy rice
[2] B-R-R and M-B-M-M treatment pooled together

It is widely acknowledged that a considerable amount of carbon can be sequestered by converting tropical pastures to tree plantations (Paul et al. 2009, Ashton et al. 2012). Data on carbon sequestration of *T. grandis* stands (Kraenzel et al. 2003, Derwisch et al. 2009) and mixed plantations of native tree species (Montagnini and Porras 1998, Redondo-Brenes and Montagnini 2006, Wolf et al. 2011) are available for the study region. However, when holding tree density constant (which is commonly 3 x 3 m), intercropping of tree plantations might lead to a considerable increase in carbon sequestration. In this study, intercropping of trees with woody pigeon pea shrubs sequestered an additional 18 t CO_2/ha within a period of 8 months[105]. The same amount was sequestered within the first 12 months of the M-B-M-M treatment (summing up the results of the first two maize and one bean rotation). During the same time period cassava sequestered 13 t CO_2/ha[106], without the use of agrochemicals. It should be mentioned, that ground vegetation, which often stores a considerable amount of carbon (Wilsey et al. 2002), needs to be cut to convert pasture into an agrisilvicultural system. However, it has been shown that overgrazed pasture ecosystems can represent strong sources of carbon dioxide, even if emissions from cattle are not considered (Wolf et al. 2011). Hence, intercropping of tree plantations might be an interesting option for additional carbon sequestration.

Overall effect of agroforestry on crop production

This study did not show a yield-reducing effect of trees on agricultural crops within the first 18 months after planting. This finding is in accordance to other studies that did not find effects of fast growing tropical timber species on maize (Imo 2009), beans (Ceccon 2005) or rice yields (Ceccon 2005) during the first year, while a decline was often observed during the second year after establishment (Pinto et al. 2005, Ceccon 2008, Prasad et al. 2010b, see also review in chapter 2.1.4). In this study, yields tended to be even higher in the agroforestry plots during the first 18 months, which might be attributed to a more intensive weeding between trees during the

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[105] When only considering aboveground biomass, using a dry matter carbon content of 0.5 and a factor of 3.66 to convert sequestered carbon into carbon dioxide (see Table 4.32).
[106] This figure includes extracted belowground biomass

first four months (Imo 2009). Only pigeon pea showed a significantly higher yield on control plots, which might, however, be attributed to high yields on the edges of the pure agricultural plots[107].

Influence of tree species and planting distance on crop yields and biomass

Chapter 4.4.3 revealed no consistent effect of tree species identity on crop yields. Due to the short observation period of 18 months, it appears plausible that species-specific characteristics of trees, such as the ability to fix nitrogen – which applies to *D. retusa* -, a deep root system that helps to relocate nutrients - as described for *H. alchorneoides* (Jiménez et al. 2007) - and rapidly decomposing leaves - as described for *T. amazonia* (Dzib 2003) - did not yet have any positive effects on crop production. The same is true for species traits that were assumed to have negative effects on crop production, such as the potentially allelopathic effect of *T. grandis* (Lacret et al. 2011), or effects of variations in crown structure and growth form among the various tree species (Waltenberger 2013) (see also review of potential effects in chapter 2.2.1). Differences in growth performance and crown structure are, however, likely to affect future crop yields, as demonstrated in chapter 4.5.3.2.

The negative correlation between tree spacing and crop production which has often been reported in such trials (Khybri et al. 1992, Schlönvoigt and Beer 2001, Pinto et al. 2005, Prasad et al. 2010a, Ding and Su 2010, see also chapter 2.1.4) was not proven in this study during the first 18 months of tree development. A longer observation period might be necessary in order to detect such effects. However, it was found that that the effect of planting distance differed between tree species combinations. Contrary to expectations, most tree species combinations showed a negative relationship between planting distance and crop production. This result should, however, be interpreted with caution given the methodological problems presented in chapter 5.1 and the generally low correlation. Nevertheless, weeding activities might in parts explain this effect. Particularly during the first months after stand establishment, trees were weeded intensively by cutting vegetation to the ground within a circle around each tree. Even though the radius of this circle was usually approximately 0.5 m, it is likely that weeding was carried out more intensively at low tree spacing, thus also benefitting crop production. This was shown by the fact that planting distance showed the strongest and consistent effect on yield and biomass production of cassava and beans, which are both highly sensitive to competition with grasses (Norman et al. 1995) and were both grown during the time of intensive spot-weeding of trees. It was further shown that cassava yields were positively correlated with tree height, which might accordingly reveal that the ability of trees to repress aggressive grasses might be of more importance for cassava production than potential above and belowground competition of cassava with trees. These effects remain, however, speculative, due to low model fit.

In contrast to most species, the spacing of *T. grandis* was positively correlated with cassava yields. This effect was however not present for other crops, which appears plausible, as cassava had the longest rotation period and strongly competed with *T. grandis* for both light and space during its entire development[108], which might be a hint to the potential presence of negative effects of this species, as stated above.

Taken together both Hypothesis 2 and 3

> *H2: The presence of commercially valuable timber species negatively influences crop production.*
>
> *H3: Tree spacing is positively correlated with crop yield and biomass.*

were rejected. Nevertheless, it should be taken into account, that the methods used might not be adequate to completely settle these questions. Suggestions for improvement are given in chapter 5.1

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[107] A buffer zone of one meter was not measured on control plots, however in the case of pigeon pea it still appeared that even the second row of pigeon pea shrubs had higher yields compared to those in the center and those within the agroforestry plots.

[108] *T. grandis* quickly over towered cassava see chapter 4.3.1.2

Suitability of crops for use in agrisilvicultural systems

As no consistent patterns proving a negative influence of trees on any of the crops was found, no optimal tree-crop combination from an agronomic perspective could be identified. However, other characteristics which could potentially influence the suitability of the tested crops will be discussed briefly.

Maize showed a high rate of production, and thus a good economic performance, even under traditional low-input practices. This was true, despite the high clay content of the soils in the study site. Rising prices, ease of management, availability of seeds and high nutritional value make maize a desirable crop for timber-based agrisilvicultural systems. It can be harvested in different maturity stages and marketed for a range of different uses. However, the high mortality of all tree species after the first maize harvest suggests that maize should only be planted following the first dry season after tree establishment to avoid extreme changes in microclimate that can stress tree seedlings. It should furthermore only be planted during the first to second year, as it is strongly light-demanding. Intercropping a rotation of maize with beans seems reasonable due to the ability of the legume to fix nitrogen and to act as soil cover (Nichols et al. 2001). Harvesting of beans is, however, very labor-intensive in relationship to the rather low prices which are currently obtainable for dried seeds, thus making beans less attractive from an economic perspective.

Cassava has received growing attention among agronomists and has been promoted as "21st century crop" (FAO 2011): In addition to its high caloric value and importance as a staple food crop, cassava also has a range of industrial uses as a source of starch and bioethanol. Cassava is furthermore expected to be the food crop least affected by advancing climate change in many regions of the world (FAO 2011). Despite its multiple uses, cassava could, however, be problematic for use in agroforestry due to potential damages to trees during the extraction of tuber roots. In this study we did not observe any damages to roots of young tree seedlings, which might be due to very careful harvesting by the students and workers in the trial. Nevertheless, intercropping with cassava tended to reduce tree growth and might thus only be an option on dry and sandy soils, which impede the economic feasibility of growing other crops.

The woody pigeon pea appears particularly suitable for agrisilvicultural systems, due to the positive effect it has on trees, discussed in the previous chapter. Its high content of proteins, vitamins and minerals also make it an important food crop (Das and Ghosh 2012) and it has increasingly been discussed as an alternative to soy beans (Sharma et al. 2011), especially as a protein source for industrial meat production (Amaefule and Onwudike 2000). It has furthermore been used in traditional medicine to cure skin diseases, mycosis, diabetes, malaria and hepatitis (Nene et al. 1990). Due to its high content of polyphenols, flavonoids and natural antioxidants and its toxicological and antifungal extracts, the leaves and seeds of pigeon pea are now increasingly considered for pharmaceutical and cosmetic uses and in the food industry (Wu et al. 2009). The shrub also provides fire wood and fodder of high nutritional value and can hence meet multiple demands (Daniel and Ong 1990), while recovering soil quality and reducing erosion (Vieira et al. 2009, Glover et al. 2012). Depending on the intended uses, traditional perennial branching types can be selected for agrisilvicultural systems instead of modern, dwarf, seasonal breeds (Daniel and Ong 1990).

Soybeans, ginger and rice showed extremely poor performance, which might be attributed in part to extreme weather conditions and low-input management practices. Ginger is certainly not adequate for waterlogged sites, but might have high potential as a partially shade-tolerant crop, especially on sandy soils and in later stages of stand development (Ewers 2013). Soybeans and rice appear to be rather sensitive to extreme weather conditions and strongly dependent on agrochemicals. It is, however, expected that climate change might strengthen the negative impacts of the El Niño phenomenon, leading to droughts followed by heavy rainfalls. The use of crop species that are more drought and water resistant appears advisable. General criteria for crop selection for timber-based agrisilvicultural systems are given in chapter 6.2, while more specific criteria to consider at the individual farm level are given in Beer et al. (2003) and Detlefsen and Somarriba (2012).

5.2.4 Economic evaluation

The following chapter will review the hypotheses *H4a* and *H4b* which refer to the economic performance of the agrisilvicultural systems:

Can intercropping of trees with crops generate positive Net Cash-Flows within the first years after tree establishment?

Chapter 4.5.4 showed that this question could be answered with a “yes” for all of the agrisilvicultural systems investigated, with the exception of those which included cassava. However, the intercropping of forest plantations generally did not succeed in offsetting tree establishment costs (in year 0) - as was also reported by Haggar et al. (2003) - for two reasons: First, the establishment costs recorded for the trial site were comparably high, due to the use of hig quality seeds, intensive weed management and the fertilization of tree seedlings. This management strategy was, however, based on the long-term experience of the cooperating companies, while the low establishment costs of $524/ha reported by Coomes et al. (2008) assumed very low day wages and the use of subsidized tree seedlings. Agroforestry technologies should, however, be financially profitable and adoptable for farmers without subsidies. These were, therefore, not considered in this thesis, even though they might support the choice of reforestation and agrisilviculture over other land uses. Secondly, intercropping did not offset tree establishment costs, as most of the crops that were planted simultaneously with trees were only harvested in the following calendar year. For ease of interpretation, the calendar year was used for analysis of Net Cash Flow. However, even when calculating cash flows within the period of one year, establishment costs were not offset by income from crop harvests.

Nevertheless, in year one, positive Net Cash Flows (NCFs) were generated by the intercropping of trees with maize-beans-maize and pigeon pea. Despite the additional management costs for trees, the NCF in year one was 87 to 346 $/ha when trees were intercropped with maize and 248 to 508 $/ha when they were intercropped with pigeon pea (planted in year zero). Even though these figures appear relatively low, the clear economic advantage is illustrated when comparing them to the NCF of the pure forest plantations in the same year, which ranged between -1121 and -602 $/ha. The highest NCFs during the first years were generated by pigeon pea, which can be attributed to the different characteristics of management of this crop: First, the profit margin of pigeon pea is comparably high, as it requires minimal input labor, while the prices for peas are high, even if they are not further processed. Second, pigeon pea shades out grasses from three months after planting until approximately nine months[109] after planting, and hence saves the expense of approximately two weeding operations for trees. The lowest NCF was generated by cassava. As previously delineated in chapter 4.5.4 this could be attributed mainly to low yields and high weeding costs. Accordingly, the cultivation of pure cassava achieved only a marginal profit. The analysis of this intercropping system has, however, shown that even if the cropping system itself is barely cost-effective, it still significantly offsets the management costs of forest plantations. Hence, the key advantage of intercropping of forest plantations from an economic perspective lies in the reduction of weeding costs, which constitute the highest costs in tropical reforestation during the first years (Griscom et al. 2009). This finding is in accordance with the studies of Haggar et al. (2003), Coomes et al. (2008) and Martin and van Noordwijk (2011). Considering that costs during the first years have a higher weight compared to later costs when taking into account the time value of money, offsetting these costs or saving these expenses can

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[109] Even longer if perennial shrubs remain on the fields after harvest – which was not considered in this calculation.

be critical for the economic profitability of the whole rotation. Furthermore, substituting weeding operations by such activities as planting shrubs such as pigeon pea can save the use of herbicides and their associated impacts on human health and the environment.

Due to the time limitations of this study, the cash flows of intercropping could only be observed up to 18 months after tree planting. Based on extensive crown and light measurements at different ages (Waltenberger 2013) that until this study were not available for the tree species investigated, a future decrease in crop yields and the expected timing of first thinning of trees was estimated. This allowed for the detailed differentiation of the NCFs among the different tree species, as this might be crucial to species selection by farmers. The results revealed that a positive NCF was obtained up to years three to five for the native tree species intercropped with pigeon pea and two to three years when the natives were intercropped with maize. The intercropping of *C. odorata* generally achieved the lowest NCFs, due to high costs for pest control, while *T. amazonia* generated the highest NCFs during the first years among the native tree species. This could be attributed to the fact that *T. amazonia* naturally loses its lower branches, which reduces pruning costs. *H. alchorneoides* was the only tree species that allowed crop planting until year four, due to its slow initial growth, which resulted in the longest offset of management costs. In contrast, the fast-growing *T. grandis* only allowed intercropping until year two[110]. Due to high initial pruning and singling costs, the intercropping of *T. grandis* only generated positive NCFs in year one when combined with maize, and up to year three when combined with pigeon pea. However, a yield reduction of crops due to shading by trees implies that expenses for weeding in pure forest stands would also decrease. Experiences in this and other trials (Evans and Turnbull 2004, Dylan Craven et al. 2009, ANAM 2010) have demonstrated that *T. grandis* starts to shade out grasses at age two to three years. Due to the resulting lower initial labor demand many farmers favor the use of *T. grandis* over native tree species for timber plantations. This study has, however demonstrated that this disadvantage of native tree species can be turned into an advantage, as the longer period available for the generation of income from cropping and the provision of agricultural goods might speak for the selection of native tree species[111].

Agrisilvicultural systems in general cannot compete with pure agricultural systems in terms of the magnitude and distribution of NCF. Net income from agriculture is – under the assumption of constant yields - evenly distributed over time, while that from forestry and agroforestry strongly varies between years. Nevertheless, a significant improvement in providing earlier net returns can be achieved by the intercropping of trees with crops as compared to pure forestry. Hence, this study proves hypothesis *H4a*: *"The initial intercropping of trees with crops generates positive Net Cash-Flows in the first years after tree establishment."*

This is in accordance with other studies which have investigated the NCFs of timber-based agroforestry systems in Central America (Aguirre 1963, Somarriba 1981, Current 1995). A further advantage of integrating trees in farms is that the land and labor invested in the forestry component will eventually generate a considerable amount of cash – both through thinnings and the final harvest - which is often difficult to obtain for farmers, who generally have limited financial resources (Franzel 2005). Net revenues from thinnings accounted for \$3852 (*T. amazonia* year 14) to \$10939 per ha (*H. alchorneoides* year 17), and net revenues from final harvest after 25 years reached \$17,000 (*A. graveolens*) to \$80,000 (*T. grandis*) per ha. From this perspective, tree species that have a high volume production within 25 years such as *T. amazonia*, *H. alchorneoides*, *C. odorata* and *T. grandis* (see Figure 4.42) will be the most

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[110] With the last crops being harvested in year three

[111] One should, however, bear in mind that *T. grandis* also provides earlier returns from timber, as the first thinning was predicted to be carried out in year five. Even though the first thinning was assumed not to produce marketable products, it could still provide material such as posts, firewood or others, which might also be of monetary value for the farmer. The period between the last crop harvest and first thinning was, however, constant among all tree species, and amounted to approximately three years.

attractive for farmers. *T. amazonia* had the lowest wood prices, so that even though it produced the highest wood volume it might be less attractive from an economic perspective which will be further discussed in the following section.

Is intercropping of tree plantations an economically viable alternative to pure forest plantations?

The Net Present Value (NPV) was used to assess the overall economic performance of the different land-use options. The agrisilvicultural concept was proven to be more profitable than pure forestry at a rotation period of 25 years. This was true for all tree-crop combinations, even for the barely profitable cultivation of cassava: Interplanting of trees with this crop still led to an increase in NPV of 8 – 26% over pure timber plantations. This demonstrates the important effect of offsetting initial management costs on the long-term economic performance of reforestation, even if crop cultivation itself only generates low profits. This is an important finding, as reforestation is usually carried out on marginal sites that are abandoned or fallowed by farmers due to difficult soil conditions, steep slopes, erosion, compaction or bad drainage, as was the case in the trial site. Crop yields in such agrisilvicultural systems will therefore inherently be rather low. This effect can, however, be reduced by a careful selection of crops, such as leguminous crops, that can be economically grown even on poor or degraded sites. The Internal Rates of Returns (IRRs) calculated for pure forestry were in accordance with those estimated for forest plantations in Central America (Griess and Knoke 2011, Piotto et al. 2010) and other parts of the world (Cubbage et al. 2010) and ranged between 10 and 12%, with the exception of *D. retusa* and *A. graveolens*, which only achieved IRRs of 2 and 3%, respectively. The IRRs of the agrisilvicultural systems were 2-4% higher than those obtained from pure forest plantations. It should, however, be noted that these values do not include the costs of purchasing land.

An improvement in economic performance over the entire rotation in timber-based agrisilvicultural systems compared to pure forestry was also found by Espino (1975), Chamshama et al. (1992), Gómez (1995), Agyeman et al. (2003), Martin and van Noordwijk (2011) and others. In accordance with these studies, differences in tree growth were not considered as economic effects, even though the observed positive effects of intercropping on tree growth might favor agrisilvicultural systems. Only the recorded reduction of pest management in intercropped *C. odorata* stands was taken into account. This resulted in a 50% higher NPV for *C. odorata* intercropped with pigeon pea (planted in year zero) than that for pure forestry. A reduced infestation rate will, however, also have considerable effects on growth rates and wood quality. Hence, intercropping of tree plantations can have clear silvicultural and economic advantages. Summing up the first part of Hypothesis 4b

– “*When the whole rotation period is considered, the agrisilvicultural concept is more profitable than monocultures of trees*” –

could therefore be accepted for all tree species.

Which tree-crop combination had the highest economic value?

The highest NPV was achieved when trees were intercropped with pigeon pea for all tree species, especially when pigeon pea was planted simultaneously with tree seedlings. The reasons for the high profitability of pigeon pea in this study have already been described above. Among the various tree species, *T. grandis* showed the best economic performance. This superiority could be attributed to its fast growth and hence its early returns from thinnings, its high volume production and high wood prices. The latter are however very uncertain. Scientists argue that the wood prices for *T. grandis* might decrease in the future, when the market becomes flooded with roundwood from even-aged plantations of this species that have been established throughout the world since the 1990s, due to worldwide incentives for reforestation generated by the Kyoto Protocol and national initiatives such as, Law 24 in Panama, for example (see chapter 3.1.2) (FAO 2002, Zanin 2005, Zimmermann and Glauner 2011). This effect has already been observed in Costa Rica, where the markets for products from thinnings quickly became saturated and left many farmers with lower than expected revenues from young *T. grandis* plantations (Current 1995). This development might favor native tree species. Especially *H. alchorneoides* and *C. odorata* might have the potential to achieve a similar NPV to that of *T. grandis,* due to their high wood quality and volume production (Piotto et al. 2010, Griess and Knoke 2011). Even though *T. amazonia* had the highest volume production among tree species, as was also demonstrated by Griess and Knoke (2011), wood prices might remain lower than those of *T. grandis* due to lower wood quality and demand (Piotto et al. 2010). Planting *D. retusa* and *A. graveolens* in pure timber plantations at a rotation length of 25 years was not profitable at a 6% interest rate, even when the same wood prices as for *T. grandis* were assumed. A positive NPV for these species was only achieved when trees were intercropped with pigeon pea from the year of establishment on. Extending the rotation length was also shown to improve economic performance of these tree species, but might not present an attractive option for farmers. However, considering the high wood quality of both tree species, their scarcity and the fact that *D. retusa* is listed as vulnerable on the IUCN list (IUCN 2012) the absolute wood prices and their relationship to prices for *T. grandis* might have been underestimated. It is furthermore likely that wood provided by the first thinning might already be marketable, even in small amounts, as *D. retusa* is commonly used for handicrafts in the region. Nevertheless, due to the low growth rates of these tree species, the potential for adoption might be higher for *T. amazonia*, *T. grandis*, *C. odorata* and *H. alchorneoides*, which are already being used by farmers in Panama (Garen et al. 2011). In Tortí *C. odorata* has been the most frequently planted or protected tree species, followed by *T. grandis* and *T. amazonia* (Schuchmann 2011).

Can the timber-based agrisilvicultural concept compete with other prevalent land uses?

The hypothesis that interplanting trees with crops is more profitable than the corresponding sole cropping systems could not be proven for all tree species. Due to their poor expected growth performance *D. retusa* and *A. graveolens* could not produce a NPV anywhere close to the NPV of pure agricultural cropping, even when grown in the agrisilvicultural system. However, all agrisilvicultural systems which included the tree species *T. amazonia*, *C. odorata, H. alchorneoides* or *T. grandis* had higher NPVs than the corresponding pure cropping systems. In contrast, *T. amazonia* and *C. odorata* could not compete with pure maize and pigeon pea when grown in pure forest plantations. This result illustrates the potential of the timber-based agrisilvicultural concept to improve the competitiveness of reforestation with other land use options.

The relatively good economic performance of the agrisilvicultural systems compared to sole cropping was rather surprising, considering the high labor and input demand calculated for pure forestry compared to those reported in other studies (Coomes et al. 2008, Cubbage et al. 2010), while assumptions concerning pure agriculture were rather optimistic: It was, for instance, assumed that crop yields would remain constant over time. This might, however, be questioned under the difficult soil conditions present in the trial site. The only measure taken to maintain soil productivity was substitution of mineral fertilizer in one of the two annual maize rotations through the use of a previous planting of beans. This management technique led, however, to lower maize yields, following the beans rotation.

Gómez (1995) found that initial intercropping of tree plantations could not compete with pure maize cultivation, while Current et al. (1995a) found that the majority of timber-based agrisilvicultural systems (TBAS) in Central America could compete with pure agriculture. As already mentioned, such comparisons might be problematic as the sites on which farmers agree to carry out reforestation are usually those, which appear less adequate for cultivation of crops (Knoke et al. 2009b). In this trial, site conditions and management practices were identical in both land use types and thus the results suggest a real economic advantage of the agrisilvicultural concept over pure agriculture on poor sites. Comparing the agrisilvicultural systems with pure cropping systems might furthermore only be realistic on rather small plots.

Reforestation with plantations designed to produce high-quality wood is, however usually carried out on a larger scale - at least 10 ha. It seems, however, implausible that an area of this size could be cultivated solely with maize or pigeon pea using traditional agricultural practices. Schuchmann (2011) found that farmers around Tortí usually grow more than one crop, with an individual parcel size of 0.5 – 5 ha, each. As soils in this region are hard to work, cropping is usually only carried to produce subsistence foodstuffs. While only small amounts of excess agricultural yields are sold in local markets, the majority of farm area is used for cattle farming, which also provides the main household income (Schuchmann 2011). Hence, a direct comparison of the agrisilvilcultural concept with cattle farming appears more appropriate than a comparison with pure agriculture. Indeed, most of the area under reforestation in the region of Panama and Darien has formerly been used as grazing ground (Tschakert et al. 2007, Sloan 2008).

At a rotation length of 25 years, all tree-crop combinations excluding those with *D. retusa* and *A. graveolens* were more profitable than cattle farming. This was true even for pure forestry. By calculating the costs and revenues of advanced cattle farming practices, which also assume that access to a livestock market is given, an underestimation of the revenues from cattle farming was avoided. Accordingly, a relative high stocking level of 4 cows per ha was assumed, resulting in an annual net revenue of 452 $/ha (from year two on), which is high in comparison to that found in other studies in the region (Tschakert et al. 2007, Coomes et al. 2008, Hänsela et al. 2009) or in other Latin American countries (Knoke et al. 2009b). Despite these high values for cattle farming, the NPV was between 30 - 40% higher for forestry and up to 213% higher for the agrisilvicultural systems with pigeon pea.

Hypothesis 4b - "*When the whole rotation period is considered, the agrisilvicultural concept is more profitable than monocultures of either trees or crops or cattle farming.*"- could therefore be accepted for the intercropping systems where the tree species *C. odorata*, *H. alchorneoides*, *T. amazonia* or *T. grandis* were combined with maize and beans or pigeon pea. This hypothesis could also be accepted for intercropping with cassava. This hypothesis was rejected for the tree species *A. graveolens* and *D. retusa*.

How sensitive are the different land use options to possible changes of cash in- and outflows?

The last question to be answered was how sensitive the land use options investigated are concerning changes in costs and revenues. The agrisilvicultural systems were found to be less sensitive to changes in costs than both pure forestry and agriculture. Even at an increase in costs of 50%, the more labor-intensive agrisilvicultural concept was more profitable than the other land-use options. Considering the actual increase in agricultural labor costs of 30% between 2006 and 2009, and the clear increase in costs for such things as fuel or tools (see retrospective data in 4.5.7), an increase in costs of 50% appears high, but not unrealistic within the next 10 years. Rising labor costs might in the long run, however favor the use of mechanized agricultural. According to local companies and landholders, mechanization in agriculture and reforestation has to date been impeded by the extremely high prices for machinery (due to low demand) and the lack of infrastructure, making access to farms difficult, while the knowledge needed for maintaining machinery among local workers is mostly low. On sites that are likely to become available for reforestation, mechanization is often hindered by steep slopes or waterlogged soils, as was the case in this study. However, on adequate sites, tree planting design could be easily adjusted in order to facilitate the use of machinery in agroforestry systems and sustain competitiveness with mechanized agriculture, as demonstrated by Eichhorn et al. (2006) and Palma et al. (2007) in temperate regions. This also demonstrates the high level of adaptability of timber-based agrisilvicultural systems.

It was also shown that even if revenues from crops decreased by 50% because of a decline in yield and/or prices, the agrisilvicultural practice was still more economically advantageous than pure reforestation with one exception - intercropping with maize-beans-maize rotations. Maize and beans are both very labor intensive. The beans rotation in the trial was itself barely profitable, and hence, only small changes in revenues at constant costs resulted in a net loss from the agricultural component. Accordingly, the agrisilvicultural systems were also more financially viable than the pure agricultural options under the assumption of a decrease in revenues from crops. The potential of agrisilvicultural systems to reduce the dependency of farm income on the often volatile prices for agricultural commodities through the integration of wood products into the farm portfolio has also been demonstrated by Blandon (1985), Gómez (1995), Blay et al. (2008), Castro et al. (2012); Martin and van Noordwijk (2011) and others. Integrating trees is particularly interesting, as wood prices are usually not correlated with those of agricultural commodities (Knoke 2012, p. 111). Studies by Tschakert et al. (2007) and Schuchmann (2011) showed that small- to medium-scale farmers in the region intuitively apply diversification to avoid risk. Increased economic robustness is a major factor affecting the possibility for adoption of agroforestry technologies, while it is seldom included in their economic assessment (Alavalapati et al. 2004, Castro et al. 2012).

Recent developments in national and international markets suggest an increase rather than a decrease in food prices. Since 2009, when the trial was established, prices on the central market in Panama have increased by 52% for pigeon pea, 68% for fresh maize cobs, 58% for beans and 125% for cassava. Thus, due to these increases, the prices received in this study are rather low compared to current market prices. An increase in 50% in crop revenues has therefore already been achieved in Panama for most crops, while a high future price fluctuation can be expected. Thus, in the future the agroforestry approach might even be more financially viable than pure reforestation. However, this also implies that pure agriculture might become more financially attractive compared to reforestation. Under the agricultural practices used in the trial, a 50% increase in revenues from crops would result in a NPV of $29,675 for maize and beans, $21,970 for pure pigeon pea, $5,938 for pure cassava and $20,817 for cattle farming. Under constant wood prices, none of the agrisilvicultural systems would be competitive with pure maize-beans-maize or pigeon pea cultivation. These differences are however rather small. For instance, under an increase in revenues from crops of 50%, NPV of T. grandis would reach $19,641 when intercropped with maize-beans-maize, and $18,257 when intercropped with pigeon pea. In contrast to the rising prices for food crops, the latest trends suggest constant to declining meat prices in the study area (Figure 5.2, next page). Yet, considering the rising world demand, which is reflected in the rising export figures for cattle meat in Panama (exported volume increased by 30% between 2011 and 2012 (INEC, 2012) can be predicted to increase.

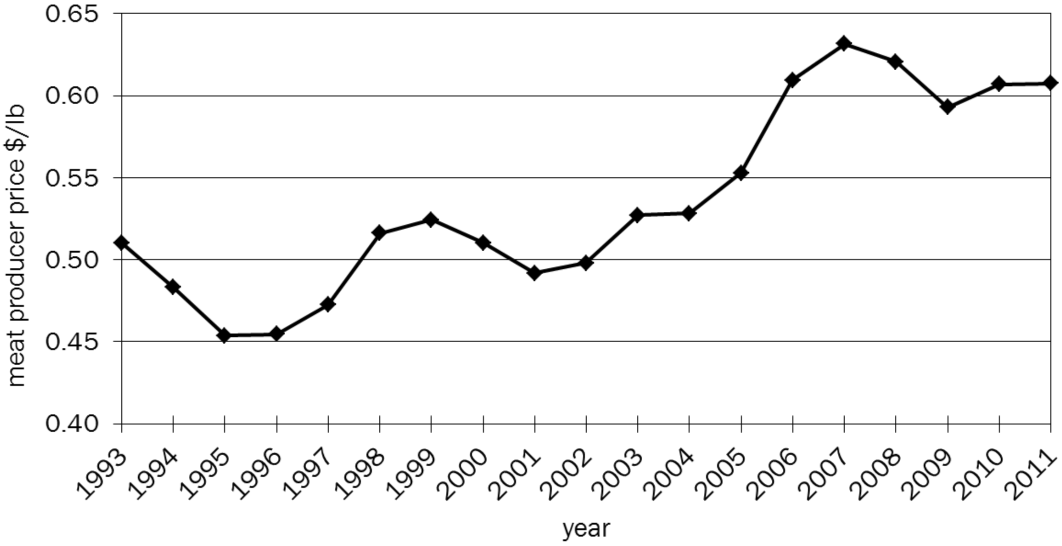

Figure 5.2: Fluctuation of the producer meat price for young bulls (weight corresponds to live weight) at the cattle market in Chepo (Panama) from 1993 to 2011. Data taken from INEC (2011).

A slight increase in prices received by producers has, however, also been observed on wood markets (ITTO 2011, Zimmermann and Glauner 2011, ONF 2012) while wood prices generally suffer from high price fluctuations (Hildebrandt and Knoke 2011, Knoke and Huth 2011). This problem can be minimized by a flexible harvest approach (Knoke and Wurm 2006), which requires a certain amount of insight into wood markets that farmers often do not have. While knowledge about raising and selling cattle has been passed on for generations, and considerable efforts have been made by the government of Panama to promote the productivity of cattle farms (such as the provision of training and support in the use of improved grasses and vaccinations), little knowledge and support has been made available in regards to the marketing of wood products (Fischer and Vasseur 2000). Large scale wood-dealing and processing companies in the region have focused on wood from natural forests, while the prices for wood from plantation forests remain low on local markets (ANARAP 2011). These are mostly dominated by a very few local saw mills and traders, while only large-scale reforestation companies have access to international markets and wood prices. Therefore, the reduction in wood prices by 50% tested in chapter 4.5.7 seems plausible for small- to medium farmers. In contrast, the export-prices assumed in this study appear rather conservative in comparison to the wood prices actually received by local (medium to large-scale) reforestation companies (Schnall, 2012, pers. comm.).

Under the assumption of a decrease by 50% in wood prices, neither forestry nor agroforestry exceeded the NPV of cattle farming with the exception of *T. grandis* initially intercropped with pigeon pea. However, by intercropping forest plantations, the required felling value to reach an IRR of 6% was reduced by 38% to 91%. Native tree species were considerably more efficient in reducing the dependency on future wood prices, as they allowed intercropping during a longer time period. This might be another effective argument for promoting the use of native tree species. Even though agrisilvicultural systems can help buffer the risk of uncertain wood prices, improving market organization and fostering capacity-building among farmers with regard to marketing strategies for wood products will continue to be vital to facilitating reforestation. The results of this study stress the importance of product diversification for large-scale reforestation, which up to now, has received scant attention in agroforestry research.

5.2.5 Potential for adoption

In view of the evident advantages of the agrisilvicultural option, one could raise the question of why it has not already been more widely applied. Indeed, a comprehensive assessment of agroforestry projects in Central America showed that adoption was highest for Taungya systems and wood lots (Current et al. 1995a). In Panama, Garen et al. (2009) found that 78% and 40% of participants in the PRORENA[112] reforestation programs in Rio Hato and Los Santos respectively mixed crops with trees intuitively. In these western parts of Panama, the main motivation for farmers to plant trees has been to fight environmental problems, especially the quality and availability of water and changes in climate, which farmers believe to be hotter now than before (Garen et al. 2009). In fact, these areas suffer from the consequences of heavy deforestation and degraded soils, which has led to the migration of people from Los Santos to the eastern parts of Panama, as described in chapter 3.1.2. However, in recently deforested areas, awareness of environmental problems played only a minor role as motivation for reforestation (Schuchmann 2011). Having fruits for consumption, wood and financial resources for the children were identified as the main reasons (Schuchmann 2011). This “widespread knowledge about and interest in trees” among Panamanian landholders stated by Garen et al. (2009) supports the thesis that reforestation is gaining importance for farmers. However, the potential environmental impact of these planting activities strongly depends on the size of reforested area. Until now, systematic reforestation by Panamanian landholders is rather uncommon, and the largest tree plantation areas are planted by foreign investors (Sloan 2008). Among these, there is also a rising interest in integrating crops into reforestation projects in order to improve profitability and reduce financial risks[113].

Despite this development, timber-based agrisilvicultural systems and reforestation still play a minor role at the landscape level. Even though profitability is certainly one - if not the most - important criterion for decision-making, other factors such as cultural taboos, farmer preferences, resource bottlenecks, policy constraints and market failures play important roles (Mercer and Miller 1997, Franzel 2005, McGinty et al. 2008). Furthermore, farmer’s objectives and requirements with regard to land use strongly depend on the size of their land:

Potential for adoption on small-scale farms

For smallholders who depend on their farms for their livelihoods, establishing a forest plantation on their land might put the family’s food security at risk. Agroforestry systems that integrate a number of multipurpose trees, such as home gardens with fruit trees, living fences, and scattered trees on pastures or contour plantings might be more appropriate, as they can constantly provide food, firewood and materials, and help to maintain soil fertility (see Nair 1993 and Beer et al. 2003). Studies have proven that smallholders traditionally carry out some kind of agroforestry system and are less likely to change their management practices unless they provide more food resources (Fischer and Vasseur 2000, Cochran and Bonnell 2005). The owner of a medium- to large-scale farm (including landholders of small-scale farms who do not depend on food resources from their farm) might be more likely to have capital and land and labor resources and hence, might be more willing to change current land uses on at least part of his land- if a long-time profit is expected (Knoke et al. 2012). Promotion of reforestation using agrisilvicultural practices should therefore, focus on medium- to large-scale farms to increase the ecologic effect without compromising subsistence needs.

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[112] Proyecto de Reforestación con Especies Nativas (Native Species Reforestation Project) carried out by the Smithsonian Institute and the Yale School of Forestry & Environmental Studies in Panama (Wishnie et al. 2007)

[113] To mention only some: see Forest Finance, Bauminvest and Planting Empowerment. Furthermore SENACYT (Secretaría Nacional de Ciencia, Tecnología e Innovacion) has funded various reforestation projects in Panama applying intercropping techniques.

Potential for adoption on medium to large-scale farms

The smallest landholding of the farmers interviewed by Schuchmann (2011) in the vicinity of the project was 2.5 ha, while the average farm size was 85 ha. Nevertheless, the majority of these farms are dependent on agriculture for their household income. As described in chapter 3.1.2, the region is dominated by traditional cattle farming techniques with a high percentage of natural pasture, which implies a stocking of one cow per ha, or even less on already degraded areas (Hänsela et al. 2009). On these farms, integrating forest plantations into the farm portfolio at the expense of one cow per ha might be viable considering the potential for high NCF from the harvest of wood approximately 15 to 25 years after plantation establishment – not considering materials extracted in the first thinning – and the substantial effect of product diversification, as described by Knoke et al. (2009a). However, compared to the yearly cash-flow of cattle farming, the long-term opportunities of reforestation might still lack appeal for farmers. This could be overcome by intercropping tree seedlings during the first years, and thus generating income, as proven in this study. An estimated time period of around three years lay between the last crop harvest and the first thinning in all of the agrisilvicultural systems tested. However between the first and second thinning a period of around 10 years without revenues was estimated. Even though this period required very few inputs or labor, the land in plantation could be considered fallow from an agricultural perspective, which might discourage farmers. If reforestation were carried out on unproductive wasteland, however, as described by Knoke et al. (2009b), or if the landowner migrated to the city (Sloan 2008) this might not be as restrictive for the farmer. However, if low productivity cattle farming is to be substituted with a more sustainable land use, the problem of low cash flow during the period between the commercial thinning and final harvest might be overcome by applying a sequence of different timber-based agroforestry practices (Vieira et al. 2009)(see also Table 2.1). For instance, at the end of the cultivation period for light demanding plants, shade-tolerant woody crops, such as coffee or cocoa could be planted, thus offering additional interesting financial opportunities for farmers (Kapp and Beer 1995, Castro et al. 2012). However, as these crops have restrictive site requirements, alternative shade-tolerant crops were investigated in the course of this study, based on literature research and expert interviews (see thesis of Ewers 2013). Under light shadow (defined in the study as up to 30% shade) ginger (*Zingiber officinale*), cananga (*Cananga odorata*) and coriander (*Coriandrum sativum*) might offer additional income when grown in forest plantations. At a light interception level of more than 50 but less than 70%, cananga, the panama hat palm (*Carludovica palmate*) and garlicvine (*Mansoa alliaceae*) might all be suitable crops. In deep shade, the panama hat palm, caña agria (*Costus scaber*) and ipecac (*Cephalis ipecacuanha*) fulfilled most of the criteria, defined for crop selection. Other species which were recommended by experts, such as pepper, orchids or vanilla, require more advanced knowledge for successful management and marketing. Another approach to overcoming the financial downside of the time period between the second and final thinnings might be to plant lightly shade-tolerant fodder species such as maní forrajero (pinto peanut, *Arachis pintoi*), canavalia (*Canavalia brasiliensis* or *C. ensiformis*) or small trees like *Leucaena leucocephala* between thinned stands, in order to use the space between trees as a grazing ground or protein bank for cattle (see Cordero and Boshier 2003, FAO 2010a). This silvopastoral sequence might especially help to improve the chances for adoption of agroforestry on cattle farms, and could be upscaled and integrated into an agricultural matrix dominated by intensive silvopastoral systems, as suggested by Murgueitio et al. (2011). These systems might offer improved ecosystem services and reduce the use of slash and burn practices (see chapter 3.1.2).

Both long-term scenarios imply, however, a higher demand for labor, which is often a limited resource for farmers. Current et al. (1995a) found that if the labor demand of potential agroforestry systems conflicted with major agricultural work load, adoption was particularly unlikely. The agrisilvicultural option might not appear as attractive if it required additional personnel. In this case, pure reforestation might be a more feasible option if the landowner is willing to fallow a piece of land (see above). However, this problem can also be overcome by using periods when the work load in the agricultural systems is low for the management of the agrisilvicultural system. Furthermore, this conflict could be minimized by selecting crops that require a minimal amount of labor that does not have to be accomplished in times of the year when the workload of cattle farming is highest or that do not require a fixed harvest date. For instance, *Cajanus cajan* can be harvested in different maturity stages and also provides fodder for livestock during the dry season.

The major advantage of timber-based agrisilvicultural systems is that they can be easily adjusted to meet the demands of farmers, by changing planting density, the degree of complexity of the agroforestry system, and by using an appropriate selection of crop species and rotations. Experience from past efforts to promote agroforestry has shown that the chance of adoption can be increased by offering bundles of options rather than a standard design formula (Current et al. 1995a, Franzel 2005). The tree-crop combinations tested here give information on the performance of a variety of options and the overall agroforestry practice therefore suggests a high potential for adoption.

The factors discussed thus far have considered possible restrictions at the micro level of individual farms. Other aspects at the macro level that are likely to discourage farmers are uncertain land tenure, regulations regarding land use and tree harvesting laws (Current et al. 1995a, Mercer and Miller 1997, Fischer and Vasseur 2000). In recent years, great efforts have been made by the government to foster land titling (see chapter 3.1.2) and hence uncertain land tenure is usually not a restrictive factor in Panama. However a range of permits are necessary before a legal marketing of wood from reforestation is possible (see review of Detlefsen and Scheelje 2012): Every reforestation activity must be registered with the National Environmental Authority (ANAM). Before harvesting or thinning can be carried out, the landowner must apply for a harvesting permit which requires detailed information about land tenure and the planned harvesting operation, such as tree species, volume etc. The permit is only issued after a technical on-site inspection by ANAM. This process can take up to 3 months. In order to legally sell the wood and transport it to market, a further transport and selling license is necessary which must be presented at the military check points in Panama, along with the documents mentioned above. In order to transport roundwood from the study site to Panama City, three of those military check points would have to be passed. These regulations created to protect forests actually present a major disincentive to tree-planting activities (Fischer and Vasseur 2002, Sloan 2008) – an effect that is also known from Europe (e.g. Bender et al. 2009). If farmers do not hold a harvesting permit – which appears to be normal among small scale reforestation activities (Detlefsen and Scheelje 2012), – he will be forced to sell his wood illegally and hence, at a lower price. These regulations, therefore, need to be simplified in order to increase the feasibility of reforestation and agroforestry, also for medium-sized farms. Another macro-obstacle to the implementation of both reforestation and agrisilvicultural concepts is the lack of developed markets for wood products, lack of market knowledge and the scarcity of forestry associations to link medium-scale landholders for the purposes of joint marketing (Gómez 1995, Fischer and Vasseur 2000, Garen et al. 2009). This study has, however, shown that this dependency can be effectively reduced by sequential intercropping of tree plantations which might significantly improve the viability of reforestation projects.

Potential for adoption in commercial large-scale reforestation projects

In contrast to activities undertaken by individual farmers, large-scale reforestation projects which are often carried out by professional companies might be better able to overcome obstacles at the macro level due to their higher levels of capital and knowledge. This thesis has demonstrated the silvicultural potential of agroforestry to improve modern forest plantation technology – a widely disregarded aspect of combining trees and crops. Extending the product portfolio can furthermore, not only increase the competitiveness of reforestation with other land uses but also with other assets. In accordance with the risk-reducing effect of admixing different tree species (Clasen et al. 2011, Griess and Knoke 2013, Roessiger et al. 2013), the financial risk of the long-term investment in trees – which often discourages investors - can be reduced by sequential intercropping.

A serious obstacle to integrating crops into modern forest plantation management might, however, be the high demand for labor. In the east of Panama, forest plantation companies increasingly have problems finding employees, as especially young men in eastern Panama seek jobs in the city that are better paid and require less physical effort (Sloan 2008). Those who stay in the region favor working on cattle farms, as they are more familiar with this work. Furthermore, workers at the trial site often complained that they disliked weeding activities and did not see a reason for planting or managing trees on large areas. It was often mentioned that there were enough trees in the forest and that trees would occupy land needed for food production. When installing the agroforestry trial, workers favored agricultural work over tree management; while trees benefited from the great deal of attention the workers paid to crops. Agricultural tasks were carried out more precisely, more quickly and independently, with workers also suggesting their own ideas for intercropping; whereas constant instruction and supervision was necessary when carrying out work in the pure forest plantation, as also observed by Haggar et al. (2003). Intercropping forest plantations might, therefore, also serve as an incentive to work for a reforestation company and might improve the identification of employees with the goals of the enterprise, thus assuring more constant employment. Moreover, during the two years of trial management, a number of workers ended the employment relationship, as cultivating their own or rented land was more cost-effective than working at a company and having to buy food for their (usually large) families under rising food prices. Selling the agricultural products at lower prices to workers or including some of the products as salary would not only increase the attractiveness of companies in the forestry sector as employers, but also make a substantial contribution to food security in areas with low food production.

Hence, the high demand for labor might actually be more easily filled, as people would be more willing to carry out agricultural tasks. The strongly decreasing work load in reforestation that usually leads to suspension of workers after the first months or during the dry season, has furthermore given a problematic reputation to reforestation companies in the region. By using an appropriate selection of crops that are less labor-intensive and quickly shade out grasses (as e.g. shrubby species) and whose sowing and harvesting periods fall in periods with lower labor demand in forest plantations (especially during the dry season, e.g. beans) an equal or even higher profitability for forest companies and more constant employment in rural areas with a more efficient use of labor could be achieved (Somarriba 1981, Witcomb and Dorward 2009). Activities that require less physical effort, such as sowing, processing and marketing of crops could provide employment for women in rural areas as well.

Another aspect that should be discussed is the potential up-scaling of the agrisilvicultural option. Commercial reforestation projects are usually larger than 50 ha. It does not, however, appear realistic to establish and sell products from maize-tree intercropping on such a large area. However, different crops that are easy to manage can be selected and allocated to smaller plots within the forest plantation that are most suitable for these crops, while those parts with low site quality could remain under pure forest management. However, even on poor sites, planting of fast-growing perennial shrubs, such as pigeon pea, arazá (*Eugenia stipitata*), borojo (*Borojoa patinoi*), mangostane (*Garcinia mangostana*); or forrage crops (see above) could be considered. This is true even if they are not intended for commercial harvest, as they quickly suppress grasses and – if kept longer than 6-9 months – seeding costs are offset by the money saved for tree weeding, while shrubs can also improve tree growth performance and survival rates, as discussed earlier.

If plantations are intended to be certified under the principles of sustainable forest management (e.g. FSC) only low crop yields can be expected, as demonstrated in this trial, as the use of pesticides is not permitted. Integrated pest management (IPM) or methods known from organic agriculture (see FAO 2011) can help to increase yields. The only recently developing market for organic products in Panama might offer interesting marketing opportunities. Accordingly, Dey (2010, unpublished data) investigated alternative marketing schemes for crops from the study site. Restaurants and markets, particularly in the city, were willing to pay a premium for products originating from an agricultural system that supports reforestation. Indeed, this premium was paid by an organic market for a sample of beans from the trial. Even though production of these beans was not completely organic, the fact that they originated from a reforestation project resulted in a 75% higher producer price. These price premiums can only be realized, however, if knowledge of alternative marketing schemes is available and sufficient quantities can be provided.

Future prospects for timber-based agrisilvicultural systems

Considering that the caloric self-sufficiency ratio of Panama is only 54.4 (FAO 2012), an increase in food production in the own country to ensure food security under the alarmingly high global food prices will be one of the governments priorities, which will inherently conflict with conservation and restoration of forest area. Simultaneously, reforestation is prompted in Panama and on a global scale by schemes such as CDM[114], by national incentives and private investors, while the REDD+ program is intended to control deforestation and hence the expansion of the agriculture frontier. The varying success rates in the implementation of these political and private reforestation initiatives in Panama and the conflicts that arise are discussed by Sloan (2008), Coomes et al. (2008), Peterson St-Laurent et al. (2013) and others. Even if potential financial losses of the farmer through less destructive land use practices are compensated by the international community (cf. Knoke et al. 2009b) – and might financially favor reforestation in the future - the lack of food and energy resources for a rising population will remain (FAO et al. 2012). In view of these conflicts, approaches to land sparing under agricultural intensification (Wise et al. 2009, Phalan et al. 2011) might not offer a long-term method for securing natural resources and at the same time sustaining - or increasing - agricultural production (Fischer et al. 2011, Knoke et al. 2012). Thus, if active reforestation is to be expanded to restore ecological services, the integration of crops might be vital in order to 1) financially compete with other land uses but also 2) provide staple food crops and thus ensure the right to food. This study has shown that, even under the difficult soil conditions of the study site and low-input practices, a considerable amount of food was still produced. Even though the agrisilvicultural approach might not provide a feasible option on all sites, it seems rather unlikely that large-scale forest plantations, such as those that have already been established in eastern Panama, do not include sites that would be adequate for food production. This study provides techniques to make effective use of the advantages of agroforestry in modern plantation technology. Hence, timber-based agroforestry systems might also facilitate the integration of reforestation at the farm level, and thus contribute to achieving sustainable intensification within a diversified agricultural matrix (Perfecto and Vandermeer 2010, Knoke et al. 2012) at the landscape level.

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[114] Which do however play a minor role in increasing revenues from forest plantations (s. Derwisch et al. 2009)

6 Conclusions and Recommendations

6.1 Overall evaluation of timber-based agrisilvicultural systems

The aim of this study was to evaluate timber-based agrisilvicultural systems (TBAS) as a method of facilitating reforestation efforts on small- and large-scale farms in Panama. From a silvicultural point of view this analysis has shown that the intercropping of tree seedlings does not have a negative effect on initial tree growth and quality development. On the contrary, potential silvicultural and economic benefits of the TBAS were found that might help to overcome substantial barriers to reforestation. Key findings of the thesis were:

- Crops shaded out weeds, thus improving tree growth and saving money on weeding.
- Lateral shading helped to induce straight height growth and effectively helped to reduce the infestation rate of *C. odorata* with *Hypsipyla grandella*.
- Waterlogged sites were drained by crops during the rainy season.
- Intercropping offset management costs, resulting in positive Net Cash Flows during the first years and providing substantial cash savings after 14 years at the latest, while improving competitiveness with other land uses (under moderate interest rates).
- The financial risk of the long-term investment in trees was reduced by initial interplanting.
- The slower growth of native tree species was advantageous for TBAS, as it allowed a longer period of intercropping
- The system has a high potential for adoption due to the high level of flexibility in planting distances and tree-species combinations that were shown here to have no significantly negative influence on crop production in juvenile forest plantations.

In order to tap the full potential of these observed advantages, an appropriate selection of tree-crop combinations is necessary. Based on the data collected in this case study, the following recommendations can be given for the site studied. However they can be equally apply to other tropical sites.

6.2 Management implications

Selection of crop species

In order to contribute to food security, initial intercropping of tree plantations should focus on staple food crops with a high nutritional value. It is self-explanatory that crops with a high benefit-cost ratio should be selected. In this study, maize and pigeon pea showed the highest economic performance, because of high maize prices and the less labor-intensive management of pigeon pea, respectively. Cassava might also show good results on very dry sites that might not be adequate for other crop species, if invasive grasses are not a problem. Crops that have the ability to quickly shade out grasses, such as maize and pigeon pea should be favored. Shrubby species with longer rotations might be especially recommendable during the year of establishment (until the first dry season) as intercropping with short rotation crops such as maize might cause a higher rate of tree mortality due to sudden changes in microclimate and damages to small tree seedlings during crop harvest. In contrast, shrubs can help to reduce competition with grasses in the rainy season and later reduce the extreme solar radiation and evaporation during the first dry season[115]. Diversification of agricultural products within an agrisilivicultural system is advisable in order to diversify products, and thus reduce the risk of failure through extreme weather conditions or pest invasion and provide a more equal distribution of labor demand. On cattle farms, intercropping of trees with leguminous fodder crops might be an interesting option in addition to staple food crops.

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[115] See also mentioned species in chapter 5.2.5

In the long run, a well-synchronized sequence of different shade-tolerant crop species and the development of silvopastoral use in later stages of stand development should be considered in order to sustainably intensify the use of land resources. Examples are given in chapter 5.2.5.

Selection of tree component

None of the tree species showed a significant negative reaction to intercropping that might limit its use in timber-based agroforestry systems. *C. odorata* might be particularly suitable for use in these systems, as its establishment in pure forest stands is impeded by *H. grandella*. *T. amazonia* furthermore showed a particularly positive growth development especially when combined with pigeon pea. Due to their low growth rates *A. graveolens* and *D. retusa* should only be planted in mixture with other fast-growing tree species. *T. grandis* was found to show the best growth performance during the first years and the best economic performance over the predicted rotation period. However, the slower initial growth of native tree species facilitates a longer period of intercropping with crops which can reduce dependency of the financial performance on the felling value and might offset the relatively higher wood prices for *T. grandis* in the long run. Admixing plots of *T. grandis* with native tree species is therefore recommended. Other tree traits, besides growth behavior such as canopy foliage, root structure, ability to fix nitrogen and others (see Nair 1993, Wilkinson and Elevitch 2000, Detlefsen and Somarriba 2012) should generally be taken into account during tree species selection for agroforestry systems, especially if permanent intercropping is intended. However, during the first two years, these characteristics only played a minor role. In contrast, results of the economic analysis suggest that the growth performance and market value of trees species in timber-based agrisilvicultural systems should be the primary selection criteria.

The optimal rotation length of *C. odorata*, *T. grandis* and *T. amazonia* was shown to be 25 years, and for *H. alchorneoides* 30 years, while *A. graveolens* and *D. retusa* might exceed this rotation length. Optimization of rotation lengths however strongly depends on diameter classes used to set wood prices and should therefore be taken into account when estimating rotation lengths.

Experience from the trial has shown that the microrelief should be carefully taken into account during planting to increase growth performance and survival of tree seedlings, especially on sites with high clay contents. The high mortality and low replanting success in relative depressions suggest that a departure from the commonly applied strict rectangular planting design can effectively save costs for replanting, while requiring only minimally more time for planting and initial instruction of workers. On such sites, payment per tree planted might not be advisable.

Planting distance

As far as is possible, a rectangular planting design is also recommended for timber-based agrisilvicultural systems. The results of this study show that a distance of approx. 1 m between trees and crops does not have any severe impact on tree growth. If aggressive grasses are abundant on the site, competition with grasses appears more limiting for tree growth than competition with crops, and tree-crop distance can be reduced to 0.5 to 1 m. Planting density was not found to have a significant effect on crop production during the first 18 months. Hence, in order to retain crop yields, reduction of initial tree density or adjustment of planting design should be considered, especially if no returns from the first thinning are expected. Small adjustments of the original 3 x 3 m design to 4 x 2, 4 x 2.5 or 4 x 3 m might also reduce damages to trees during crop harvest, if tree rows are clearly marked.

6.3 Policy implications

A key factor for promoting endogenous reforestation on farms is improving the access and information policies of wood markets. This implies capacity building and provision of market information to farmers, which could be focused on already established farmer's associations which could assist with joint commercialization of wood from farms as well as agricultural products from agroforestry systems. Technical assistance will, furthermore, be needed to improve tree management and thus, stem quality. Profound knowledge of national and global wood market dynamics and silvicultural fundamentals will be needed to promote the national forest and wood processing sector. Therefore, the reintroduction of forest and wood sciences into university education in Panama will be of crucial importance at the national level. Restrictive and complex harvesting permits, furthermore, discourage farmers from integrating trees into their farms. Simplifying the regulations for small to medium-sized planted forests should therefore be considered, as proposed by Detlefsen and Scheelje (2012).

6.4 Research needs

It is needless to say that more research is necessary to increase knowledge about the performance of different tree-crop combinations, especially long-term studies designed to improve prediction of tree growth during the entire rotation. For such research projects, systematic designs offer an interesting option, as they can also be used as demonstration plots, thus allowing for an easy empirical observation of different tree crop combinations and planting densities, even under restricted financial resources. Detailed recommendations for such a design, based on experiences of the present research are given in chapter 5.1. This study also demonstrates the importance of combining biophysical and socio-economic data in the scope of modern silvicultural and particularly agroforestry research. The interdisciplinary character of these sciences should accordingly be further integrated into research projects in order to generate results with greater relevance for farmers and industry at both the individual farm and landscape levels (Höllerl 2009, Nair and Garrity 2012).

In order to improve the competitiveness of reforestation with other land uses and achieve a more efficient use of limited land resources, a sequential chronology of the formerly classified Taungya practice, alley cropping and shade trees for woody crops should be considered as a silvicultural tool in forest plantation technology. For this purpose, a modern, reconciled view of these timber-based agrisilvicultural practices and sequential silvopastoral approaches in science and policy that allows for up scaling to an industrial level will be necessary.

7 Summary

The accelerating deforestation in the tropics, caused by unsustainable land use has been recognized as one of the major causes for climate change, loss of biodiversity and long-term degradation of land. Politicians and scientists therefore widely acknowledge the need for reforestation in order to restore environmental services including the provision of timber and other forest resources. In this context tropical timber plantations are considered a sustainable and economically feasible way to foster reforestation of degraded lands. However, the greatest obstacle to the implementation of timber plantations remains the long term investment of land, labor and other farm resources, as trees do not provide returns during the first 5 to 10 years. This study aims at developing methods to generate earlier returns from tropical timber plantations and, hence, turn reforestation into a more attractive land use option for both small- and large-scale land owners.

Research approach and objectives

This study was designed to evaluate the potential for agroforestry systems which combine trees with agricultural production to potentially overcome the aforementioned obstacle of delayed economic returns from investments in forestry. In the past, agroforestry research has focused on the integration of trees into agricultural farming systems. Scant attention has been dedicated to the possible advantages of integrating crops into forest plantations. The approach used in the present study was the integration of understory crops with timber plantations in order to generate earlier returns, to provide alimentary products and allow for a more efficient use of land and labor resources. Sequential intercropping of juvenile tree plantations has traditionally been carried out in Asia and was systematically introduced in the 19th century under the name “Taungya,” and used to promote teak plantations (*Tectona grandis*) in Burma (today Myanmar), and later on throughout the tropics. Since that time, the traditional Taungya practice has undergone various modifications, but is still generally applied only on a very small scale. The objective of this study therefore, was to quantify both the growth performance of trees and the amount of agricultural crops produced under different tree-crop combinations and planting distances. The data obtained was then used to evaluate these timber-based agrisilvicultural systems from both a silvicultural and an economic perspective.

In the course of this study, the following hypotheses were tested:

H1: *Intercropping tree seedlings with crops does not negatively influence growth, survival and quality of timber species.*

H2: *The presence of commercially valuable timber species negatively influences crop production.*

H3: *Tree spacing is positively correlated with crop yield and biomass production.*

H4 a) *The initial intercropping of trees with crops generates positive Net Cash-Flows in the first years after tree establishment.*

H4 b) *When the whole rotation period is considered, the agrisilvicultural concept is more profitable than monocultures of either trees or crops or cattle farming.*

Materials and Methods

The township of Tortí, located in the east of the Republic of Panama, was selected for this case study. One exotic hardwood species (*Tectona grandis*) and five valuable native hardwoods (*Astronium graveolens, Cedrela odorata, Dalbergia retusa, Hieronyma alchorneoides and Terminalia amazonia*) were selected for the trial. The emphasis was placed on natives, because the lack of experience with the growth performance and management of native species has often impeded their commercial use. The crop species used - maize (*Zea mays*), beans (*Phaseolus vulgaris*), cassava (*Manihot esculenta*), rice (*Oryza sativa*), pigeon pea (*Cajanus cajan*), soy beans

(*Glycine max*) and ginger (*Zingiber officinale*) - were chosen both because of their potential to provide returns within one year and the fact that they are commonly grown as staple food crops in the region. Crop species were grown in four different rotations – maize-beans-maize-maize, beans-rice-rice, cassava-soy beans and ginger-pigeon pea - which from here on, will be referred to as “intercropping treatments”.

In order to answer the research questions stated above, a systematic agroforestry trial was designed, based on the concepts of mixed fan (Nelder 1962) and parallel row design (Bleasdale 1967). This combination made it possible to test one crop rotation between six different tree species at eight different planting distances within one systematic plot. For this purpose, trees were arranged in fans with a constant planting distance of 3 m within each line and increasing distances of 2 to 7 m between each pair of lines. Two lines with 16 tree seedlings of each tree species were planted within one plot. Crops were sown in a regular grid between trees using different planting distances for each crop based on those commonly used by local farmers. Each plot covered a total of 1,210 m^2 on which one intercropping treatment was planted. Four plots were established for each intercropping treatment. In addition, four plots of pure forest plantation (without crops) using the same tree planting design served as control plots. Pure agricultural production was also monitored on four plots for each of the crop rotations used as intercropping treatments, with an individual plot size of 225 m^2.

Tree growth was monitored every 3 months during the 18 months of active intercropping. Six months after the last crop harvest (24 months after tree planting) a final growth performance survey was carried out, in order to evaluate possible mid-term effects of intercropping. The parameters used to assess tree growth performance were height, root collar diameter (rcd), crown diameter and crown height, and other parameters used to characterize growth form, vitality and damage. Crop yield and biomass production were assessed on trapezoidal subplots which were defined by the different tree species combinations and planting distances. The competitive situation of individual trees was assessed by summing up the distance-adjusted relative size of the three nearest crops to each tree. The height and diameter increments of trees within different time periods were compared between intercropping treatments and pure forest stands, using a linear mixed model. Tree survival was tested for significant differences between treatments by fitting a Cox Proportional Hazard Model. Damages and tree quality were analyzed using a logarithmic regression, and the effect of competition on single-tree performance was assessed using regression analysis. The effect of tree species and planting distance on crop production was analyzed using analysis of variance and a weighted regression.

In contrast to the majority of systematic research designs used to investigate the impacts of different planting systems, this trial also allowed for the economic evaluation of different tree-crop combinations. All management costs were recorded, crops were sold on the local market, and the money obtained from them was also noted. The economic performances of the various land-use options were compared using the Net Cash Flow (cash inflows minus cash outflows), the Net Present Value (sum of discounted Net Cash Flows) and the Internal Rate of Return (requested rate of return at which Net Present Value equals zero).

Results

The exotic, *T. grandis*, showed the best height performance, reaching 6.2 m (± 1.8 m) after 2 years, while the heights of the native tree species ranged between 2.1 m (± 0.6) and 3.0 m (± 1.1 m). Among the natives, *H. alchorneoides* generally showed the lowest and *T. amazonia* the highest growth performance. In contrast, the survival rates of the native species *T. amazonia*, *C. odorata* and *A. graveolens* (each more than 85%) were all higher than that of *T. grandis* (82%). The survival rate was particularly low for *H. alchorneoides* (36%). This species clearly had the greatest difficulties coping with the dry weather conditions during planting and the high clay content at the trial site, which resulted in heavy swelling and shrinking of the seasonally waterlogged soils.

The results of the intercropping experiment show that the height increment of *C. odorata*, *D. retusa*, *H. alchorneoides* and *T. amazonia* was stimulated by interplanting with maize during the first 3 months. This effect might be attributed mainly to tree seedlings seeking light in the dense maize fields. However, after the maize harvest, the mortality rate of tree seedlings was significantly higher in the former maize fields than in the other treatments. It was assumed that the sudden change in microclimate and damages to the small tree seedlings during the harvest process might have increased mortality during the first dry season. In contrast to the first harvesting cycle, the subsequent beans and maize planting in this rotation did not show any effects on either height growth or survival. The trees associated with the beans-rice-rice treatment showed low height and diameter increments relative to those in the pure forestry stands, especially in the case of *T. amazonia*. Differences to pure forest stands were, however, only significant during the presence of beans in the first 9 months. Intercropping with cassava also showed either no effect or a slight negative effect on tree growth, especially for *T. grandis*, *A. graveolens* and *T. amazonia*. These effects might be attributed to the fact that beans, rice and cassava did not succeed in suppressing aggressive grasses abundant at the study site. However, it was proven that cassava had a rather positive effect on the survival rate of all tree species compared to other treatments. This effect was only significant for *T. amazonia*. It is possible that this effect was due to the shrubby growth habit of the cassava which protected the tree seedlings from evaporation and extreme solar radiation during the first dry season.

The most evident positive effect of intercropping on tree growth was proven for the association with woody pigeon pea, which itself reached heights of up to 3 m. The growth increments of *A. graveolens*, *C. odorata* and *T. amazonia* were all up to four times higher in association with pigeon pea than in the pure forest stands during the six months of the pigeon pea rotation. This effect was assumed to be mainly due to the suppression of grasses by pigeon pea shrubs. Other effects that could have been advantageous are the crop's ability to fix nitrogen, improved nutrient input from the nutrient-rich foliage of pigeon pea, the reduced reduction of soil compaction and improved drainage of waterlogged sites due to root penetration. Even six months after the crop harvest, individuals of the species *A. graveolens*, *C. odorata* and *T. amazonia*, were still significantly taller on the former pigeon pea fields than those in the pure forest stands. None of the other intercropping treatments showed any mid-term effects six months after the last crop harvest that were consistent across tree species.

After two years, other agroforestry treatments only showed a significant effect on height and diameter status of *C. odorata*. The cultivation of this hardwood species is mostly restricted by the mahogany shoot borer (*Hypsipyla grandella*), whose attacks reduce stem quality in pure forest plantations. However, when associated with pigeon pea, maize and cassava, the growth performance of *C. odorata* was clearly higher than its performance in pure forest stands, due to a significantly reduced infestation rate in these treatments. Intercropping with small herbaceous crops, such as beans, rice and soybeans did not produce any improvement, as they do not provide lateral shade. It was therefore concluded that no negative long-term effects of intercropping on tree growth are to be expected. On the contrary, shrubby crop species, or species with other growth habits that produce lateral shade, might help to increase growth performance and survival of tree species. Hypothesis *H1* was therefore accepted.

On the single-tree level, a negative correlation between competition for growing space and both growth performance and survival rate was found. However, these effects were hardly evident if extreme competition was avoided (tree-crop distance of less than one meter and extremely high height ratios).

Another important finding not directly related to intercropping was that even though the trial site was located on a plain, trees planted in relative depressions showed significantly lower survival rates and growth performance compared than those planted on the flank or top of a mound. It is therefore recommended to carefully take into account the microrelief during planting, even if this requires a departure from a regular planting grid.

Overall, crop production of maize, pigeon pea and beans was comparable to the Panamanian average. However, the production of ginger, cassava, soy beans and rice was low, due both to the waterlogged site and the limited use of agrochemicals relative to common practices in the region. Differences in crop production due to tree species and planting distance of trees were not found during the first 18 months of intercropping and hence, H3 and H4 were rejected. It was assumed that these effects only become evident in later stages of stand development. The inherent reduction in agricultural yields, due to the area occupied by trees was, however, considered in the economic analysis.

The financial assessment showed that all agrisilvicultural systems succeeded in generating positive Net Cash Flows during the first years, even though the establishment costs of trees were not completely offset by intercropping. The cultivation of crops was predicted to be possible for up to two years between *T. grandis* and up to four years between native tree species, based on data on crown and height development, taken in older plantations. Hypotheses *H4a* was therefore accepted.

Over the entire rotation period, all agrisilvicultural systems showed a better economic performance, in terms of NPV (at an interest rate (IR) of 6%), than pure forestry. This was true even for intercropping with cassava, even though crop production in these systems only produced low revenues. However, selling of even these low yields still succeeded in offsetting parts of the management costs of trees, and hence, improved the economic performance by up to 26% compared to pure forestry. Intercropping with maize-beans-maize and pigeon pea improved the NPV by up to 50%. Intercropping of *T. grandis* with pigeon pea resulted in the highest NPV - 17,836 $/ha (at a 6% IR) - of all of the tree-crop combinations (this corresponds to an Internal Rate of Return (IRR) of 16%, excluding costs for the purchase of land), due to the high wood prices and high production performance of *T. grandis* combined with the less labor intensive management of pigeon pea at currently high prices for green pods. Among the native tree species, the economic performances of *T. amazonia*, *C. odorata* and *H. alchorneoides* were similar, with an IRR of 10% in pure forest stands; while the slow-growing natives, *D. retusa* and *A. graveolens*, only showed an IRR of 2-3% at a rotation length of 25 years. The IRRs of the agrisilvicultural options were, however 2-4% higher for all tree species, while the association with pigeon pea presented the highest and cassava the lowest difference. All agrisilvicultural options, with the exception of those including *D. retusa* and *A. graveolens*, performed better financially than either the corresponding pure cropping systems or cattle farming. Even pure forest plantation was able to compete with cattle farming, when the whole rotation period was considered, due to substantial revenues achieved from thinnings and final timber harvest. Hypothesis *H4b* was therefore fully accepted for all agrisilvicultural systems excluding *D. retusa* and *A. graveolens*.

The NPV of the agrisilvicultural system was furthermore shown to be less sensitive towards changes in costs than pure forestry and pure agriculture. Accordingly, even though the agrisilvicultural concept was more labor intensive it was still able to compete with the other land uses under an increase in costs for labor and materials of 50%. Accordingly, less labor-intensive intercropping – for example, pigeon pea was less sensitive towards cost changes than other labor intensive rotations such as maize-beans-maize. Furthermore, it was proven that under increasing food prices, pure agriculture quickly became more financially viable than both forestry and agroforestry. This situation combined with uncertain wood prices make tree planting financially unattractive for farmers. However, this study was able to show that by intercropping forest plantations, the dependency of the investment on the final felling value can be considerably reduced. This is especially true for native tree species, as they allow a longer period of crop planting. Accordingly, the required felling value for a moderate IRR of 6% was reduced by up to 90% by intercropping, making tree planting more attractive for decision makers, even under low expected wood prices.

Conclusions and recommendations

This study has shown that there are no severe silvicultural constraints to the intercropping of young tree plantations. On the contrary, silvicultural and economic benefits were identified that might help to overcome the most substantial barriers to reforestation. Particularly important among these benefits was the fact that the crops helped suppress aggressive grasses, which often impede successful reforestation, thus improving tree growth and survival rates, and substantially lowering costs for weeding. Management costs for trees can be offset by selling agricultural products. The lower initial height growth of native tree species, which makes them more labor-intensive and less attractive for reforestation, can be an advantage in agrisilvicultural systems, due to the longer potential intercropping period. Thus, reforestation with native species can be supported by agroforestry approaches. Furthermore, the system has a high potential for adoption, as it can be easily adjusted to meet the individual demands of small farmers or large-scale reforestation projects by a sound selection of species combinations and planting design. Crops that have the ability to quickly shade out grasses should be favored, as was the case, for example, in this trial for maize and pigeon pea. Woody crops with longer rotations might be especially appropriate during the year of forest plantation establishment (until the first dry season). In large-scale reforestation projects, shrubby species are less labor intensive and harvest can often be more flexibly organized. Species that can be harvested during the dry season - the period, which usually demands less labor in forest plantations - such as beans or peas might be particularly suitable. In this manner, additional employment in rural areas can be created while achieving a more efficient use of land and labor in forest plantations. Future studies should also investigate potential sequences of shade-tolerant crop species and silvopastoral approaches for later stages of stand development, in order to allow for a continued extension of the product portfolio in forest stands, and to sustainably intensify the use of land resources. Further measures which are key to promoting reforestation are the provision of information on wood markets to farmers, assistance with joint marketing and simplification of the process of obtaining harvesting permits for planted forests.

In view of a rising world population and a rising demand for food and energy resources, the integration of crops in reforestation efforts might be vital to making forestry financially competitive with other land uses while also contributing to food security. A more modern view of timber-based agrisilvicultural practices (and in later stages of stand development also silvopastoral systems) in science, policy and land-use planning that allows for up-scaling to an industrial level will be needed in order to tap the full silvicultural and economic potential of agroforestry for modern forest plantation technology. The approach suggested here is an important tool for achieving the necessary restoration of degraded and unproductive land at the landscape level.

8 Resumen

En los trópicos la deforestación acelera continuamente debido al uso no sostenible de la tierra. Eso es una de las principales causas del cambio climático, la pérdida de biodiversidad y la degradación de los suelos. No se cuestiona que la reforestación de suelos degradados con árboles maderables de rápido crecimiento asegura y/o reestablece la función ecológica de los bosques y su beneficio económico. El atascamiento más grande para realizar un proyecto de reforestación es la alta inversión inicial y la demora de 5 a 10 años de crecimiento hasta poder contar con primeras ganancias de los raleos. El objetivo del presente trabajo de investigación es el desarrollo de métodos para establecer plantaciones tropicales que generen ingresos en los primeros años y así aumentar su atractivo ecológico y económico.

Aproximación a la investigación y objetivo

Sistemas agroforestales, en los cuales se combina la siembra de árboles con plantas de cultivo y/o animales, representan una posible solución para evitar ingresos retardados. En el pasado el enfoque de investigaciones agroforestales consistió en la integración de árboles maderables en cultivos agrícolas. Poca atención se dedicó a la posible ventaja de integrar plantas de cultivo en plantaciones forestales. La aproximación de este estudio fue complementar reforestaciones por un componente agrícola que permita una pronta cosecha y así genere ingresos económicos a corto plazo, produciendo alimentos y facilitando el uso eficiente de recursos. La fomentación de plantaciones forestales por pequeños productores integrando plantas de cultivo es tradicionalmente conocida bajo el nombre “Taungya” en Myanmar (Asia). En el siglo 19 se introdujo a nivel mundial para promover la siembra de teca *(Tectona grandis)*. Hoy en día este concepto agroforestal principalmente se realiza para pequeños productores, pero de una manera fuertemente modificada. La evaluación del potencial forestal y económico en sistemas agroforestales con el fin de mejorar la actual tecnología de plantaciones forestales debe ser facilitada a través de los datos obtenidos en este trabajo.

Las siguientes hipótesis han sido montadas:

- *H1:* *Insertar plantas de cultivo en una plantación forestal no tiene efectos negativos al acrecimiento, la sobrevivencia y la calidad de los árboles.*
- *H2:* *Todo tipo de maderables insertados en sistemas agrícolas traen efectos negativos a la producción de alimentos.*
- *H3:* *La distancia de siembra de los árboles correlaciona de forma positiva con la cosecha y la producción de biomasa en el cultivo.*
- *H4 a)* *La siembra de plantas de cultivo en una reforestación puede generar flujo de caja positivos en los primeros años.*
- *H4 b)* *Tomado en consideración el periodo completo del uso de la tierra, el sistema agroforestal tiene un valor actual neto más alto que la exclusiva reforestación o agricultura.*

Material y métodos

Para la investigación del planteamiento se ha establecido una parcela de ensayo ubicada cerca de la comunidad de Tortí en el oeste de la Rep. de Panamá. Entre los árboles escogidos están la especie introducida *Tectona grandis* y cinco especies nativas (Zorro [*Astronium graveolens*], Cedro amargo [*Cedrela odorata*], *Cocobolo* [*Dalbergia retusa*], Zapatero [*Hieronyma alchorneoides*], Amarillo [*Terminalia amazonia*]). Entre los árboles se han plantado plantas de cultivo conocidas y cultivadas como alimento básico en la región y que generan ingresos dentro de un año. Según estas especificaciones se han sembrado maíz (*Zea mays*), frijoles (*Phaseolus vulgaris*), yuca (*Manihot esculenta*), arroz (*Oryza sativa*), guandú (*Cajanus cajan*), soya (*Glycine max*) y jengibre (*Zingiber officinale*) en las siguientes rotaciones de cultivo: maíz-frijol-maíz-maíz, frijol-arroz-arroz, yuca-soya y jengibre-guandú.

El montaje del ensayo está basado al sistemático „diseño abanico“ de Nelder (1962) y al „parallel row design“ según Bleasdale (1967) que permite la investigación de rotaciones de cultivo entre seis diferentes especies de árboles y respectivamente ocho diferentes distancias de siembra en una parcela de 1210 m². Para este objetivo los árboles están ordenados en abanico y sembrados con 3 m de distancia en hileras y una variable de 2 a 7 m entre las hileras. Por parcela se han sembrado dos hileras con 16 árboles de cada especie. En cada parcela se ha sembrado una planta de cultivo según las normas locales, independientemente de la posición del gradiente de luz. Para cada una de las cuatro rotaciones de cultivo se han establecido cuatro parcelas. Como parcelas de referencia para una exclusiva reforestación se han establecido cuatro lotes con el mismo diseño pero sin la siembra de plantas de cultivo. Cuatro parcelas de 15 x 15 m han sido establecidas para la comparación con la exclusiva producción agrícola de cada rotación de cultivo.

Entre los árboles de las parcelas recién establecidas se han sembrado plantas de cultivo en un periodo de 18 meses. En este tiempo cada 3 meses se han registrado los parámetros de crecimiento de los árboles, la altura, el diámetro de la base del tronco, diámetro de la copa, distancia entre la base de la copa hasta el suelo, tanto como datos referentes a la vitalidad, los daños y la forma de crecimiento. Para controlar el impacto de la siembra de plantas de cultivo a largo plazo, en la plantación forestal se ha realizado otra toma de datos 6 meses después de la última cosecha (24 meses después de la siembra). La cosecha y la producción de biomasa de las plantas de cultivo en el sistema agroforestal se han evaluado en sub-parcelas trapeciales que han sido definidas por la correspondiente combinación de árboles y su distancia de siembra. Adicionalmente se ha definido la competencia lateral de cada árbol a través de un índice de competencia (sumado por la distancia y la relación de altura de los árboles) hacia las siguientes tres siembras de plantas de cultivo. A través de un modelo linear con una mezcla de diferentes cultivos se ha comparado el acrecimiento en altura y el diámetro en diferentes periodos. Los resultados han sido evaluados en estadísticas. La diferencia entre este modelo de ensayo a la mayoría de diseños sistemáticos es que este modelo permite una valoración económica de un cultivo en plantación por la regular y práctica siembra de plantas de cultivo. Se han registrado todos los gastos de la explotación. Las cosechas se han vendido en el mercado local para determinar sus precios reales. La valoración económica se ha calculado a través de la siguiente toma de datos: Neta de los pagos (diferencia entre ingresos y gastos), valor actual neto (flujos de efectivo descontados), interés interno (interés donde el valor actual neto llega a 0).

Resultados

La *T. grandis,* una especie introducida en América Central, ha presentado los mejores resultados de crecimiento con alturas de 6.2 m (± 1.8 m) después de dos años, mientras las especies nativas han obtenido alturas entre 2.1 m (± 0.6 m) y 3,0 m (± 1.1 m). Entre ellas, la *H. alchorneoides* ha mostrado el menor crecimiento y la *T. amazonia* el mejor crecimiento. A diferencia, la mortalidad de la *T. amazonia*, la *C. odorata* y la *A. graveolens* con un 15% ha sido menor que la de la *T. grandis* con un 18 %. La mortalidad mas alta se ha observado en la *H. alchorneoides* con un 64 % en los primeros dos años. Esta especie evidentemente ha sido menos adaptada a las condiciones secas en el periodo de la siembra y a los suelos extremamente arcillosos con aguas parcialmente estancadas en el área del ensayo.

Los resultados de este ensayo agroforestal muestran que en los primeros tres meses la influencia del cultivo de maíz entre los árboles ha sido positiva para el crecimiento en altura de la *C. odorata*, la *D. retusa*, *H. alchorneoides* y la *T. amazonia*. Este efecto se debe principalmente a la competencia por luz en el denso cultivo de maíz que estimula el crecimiento de los plantones. Después de la cosecha del maíz se ha observado una mortalidad significativamente más alta de plantones en comparación con siembras de árboles combinados con otros tipos de cultivo. Posiblemente eso se debe a la brusca liberación de los plantones después de la cosecha que provoca un cambio del microclima y también a daños físicos de los plantones durante la cosecha.

Las subsecuentes siembras de frijol y de maíz no han afectado el crecimiento de los árboles. Árboles sembrados en rotaciones de frijol-maíz-maíz han mostrado bajo crecimiento en altura y diámetro.

Una diferencia significativa entre este sistema agroforestal y la exclusiva plantación forestal ha sido observada en la *T. amazonia* sembrada en combinación con frijoles durante los primeros tres meses. También la siembra de yuca con *T. grandis, A. graveolens* y *T. amazonia* ha causado un crecimiento tendencial menor en comparación con el crecimiento en las parcelas de referencia. Este efecto puede ser causado por el fuerte crecimiento de hierbas competitivas que no han podido ser controlado a través de la siembra de frijol, arroz y yuca. Al contrario se ha notado que la mortalidad en siembras de yuca ha sido claramente menor que en otros cultivos de rotación. Para la *T. amazonia* este efecto ha sido definido como significante. La tendencial menor mortalidad de plantones puede ser debido al extendido tiempo de rotación (12 meses) de la yuca que en la primera sequía ha brindado una sombra moderada a los plantones y así evitado una intensa radiación solar y evaporación.

El efecto más llamativo en el crecimiento de los árboles se ha notado en las plantaciones forestales que han sido combinadas con el cultivo de guandú. Durante los 6 meses del periodo de siembra de guandú, el crecimiento de la *A. graveolens*, la *C. odorata* y la *T. amazonia* ha sido hasta cuatro veces mas grande que en una exclusiva plantación forestal. Este efecto se debe principalmente a la dominante presión de los arbustos de hasta 3 m de altura sobre las malezas, especialmente sobre el pasto mejorado. También la capacidad del guandú de fijar nitrógeno, la mineralización por las nutritivas hojas y la distensión del suelo por el desarrollo de las raíces puede explicar este efecto. Hasta 6 meses después de la cosecha se ha notado un crecimiento significante mas alto de la *A. graveolens*, la *C. odorata* y la *T. amazonia* en las anteriores parcelas de guandú que en las parcelas de referencia. Salvo a la *C. odorata*, ningún otro cultivo ha mostrado un efecto consistente y de larga duración hacia las diferentes especies de árboles.

El monocultivo de la *C. odorata* principalmente se evita porque el gusano *Hypsipyla grandella* ataca a los brotes y el tallo del árbol lo que reduce su crecimiento y su calidad. Comparado con una exclusiva plantación forestal, la siembra de guandú, maíz y yuca entre los árboles ha podido reducir claramente el ataque por este gusano y así mejorar el crecimiento y la calidad de los árboles. Las plantas herbáceas como el frijol, el arroz y la soya no han mostrado este efecto porque no producen una sombra lateral. Este ensayo muestra que en la simultánea siembra de plantas de cultivo en plantaciones forestales no hay que contar con efectos negativos - eso confirma la hipótesis H1.

En el análisis puntual de los árboles se ha registrado una correlación negativa entre la competencia individual por el espacio y el crecimiento de los árboles. Sin embargo la relación no ha sido llamativa. Resulta difícil probar que el impacto al desarrollo del árbol es negativo cuando la distancia entre plantón y planta de cultivo es menor de un metro.

Otro resultado importante no directamente relacionado a este ensayo agroforestal es el hecho que la ubicación relativa en el micro relieve del área plana en la parcela tiene un impacto significante al crecimiento del árbol. El crecimiento inicial de los plantones sembrados en un badén ha sido menos exitoso que el de plantones sembrados en una cima. Especialmente en suelos arcillosos se recomienda tomar en cuenta el micro relieve para la siembra, aunque haya que desviarse de la exacta cuadrícula propagada.

La cosecha de maíz, guandú y frijoles se ha movido en el margen promedio de cosechas en Panamá, mientras la cosecha de jengibre, yuca, soya y arroz ha sido menor debido a aguas estancadas en el suelo y al ceder de agroquímicos. Diferencias entre la cantidad de cosecha en relación a las especies de árboles escogidos no ha sido observada durante los primeros 18 meses. Se supone que tales efectos solo serán comprobables en el transcurso del desarrollo de la siembra a largo plazo. Las hipótesis H2 y H3 no han sido confirmadas. La única diferencia que ha sido incluida en la evaluación económica es el hecho que se reduce el área de producción agrícola en una siembra de plantas de cultivo combinada con árboles.

La evaluación económica de los sistemas agroforestales ha mostrado que no pueden ser compensados los gastos de establecimiento de una plantación forestal a través de la simultánea siembra de plantas de cultivo. Sin embargo en los siguientes años se han podido generar ingresos. A base de los datos tomados del crecimiento en altura y del desarrollo de la copa del árbol se ha podido definir el tiempo máximo apto para la combinación con plantas de cultivo. Para la *T. grandis* es de dos años y para las especies nativas de 4 años.

Considerando el periodo de crecimiento completo, el valor actual neto de todas las combinaciones de siembras de árboles con plantas de cultivo ha sido mas alto que en exclusivas reforestaciones. Eso también aplica para la combinación de árboles con yuca, a pesar de que el cultivo de la misma ha sido de poca ganancia. Aunque la venta de yuca ha sido relativamente baja los gastos de mantenimiento de los árboles han sido cubiertos. Así se ha podido mejorar el valor actual neto durante el periodo completo de crecimiento por un 26% en comparación con una exclusiva reforestación, las siembras con maíz-frijol-maíz y guandú lo han mejorado por hasta un 50%. El mejor resultado económico con un valor actual neto de 17,836 $/ha con un interés de 6% y un periodo de siembra de 25 años (interés interno = 15%, excluyendo la compra de la tierra) ha sido logrado en la combinada siembra de *T. grandis* con guandú. Eso se debe al alto valor de mercado de la *T. grandis* y su producción de volumen como al comparativamente poco mantenimiento que exige el guandú y un precio de mercado alto del mismo. Entre las especies nativas la *T. amazonia*, la *C. odorata* y la *H. alchorneoides* han mostrado un parecido alto valor de interés interno de 10% en la exclusiva reforestación, mientras las especies *D. retusa* y *A. graveolens* con un crecimiento mas lento en 25 años solamente han logrado un 2-3%. El interés interno en los sistemas agroforestales para todos los árboles ha sido por un 2-4% mas alto que en exclusivas reforestaciones. En las siembras de árboles combinados con guandú el valor agregado ha sido el mas alto y con yuca el mas bajo. Todos los sistemas agroforestales excepto los cultivos combinados con *D. retusa* y *A. graveolens* han mostrado una ganancia mas alta que los respectivos sistemas solo agrícolas. Eso también vale para la ganadería que ha sido evaluada para poder comparar los datos. Hasta la exclusiva reforestación en un periodo de 25 años ha podido competir con la exclusiva ganadería extendida en la región, debido a las ganancias relativamente altas a través de la venta de madera de raleos y la cosecha final de los árboles. La hipótesis H4b se ha podido confirmar, con excepción de las especies *D. retusa* y *A. graveolens*.

Adicionalmente, en un análisis de sensitividad, se ha podido comprobar que el valor actual neto en un sistema agroforestal es menos débil referente a la constancia de ingresos y gastos que la exclusiva reforestación o agricultura. Quiere decir que el concepto agroforestal pese a su alto esfuerzo de trabajo y calculando un aumento de salario y de costos de materiales por un 50% puede competir con otros sistemas de uso de la tierra. Siembras de guandú que requieren menos trabajo de mantenimiento han sido mas estables contra aumentos de gastos en relación con rotaciones de maíz-frijol-maíz que requieren un mantenimiento mas intenso. Pero también se ha mostrado que a causa del esperado aumento de precios de alimentos, el uso de la tierra con sistemas agroforestales o forestales no puede competir con la exclusiva agricultura. Los dueños de las tierras ven la reforestación poco atractiva tomado en consideración los precios de madera inestables. Sin embargo el presente ensayo muestra que la alta dependencia de inversión en una reforestación puede ser reducida a través de ingresos generados por la venta de madera y la cosecha de plantas de cultivo en los primeros años de la plantación. Eso se aplica especialmente para especies nativas que permiten un tiempo relativamente largo para la siembra de plantas de cultivo. Correspondiente a eso el valor final de la plantación con un interés moderado de un 6%, en una plantación forestal combinada con plantas de cultivo ha podido ser reducido por un 90%. Así la reforestación puede ser rentable aunque los precios de madera fueran bajos.

Conclusiones y recomendaciones

Finalmente no hay que contar con limitaciones por la paralela siembra de plantas de cultivo en una joven reforestación desde el punto de vista forestal. Al contrario, se han destacado ventajas forestales como económicas que pueden ayudar a superar problemas básicos en la reforestación tropical. Sobre todo la siembra de plantas de cultivo puede disminuir el agresivo crecimiento de malezas (especialmente pastos mejorados) que permite un mejor desarrollo de los plantones y reduce los altos gastos necesarios para el control de malezas. Gastos de mantenimiento para la agricultura como la reforestación pueden ser compensados a través de la venta de cosechas agrícolas y así generar ingresos neto durante los primeros años. En este caso el lento crecimiento de especies nativas, que frecuentemente es la causa para la siembra de especies introducidas, es de gran ventaja porque el periodo para la paralela siembra de plantas de cultivo es mucho mas largo. El concepto agroforestal evaluado en este estudio tiene una alta relevancia práctica. Puede ser adaptado fácilmente a las necesidades individuales de pequeños productores porque se pueden elegir plantas forestales y de cultivo apropiadas con sus referentes distancias de siembra. Este estudio suministra experiencias con 36 combinaciones de árboles con plantas de cultivo. En general se prefiere la siembra de plantas de cultivo que tienen la capacidad de amenazar a las hierbas rápidamente. Para el año de siembra de los árboles (o hasta la primera sequía) se recomiendan arbustos de lento crecimiento porque plantas que en poco tiempo crecen mucho como por ejemplo el maíz pueden causar una alta mortalidad de los plantones. Al contrario una sombra moderada por los arbustos puede evitar un choque de las plantas por la extrema radiación solar directa. Arbustos leñosos también pueden servir para leña, pasto o como plantas medicinales. En reforestaciones grandes los arbustos tienen la ventaja de un mantenimiento relativamente bajo y un tiempo de cultivo alto, lo que permite un cuidado de la siembra más flexible. También se recomiendan especies de plantas que se cosechan en verano, como el guandú, ya que en esa época el trabajo de mantenimiento en una joven reforestación es menor. Así también se crean empleos y se logra un eficiente uso de trabajo. Futuros estudios deberían incorporar el análisis de la siembra de especies de plantas de cultivo tolerantes a la sombra (o de animales) en una plantación mas avanzada para así intensificar el uso de la tierra. Otros formas para promocionar y apoyar el uso de la tierra en un sistema (agro)forestal es facilitar el acceso a informaciones sobre mercados de madera, el mercadeo en si y la simplificación de permisos para la cosecha de árboles en reforestaciones.

Tomando en consideración el crecimiento de la población mundial y la creciente demanda alimentaria y de recursos de combustibles, el uso agrícola del área establecida para una plantación forestal parece ser razonable en los primeros años de la siembra. Así por un lado la reforestación se hace competitiva para sistemas del uso de la tierra y por otro lado un proyecto agroforestal por parte contribuye a la seguridad alimentaria. La necesaria transmisión de este concepto de uso de la tierra por pequeños productores a un nivel industrial requiere de una consideración moderna en la ciencia como en la política de estos sistemas agrosilviculturales. En el marco del presentado concepto agroforestal suelos degradados pueden ser valorados nuevamente por un aspecto económico y ecológico.

9 Zusammenfassung

Die fortschreitende Entwaldung in den Tropen ist eine der Hauptursachen für Klimawandel, Verlust von Biodiversität und Bodenfruchtbarkeit. Durch nicht nachhaltige Landnutzungspraktiken wird die gewonnene landwirtschaftliche Fläche meist schnell degradiert und fällt brach. Die Aufforstung solcher degradierter Flächen mit schnell wachsenden Wertholzarten stellt eine ökonomisch vorteilhafte Möglichkeit dar, um Waldfunktionen wiederherzustellen. Die größten Hindernisse für ihre Umsetzung sind jedoch die hohe Anfangsinvestition und der lange Zeitraum von 5-10 Jahren, bis erste Rückflüsse aus Durchforstungen erwartet werden können. Ziel der vorliegenden Forschungsarbeit war es, Methoden zu entwickeln, um bereits in den ersten Jahren Einnahmen aus tropischen Forstplantagen zu generieren und somit neben der ökologischen auch die wirtschaftliche Attraktivität der Aufforstung zu steigern.

Forschungsansatz und Zielsetzung

Einen möglichen Lösungsansatz hierfür könnte die Agroforstwirtschaft – die Kombination aus Bäumen und Kulturpflanzen (und/ oder Tieren) – liefern. Bisher beschäftigte sich dieser junge Forschungszweig jedoch hauptsächlich mit der Einbringung von verholzten Pflanzen in Agrarsysteme. Wenig Aufmerksamkeit wurde hingegen den möglichen Vorteilen einer Einbringung von Nutzpflanzen in Forstplantagen gewidmet. Der Ansatz der vorliegenden Arbeit war es daher, die Baumpflanzungen in den ersten Jahren um eine landwirtschaftliche Komponente mit kurzer Produktionszeit zu ergänzen, um so rasche finanzielle Rückflüsse zu generieren, gleichzeitig Nahrungsmittel zu produzieren und eine effizientere Nutzung von Ressourcen zu ermöglichen. Versuche, die Wiederaufforstung durch Kleinbauern mittels der Beipflanzung landwirtschaftlicher Nutzpflanzen zu fördern, sind traditionell im Rahmen des „Taungya-Systems“ aus Myanmar bekannt - ein Konzept, welches später auch in anderen Teilen der Welt eingeführt wurde. Heute wird dieses Agroforstsystem in stark modifizierter Form angewandt, meist jedoch nur auf kleinbäuerlicher Ebene. Entsprechend war das Ziel dieser Arbeit, die waldbaulichen und ökonomischen Potenziale solcher agroforstlicher Systeme zur Verbesserung moderner Forstplantagentechnologie umfassend zu bewerten.

Hierfür wurden folgende Hypothesen aufgestellt:

- *H1: Die Pflanzung von Feldfrüchten in jungen Wertholzplantagen hat keinen negativen Einfluss auf Anwuchserfolg, Wachstum und Qualität der Bäume.*
- *H2: Die landwirtschaftliche Produktion wird durch die Wertholzarten negativ beeinflusst.*
- *H3: Der Pflanzabstand der Bäume korreliert positiv mit Ertrag und Biomasseproduktion der Feldfrüchte.*
- *H4 a) Durch die landwirtschaftlichen Beipflanzungen können bereits in den ersten Jahren Zahlungsüberschüsse aus Forstplantagen erwirtschaftet werden.*
- *H4 b) Über den gesamten Betrachtungszeitraum ist der Kapitalwert des Agroforstsystems höher als der reiner Forst- oder Landwirtschaft.*

Material und Methoden

Zur Untersuchung der dargestellten Fragestellung wurden Versuchspflanzungen nahe der Gemeinde Tortí im Osten der Republik Panama angelegt. Hierfür wurden eine fremdländische (*Tectona grandis*) und fünf einheimische Baumarten (*Astronium graveolens, Cedrela odorata, Dalbergia retusa, Hieronyma alchorneoides* und *Terminalia amazonia*) ausgewählt. Zwischen diesen wurden Feldfrüchte gepflanzt, die innerhalb eines Jahres Einnahmen liefern können und in der Region als Grundnahrungsmittel verbreitet angepflanzt werden. Gemäß dieser Vorgaben wurden Mais (*Zea mays*), Bohnen (*Phaseolus vulgaris*), Maniok (*Manihot esculenta*), Reis (*Oryza sativa*), Straucherbse (*Cajanus cajan*), Sojabohnen (*Glycine max*) und Ingwer (*Zingiber officinale*) ausgewählt. Diese wurden in vier verschiedenen Feldfruchtwechseln angebaut: Mais-Bohnen-Mais-Mais, Bohnen-Reis-Reis, Maniok-Sojabohnen und Ingwer-Straucherbsen.

Der Versuchsaufbau basiert auf dem systematischen Fächerdesign nach Nelder (1962) und dem so genannten „parallel row design“ nach Bleasdale (1967) und erlaubt die Untersuchung eines Feldfruchtwechsels unter sechs verschiedenen Baumarten und jeweils acht verschiedenen Pflanzabständen innerhalb einer Parzelle mit 1210 m². Zu diesem Zweck sind die Bäume auf Fächern mit Pflanzabständen von 3 m innerhalb der Reihe und variablen Abständen von 2 bis 7 m zwischen den Reihen angeordnet. In jeder Parzelle wurden zwei solcher Reihen (mit 16 Bäumen) für jede der sechs Baumarten gepflanzt. Unabhängig von der Lage der Lichtgradienten, wurde dann eine Feldfrucht (bzw. Feldfruchwechsel) je Parzelle angebaut. Für jede der vier Feldfruchtwechsel wurden vier solcher Parzellen angelegt. Als Referenz für reine Forstwirtschaft dienen vier Parzellen im gleichen Pflanzdesign, ohne die Beipflanzung der landwirtschaftlichen Komponente. Die reine landwirtschaftliche Produktion jedes Feldfruchtwechsels wurde auf vier Probeflächen á 15 x 15 m gegengeprüft.

Während eines Zeitraumes von 18 Monaten wurde in den neu begründeten Beständen Landwirtschaft betrieben. In dieser Zeit wurden alle drei Monate Parameter zum Baumwachstum erhoben - darunter die Höhe, Wurzelhalsdurchmesser, Kronendurchmesser und –ansatzhöhe sowie weitere Kenngrößen zu Vitalität, Schäden und Wuchsform. Sechs Monate nach der letzten Ernte (d.h. 24 Monate nach Baumpflanzung) erfolgte eine weitere Messung, um längerfristige Auswirkungen der Beipflanzungen auf das Baumwachstum zu überprüfen. Erträge und Biomasseproduktion der Feldfrüchte im Agroforstsystem wurden auf trapezförmigen Subparzellen, definiert durch die jeweilige Baumartenkombination und den Pflanzabstand, untersucht. Zusätzlich wurde die Standraumkonkurrenz der Einzelbäume mit Hilfe eines Konkurrenzindex beschrieben, der sich aus Abstand und Höhenrelation zu den drei nächsten Feldfrüchten ergibt. Der Vergleich des Höhen- und Durchmesserzuwachs zwischen den verschiedenen Beipflanzungen erfolgte innerhalb verschiedener Zeitabschnitte mittels eines linearen, gemischten Modells. Unterschiede in der Mortalität wurden mit Hilfe der Cox-Regression untersucht. Die Analyse von Qualität und Schäden erfolgte mit Hilfe einer logarithmischen Regression. Eine Regressionsanalyse wurde ebenfalls zur Untersuchung des Einflusses der individuellen Konkurrenzsituation auf Zuwachs und Mortalität herangezogen. Die Versuchsanlage erlaubt, im Gegensatz zu den meisten systematischen Designs, durch die regelmäßige und praxisnahe Pflanzung der Feldfrüchte auch eine ökonomische Bewertung der Zwischenpflanzung. Die Bewirtschaftungskosten wurden vollständig erfasst und die Feldfrüchte auf dem lokalen Markt verkauft, um reale Preise zu ermitteln. Die ökonomische Bewertung erfolgte anhand der jährlichen Nettozahlungsströme, des Kapitalwertes über den gesamten Betrachtungszeitrum und der internen Verzinsung der verschiedenen Landnutzungsoptionen.

Ergebnisse

Die in Mittelamerika fremdländische Baumart *T. grandis* wies das beste Wachstum mit Höhen von 6,2 m (± 1,8 m) nach zwei Jahren auf, während die einheimischen Baumarten Höhen zwischen 2,1 m (± 0,6 m) und 3,0 m (± 1,1 m) erreichten. *H. alchorneoides* zeigte hierbei das niedrigste und *T. amazonia* das beste Wachstum. Im Gegensatz dazu war die Mortalität von *T. amazonia*, *C. odorata* und *A. graveolens* mit 15% niedriger als die von *T. grandis* (18%). Die höchste Mortalität wurde allerdings für die einheimische Art *H. alchorneoides* mit 64% innerhalb der ersten zwei Jahre festgestellt. Diese Baumart war offensichtlich am schlechtesten an die trockenen Wetterbedingungen während der Pflanzung und die extrem tonhaltigen, saisonal staunassen Böden der Versuchsflächen angepasst.

Die Ergebnisse des Agroforstversuchs zeigen, dass der Höhenzuwachs von *C. odorata*, *D. retusa*, *H. alchorneoides* und *T. amazonia* durch die Beipflanzung von Mais während der ersten drei Monate deutlich positiv beeinflusst wurde. Dieser Effekt kann hauptsächlich auf die Konkurrenz um Licht zurückgeführt werden, welche das Höhenwachstum der Jungpflanzen in den dichten Maisfeldern anregte. Nach der Maisernte wurde jedoch eine deutlich erhöhte Mortalität der Bäume im Vergleich zu anderen Beipflanzungen festgestellt. Dies steht vermutlich in Verbindung mit der plötzlichen Freistellung und damit einhergehenden Veränderung des Mikroklimas sowie mit Beschädigungen der noch sehr kleinen Jungpflanzen bei der Maisernte. Die folgenden Bohnen- und Maispflanzungen zeigten jedoch keinen Einfluss auf die Baumzuwächse. Bäume zwischen der Bohnen-Reis-Reis Rotation zeigten vergleichsweise niedrige Höhen- und Durchmesserzuwächse. Die Unterschiede zur reinen Forstplantage waren jedoch nur für *T. amazonia* während der Beipflanzung von Bohnen in den ersten neun Monaten signifikant. Ebenso führte auch die Pflanzung von Maniok zu einem tendenziell schlechteren Baumwachstum von *T. grandis*, *A. graveolens* und *T. amazonia* im Vergleich zur Referenzfläche. Dieser Effekt kann auf die starke Verbreitung von konkurrierenden Gräsern zurückgeführt werden, welche durch den Anbau von Bohnen, Reis und Maniok kaum unterdrückt wurden. Im Gegensatz zu diesem Ergebnis wurde jedoch festgestellt, dass die Mortalität in Maniokfeldern deutlich niedriger als in anderen Feldfruchtwechseln war. Dieser Effekt wurde jedoch lediglich für *T. amazonia* als signifikant belegt. Die tendenziell geringere Mortalität kann auf die längere Rotationsperiode der Maniokpflanzen von zwölf Monaten zurückgeführt werden, wodurch diese eine moderate Beschattung der Sämlinge während der ersten Trockenzeit und somit Schutz vor extremer Sonneneinstrahlung und Verdunstung bot.

Der deutlichste Effekt auf das Baumwachstum wurde durch die Beipflanzung von Straucherbsen festgestellt. Während der sechsmonatigen Wachstumsphase der Feldfrucht wiesen die Baumarten *A. graveolens*, *C. odorata* und *T. amazonia* einen bis zu viermal höheren Zuwachs als in reinen Forstplantagen auf. Dieser Effekt kann hauptsächlich auf die starke Unterdrückung des Begleitwuchses, insbesondere der exotischen Weidegräser, durch die bis zu 3 m hohen Sträucher zurückgeführt werden. Weitere Erklärungsansätze liefert die stickstoffspeichernde Wirkung der Straucherbsen, die schnelle Mineralisierung des nährstoffreichen Laubes und die Auflockerung der Erde durch die rasche Wurzelentwicklung. Sogar sechs Monate nach der Ernte der Sträucher waren die Baumarten *A. graveolens*, *C. odorata* und *T. amazonia* auf den ehemaligen Straucherbsenfeldern immer noch signifikant höher als auf den Vergleichsflächen. Hingegen zeigte keine der anderen Beipflanzungen einen über Baumarten hinweg konsistenten, längerfristigen Effekt. Ein solcher wurde lediglich für *C. odorata* festgestellt. Der Anbau dieser Wertholzart in reinen Frostplantagen wird bisher weitgehend durch den Mahagonietriebbohrer (*Hypsipyla grandella*) verhindert, der die Triebspitzen und den Stamm befällt und so zu Wachstumseinbußen und starker Qualitätsminderung führt. Durch die Beipflanzung von Straucherbsen, Mais und Maniok konnte die Befallsrate im Vergleich zu reinen Forstflächen hier signifikant reduziert und somit das Wachstum und die Qualität deutlich verbessert werden. Die krautigen und niedrigwüchsigen Feldfrüchte Bohnen, Reis und Sojabohnen zeigten diesen Effekt nicht, da sie keine laterale Beschattung erzeugten. Die simultane landwirtschaftliche Nutzung hatte damit keinen negativen Einfluss auf die Entwicklung der jungen Forstplantage - H1 wurde bestätigt. Im Gegenteil kann der Anbau von Feldfrüchten sogar den Anwuchserfolg und das Wachstum der forstlichen Komponente erhöhen.

Die Einzelbaumanalyse ergab eine negative Korrelation zwischen individueller Standraumkonkurrenz und Zuwachs. Der Zusammenhang war jedoch schwach ausgeprägt. Die Ergebnisse zeigen aber, dass der negative Einfluss kaum nachweisbar war, wenn extrem kleine Abstände von weniger als einem Meter zwischen Baumsämling und Feldfrucht vermieden wurden.

Ein weiteres, wichtiges Ergebnis, welches jedoch nicht direkt mit dem Agroforstversuch in Verbindung steht, ist die Tatsache, dass der relative Standort im Mikrorelief sogar auf der ebenen Versuchsfläche einen signifikanten Einfluss auf das Baumwachstum hatte. Anwuchserfolg und Wachstum waren für alle Baumarten deutlich reduziert, wenn der Baumsämling in einer Mulde, im Vergleich zu einer relativen Kuppe bzw. Kuppenschulter gepflanzt wurde. Es wird insbesondere auf tonigen Böden empfohlen das Mikrorelief während der Pflanzung mit einzubeziehen, auch wenn so von dem häufig verbreiteten, exakten Pflanzraster abgewichen werden muss.

Erträge von Mais, Straucherbsen und Bohnen lagen im Bereich des panamaischen Durchschnitts, während die Erträge von Ingwer, Maniok, Sojabohnen und Reis durch die starke Staunässe und den Verzicht auf Agrochemikalien sehr gering waren. Weder die Baumartenkombination noch der Pflanzabstand hatten einen signifikanten Einfluss auf die Erträge währen der ersten 18 Monate. Es wird vermutet, dass solche Effekte erst im weiteren Verlauf der Bestandsentwicklung nachweisbar würden. H2 und H3 konnten somit nicht bestätigt werden. Der einzige Unterschied, der daher in der ökonomischen Bewertung mit einbezogen wurde, ist die Reduzierung der landwirtschaftlichen Anbaufläche durch den Standraum der Bäume.

Die finanzielle Bewertung der Agroforstsysteme zeigte, dass die Etablierungskosten der Forstplantage nicht vollständig durch die simultane Landwirtschaft kompensiert werden konnten. Allerdings wurden bereits in den folgenden Jahren positive Zahlungsströme erwirtschaftet – H4a wurde bestätigt. Auf Grund von Daten zur Höhen und Kronenentwicklung der Baumarten konnte der maximale Zeitraum für eine solche temporäre Zwischenpflanzung ermittelt werden. Dieser beträgt in *T. grandis* Beständen maximal zwei und in Beständen aus einheimischen Baumarten maximal vier Jahre.

Betrachtet man die gesamte Umtriebszeit, so wiesen alle Baum-Feldfrucht Kombinationen einen höheren Kapitalwert auf als die reine Aufforstung. Dies galt sogar für die Beipflanzung von Maniok, obwohl der Anbau dieser Feldfrucht nur zu geringen Erträgen führte, durch welche jedoch der Großteil der Pflegekosten für die Bäume kompensiert wurde. So lag der Kapitalwert (bei einer Umtriebszeit von 25 Jahren) um bis zu 26% über dem der reinen Forstplantage, während die gleichzeitige Pflanzung von Mais-Bohnen-Mais und Straucherbsen einen bis zu 50% höheren Kapitalwert lieferte. Bei einer Verzinsung von 6% und einer Umtriebszeit von 25 Jahren wurde das beste finanzielle Ergebnis durch die Kombination von *T. grandis* und Straucherbsen mit einem Kapitalwert von 17,836 $/ha (entspricht einer internen Verzinsung von 15%, exklusive Landkauf) erreicht. Dieses Ergebnis wird durch die hohe Volumenproduktion sowie den vergleichsweise hohen Holzpreisen für *T. grandis* kombiniert mit der weniger arbeitsintensiven Bewirtschaftungsweise von Straucherbsen bei gleichzeitig hohen Erbsenpreisen erreicht. Für die einheimischen Baumarten *T. amazonia*, *C. odorata* und *H. alchorneoides* errechnete sich eine interne Verzinsungen von 10% in reinen Forstplantagen, während die langsam wachsenden Arten *D. retusa* und *A. graveolens* innerhalb einer Umtriebszeit von 25 Jahren in Monokultur nur 2-3% erreichten. Die interne Verzinsung der agroforstlichen Anbausysteme lag für alle Baumarten zwischen 2-4% höher als das Ergebnis in den entsprechenden reinen Forstsystemen, wobei die Beipflanzung von Straucherbsen den höchsten, die von Maniok den niedrigsten Mehrwert zeigte. Alle Agroforstsysteme, mit Ausnahme der Kombinationen mit *D. retusa* und *A. graveolens*, erreichten ein höheres finanzielles Ergebnis als die entsprechenden reinen landwirtschaftlichen Systeme. Dies gilt auch gegenüber der als Vergleich herangezogenen Viehwirtschaft. Sogar reine Forstwirtschaft konnte – über den Zeitraum von 25 Jahren gesehen - durch die verhältnismäßig hohen Einnahmen aus Durchforstung und Holzernte mit der im Versuchsgebiet verbreiteten extensiven Viehwirtschaft konkurrieren. H4b konnte damit außer für die Baumarten *D. retusa* und *A. graveolens* bestätigt werden.

Die Sensitivitätsanalyse belegte, dass der Kapitalwert der Agroforstsysteme weniger anfällig hinsichtlich Veränderungen in Einnahmen oder Ausgaben ist als der reiner Forst- oder Landwirtschaft. So konnte das Agroforstkonzept trotz des höheren Arbeitsaufwandes sogar unter der Annahme eines Anstieges der Lohn- und Materialkosten um 50% immer noch mit anderen Landnutzungen konkurrieren. Weniger arbeitsintensive Zwischenpflanzungen wie Straucherbsen waren dabei robuster gegenüber Preissteigerungen im Verhältnis zur arbeitsintensiven Mais-Bohnen-Mais Rotation. Es wurde allerdings auch gezeigt, dass die forstliche und agroforstliche Landnutzung angesichts der aktuellen Preissteigerung von Nahrungsmitteln finanziell kaum mehr mit reiner Landwirtschaft konkurrieren kann. In Verbindung mit unsicheren Holzpreisen lässt dies die Aufforstung für Landbesitzer unattraktiv erscheinen. Die vorliegende Studie verdeutlichte jedoch, dass die hohe Abhängigkeit der Investition in eine Aufforstung von den Rückflüssen aus der Holzernte durch den gleichzeitigen Anbau von Kulturpflanzen im Jugendstadium stark reduziert werden kann. Dies gilt insbesondere für einheimische Baumarten, da diese die landwirtschaftliche Nutzung während eines längeren Zeitraumes erlauben. Entsprechend konnte der notwendige Bestandsendwert bei einer moderaten Zinsforderung von 6% durch die landwirtschaftliche Nebennutzung um bis zu 90% reduziert werden. So stellt die Aufforstung auch unter der Annahme niedriger Holzpreise eine rentable Landnutzungsalternative dar.

Schlussfolgerungen und Empfehlungen

Die Untersuchung führt zu dem Ergebnis, dass aus waldbaulicher Sicht keine Einschränkungen durch die gleichzeitige landwirtschaftliche Nutzung junger Aufforstungsflächen zu erwarten sind. Im Gegenteil wurden sogar waldbauliche und ökonomische Vorteile identifiziert, die zur Überwindung grundlegender Hindernisse der tropischen Aufforstung beitragen können. Insbesondere kann die Einbringung von Kulturpflanzen die vorherrschende Konkurrenzvegetation eindämmen und damit den Anwuchserfolg und das Wachstum der Bäume deutlich verbessern sowie die hohen Kosten zur Unkrautbekämpfung reduzieren. Pflegekosten für die Land- aber auch Forstwirtschaft können durch den Verkauf der landwirtschaftlichen Erträge kompensiert werden, wodurch bereits während der ersten Jahre positive Nettozahlungsströme erreicht werden. Das geringere Wachstum einheimischer Baumarten im Jungendstadium, welches häufig zur Verwendung exotischer Arten führt, hat hier jedoch einen entscheidenden Vorteil, da der Zwischenanbau von Kulturpflanzen über einen längeren Zeitraum möglich ist. Das untersuchte Agroforstkonzept hat insgesamt eine hohe praktische Relevanz, da es leicht durch die Auswahl geeigneter Forst- und Kulturpflanzen und entsprechender Pflanzabstände auf individuelle Bedürfnisse von Klein- und Großgrundbesitzer angepasst werden kann. Diese Studie liefert hierzu Erfahrungen mit 36 Baum-Feldfrucht Kombinationen. Generell sollten Kulturpflanzen, die die Fähigkeit haben Gräser rasch zu unterdrücken, bevorzugt werden. Strauchige Arten sind insbesondere im Jahr der Baumpflanzung (bzw. bis zur ersten Trockenzeit) zu empfehlen, da hochwachsende Arten mit einer kurzen Kulturphase (wie z.B. Mais) zu einer erhöhten Mortalität der jungen Bäume führen können. In kommerziellen Aufforstungen sollten Arten gewählt werden, die während der Trockenzeit – in der meist weniger forstliche Arbeiten in jungen Forstplantagen anfallen – geerntet werden, wie z.B. Bohnen oder Erbsen. So können Arbeitsplätze geschaffen und ein effizienter Einsatz der Arbeitskraft erreicht werden. Zukünftige Studien sollten auch die spätere Einbringung von schattentoleranten Arten oder Tieren in Forstplantagen untersuchen, um so eine dauerhafte Intensivierung der Flächennutzung zu erreichen. Weitere Erfolgsfaktoren zur Förderung (agro)forstlicher Landnutzungsformen sind die Bereitstellung von Informationen über Holzmärkte, Hilfe bei der Vermarktung und die Vereinfachung von Erntegenehmigungen für Aufforstungen.

Vor dem Hintergrund einer wachsenden Weltbevölkerung mit einer steigenden Nachfrage nach Nahrungs- und Energieressourcen erscheint die landwirtschaftliche Nutzung der in jungen Forstplantagen zur Verfügung stehenden Flächen als sinnvoll, um einerseits die Aufforstung als Landnutzung konkurrenzfähig zu gestalten, aber auch einen Beitrag zur Nahrungsmittelsicherheit zu leisten. Die notwendige Übertragung dieses Landnutzungskonzepts von der kleinbäuerlichen auf eine industrielle Ebene erfordert jedoch eine moderne Betrachtung solcher silvoarablen Systeme in Wissenschaft und Politik. Im Rahmen des vorgeschlagenen Agroforstkonzeptes können degradierte oder brach liegende Flächen ökonomisch und ökologisch aufgewertet werden und so eine bedeutende Rolle zur Lösung von Landnutzungskonflikten spielen.

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11 Appendix

Tables

Figures

Table 11.1: Content of cations and Olsen P by plot, sampling type (ST) and Intercropping Treatment (Treatment). 95% confidence intervals are given in brackets (AF = agroforestry, FP = pure forest plantation, CP = pure agriculture, N = sample size, for abbreviations of Treatment see Table 3.7)

Plot #	ST	N	Ca [µmol IE/g]		Mg [µmol IE/g]		Na [µmol IE/g]		K [µmol IE/g]		Al [µmol IE/g]		Fe [µmol IE/g]		Mn [µmol IE/g]		Olsen P [mg/kg]	
1	AF	6	663.6	(598.2 - 729.0)	156.6	(139.9 - 173.3)	4.9	(3.4 - 6.4)	14.1	(11.2 - 17.0)	0.2	(0.0 - 0.8)	0.0	(0.0 - 0.1)	5.4	(2.7 - 8.1)	7.2	(2.7 - 11.6)
2	AF	6	709.9	(657.9 - 761.9)	178.8	(157.7 - 199.9)	6.1	(4.8 - 7.4)	20.6	(8.4 - 32.8)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	5.2	(2.2 - 8.2)	12.6	(1.4 - 23.7)
3	AF	6	609.8	(528.2 - 691.5)	149.1	(135.0 - 163.1)	5.4	(4.2 - 6.6)	16.4	(12.0 - 20.8)	0.2	(0.0 - 0.4)	0.0	(0.0 - 0.0)	7.8	(2.5 - 13.0)	20.9	(4.2 - 46.0)
4	AF	6	675.7	(606.0 - 745.3)	162.5	(134.4 - 190.6)	7.1	(5.1 - 9.2)	11.8	(8.6 - 15.0)	0.2	(0.0 - 0.6)	0.2	(0.1 - 0.5)	3.8	(2.0 - 5.5)	4.6	(2.4 - 6.9)
5	AF	6	753.3	(721.4 - 785.2)	156.7	(129.6 - 183.9)	5.7	(4.0 - 7.4)	12.4	(8.6 - 16.3)	0.2	(0.0 - 0.6)	0.0	(0.0 - 0.1)	3.8	(3.1 - 4.5)	15.9	(1.2 - 30.7)
6	AF	6	712.3	(621.0 - 803.6)	174.3	(164.2 - 184.5)	5.2	(3.9 - 6.4)	15.2	(13.2 - 17.2)	0.2	(0.0 - 0.5)	0.0	(0.0 - 0.0)	5.9	(0.6 - 11.1)	42.4	(35.4 - 49.3)
7	AF	4	899.3	(703.0 - 1095.6)	150.7	(119.8 - 181.7)	4.7	(2.8 - 6.7)	19.1	(3.6 - 34.6)	0.0		0.2	(0.1 - 0.6)	2.2	(0.1 - 5.0)	38.4	(10.2 - 66.5)
8	AF	6	844.6	(778.6 - 910.5)	158.0	(136.8 - 179.3)	4.5	(3.9 - 5.1)	17.0	(13.8 - 20.2)	0.3	(0.1 - 0.5)	0.0	(0.1 - 0.2)	2.3	(1.4 - 3.2)	39.4	(12.5 - 66.3)
9	AF	6	790.1	(733.5 - 846.6)	148.8	(105.0 - 192.6)	5.7	(4.0 - 7.4)	21.5	(5.8 - 37.2)	2.0	(0.0 - 5.5)	0.0	(0.0 - 0.1)	6.4	(1.4 - 11.4)	60.1	(42.6 - 77.7)
10	AF	6	827.1	(768.3 - 885.8)	164.8	(130.9 - 198.8)	5.6	(4.4 - 6.9)	14.3	(7.7 - 20.9)	0.9	(0.0 - 2.7)	0.0	(0.0 - 0.0)	4.1	(1.3 - 6.8)	26.6	(4.6 - 48.6)
11	AF	6	827.0	(707.1 - 946.9)	189.9	(173.7 - 206.2)	6.3	(5.3 - 7.3)	9.0	(4.7 - 13.2)	1.0	(0.0 - 3.0)	0.1	(0.1 - 0.4)	6.4	(4.9 - 7.9)	60.0	(49.6 - 70.4)
12	AF	6	874.6	(820.4 - 928.7)	179.0	(157.3 - 200.8)	4.4	(3.6 - 5.2)	20.9	(12.6 - 29.2)	0.1	(0.0 - 0.3)	0.1	(0.1 - 0.3)	4.8	(2.3 - 7.3)	57.6	(27.6 - 87.7)
13	AF	6	872.2	(799.6 - 944.8)	198.4	(144.5 - 252.3)	5.7	(4.3 - 7.1)	16.3	(10.2 - 22.4)	0.1	(0.0 - 0.3)	0.0	(0.0 - 0.0)	3.4	(1.8 - 5.0)	39.9	(12.8 - 67.0)
14	AF	6	792.4	(661.0 - 923.8)	225.8	(200.6 - 251.0)	7.0	(3.8 - 10.2)	17.3	(2.2 - 32.5)	1.1	(0.0 - 3.6)	0.0	(0.0 - 0.0)	4.7	(2.6 - 6.8)	32.8	(13.6 - 52.0)
15	AF	6	715.2	(654.8 - 775.7)	161.3	(133.9 - 188.7)	6.8	(4.7 - 8.9)	9.6	(4.8 - 14.5)	0.3	(0.0 - 1.0)	0.0	(0.0 - 0.1)	8.0	(3.5 - 12.4)	39.1	(35.2 - 43.1)
16	AF	6	777.7	(680.6 - 874.7)	163.7	(133.0 - 194.3)	4.9	(4.3 - 5.6)	17.7	(13.1 - 22.4)	0.7	(0.0 - 1.7)	0.0	(0.0 - 0.1)	4.7	(2.7 - 6.8)	44.8	(34.2 - 55.3)
17	FP	6	725.4	(678.9 - 771.9)	182.7	(172.2 - 193.3)	6.3	(5.0 - 7.6)	15.9	(12.3 - 19.5)	0.4	(0.0 - 0.9)	0.0	(0.0 - 0.0)	3.0	(1.3 - 4.7)	25.3	(2.0 - 48.6)
18	FP	6	655.8	(583.7 - 727.9)	186.9	(156.6 - 217.2)	5.7	(4.5 - 7.0)	16.8	(12.3 - 21.4)	0.4	(0.0 - 1.5)	0.0	(0.0 - 0.0)	4.5	(2.0 - 7.0)	18.5	(7.1 - 30.0)
19	FP	6	701.5	(638.6 - 764.4)	178.1	(170.1 - 186.1)	5.3	(3.1 - 7.6)	17.3	(14.7 - 19.9)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	3.8	(2.4 - 5.2)	19.2	(2.7 - 35.7)
20	FP	6	719.0	(643.0 - 795.0)	177.1	(169.3 - 184.8)	4.7	(3.5 - 5.9)	17.7	(9.9 - 25.6)	0.2	(0.0 - 0.6)	0.0	(0.0 - 0.0)	4.1	(2.7 - 5.6)	12.6	(9.3 - 15.8)
I	CP	1	574.3		125.3		3.3		22.5		18.0		0.0		5.1		7.0	
II	CP	2	754.4	(343.1 - 1165.8)	145.8	(141.2 - 150.4)	4.0	(0.0 - 10.4)	10.3	(0.0 - 72.1)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	1.1	(0.1 - 13.3)	21.7	(0.0 - 244.4)
III	CP	2	661.2	(623.1 - 699.2)	121.6	(115.3 - 127.9)	4.2	(2.6 - 5.9)	13.7	(0.0 - 39.7)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	9.5	(0.0 - 30.3)	1.1	(0.0 - 10.3)
IV	CP	2	729.2	(511.7 - 946.7)	121.1	(71.1 - 171.1)	4.6	(0.0 - 17.3)	12.5	(0.0 - 45.6)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	5.0	(0.1 - 32.6)	2.3	(0.0 - 33.0)
V	CP	2	689.9	(467.5 - 912.3)	146.9	(128.1 - 165.8)	4.3	(0.0 - 9.4)	11.3	(0.0 - 35.6)	0.2	(0.0 - 2.7)	0.0	(0.0 - 0.0)	4.1	(0.0 - 10.2)	18.5	(0.0 - 101.5)
VI	CP	2	677.7	(420.4 - 935.0)	144.0	(126.5 - 161.6)	4.9	(0.0 - 24.9)	12.1	(11.9 - 12.3)	0.0	(0.0 - 0.3)	0.0	(0.0 - 0.0)	9.0	(4.9 - 13.2)	25.6	(0.0 - 115.1)
VII	CP	2	709.1	(544.2 - 873.9)	94.5	(44.3 - 144.7)	4.9	(0.0 - 10.4)	6.3	(0.0 - 23.3)	0.0	(0.0 - 0.3)	0.0	(0.0 - 0.0)	8.7	(0.1 - 92.5)	7.2	(4.6 - 9.8)
VIII	CP	2	639.0	(543.9 - 734.1)	133.4	(72.8 - 194.1)	4.8	(0.0 - 12.0)	12.7	(0.0 - 90.7)	0.5	(0.0 - 6.4)	0.0	(0.1 - 0.5)	12.5	(0.1 - 53.8)	14.2	(4.3 - 32.8)
IX	CP	2	762.1	(115.4 - 1639.6)	136.2	(0.0 - 340.9)	3.6	(3.4 - 3.7)	16.8	(0.0 - 43.7)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	5.1	(0.1 - 42.1)	28.2	(0.0 - 313.5)
X	CP	2	768.6	(206.8 - 1330.3)	134.5	(0.0 - 407.6)	3.5	(0.0 - 12.6)	9.6	(0.0 - 39.3)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	4.1	(0.1 - 19.8)	38.8	(0.0 - 355.2)
XI	CP	2	683.9	(652.2 - 715.6)	150.7	(144.4 - 157.0)	17.8	(0.0 - 189.6)	21.2	(0.0 - 93.4)	0.0	(0.0 - 0.0)	0.0	(0.0 - 0.0)	5.1	(0.1 - 14.1)	13.1	(0.0 - 110.3)

Table 11.1 (continued): Content of cations and Olsen P by plot, sampling type (ST) and Intercropping Treatment (Treatment). 95% confidence intervals are given in brackets (AF = agroforestry, FP = pure forest plantation, CP = pure agriculture, N = sample size, for abbreviations of Treatment see Table 3.7)

Plot #	ST	N	Ca [µmol IE/g]	Mg [µmol IE/g]	Na [µmol IE/g]	K [µmol IE/g]	Al [µmol IE/g]	Fe [µmol IE/g]	Mn [µmol IE/g]	Olsen P [mg/kg]
XII	CP	2	709.2 (280.0 - 1138.5)	150.1 (0.0 - 434.3)	4.1 (0.0 - 22.1)	14.8 (0.0 - 102.1)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	6.9 (0.1 - 36.1)	37.4 (0.0 - 465.2)
XIII	CP	2	625.3 (184.1 - 1066.6)	200.1 (16.3 - 383.9)	4.1 (0.0 - 11.2)	15.6 (11.2 - 19.9)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	5.5 (0.1 - 27.4)	21.9 (0.0 - 166.5)
XIV	CP	2	617.6 (516.1 - 719.0)	173.4 (0.0 - 370.0)	3.9 (0.0 - 8.1)	14.5 (0.0 - 29.8)	0.2 (0.0 - 3.0)	0.0 (0.0 - 0.0)	6.7 (5.4 - 8.0)	5.2 (0.0 - 109.7)
XV	CP	2	609.1 (133.6 - 1084.6)	214.4 (0.0 - 768.6)	4.4 (0.0 - 9.0)	12.8 (5.3 - 20.2)	0.0 (0.0 - 0.0)	0.0 (0.0 - 0.0)	4.9 (0.1 - 12.7)	31.4 (0.0 - 430.2)
XVI	CP	2	707.7 (310.2 - 1105.3)	178.1 (0.0 - 357.7)	6.2 (0.0 - 18.7)	10.0 (8.2 - 11.8)	0.1 (0.0 - 1.8)	0.0 (0.0 - 0.0)	3.2 (0.1 - 22.8)	24.9 (0.0 - 199.5)
outside trial		10	805.5	162.4	4.7	13.9	0.0	0.0	4.3	
Total		*159*	*743.9 (727.8 - 760.1)*	*167.1 (162.1 - 172.1)*	*5.5 (5.1 - 5.9)*	*15.4 (14.3 - 16.4)*	*0.6 (0.1 - 1.0)*	*0.0 (0.0 - 0.0)*	*5.0 (4.5 - 5.4)*	*27.0 (23.5 - 30.5)*

Table 11.2: Schwarz's Bayesian Information Criterion (BIC) to assess goodness-of-fit of the defined model including fixed factors treatment and microrelief and random factor plot nr, as described in Equation 3.2. BIC is reported for ln-transformed height (ln(h)) and diameter (ln(d)) increment of target trees by tree species and time period.

Tree species	**time period [months after planting]**							
	0-3		**0-9**		**9-18**		**18-24**	
	ln(h)	**ln(d)**	**ln(h)**	**ln(d)**	**ln(h)**	**ln(d)**	**ln(h)**	**ln(d)**
A. graveolens	7.7	-109.1	31.6	-78.3	-57.3	-128.1	6.0	97.6
C. odorata	40.5	-24.2	35.7	-22.4	111.0	27.8	70.9	149.0
D. retusa	105.3	-77.9	109.8	-3.6	15.8	-28.2	54.4	110.1
H. alchorneoides	-47.7	-76.5	17.6	-20.9	-15.8	-37.3	9.2	67.1
T. grandis	41.8	-26.6	64.0	-23.7	-34.4	-140.5	50.2	89.5
T. amazonia	75.8	-64.7	55.8	-51.0	10.8	-61.0	42.3	30.1

Table 11.3: Estimation of fixed parameters (b) for effects of treatment and microrelief and their standard errors (SE) on the independent variable height increment of target trees in different time periods (ln-transformed) (see Equation 3.2). Both, Pure forest plantation treatment (FP) and a planting position in a relative depression were set zero (See Equation (3.2).

Tree species	Parameter (Treatment)	Time interval [months after tree establishment]											
		0-3			0-9			9-18			18-24		
		b	SE	p	b	SE	p	b	SE	p	b	SE	p
Terminalia amazonia	Intercept	3.64	0.12	<0.01	4.35	0.09	<0.01	5.41	0.09	<0.01	5.17	0.09	<0.01
	G-P	0.16	0.17	0.38	-0.01	0.12	0.92	0.27	0.12	0.04	0.14	0.13	0.28
	M-B-M-M	0.55	0.17	0.01	-0.02	0.12	0.86	<0.01	0.12	0.99	0.03	0.13	0.84
	B-R-R	0.06	0.17	0.71	-0.37	0.12	0.01	-0.11	0.12	0.37	-0.01	0.13	0.97
	C-S	0.11	0.17	0.54	-0.17	0.12	0.20	-0.10	0.12	0.41	0.13	0.13	0.32
	FP	0			0			0			0		
	microrelief	-0.06	0.09	0.49	-0.01	0.08	0.87	-0.03	0.06	0.65	0.08	0.08	0.30
Cedrela odorata	Intercept	3.73	0.09	<0.01	4.54	0.09	<0.01	4.68	0.10	<0.01	5.12	0.11	<0.01
	G-P	0.14	0.12	0.28	-0.30	0.12	0.03	0.92	0.15	<0.01	-0.14	0.16	0.39
	M-B-M-M	0.51	0.12	<0.01	-0.14	0.12	0.28	0.36	0.15	0.02	0.19	0.16	0.26
	B-R-R	0.05	0.12	0.66	-0.14	0.12	0.27	0.30	0.15	0.06	0.07	0.16	0.67
	C-S	-0.01	0.12	0.92	-0.04	0.12	0.74	0.47	0.15	0.01	0.10	0.16	0.54
	FP	0			0			0			0		
	microrelief	-0.11	0.06	0.10	-0.15	0.06	0.02	-0.23	0.10	0.02	0.15	0.08	0.05
Dalbergia retusa	Intercept	3.97	0.11	<0.01	4.92	0.14	<0.01	5.13	0.05	<0.01	5.07	0.11	<0.01
	G-P	0.11	0.14	0.47	-0.10	0.20	0.64	0.11	0.07	0.15	-0.12	0.15	0.45
	M-B-M-M	0.47	0.15	0.01	-0.30	0.21	0.17	0.08	0.08	0.32	0.08	0.15	0.62
	B-R-R	0.15	0.14	0.31	-0.04	0.20	0.84	-0.12	0.07	0.10	0.17	0.15	0.28
	C-S	0.02	0.14	0.91	0.04	0.20	0.85	0.03	0.07	0.69	0.06	0.15	0.67
	FP	0			0			0			0		
	microrelief	-0.15	0.11	0.17	-0.24	0.12	0.04	0.22	0.07	<0.01	0.11	0.08	0.20
Tectona grandis	Intercept	3.82	0.14	<0.01	4.89	0.14	<0.01	6.04	0.07	<0.01	5.58	0.09	<0.01
	G-P	0.25	0.18	0.20	0.14	0.18	0.44	0.04	0.09	0.68	0.30	0.12	0.02
	M-B-M-M	0.32	0.18	0.11	-0.22	0.18	0.25	-0.01	0.09	0.89	-0.02	0.12	0.85
	B-R-R	0.24	0.18	0.20	0.09	0.18	0.63	0.04	0.09	0.64	-0.09	0.12	0.48
	C-S	0.06	0.18	0.76	0.07	0.18	0.69	-0.27	0.09	0.01	0.16	0.12	0.21
	FP	0			0			0			0		
	microrelief	-0.20	0.09	0.04	-0.45	0.11	<0.01	-0.09	0.06	0.15	0.18	0.10	0.08
Hieronyma alchorneoides	Intercept	3.81	0.04	<0.01	4.33	0.07	<0.01	5.31	0.07	<0.01	4.94	0.07	<0.01
	G-P	0.12	0.05	0.02	-0.18	0.09	0.06	-0.04	0.09	0.67	-0.20	0.09	0.05
	M-B-M-M	0.19	0.06	<0.01	-0.29	0.11	0.02	-0.12	0.11	0.27	0.02	0.11	0.88
	B-R-R	0.10	0.06	0.07	-0.22	0.10	0.04	-0.07	0.10	0.52	-0.13	0.10	0.21
	C-S	0.07	0.05	0.18	-0.10	0.09	0.30	-0.28	0.09	0.01	-0.04	0.09	0.67
	FP	0			0			0			0		
	microrelief	-0.03	0.07	0.65	-0.21	0.13	0.11	-0.01	0.09	0.89	-0.04	0.11	0.70
Astronium graveolens	Intercept	3.75	0.05	<0.01	4.76	0.06	<0.01	5.25	0.05	<0.01	4.87	0.07	<0.01
	G-P	-0.17	0.07	0.02	-0.25	0.08	0.01	0.23	0.07	<0.01	0.04	0.09	0.65
	M-B-M-M	0.04	0.07	0.62	-0.31	0.08	<0.01	0.01	0.07	0.89	0.01	0.09	0.90
	B-R-R	-0.02	0.07	0.76	-0.43	0.08	<0.01	0.17	0.07	0.02	0.10	0.09	0.30
	C-S	-0.06	0.07	0.43	-0.25	0.08	0.01	-0.08	0.07	0.27	-0.05	0.09	0.60
	FP	0			0			0			0		
	microrelief	-0.08	0.10	0.43	0.03	0.12	0.79	0.05	0.07	0.46	0.05	0.10	0.60

Table 11.4: Estimation of fixed parameters (b) for effects of treatment and microrelief and their standard errors (SE) on the independent variable root collar diameter increment of target trees in different time periods (ln-transformed) (see Equation (3.2). Both, Pure forest plantation treatment (FP) and a planting position in a relative depression were set zero.

Tree species	Parameter (Treatment)	Time interval [months after tree establishment]											
		0-3			0-9			9-18			18-24		
		b	SE	p	b	SE	p	b	SE	p	b	SE	p
Terminalia amazonia	Intercept	2.82	0.06	<0.01	3.37	0.05	<0.01	4.09	0.05	<0.01	3.34	0.09	<0.01
	G-P	0.02	0.09	0.80	-0.11	0.06	0.12	-0.15	0.08	0.07	0.38	0.12	0.01
	M-B-M-M	-0.09	0.09	0.32	-0.26	0.06	<0.01	0.01	0.08	0.90	-0.09	0.12	0.46
	B-R-R	-0.04	0.09	0.67	-0.25	0.06	<0.01	-0.10	0.08	0.20	-0.15	0.12	0.25
	C-S	<0.01	0.09	0.98	-0.20	0.06	0.01	-0.23	0.08	0.01	0.17	0.12	0.18
	FP	0			0			0			0		
	microrelief	-0.06	0.04	0.17	-0.07	0.05	0.16	<0.01	0.04	0.97	-0.02	0.07	0.77
Cedrela odorata	Intercept	3.27	0.07	<0.01	3.79	0.06	<0.01	4.05	0.07	<0.01	2.77	0.21	<0.01
	G-P	0.01	0.10	0.91	-0.01	0.08	0.90	0.09	0.10	0.40	0.29	0.30	0.34
	M-B-M-M	-0.27	0.10	0.02	-0.21	0.08	0.02	0.24	0.10	0.03	0.28	0.30	0.36
	B-R-R	-0.02	0.10	0.85	-0.11	0.09	0.22	0.13	0.10	0.20	-0.02	0.30	0.94
	C-S	-0.17	0.10	0.10	-0.15	0.09	0.09	0.14	0.10	0.19	0.38	0.30	0.23
	FP	0			0			0			0		
	microrelief	-0.07	0.05	0.15	-0.06	0.05	0.18	-0.07	0.06	0.27	<0.01	0.11	0.97
Dalbergia retusa	Intercept	3.12	0.04	<0.01	3.73	0.06	<0.01	4.02	0.04	<0.01	2.92	0.11	<0.01
	G-P	0.01	0.05	0.78	-0.04	0.09	0.63	-0.21	0.06	<0.01	-0.11	0.15	0.48
	M-B-M-M	-0.08	0.05	0.13	-0.10	0.09	0.29	-0.15	0.06	0.03	0.14	0.15	0.38
	B-R-R	-0.05	0.05	0.29	-0.07	0.09	0.41	-0.14	0.06	0.04	0.12	0.14	0.40
	C-S	-0.02	0.05	0.74	-0.12	0.09	0.20	-0.14	0.06	0.04	0.22	0.15	0.16
	FP	0			0			0			0		
	microrelief	-0.09	0.04	0.03	-0.13	0.06	0.04	0.02	0.05	0.75	0.01	0.11	0.90
Tectona grandis	Intercept	3.29	0.09	<0.01	3.83	0.08	<0.01	4.36	0.03	<0.01	3.55	0.20	<0.01
	G-P	0.01	0.12	0.91	0.10	0.11	0.37	<0.01	0.04	0.98	0.38	0.27	0.17
	M-B-M-M	-0.16	0.12	0.21	-0.15	0.11	0.19	0.05	0.04	0.28	<0.01	0.27	0.99
	B-R-R	0.01	0.12	0.93	0.03	0.11	0.76	0.03	0.04	0.49	-0.12	0.27	0.66
	C-S	-0.15	0.12	0.23	-0.03	0.11	0.80	-0.07	0.04	0.11	0.03	0.27	0.90
	FP	0			0			0			0		
	microrelief	-0.18	0.06	0.01	-0.18	0.07	0.01	-0.03	0.04	0.45	0.06	0.12	0.61
Hieronyma alchorneoides	Intercept	2.95	0.03	<0.01	3.32	0.06	<0.01	4.03	0.08	<0.01	2.97	0.11	<0.01
	G-P	-0.07	0.04	0.13	-0.23	0.08	0.01	-0.16	0.10	0.13	-0.15	0.15	0.34
	M-B-M-M	-0.13	0.05	0.03	-0.27	0.09	0.02	-0.04	0.12	0.73	-0.08	0.18	0.67
	B-R-R	-0.11	0.05	0.03	-0.19	0.09	0.05	-0.04	0.11	0.72	-0.27	0.16	0.13
	C-S	-0.07	0.04	0.13	-0.25	0.08	0.01	-0.17	0.10	0.13	-0.09	0.16	0.58
	FP	0			0			0			0		
	microrelief	-0.10	0.06	0.10	-0.08	0.09	0.38	-0.07	0.07	0.32	0.06	0.16	0.71
Astronium graveolens	Intercept	2.92	0.06	<0.01	3.51	0.04	<0.01	4.12	0.03	<0.01	2.95	0.14	<0.01
	G-P	-0.17	0.08	0.06	-0.22	0.06	<0.01	-0.18	0.05	<0.01	0.19	0.19	0.33
	M-B-M-M	-0.24	0.08	0.01	-0.26	0.06	<0.01	-0.12	0.05	0.02	-0.28	0.19	0.17
	B-R-R	-0.13	0.08	0.12	-0.28	0.06	<0.01	-0.07	0.05	0.14	-0.23	0.19	0.25
	C-S	-0.17	0.08	0.06	-0.32	0.06	<0.01	-0.20	0.05	<0.01	-0.07	0.19	0.73
	FP	0			0			0			0		
	microrelief	-0.02	0.05	0.74	-0.06	0.07	0.38	0.03	0.05	0.56	-0.32	0.16	0.06

Table 11.5: Estimation of fixed parameters (b) and their standard errors (SE) of the effects of treatment and microrelief on the independent variables ln-transformed height (ln(h), ln-transformed root collar diameter (ln(rcd)) and slenderness (h/rcd) of target trees after 24 months (see Equation 3.2). Both, Pure forest plantation treatment (FP) and a planting position in a relative depression were set zero.

Tree species	**Parameter (Treatment)**	**Dependent variable**								
		ln(h)			**ln(rcd)**			**h/rcd**		
		b	SE	p	b	SE	p	b	SE	p
Terminalia amazonia	Intercept	5.83	0.08	<0.01	4.39	0.07	<0.01	4.87	0.32	<0.01
	G-P	0.25	0.11	0.04	0.02	0.10	0.82	1.19	0.45	0.02
	M-B-M-M	0.02	0.11	0.83	-0.11	0.10	0.26	0.80	0.45	0.09
	B-R-R	-0.17	0.11	0.15	-0.24	0.10	0.03	0.60	0.45	0.20
	C-S	-0.03	0.11	0.77	-0.17	0.10	0.09	0.92	0.45	0.06
	FP	0			0			0		
	microrelief	0.01	0.04	0.81	-0.04	0.05	0.43	0.24	0.29	0.40
Cedrela odorata	Intercept	5.54	0.07	<0.01	4.45	0.07	<0.01	3.39	0.28	<0.01
	G-P	0.37	0.10	<0.01	0.11	0.10	0.27	1.00	0.40	0.02
	M-B-M-M	0.25	0.10	0.02	0.12	0.10	0.22	0.42	0.40	0.31
	B-R-R	0.14	0.10	0.16	0.06	0.10	0.57	0.28	0.40	0.49
	C-S	0.28	0.10	0.01	0.13	0.10	0.19	0.50	0.40	0.23
	FP	0			0			0		
	microrelief	-0.05	0.04	0.19	-0.10	0.04	0.02	0.23	0.16	0.16
Dalbergia retusa	Intercept	5.87	0.07	<0.01	4.41	0.05	<0.01	5.03	0.31	<0.01
	G-P	-0.05	0.10	0.60	-0.18	0.07	0.02	0.80	0.43	0.08
	M-B-M-M	-0.05	0.10	0.62	-0.10	0.07	0.16	0.36	0.44	0.42
	B-R-R	-0.05	0.10	0.64	-0.11	0.07	0.11	0.38	0.42	0.39
	C-S	0.01	0.10	0.92	-0.10	0.07	0.17	0.61	0.43	0.17
	FP	0			0			0		
	microrelief	0.05	0.05	0.32	-0.04	0.05	0.37	0.39	0.27	0.15
Tectona grandis	Intercept	6.56	0.07	<0.01	4.82	0.06	<0.01	6.27	0.33	<0.01
	G-P	0.13	0.09	0.18	0.16	0.08	0.09	-0.29	0.44	0.51
	M-B-M-M	-0.10	0.09	0.30	-0.02	0.08	0.86	-0.51	0.44	0.26
	B-R-R	-0.03	0.09	0.73	0.01	0.08	0.93	-0.22	0.44	0.63
	C-S	-0.12	0.09	0.20	-0.06	0.08	0.52	-0.40	0.44	0.38
	FP	0			0			0		
	microrelief	-0.03	0.04	0.45	-0.04	0.04	0.28	0.04	0.29	0.88
Hieronyma alchorneoides	Intercept	5.57	0.07	<0.01	4.23	0.05	<0.01	4.56	0.28	<0.01
	G-P	-0.21	0.09	0.05	-0.30	0.07	<0.01	0.80	0.37	0.05
	M-B-M-M	-0.17	0.11	0.15	-0.18	0.09	0.06	0.17	0.44	0.71
	B-R-R	-0.22	0.10	0.05	-0.21	0.08	0.02	0.14	0.40	0.74
	C-S	-0.28	0.10	0.01	-0.27	0.07	<0.01	0.23	0.38	0.55
	FP	0			0			0		
	microrelief	-0.13	0.10	0.18	-0.08	0.09	0.39	-0.11	0.32	0.73
Astronium graveolens	Intercept	5.72	0.06	<0.01	4.36	0.06	<0.01	4.51	0.24	<0.01
	G-P	0.07	0.08	0.40	-0.18	0.09	0.07	1.49	0.34	<0.01
	M-B-M-M	-0.12	0.08	0.15	-0.30	0.09	<0.01	1.26	0.34	<0.01
	B-R-R	<0.01	0.08	1.00	-0.23	0.09	0.02	1.42	0.34	<0.01
	C-S	-0.21	0.08	0.02	-0.35	0.09	<0.01	1.05	0.34	0.01
	FP	0			0			0		
	microrelief	0.04	0.06	0.50	-0.08	0.07	0.25	0.73	0.41	0.08

Table 11.6: Schwarz's Bayesian Information Criterion (BIC) to assess goodness-of-fit of the defined model including the fixed factors treatment and microrelief and the random factor plot nr., as described in Equation (3.2). BIC is reported for the dependent variables ln-transformed height (ln(h)), diameter (ln(d)) and untransformed slenderness (h/rcd) of target trees after 24 months by tree species.

Tree species	ln(h)	ln(d)	h/rcd
A. graveolens	-98.42	-58.72	266.84
C. odorata	-40.82	-39.27	215.83
D. retusa	-40.12	-54.02	273.20
H. alchorneoides	-98.42	-17.84	161.93
T. grandis	-116.23	-114.56	236.32
T. amazonia	-73.78	-29.77	285.74

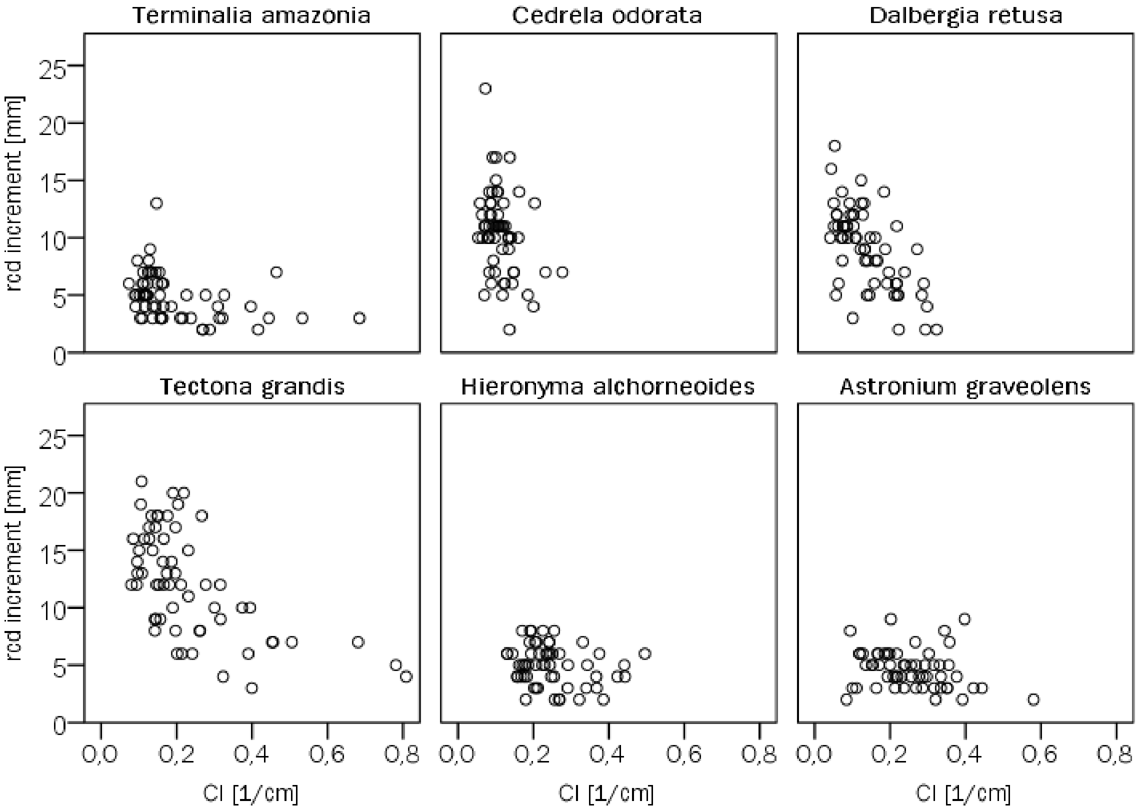

Figure 11.1: Root collar diameter increment (rcd) of trees in maize fields (M-B-M-M treatment) during the first three months plotted against the competition index (CI) at the end of the maize rotation.

Table 11.7: Results of regression analysis with dependent variable height increment between 12 and 15 months ($h_{15}–h_{12}$) and independent variable ln(CI_{maize}) after 15 months in the M-B-M-M treatment. Given are goodness of fit (R^2), intercept (b_0), slope (b_1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$h_{15}–h_{12}$	0.09	40.49	(6.18)	-348.02	(162.72)	0.038
C. odorata	$h_{15}–h_{12}$	0.14	47.70	(8.02)	-410.02	(167.84)	0.020
D. retusa	$h_{15}–h_{12}$	0.02	21.47	(6.86)	-123.47	(179.91)	0.498
H. alchorneoides	$h_{15}–h_{12}$	0.01	34.02	(12.70)	55.44	(258.61)	0.836
T. amazonia	$h_{15}–h_{12}$	0.09	106.49	(7.80)	-871.99	(424.85)	0.047
T. grandis	$h_{15}–h_{12}$	0.07	26.75	(4.72)	-220.77	(122.92)	0.080

Table 11.8: Results of regression analysis with dependent variable root collar diameter increment between 12 and 15 months (rcd15–rcd12) and independent variable ln(CImaize) after 15 months in the M-B-M-M treatment. Given are goodness of fit (R^2), intercept (b0), slope (b1) and p-value of the regression model. Standard errors of estimated coefficients are given in brackets.

Tree species	dependent variable	R^2	b_0		b_1		p-value
A. graveolens	$rcd_{15}–rcd_{12}$	0.01	7.13	(1.01)	-20.78	(26.48)	0.436
C. odorata	$rcd_{15}–rcd_{12}$	0.26	19.66	(2.89)	-216.89	(60.46)	0.001
D. retusa	$rcd_{15}–rcd_{12}$	0.23	9.53	(1.96)	-152.25	(51.36)	0.006
H. alchorneoides	$rcd_{15}–rcd_{12}$	0.15	14.65	(4.56)	-101.54	(92.89)	0.311
T. amazonia	$rcd_{15}–rcd_{12}$	0.01	14.36	(2.19)	65.91	(119.24)	0.583
T. grandis	$rcd_{15}–rcd_{12}$	0.12	9.57	(1.07)	-66.58	(27.65)	0.021

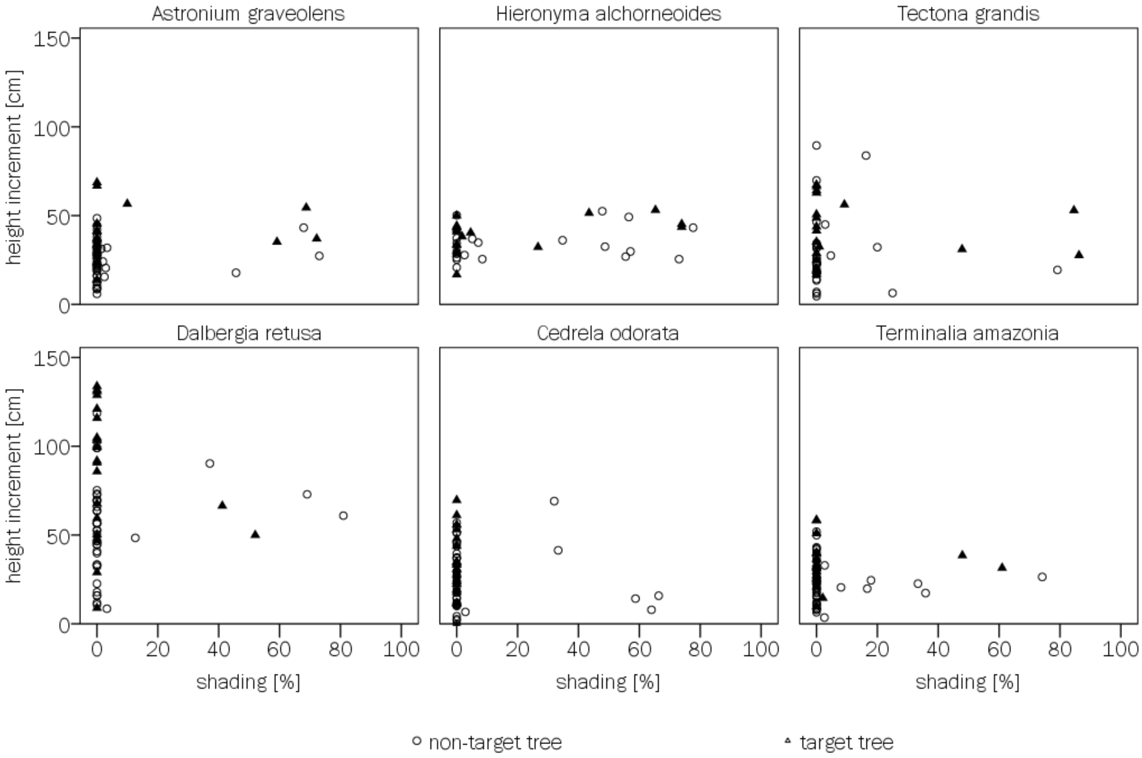

Figure 11.2: Relationship between the height increment of trees during the period from 0 to 6 months in the C-S treatment and the relative shading by cassava, based on PAR measurements. The 20 tallest trees (out of 64) after 24 months ("target trees") are displayed as triangles.

Table 11.9: Factors for conversion of fresh weight into dry weight for pigeon pea by plant fraction. The conversion factor was weighed by the weight proportion of the various plant fractions.

Plant fraction	Weight proportion [%]	Conversion factor for dry matter [%]	Weight proportion*conversion factor [%]
Leaves	7.79	0.50	0.04
Woody debris	23.72	0.47	0.11
Stem	59.35	0.45	0.27
Remaining green pods	7.76	0.53	0.04
Remaining dried pods	1.38	0.81	0.01
Total			***0.47***

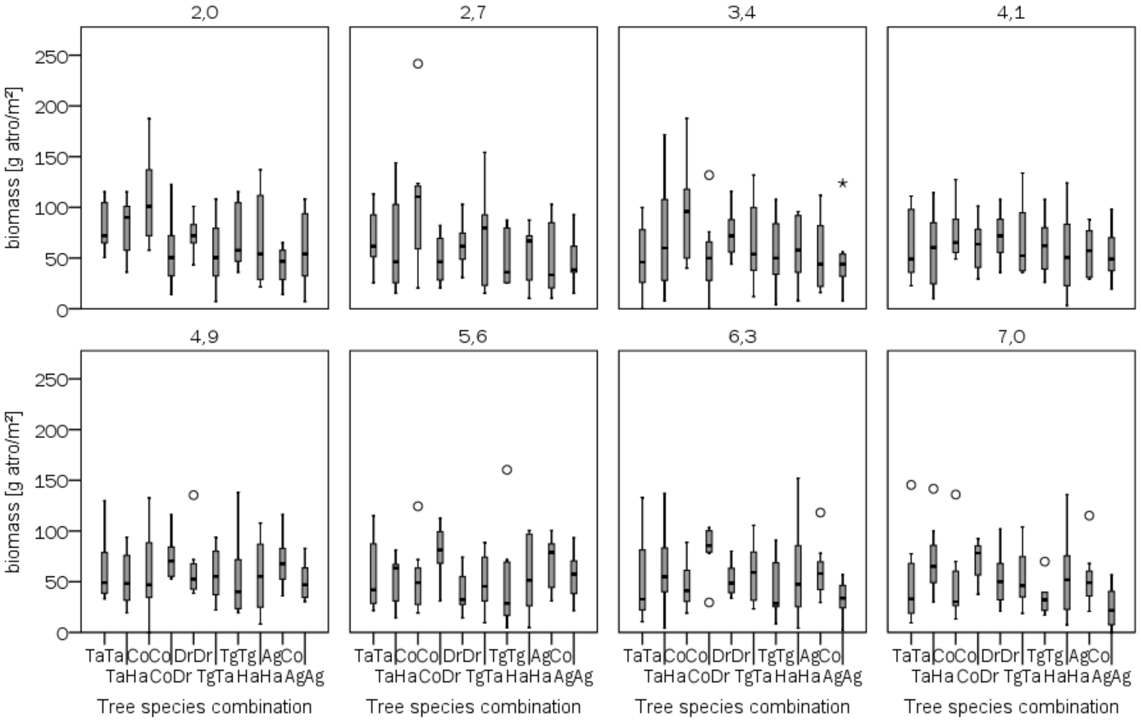

Figure 11.3: Aboveground biomass production of beans (excluding pods) by tree species combination at each planting distance [m] (see Table 3.8, page 29 for abbreviations). Biomass production in the M-B-M-M and B-R-R treatment was pooled together.

Table 11.10: Yield projection and expected revenues and costs due to harvesting, by tree species. (N = Number of stems, dbh = diameter at breast height, h = height, vol. = Volume, Merch. = merchantable)

Astronium graveolens

Age	N	N extracted	dbh [cm]	h [m]	Remaining vol. [m³/ha]	Harvested vol. [m³/ha]	Acc. Vol. [m³/ha]	Merch. Vol. [m³/ha]	Revenues [$/ha]	Harvesting costs [$/ha]
1	1111	0								
2	1089	0	2.1	2.0	0	0	0	0	0	0
3	1067	0	3.0	2.7	1	0	1	0	0	0
4	1046	0	3.9	3.4	2	0	2	0	0	0
5	1025	0	4.8	4.1	4	0	4	0	0	0
6	1004	0	5.7	4.8	6	0	6	0	0	0
7	984	394	6.6	5.5	9	4	9	2	0	542
8	579	0	7.5	6.2	8	0	12	0	0	0
9	567	0	8.4	6.9	11	0	15	0	0	0
10	556	0	9.3	7.6	14	0	18	0	0	0
11	550	0	10.2	8.3	19	0	22	0	0	0
12	545	0	11.1	9.0	24	0	27	0	0	0
13	539	0	12.0	9.7	30	0	33	0	0	0
14	534	0	12.9	10.4	36	0	40	0	0	0
15	529	0	13.8	11.1	44	0	48	0	0	0
16	523	0	14.7	11.8	52	0	56	0	0	0
17	518	0	15.6	12.5	62	0	66	0	0	0
18	513	0	16.5	13.2	72	0	76	0	0	0
19	508	0	17.4	13.9	84	0	88	0	0	0
20	503	0	18.3	14.6	97	0	100	0	0	0
21	498	0	19.2	15.3	110	0	114	0	0	0
22	493	0	20.1	16.0	125	0	129	0	0	0
23	488	0	21.0	16.7	141	0	145	0	0	0
24	483	0	21.9	17.4	158	0	162	0	0	0
25	478	478	22.8	18.1	177	177	180	113	19.103	2.404

Cedrela odorata

Age	N	N extracted	d [cm]	h [m]	Remaining vol. [m³/ha]	Harvested vol. [m³/ha]	Acc. Vol. [m³/ha]	Merch. Vol. [m³/ha]	Revenues [$/ha]	Harvesting costs [$/ha]
1	1111	0								
2	1089	0	2.9	2.4	1	0	1	0	0	0
3	1067	0	4.3	3.6	3	0	3	0	0	0
4	1046	0	5.7	4.8	6	0	6	0	0	0
5	1025	0	7.1	6.0	12	0	12	0	0	0
6	1004	0	8.5	7.2	21	0	21	0	0	0
7	984	0	9.9	8.4	32	0	32	0	0	0
8	964	386	11.3	9.6	47	19	47	12	0	536
9	567	0	12.7	10.8	39	0	58	0	0	0
10	556	0	14.1	12.0	52	0	71	0	0	0
11	550	0	15.5	13.2	69	0	87	0	0	0
12	545	0	16.9	14.4	88	0	107	0	0	0
13	539	0	18.3	15.6	111	0	130	0	0	0
14	534	0	19.7	16.8	137	0	156	0	0	0
15	529	0	21.1	18.0	167	0	185	0	0	0
16	523	262	22.5	19.2	200	100	219	64	8.123	1.415
17	259	0	23.9	20.4	119	0	238	0	0	0
18	256	0	25.3	21.6	140	0	258	0	0	0
19	254	0	26.7	22.8	162	0	281	0	0	0
20	251	0	28.1	24.0	187	0	306	0	0	0
21	249	0	29.5	25.2	215	0	334	0	0	0
22	246	0	30.9	26.4	244	0	363	0	0	0
23	244	0	32.3	27.6	276	0	395	0	0	0
24	241	0	33.7	28.8	311	0	429	0	0	0
25	239	239	35.1	30.0	347	347	466	222	62.547	1.312

Table 11.10 (continued): Yield projection and expected revenues and costs due to harvesting, by tree species. (N = Number of stems, dbh = diameter at breast height, h = height, vol. = Volume, Merch. = merchantable)

Dalbergia retusa

Age	N	N extracted	d [cm]	h [m]	Remaining vol. [m³/ha]	Harvested vol. [m³/ha]	Acc. Vol. [m³/ha]	Merch. Vol. [m³/ha]	Revenues [$/ha]	Harvesting costs [$/ha]
1	1667	0								
2	1634	0	2.9	2.4	1	0	1	0	0	0
3	1601	0	3.9	3.4	3	0	3	0	0	0
4	1569	0	4.9	4.0	6	0	6	0	0	0
5	1538	0	5.9	4.6	10	0	10	0	0	0
6	1507	753	6.9	5.2	15	7	15	5	0	838
7	738	0	7.9	5.8	10	0	18	0	0	0
8	724	0	8.9	6.4	14	0	22	0	0	0
9	709	0	9.9	7.0	19	0	26	0	0	0
10	695	0	10.9	7.6	25	0	32	0	0	0
11	688	0	11.9	8.2	31	0	39	0	0	0
12	681	0	12.9	8.8	39	0	46	0	0	0
13	674	0	13.9	9.4	48	0	55	0	0	0
14	668	0	14.9	10.0	58	0	66	0	0	0
15	661	0	15.9	10.6	70	0	77	0	0	0
16	654	0	16.9	11.2	82	0	90	0	0	0
17	648	0	17.9	11.8	96	0	103	0	0	0
18	641	0	18.9	12.4	112	0	119	0	0	0
19	635	317	19.9	13.0	128	64	136	41	6.489	1.156
20	314	0	20.9	13.6	73	0	145	0	0	0
21	311	0	21.9	14.2	83	0	155	0	0	0
22	308	0	22.9	14.8	94	0	165	0	0	0
23	305	0	23.9	15.4	105	0	177	0	0	0
24	302	0	24.9	16.0	118	0	189	0	0	0
25	299	299	25.9	16.6	131	131	202	84	17.396	1.585

Hieronyma alchorneoides

Age	N	N extracted	d [cm]	h [m]	Remaining vol. [m³/ha]	Harvested vol. [m³/ha]	Acc. Vol. [m³/ha]	Merch. Vol. [m³/ha]	Revenues [$/ha]	Harvesting costs [$/ha]
1	1111	0								
2	1089	0	1.5	1.7	0	0	0	0	0	0
3	1067	0	2.6	3.1	1	0	1	0	0	0
4	1046	0	4.0	4.8	3	0	3	0	0	0
5	1025	0	5.4	6.5	8	0	8	0	0	0
6	1004	0	6.8	8.2	15	0	15	0	0	0
7	984	0	8.2	9.9	26	0	26	0	0	0
8	964	0	9.6	11.6	40	0	40	0	0	0
9	945	378	11.0	13.3	60	24	60	15	0	530
10	556	0	12.4	15.0	50	0	74	0	0	0
11	550	0	13.8	16.7	69	0	93	0	0	0
12	545	0	15.2	18.4	91	0	115	0	0	0
13	539	0	16.6	20.1	117	0	141	0	0	0
14	534	0	18.0	21.8	148	0	172	0	0	0
15	529	0	19.4	23.5	184	0	207	0	0	0
16	523	0	20.8	25.2	224	0	248	0	0	0
17	518	259	22.2	26.9	270	135	294	86	10.939	1.403
18	256	0	23.6	28.6	160	0	319	0	0	0
19	254	0	25.0	30.3	189	0	348	0	0	0
20	251	0	26.4	32.0	220	0	379	0	0	0
21	249	0	27.8	33.7	254	0	413	0	0	0
22	246	0	29.2	35.4	292	0	451	0	0	0
23	244	0	30.6	37.1	333	0	491	0	0	0
24	241	0	32.0	38.8	377	0	535	0	0	0
25	239	239	33.4	40.5	424	424	583	271	61.672	1.312

Table 11.10 (continued): Yield projection and expected revenues and costs due to harvesting, by tree species. (N = Number of stems, dbh = diameter at breast height, h = height, vol. = Volume, Merch. = merchantable)

Tectona grandis

Age	N	N extracted	d [cm]	h [m]	Remaining vol. [m³/ha]	Harvested vol. [m³/ha]	Acc. Vol. [m³/ha]	Merch. Vol. [m³/ha]	Revenues [$/ha]	Harvesting costs [$/ha]
1	1111	0								
2	1089	0	6.5	6.4	12	0	12	0	0	0
3	1067	0	7.8	7.3	19	0	19	0	0	0
4	1046	0	9.1	8.2	28	0	28	0	0	0
5	1025	410	10.4	9.1	40	16	40	10	0	556
6	603	0	11.7	10.0	32	0	48	0	0	0
7	591	0	13.0	10.9	43	0	59	0	0	0
8	579	0	14.3	11.8	55	0	71	0	0	0
9	567	0	15.6	12.7	69	0	85	0	0	0
10	556	0	16.9	13.6	85	0	101	0	0	0
11	550	0	18.2	14.5	104	0	120	0	0	0
12	545	0	19.5	15.4	125	0	141	0	0	0
13	539	0	20.8	16.3	149	0	165	0	0	0
14	530	265	22.1	17.2	175	87	191	56	9.456	1.431
15	262	0	23.4	18.1	102	0	205	0	0	0
16	260	0	24.7	19.0	118	0	221	0	0	0
17	257	0	26.0	19.9	136	0	239	0	0	0
18	255	0	27.3	20.8	155	0	258	0	0	0
19	252	0	28.6	21.7	176	0	279	0	0	0
20	249	0	29.9	22.6	198	0	301	0	0	0
21	247	0	31.2	23.5	222	0	325	0	0	0
22	245	0	32.5	24.4	247	0	351	0	0	0
23	242	0	33.8	25.3	275	0	378	0	0	0
24	240	0	35.1	26.2	304	0	407	0	0	0
25	237	237	36.4	27.1	335	335	438	214	80.293	1.304

Terminalia amazonia

Age	N	N extracted	d [cm]	h [m]	Remaining vol. [m³/ha]	Harvested vol. [m³/ha]	Acc. Vol. [m³/ha]	Merch. Vol. [m³/ha]	Revenues [$/ha]	Harvesting costs [$/ha]
1	1111	0								
2	1089	0	3.2	3.0	1	0	1	0	0	0
3	1067	0	4.8	4.3	4	0	4	0	0	0
4	1046	0	6.4	5.6	9	0	9	0	0	0
5	1025	0	8.0	6.9	18	0	18	0	0	0
6	1004	0	9.6	8.2	30	0	30	0	0	0
7	984	394	11.2	9.5	46	18	46	12	0	542
8	579	0	12.8	10.8	40	0	59	0	0	0
9	567	0	14.4	12.1	56	0	74	0	0	0
10	556	0	16.0	13.4	75	0	93	0	0	0
11	550	0	17.6	14.7	98	0	117	0	0	0
12	545	0	19.2	16.0	126	0	145	0	0	0
13	539	0	20.8	17.3	159	0	177	0	0	0
14	534	267	22.4	18.6	196	98	214	63	5.291	1.439
15	264	0	24.0	19.9	119	0	235	0	0	0
16	262	0	25.6	21.2	143	0	259	0	0	0
17	259	0	27.2	22.5	169	0	286	0	0	0
18	256	0	28.8	23.8	199	0	315	0	0	0
19	254	0	30.4	25.1	231	0	347	0	0	0
20	251	0	32.0	26.4	267	0	383	0	0	0
21	249	0	33.6	27.7	306	0	422	0	0	0
22	246	0	35.2	29.0	348	0	464	0	0	0
23	244	0	36.8	30.3	393	0	509	0	0	0
24	241	0	38.4	31.6	442	0	558	0	0	0
25	239	239	40.0	32.9	494	494	610	316	59.286	1.312

Table 11.11: Net Cash Flow [$/ha] of different land use options over a rotation period of 25 years by tree species. (FP= Pure forest plantation, FP + M-B-M = Forest plantation with initial maize-beans-maize intercropping, FP + P = Forest plantation with initial pigeon pea intercropping, with pigeon pea being planted in year 1, FP + P0 = Forest plantation with initial pigeon pea intercropping, with pigeon pea being planted in year 0, FP + C = Forest plantation with initial cassava intercropping, M-B-M = Pure cultivation of maize-beans-maize rotations, P0 = Pure pigeon pea cultivation, C = Pure cassava cultivation)

	Year after tree planting																									
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Astronium graveolens																										
FP	-2207	-688	-667	-462	-418	-271	-271	-814	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	16529
FP + M-B-M	-1664	260	260	80	-469	-271	-271	-814	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	16529
FP + P	-2207	-662	421	504	394	-271	-271	-814	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	16529
FP + P0	-2258	421	421	504	394	-271	-271	-814	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	16529
FP + C	-2386	-147	-147	-34	38	-271	-271	-814	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	16529
Cedrela odorata																										
FP	-2197	-1121	-1099	-997	-521	-418	-418	-271	-764	-271	-228	-228	-228	-271	-228	-228	6479	-228	-228	-228	-228	-228	-228	-228	-228	61007
FP + M-B-M	-1654	87	87	-86	-572	-418	-418	-271	-764	-271	-228	-228	-228	-271	-228	-228	6479	-228	-228	-228	-228	-228	-228	-228	-228	61007
FP + P	-2197	-835	248	331	292	-418	-418	-271	-764	-271	-228	-228	-228	-271	-228	-228	6479	-228	-228	-228	-228	-228	-228	-228	-228	61007
FP + P0	-2248	248	248	331	292	-418	-418	-271	-764	-271	-228	-228	-228	-271	-228	-228	6479	-228	-228	-228	-228	-228	-228	-228	-228	61007
FP + C	-2376	-320	-320	-304	-65	-418	-418	-271	-764	-271	-228	-228	-228	-271	-228	-228	6479	-228	-228	-228	-228	-228	-228	-228	-228	61007
Dalbergia retusa																										
FP	-2765	-688	-667	-565	-521	-418	-1256	-271	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	5105	-228	-228	-228	-228	-228	15583
FP + M-B-M	-2223	260	80	-83	-555	-418	-1256	-271	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	5105	-228	-228	-228	-228	-228	15583
FP + P	-2765	-662	421	587	21	-418	-1256	-271	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	5105	-228	-228	-228	-228	-228	15583
FP + P0	-2816	421	421	587	21	-418	-1256	-271	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	5105	-228	-228	-228	-228	-228	15583
FP + C	-2945	-147	-102	-209	-217	-418	-1256	-271	-228	-271	-228	-228	-228	-271	-228	-228	-228	-228	-228	5105	-228	-228	-228	-228	-228	15583
Hieronyma alchorneoides																										
FP	-2792	-688	-667	-565	-521	-418	-418	-271	-228	-801	-228	-228	-228	-271	-228	-228	-228	9307	-228	-228	-228	-228	-228	-228	-228	60190
FP + M-B-M	-2249	260	260	80	-39	-452	-418	-271	-228	-801	-228	-228	-228	-271	-228	-228	-228	9307	-228	-228	-228	-228	-228	-228	-228	60190
FP + P	-2792	-662	421	504	419	163	-418	-271	-228	-801	-228	-228	-228	-271	-228	-228	-228	9307	-228	-228	-228	-228	-228	-228	-228	60190
FP + P0	-2843	421	421	504	419	163	-418	-271	-228	-801	-228	-228	-228	-271	-228	-228	-228	9307	-228	-228	-228	-228	-228	-228	-228	60190
FP + C	-2971	-147	-147	-34	-29	-114	-418	-271	-228	-801	-228	-228	-228	-271	-228	-228	-228	9307	-228	-228	-228	-228	-228	-228	-228	60190
Tectona grandis																										
FP	-2433	-775	-667	-462	-418	-827	-271	-271	-228	-271	-228	-228	-228	-271	7797	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	78761
FP + M-B-M	-1890	173	-100	-496	-418	-827	-271	-271	-228	-271	-228	-228	-228	-271	7797	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	78761
FP + P	-2433	-749	421	622	-418	-827	-271	-271	-228	-271	-228	-228	-228	-271	7797	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	78761
FP + P0	-2484	335	421	622	-418	-827	-271	-271	-228	-271	-228	-228	-228	-271	7797	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	78761
FP + C	-2612	-233	-57	-158	-418	-827	-271	-271	-228	-271	-228	-228	-228	-271	7797	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	78761
Terminalia amazonia																										
FP	-2320	-602	-580	-478	-564	-418	-418	-814	-228	-271	-228	-228	-228	-271	3623	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	57747
FP + M-B-M	-1777	346	167	4	-598	-418	-418	-813	-228	-271	-228	-228	-228	-271	3623	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	57747
FP + P	-2320	-576	508	674	285	-418	-418	-813	-228	-271	-228	-228	-228	-271	3623	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	57747
FP + P0	-2371	508	508	674	285	-418	-418	-813	-228	-271	-228	-228	-228	-271	3623	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	57747
FP + C	-2499	-61	-16	-123	-260	-418	-418	-813	-228	-271	-228	-228	-228	-271	3623	-228	-228	-228	-228	-228	-228	-228	-228	-228	-228	57747
Pure agriculture																										
M-B-M	111	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	640	990
P0	-560	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	767	1144
C	-568	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	371
Cattle farming	-239	563	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	452	481

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