FRUIT CROPS
SCIENCE JOURNAL

Effects of canopy species over *Theobroma grandiflorum* in agroforestry systems in the Brazilian Amazon

Rafael Moysés Alves[1]*, Saulo Chaves[2], Gustavo Schwartz[1], Marcos André Piedade Gama[3], Dênmora Gomes de Araújo[3]

Abstract: *Theobroma grandiflorum* is particularly suitable for agroforestry systems (AFSs). However, to design stable, reliable and profitable AFSs, it is necessary to define which canopy species best interact with *T. grandiflorum*. This study compares two AFSs established, as participatory research, on rural properties in the municipality of Tomé Açu, Pará State, Brazil, monitored from 2005 to 2019. Along with crop species cultivated in the initial phase, *Swietenia macrophylla* and *Khaya grandifoliola* were used as canopy species. Fruit production and survival rate of *T. grandiflorum* were evaluated at four distance levels from the canopy trees. We also measured the development of both canopy species to estimate growth rates, wood, and aboveground biomass (AGB) production potential. *K. grandifoliola* had the effect of reducing production and survival rates of *T. grandiflorum* in AFSs, while *S. macrophylla* best met the required criteria to keep the AFS viable for fruit production. However, as a timber species, *K. grandifoliola* presented better responses in terms of vigor, AGB and wood production than *S. macrophylla*, and therefore offers a viable alternative to the use of the native species. Thus, despite the biological results achieved for *T. grandiflorum* production, the choice of canopy species to be included in the AFSs must also consider the goals of each farmer.

Index terms: Cultivation systems; *Swietenia macrophylla*; *Khaya grandifoliola*; Competition.

Efeitos de espécies de dossel em *Theobroma grandiflorum* em sistemas agroflorestais na Amazônia brasileira

Resumo: *Theobroma grandiflorum* é particularmente adequado para sistemas agroflorestais (SAFs). Entretanto, para projetar SAFs estáveis, confiáveis e rentáveis, é necessário definir quais espécies de dossel melhor interagem com *T. grandiflorum*. Este estudo analisa dois SAFs para comparar suas vantagens diferenciais. Os SAFs foram implantados, como pesquisa participativa, em propriedades rurais do município de Tomé-Açu, Pará, Brasil, e foram monitorados de 2005 a 2019. Junto com as espécies de sub-dossel cultivadas na fase inicial, foram utilizadas *Swietenia macrophylla* e *Khaya grandifoliola* como espécies de dossel. A produção de frutos e

1. Brazilian Agricultural Research Corporation (Embrapa), Western Amazon unit. Belém - PA, Brazil.
2. Department of Genetics, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba – SP, Brazil.
3. Federal Rural University of Amazonia, Belém - PA, Brazil.
*Corresponding author: *rafael-moyses.alves@embrapa.br*

a taxa de sobrevivência de *T. grandiflorum* foram avaliadas em quatro níveis de distância da copa das árvores. Também medimos o desenvolvimento de ambas as espécies de dossel para estimar as taxas de crescimento, o potencial de produção de madeira e biomassa acima do solo (AGB). *K. grandifoliola* teve o efeito de reduzir a produção e as taxas de sobrevivência de *T. grandiflorum* em SAFs, enquanto *S. macrophylla* atendeu melhor aos critérios exigidos para manter o SAF viável para produção de frutos. Contudo, como espécie madeireira, *K. grandifoliola* apresentou melhores respostas em termos de vigor, AGB e produção de madeira do que *S. macrophylla*, e, portanto, oferece uma alternativa viável ao uso da espécie nativa. Assim, apesar dos resultados biológicos alcançados para a produção de *T. grandiflorum*, a escolha das espécies de dossel a serem incluídas nos SAFs também deve considerar os objetivos de cada agricultor.

Termos para indexação: Sistemas de cultivo; *Swietenia macrophylla*; *Khaya grandifoliola*; Competição.

Introduction

Agroforestry systems (AFSs) are land-use models that promote simultaneous or sequential interaction among crop and canopy species. They are important alternatives to conventional models used in tropical environments, such as monoculture (UTOMO et al. 2016) and swidden or shifting cultivation systems (VASHUM; JAYAKUMAR 2016). AFSs are effective in intensifying land use as several species that would normally occupy different areas in a landscape are planted together (TORRALBA et al. 2016). Because perennial species are commonly used, AFSs also offer to rural producers the economic benefits of diversified and staggered financial returns over time. It is important to stress that when planning an AFS, the choice of species must consider economic factors such as the target consumer market, as well as agricultural inputs and the key species selected for the system, which may determine its density, and biological factors, like characteristics of adaptation and interaction between species.

AFSs are common in the Amazon region and generally occur in the form of agroforestry orchards, a subsistence model based on local peoples' traditional knowledge (CASTRO et al. 2009). In the Northeast of Pará State, Brazil, particularly in Tomé Açu municipality and surroundings, commercial AFSs are popular and appeared in the late 1960s as an adaptation of traditional cultivations by descendants of Japanese settlers in response to phytosanitary problems with monoculture crops of *Piper nigrum L*. Some of the most used species in AFSs include *Swietenia macrophylla* King and *Theobroma grandiflorum* (Willd. ex. Spreng.) Schum. *Khaya grandifoliola* A. Juss is also widely used in AFSs as well as recommended by professionals in the region.

Swietenia macrophylla, of the Meliaceae family, is a large tree native to the Amazonian regions of Brazil, Peru, and Bolivia. It can reach 70 m in height and 3.5 m in diameter. Its wood has excellent mechanical properties and is highly valuable in the international market. As such, the species has been indiscriminately exploited, resulting in the loss of 95% of adult individuals in primary forests (FREE et al. 2014). It is currently listed as an endangered species in appendix II of the Convention on International Trade in Endangered Species (CITES) (GROGAN; LOVELESS, 2013). *Khaya grandifoliola*, also from the Meliaceae family, is native to the West Coast of Africa (VERZIGNASSI et al. 2009) and was introduced into Brazil. It has similar wood properties to *S. macrophylla*, is resistant to attacks by the borer moth *Hypsipyla grandella* and currently has no legal restrictions

2

Fruit. Crop. Sci. J. 2025; v.1: e-054

on harvesting (FRANÇA 2016). *Theobroma grandiflorum*, of the Malvaceae family, produces fruits whose pulp and almonds are used in the manufacture of food, pharmaceuticals and cosmetics (ALVES et al. 2020).

With the use of morphometric and biomass analysis it is possible to assess the level of inter- and intraspecific competition among tree species of the upper stratum in an AFS, which may interfere in the luminosity reaching lower strata, as well as the water and nutrients availability (ROMAN et al. 2009). Such aspects support decision-making about the management of each system's component, whether agronomic or silvicultural, considering both their biological and economic viability (PEZZOPANE et al., 2024). Therefore, the goals of this study were to evaluate the influence of two canopy species on the development, production, and survival of the fruit species *T. grandiflorum*, and assess the growth of canopy species.

Material and Methods

The study was conducted from 2005 to 2019 in the municipality of Tomé Açu, Northeast Pará state, 120 km from the state capital, Belém, Brazil. The municipality is a pioneer in the use of commercial AFS in the Brazilian Amazon due to the influence of an agricultural cooperative created by Japanese Brazilian farmers, which processes and distributes products from these systems. The experiments were carried out in two different AFSs, located on two rural properties, in a participative approach. The farmers were responsible to maintain the experiment, following the guidelines previously established by the research team, making the research results readily visible and accessible to local producers.

According to the Köppen classification, the climate of the region is Ami, with an average annual temperature of 26.3 °C, precipitation of 2,746 mm, and relative humidity of 85.3%.

The soil in both experimental areas is deep and well-drained and classified as Oxisol with medium texture, low fertility, low organic matter content, and high acidity.

Initially, the field where AFS 1 was installed was cultivated with *Piper nigrum* for seven years, followed by an intercropping of *Capsicum chinense* Jacq., *Carica papaya* L., and *Curcubita* spp. during five years, followed by a fallow period of 10 years. Subsequently, in the last 14 years, the area was used for the agroforestry system studied herein. AFS 2 was established on a property 15 km away from the previous one. The area was initially cultivated with *P. nigrum* (10 years), then went through a fallow period (12 years) and, in the last 14 years, was occupied by the experiment presented in this study. The preparation of the experimental areas consisted in the vegetation removal from the fallow period and the application of one ton of dolomitic limestone per hectare.

The specific characteristics of each experimental area are described below:

AFS 1: consisted of *Theobroma grandiflorum* with a spacing of 5 x 5 m (density = 400 plants/ha); *Passiflora edulis*, which remained in the area for only three years, with a spacing of 5 x 2.5 m (800 plants/ha); and *Swietenia macrophylla* with a spacing of 20 x 10 m (50 plants/ha). It is located under the coordinates 02º 26' 03" S and 48º 18' 37" W.

AFS 2: *Theobroma grandiflorum* with a spacing of 6 x 4 m (416 plants/ha); *Musa* spp., with a spacing of 6 x 4 m (416 plants/ha), removed from the area after the fifth year; *P. nigrum* with a double spacing of 2 x 2 m, and 4 m between double rows (1600 plants/ha), ending its cycle in the seventh year; and *Khaya grandifoliola* at a spacing of 18 x 10 m (55 plants/ha). The tested systems were samples of the commercial AFSs adopted in the region, including the crop species. The geographical coordinates of this AFS are 02º 32' 54" S and 48º 15' 54" W.

Fruit. Crop. Sci. J. 2025; v.1: e-054

3

The recommended fertilization for *T. grandiflorum*, after the plants reached production stability from the eighth year after implementation, was 1.0 kg/plant of the formula 10-28-20, which corresponds to 40 kg of N, 112 kg of P and 80 kg of K, per hectare, applied at the beginning and the end of the rainy season. Additionally, 20 kg/ha of FTE and 120 kg/ha of dolomitic limestone were applied at the end of the rainy season.

To test the effects of canopy trees over *T. grandiflorum* plants, which can be induced by competition above and below the soil, four distance levels in each experiment were established between canopy trees and *T. grandiflorum* individuals (Figure 1). In AFS 1, each tested distance was composed of four plants of *T. grandiflorum*, thus 16 plants were measured concerning each *S. macrophylla* tree, for a total of 320 *T. grandiflorum* plants and 20 *S. macrophylla* trees (Figure 1A).
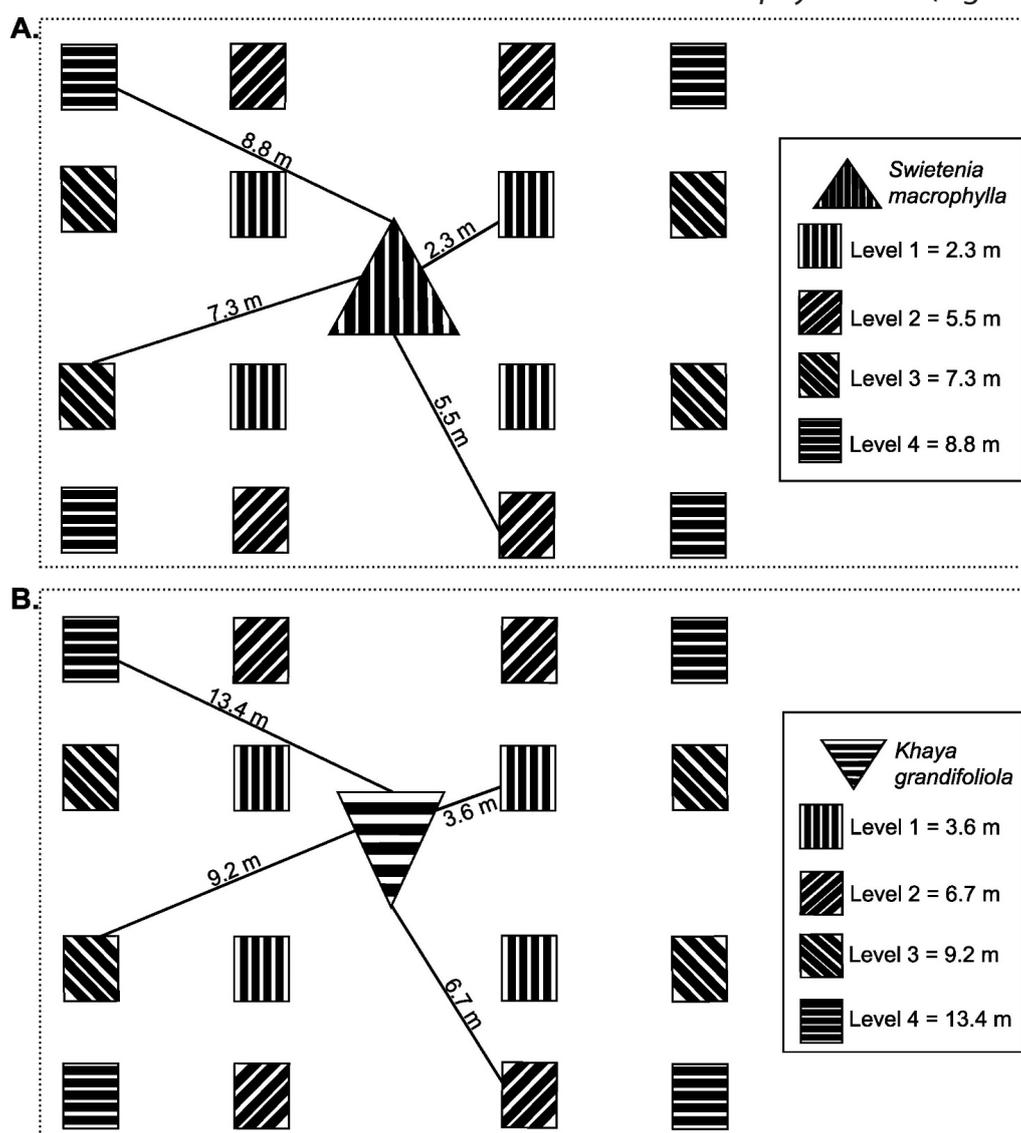
Figure 1. Schematic diagram of distance levels between *Theobroma grandiflorum* and the canopy species *Swietenia macrophylla* (A) and *Khaya grandifoliola* (B) in two experimental agroforestry systems in the municipality of Tomé Açu, Pará, Brazil. Level 1: 2.3 m from *S. macrophylla* to *T. grandiflorum* and 3.6 m from *K. grandifoliol*a to *T. grandiflorum*; Level 2: 5.5 m from *S. macrophylla* to *T. grandiflorum* and 6.7 m from *K. grandifoliola* to *T. grandiflorum*; Level 3: 7.3 m from *S. macrophylla* to *T. grandiflorum* and 9.2 m and *K. grandifoliola* to *T. grandiflorum*; Level 4: 8.8 m from *S. macrophylla* to *T. grandiflorum* and 13.4 m and *K. grandifoliola* to *T. grandiflorum*

In AFS 2, four plants also formed at each distance level, so that 16 plants of *T. grandiflorum* were measured concerning each *K. grandifoliola* tree. We sampled 144 plants

4

Fruit. Crop. Sci. J. 2025; v.1: e-054

of *T. grandiflorum* and nine individuals of *K. grandifoliola*, following the proportion 4:1 (Figure 1B).

When installing the AFS, the species were planted simultaneously. At the end of the productive period of the short-cycle species (*P. edulis*, *Musa* spp., and *P. nigrum*), *T. grandiflorum* remained in consortium only with the canopy species. This configuration began in the third year after planting and continued until the 14th year of evaluation. The following response variables were used to assess the responses of *T. grandiflorum*: number of fruits and average weight of fruits, which were used to estimate fruit production (kg/plant/crop) based on the series of 11 harvests. *T. grandiflorum* survival throughout the years was also assessed.

In the second year after the AFSs establishment, we began collecting data on tree species, measuring total height (Ht) and diameter at breast height (DBH; 1.3 m from ground level). The commercial height (Hcom) was collected in the last year of evaluation. In the first years of monitoring, the height was measured using a metric ruler and later with a digital hypsometer, model VERTEX IV. DBH was estimated from the circumference at breast height measured with a measuring tape and transformed to DBH. Beginning in the fifth year after establishment, the crown diameter (CD) of the two canopy species was also measured. All data was collected annually at the plant level.

The commercial wood volume was estimated through the equation: CWV = -9.38450 + 2.06586 x ln(DBH) + 0.72929 x ln(Hcom), as proposed by Fernandes et al. (2017) for *S. macrophylla* in a silvopastoral system; and the cylinder volume x form factor (0.5) method for *K. grandifoliola*. Some canopy-related parameters were estimated, such as crown projection area (CA = $(CD^2\pi)/4$), slenderness degree (Ht/DBH), index of protuberance (CD/DBH), and index of enclosure (CD/Ht). From height and

DBH, we estimated the aboveground biomass (AGB) of each canopy species through the general allometric equation: AGB = $0.0673(\rho DBH^2 H)^{0.976}$, where ρ is the wood density, in g cm^{-3} (CHAVE et al. 2014). The wood density of each species was obtained from Global Wood Density Database, using the BIOMASS package, at R software (CHAVE et al. 2009, RÉJOU-MÉCHAIN et al. 2017, R CORE TEAM, 2021). We considered ρ = 0.462 for *K. grandifoliola*, and ρ = 0.63 for *S. macrophylla*.

Theobroma grandiflorum production data were analyzed through an analysis of variance (ANOVA), after complying with its assumptions, considering a repeated measures design using levels as categorical variables and canopy species' AGB as a covariate. Subsequently, an additive regression model (AALEN, 1993) was fitted to analyze the survival data throughout the evaluation years, accounting for the AGB as a time-dependent covariate. All the analyses were performed in the R software, using the packages "Survival" (THERNEAU, 2021) and "Survminer" (KASSAMBARA et al. 2021) for the survival analysis. Although it was not possible to perform statistical comparisons between the canopy species, the average values of the measured and estimated variables were calculated to draw a parallel between their performances over the years of evaluation.

Results and Discussion
Performance of canopy species

In AFSs, canopy species are planted at a wider spacing than in single-species plantations, which generates less intra- and interspecific competition in the initial years (FLETCHER et al., 2012). In the current experiment, this condition allowed the species to grow optimally in the first years after the experiment began. For *Khaya grandifoliola*, Soranso et al. (2016) found a positive correlation between increases in growth

Fruit. Crop. Sci. J. 2025; v.1: e-054

5

rate and the spacing adopted, demonstrating that thinning decreases intraspecific competition, which is reflected in radial increases of the wood.

Khaya grandifoliola presented highest growth estimates (Figure 2). On average, *K. grandifoliola* grew 3.5 m in height and 5.5 cm in diameter per year in the first four years of the experiment. *Swietenia macrophylla* grew 2.0 m in height and 3.5 cm in diameter in the same period. After the initial period, there was a deceleration in tree growth. For *K. grandifoliola* this deceleration occurred later, showing the optimal adaptation of this species to local AFS growing conditions. In the 14th year after the implementation of the AFSs, there were substantial differences concerning the canopy species growth. The total height was greater for *K. grandifoliola*, presenting values 30% higher than *S. macrophylla* (Figure 2). This influenced the commercial height, in which *K. grandifoliola* was 38% greater, on average, than *S. macrophylla* (Figure 2).
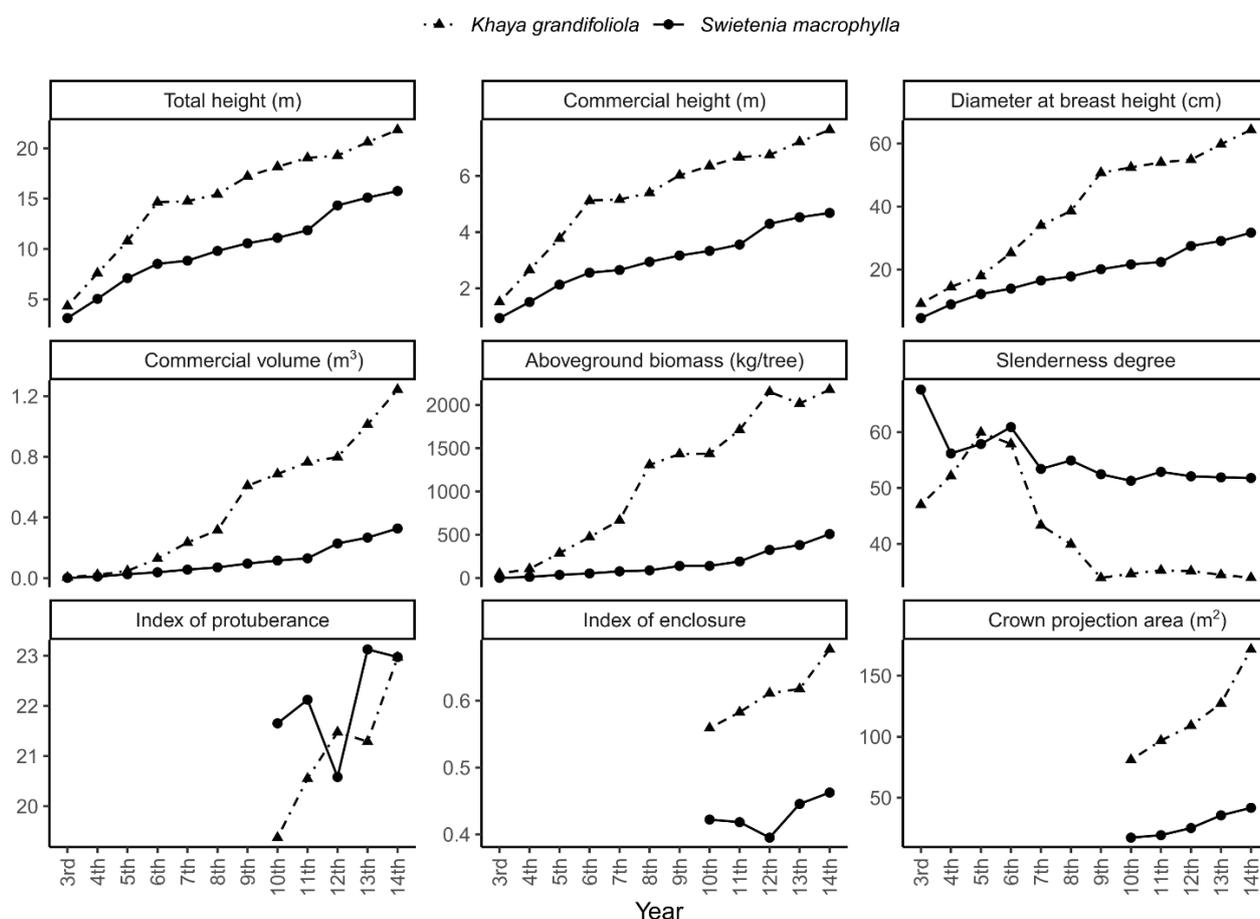
Figure 2. Evolution of growth (total and commercial height, diameter at breast height and commercial volume), morphometry traits (canopy projection area, slenderness degree, index of protuberance and index of enclosure) and aboveground biomass of the canopy species *Swietenia macrophylla* and *Khaya grandifoliola* over 14 years of cultivation in agroforestry system conditions in the municipality of Tomé Açu, Pará, Brazil.

Concerning DBH, *K. grandifoliola* also presented better performance than *S. macrophylla* (Figure 2). For estimated commercial wood volume, *K. grandifoliola* presented values almost 75% greater than *S. macrophylla*, reflecting the results obtained for height and DBH (Figure 2).

Worldwide, studies on *K. grandifoliola* showed that the species develops vigorously, both in height and diameter. Carmona et al. (2018), evaluating 16-year-old individuals in AFSs in Monte Alegre, Pará, Brazil, found lower values than the present study: 16.8 m in total height; 6.8 m in commercial

6

Fruit. Crop. Sci. J. 2025; v.1: e-054

height; and 30 cm in DBH. These differences can be explained by wider spacing used in our study, in addition to soil and climate factors and the management of the species at the local level. Results found in the present study show that *Swietenia macrophylla*, even with a slower growth rate than *K. grandifoliola*, still presents average values for total height and DBH that are greater than those normally reported in literature.

Considering an ideal cutting age of approximately 15 years for *Khaya* spp., the trees measured in this study were close to the ideal harvest age. Oliveira et al. (2018), studying *K. ivorensis* trees with a 12 x 12 m spacing in Santo Antônio do Tauá, Pará, found an average volume of 1.31 m³/ plant, which is slightly lower than the average found herein. This demonstrates that the *K. grandifoliola* individuals analyzed in this study show normal development for the soil and climate conditions of Northeastern Pará.

In commercial terms, these results indicate that the replacement of one species by the other will provide a considerable increase in wood production, which would be reflected in greater economic returns. Considering the current and corrected prices through the Brazilian inflation of Roundwood (ITTO 2017; ITTO 2021), the financial returns of *K. grandifoliola* and *S. macrophylla* in the study AFSs would be 22,749.65 USD/ha and 4,134.00 USD/ha, respectively. The revenues with production of *T. grandiflorum* fruits in 12 harvests would sum up 11,677.12 USD/ha and 18,403.40 USD/ha with *K. grandifoliola* and *S. macrophylla*, respectively. The total gross revenue can reach 34,426.77 USD/ha and 22,537.40 USD/ha. Considering a discount rate of 50% in establishment and maintenance costs of the orchards (SANTOS et al. 2020), the net revenue can reach up to 17,213.38 USD/ha and 11,268.70 USD/ha, respectively.

Given the results, *K. grandifoliola* seems to be the best recommendation for AFSs in the Amazon region, as it offers greater financial returns. Nevertheless, caution is needed before making decisions of this nature. Because the system is a consortium of plants occupying different strata, it is fundamental to understand how canopy species affect shading levels. As such, analyzing aspects of the trees' canopies is fundamental to assess this relationship (CARMONA et al. 2018).

In terms of crown morphometry, *K. grandifoliola* had the greatest canopy projection (Figure 2). The slenderness degree of *S. macrophylla* was higher than *K. grandifoliola*, indicating less stability of the tree (Figure 2). The index of protuberance was similar among the two Meliaceae (Figure 2). *K. grandifoliola* obtained a high value for the index of enclosure, reflecting a wide crown distribution (Figure 2). Anglaaere et al. (2011) emphasize that species of the genus *Khaya* have dense and wide canopies which create high levels of shading.

The above-mentioned results are important indicators not only on the vegetative development of the canopy species but also on the level of competition they can exert over *T. grandiflorum*. However, a more robust parameter is the aboveground biomass (AGB) produced by each species (Figure 2). As expected, the AGB production of *K. grandifoliola* was considerably higher than *S. macrophylla* since the first measure, in the third year after the experiment beginning (first *T. grandiflorum* harvest). Comparatively, in the 14th year (the last evaluation), *S. macrophylla* presented the same AGB production that *K. grandifoliola* had in the 6th year of the experiment.

Opuni-Frimpong et al. (2013) and Warnasooriya and Sivananthawerl (2016) report the great capacity of *Khaya* species, particularly *K. senegalensis* and *K. grandifoliola*, to produce biomass both aboveground and belowground. This is reflected in the intensification of competition for light, water

Fruit. Crop. Sci. J. 2025; v.1: e-054

7

and nutrients throughout the system, causing high mortality rates and low production levels of shaded species, as observed herein and attested by the analyses.

On the other hand, if we consider the crown projection area of *S. macrophylla*, the species seems to promote lower levels of competition. *S. macrophylla* does not project the canopy over a large area and has good growth in height, both aspects facilitate the penetration of light into the system and mitigate the negative effects resulting from the shading of the lower strata plants. This can be related to the good levels of *Theobroma grandiflorum* productivity in this AFS, although other variables like competition for water and nutrients can also have effects on it. The AGB production of *S. macrophylla* is substantially smaller than *K. grandifoliola*, probably due to its slower growth and smaller size, which contributes to the lower rates of competition. A lower biomass production indicates a lower transformation of raw materials, such as light, water, and nutrients, which will be available to species of the lower stratum. However, it is noteworthy that, despite being smaller, competition between *S. macrophylla* and *T. grandiflorum* is not null.

Relations of *Theobroma grandiflorum* with long-cycle canopy species

Using average values of *T. grandiflorum* in the AFSs as an indication of the area's uniformity, there was little variation in vegetative development and fruit production in the first harvests. These results evidence that environmental conditions such as small soil variations, fertilizer residues from companion species, and cultural management had no effect on the initial development *T. grandiflorum* (Figure 3). As expected, the analysis determined that the effects of AGB, distance levels, and years have effect on the fruit production of *T. grandiflorum* (Table 1). For *S. macrophylla*, there was also a dif-

ferential expression of year and AGB effects on plants present at different levels, a fact verified through the significance of the interactions. This result is a robust indicator of competition between species.

Table 1. Mean squares and respective significances of the aboveground biomass (AGB), distance level, and year, and their interactions.

	Khaya grandifoliola	Swietenia macrophylla
AGB	1256.96[*]	134591[*]
Level	322.48[*]	950[*]
Year	3080.69[*]	16247[*]
Level x AGB	60.06[ns]	634[*]
Level x Year	130.6[ns]	223[*]

[*] and [ns]: Significant and non-significant differences, respectively, detected by Snedecor's F test at 5% probability.

In the first five harvests, plants from both systems had similar production trends, with growth and fluctuation as expected for the crop, with no significant difference between distance levels (Figure 3). From the sixth harvest onwards the systems differ substantially, with a tendency to increase yield in the intercropping with *S. macrophylla* (Figure 3A) and decrease yield in the intercropping with *K. grandifoliola* (Figure 3B). The decrease of *T. grandiflorum* plants intercropped with *K. grandifoliola* occurred when the canopy species' biomass had great increase.

The average production in the last five harvests (stable phase) showed a clear distinction in terms of the influence of canopy species on the *T. grandiflorum* performance. The most favourable was *S. macrophylla*, as it enabled greater fruit production at all distance levels. *K. grandifoliola* caused the greatest decrease in production in the *T. grandiflorum* production. Longer distances (levels 3 and 4) from *T. grandiflorum* resulted in better fruit production. This pattern was stronger in the *S. macrophylla* intercropping, since the competition against *K. grandifoliola* was spread over all distance levels.

8

Fruit. Crop. Sci. J. 2025; v.1: e-054

A.

B.
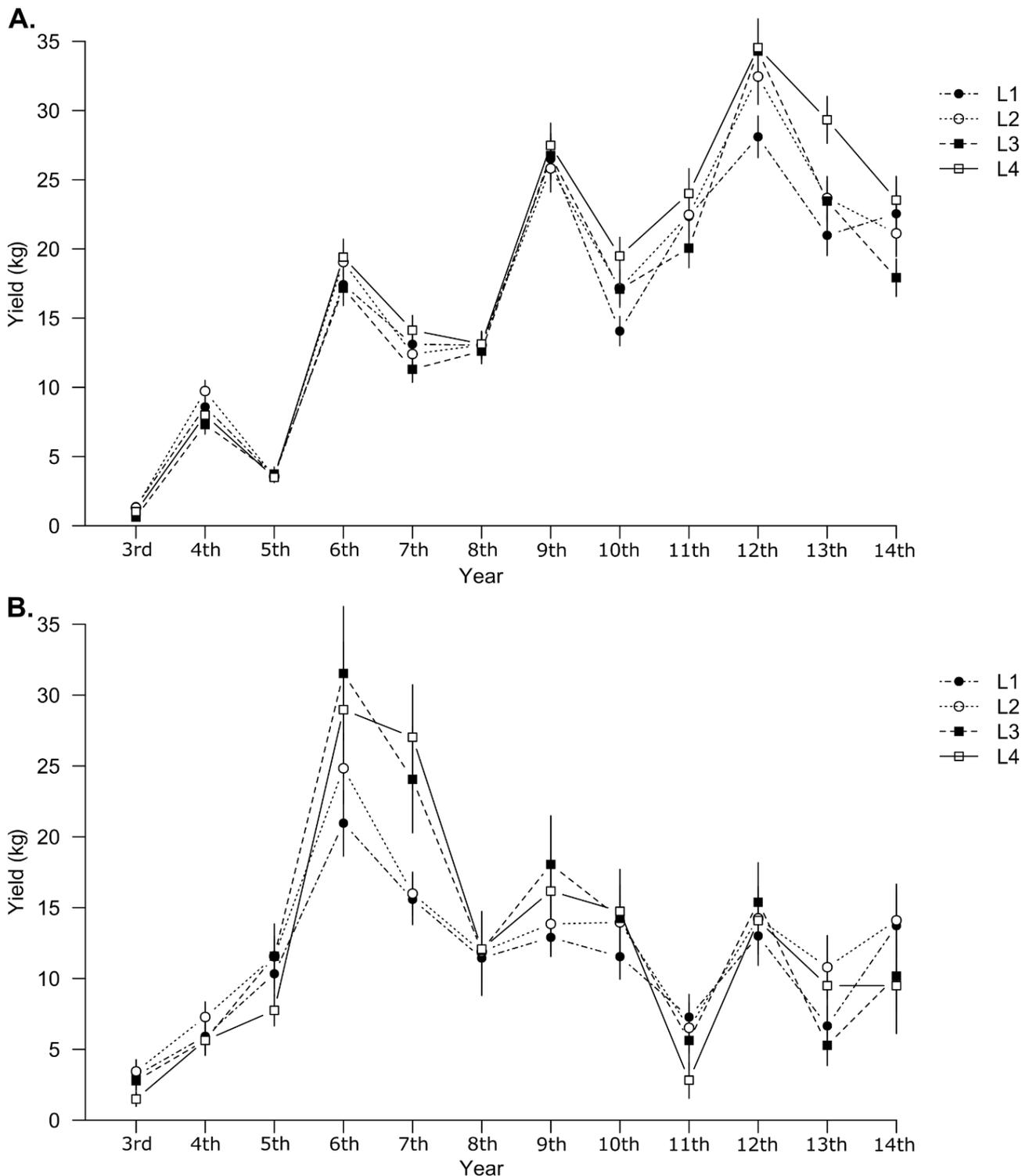
Figure 3. Average (± standard error) of *Theobroma grandiflorum* fruit production in two agroforestry systems under two canopy species: *Swietenia macrophylla* (A) and *Khaya grandifoliola* (B), throughout 11 harvests, at four distance levels (nearest = 1, most distant = 4), in Tomé Açu, Pará, Brazil.

In the survival analysis, the aboveground biomass comes as a major factor, as well as the distance of *T. grandiflorum* plants in relation to canopy species. The AFS with *S. macrophylla* presented the highest survival rate, indicating less competition between the canopy and agronomic species (Figure 4A). On the other hand, AFS with *K. grandifoliola* had lower survival rate, reaching less than 50% for levels 1, 2, and 3, in the last year of evaluation (Figure 4B).

Fruit. Crop. Sci. J. 2025; v.1: e-054

9
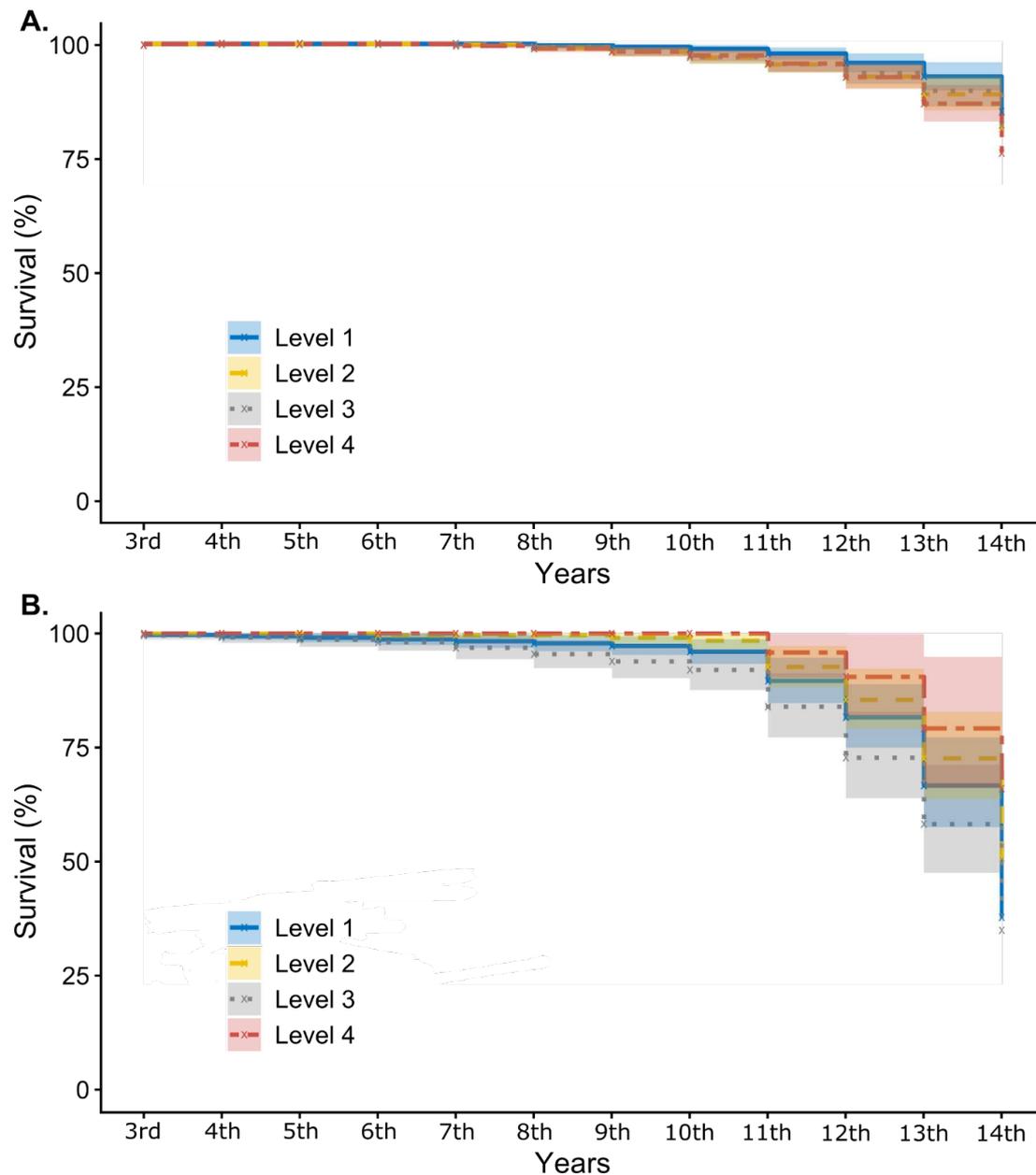
Figure 4. *Theobroma grandiflorum* survival rate in two agroforestry systems with different canopy species: *Swietenia macrophylla* (A) and *Khaya grandifoliola* (B), throughout 11 years, at four distance levels (nearest = 1, most distant = 4), in Tomé Açu, Pará, Brazil. The coloured areas above and below the lines represent the levels' standard errors.

Clearly, competition factors have influenced the different responses of *T. grandiflorum* both in terms of production and survival. *T. grandiflorum* is a species native to the Amazon region that commonly occurs with *S. macrophylla* (ALVES et al. 2013; DEGEN et al. 2013); as such, they probably have adapted for mutual coexistence. Moreover, *S. macrophylla* has a more compact growth than *K. grandifoliola*, as observed in the present study, which reflects in the lower biomass production, and therefore can temper inter-specific competition. Despite producing less AGB per plant, *S. macrophylla* can bring negative effects on the *T. grandiflorum* fruit production and survival, according to the distance level. The exotic species in this study, *K. grandifoliola*, had the most negative impact on the performance of *T. grandiflorum*. The species is well adapted to Amazonian conditions, with rapid and vigorous growth, and it can promote intense competition below-ground for water and nutrients and above-ground for light.

10

Fruit. Crop. Sci. J. 2025; v.1: e-054

Conversely, if the main objective of an AFS is timber harvesting, such as for hardwood production, *T. grandiflorum* and other initially planted species can help to offset the planting and maintenance costs, at least in the first 10 years. Santos et al. (2020), assessing an AFS in the same region, estimated a cost-benefit relation of 1.98 for *T. grandiflorum*, indicating its medium- and long-term financial viability. As such, even if these species later die or are removed due to low levels of production, their inclusion in the system is justified. For this reason, the management of plant density and spacing is dependent on the objectives of the system and are equally as important as the choice of species.

Conclusion

The exotic species *K. grandifoliola* has shown good adaptation to the soil and climate conditions in Tomé-Açu, Northeastern Pará and, consequently, better responses in terms of vigour, AGB, and wood production than *S. macrophylla*. On the other hand, *S. macrophylla* showed limited interference in the performance of the fruit tree *T. grandiflorum* under AFS conditions. *K. grandifoliola* harmed the production and increased mortality of *T. grandiflorum*. Thus, when the focus of a system is on wood commercialization and the species of the lower strata are a means to offset costs, *K. grandifoliola* would be the best option. Otherwise, the planting of the exotic Meliaceae should be done with caution, using larger planting spacing, fertilization, and irrigation in the dry period, mainly for the consortium crop species.

Data Availability

The data that support the findings of this study are available from the corresponding author, Alves, R.M., upon reasonable request.

References

AALEN, O.O. Further results on the non-parametric linear regression model in survival analysis. **Statistics in Medicine**, New York, v.12, n.17, p.1569-88, 1993. *https://doi.org/10.1002/sim.4780121705*

ALVES, R.M.; CHAVES, S.F.S.; GAMA, M.A.P.; PEDROZA NETO, J.L.; SANTOS, T.G. Simultaneous selection of cupuassu tree and Brazilian mahogany genotypes in an agroforestry system in Pará state, Brazil. **Acta Amazonica**, Manaus, v.50, n.3, p.183-91, 2020. *https://doi.org/10.1590/1809-4392202000711*

ALVES, R. M.; SILVA, C. R. S.; SILVA, M. S. C.; SILVA, D. C. S.; SEBBENN, A. M. Genetic diversity in Brazilian amazon collections of cupuassu tree germplasm [*Theobroma grandiflorum* (Willd. ex Spreng.) Schum]. **Revista Brasileira de Fruticultura**, Jaboticabal, v.35, p.818-28, 2013. *https://doi.org/10.1590/S0100-29452013000300019*

ANGLAAERE, L.C.N.; COBBINA, J.; SINCLAIR, F.L.; MCDONALD, M.A. The effect of land use systems on tree diversity: farmer preference and species composition of cocoa-based agroecosystems in Ghana. **Agroforestry Systems**, Dordrecht, v.81, p.249-65, 2011. *https://doi.org/10.1007/s10457-010-9366-z*

CARMONA, I.N.; AQUINO, M.G.C.; ROCHA, D.I.S.; SILVA, J.J.N.; FICAGNA, A.G.; BALONEQUE, D.D.; OTAKE, M.Y.F.; PAULETTO, D. Variáveis morfométricas de três espécies florestais em sistema agroflorestal. **Revista Agroecossistemas**, Marabá, v.10, n.1, p.131-44, 2018. *http://dx.doi.org/10.18542/ragros.v10i1.5158*

CASTRO, A.P.; FRAXE, T.J.P.; SANTIAGO, J.L.; MATOS, R.B.; PINTO, I.C. Os sistemas agroflorestais como alternativa de sustentabilidade em ecossistemas de várzea no Amazonas. **Acta Amazônica**, Manaus, v.39, p.279-88, 2009. *https://doi.org/10.1590/S0044-59672009000200006*

CHAVE, J.; RÉJOU-MÉCHAIN, M.; BÚRQUEZ, A.; CHIDUMAYO, E.; COLGAN, M.S.; DELITTI, W.B.C.; et al. Improved allometric models to estimate the aboveground biomass of tropical trees. **Global Change Biology**, Oxford, v.20, n.10, p.3177-90, 2014. *https://doi.org/10.1111/gcb.12629*

Fruit. Crop. Sci. J. 2025; v.1: e-054

11

CHAVE, J.; COOMES, D.; JANSEN, J.; LEWIS, S.L.; SWENSON, N.G.; ZANNE, A.E. Towards a worldwide wood economics spectrum. **Ecology Letters**, Oxford, v.12, n.4, p.351-66, 2009. *https://doi.org/10.1111/j.1461-0248.2009.01285.x*

DEGEN, B.; WARD, S.E.; LEMES, M.R.; NAVARRO, C.; CAVERS, S.; SEBBENN, A.M. Verifying the geographic origin of mahogany (*Swietenia macrophylla* King) with DNA-fingerprints. **Forensic Science International: Genetics**, New York, v.7, n.1, p.55-62, 2013. *https://doi.org/10.1016/j.fsigen.2012.06.003*

FERNANDES, A.M.V.; GAMA, J.R.V.; RODE, R.; MELO, L.O. Equações volumétricas para *Carapa guianensis* Aubl. e *Swietenia macrophylla* King em sistema silvipastoril na Amazônia. **Nativa**, Sinop, v.5, n.1, p.73-7, 2017. *http://doi.org/10.31413/nativa.v5i1.4069*

FLETCHER, E.H.; THETFORD, M.; SHARMA, J.; JOSE, S. Effect of root competition and shade on survival and growth of nine woody plant taxa within a pecan [*Carya illinoinensis* (Wangenh.) C. Koch] alley cropping system. **Agroforestry Systems**, Dordrecht, v.86, p.49-60, 2012. *http://doi.org/10.1007/s10457-012-9507-7*

FRANÇA, T.S.F.A.; FRANÇA, F.J.N.; ARANGO, R.A.; WOODWARD, B.M.; ARANTES, M.D.C. Natural resistance of plantation grown African mahogany (*Khaya ivorensis* and *Khaya senegalensis*) from Brazil to wood-rot fungi and subterranean termites. **International Biodeterioration & Biodegradation**, New York, v.107, p.88-91, 2016. *https://doi.org/10.1016/j.ibiod.2015.11.009*

FREE, C.M.; LANDIS, R.M.; GROGAN, J.; SCHULZE, M.D.; LENTINI, M.; DUNISCH, O. Management implications of long-term tree growth and mortality rates: A modeling study of big-leaf mahogany (*Swietenia macrophylla*) in the Brazilian Amazon. **Forest Ecology and Management**, Amsterdam, v.330, p.46-54, 2014. *https://doi.org/10.1016/j.foreco.2014.05.057*

GROGAN, J.; LOVELESS, M. D. Flowering phenology and its implications for management of big-leaf mahogany *Swietenia macrophylla* in Brazilian Amazonia. **American Journal of Botany**, Hoboken, v.100, n.11, p.2293-305, 2013. *https://doi.org/10.3732/ajb.1300087*

ITTO – International Tropical Timber Organization. **Towards greater transparency in the tropical timber markets**. Yokohama: Market Information Service, 1-15 dec. 2017. Disponível em: *https://www.itto.int/market_information_service/back_issues/*. Acesso em: 8 abr. 2022.

ITTO – International Tropical Timber Organization. **Towards greater transparency in the tropical timber markets**. Yokohama: Market Information Service, 16-31 jan. 2021. Disponível em: *https://www.itto.int/market_information_service/back_issues/*. Acesso em: 08 feb. 2021.

KASSAMBARA, A.; KOSINSKI, M.; BIECEK, P. **Survminer**: drawing survival curves using 'ggplot2'. R package version 0.4.9. 2021. Disponível em: *https://CRAN.R-project.org/package=survminer*. Acesso em: 10 aug. 2024

OLIVEIRA, X.M.de.; RIBEIRO, A.; FERRAZ FILHO, A.C.; MAYRINCK, R.A.; LIMA, R.R.; SCOLFORO, J.R.S. Volume equations for *Khaya ivorensis* A. Chev.plantations in Brazil. **Anais da Academia Brasileira de Ciências**, Rio de Janeiro, v.90, p.3285-98, 2018. *https://doi.org/10.1590/0001-3765201820170852*

OPUNI-FRIMPONG, E.; OPOKU, S.M.; STORER, A.J.; BURTON, A.J.; YEBOAH, D. Productivity, pest tolerance and carbon sequestration of *Khaya grandifoliola* in the dry semi-deciduous forest of Ghana: a comparison in pure stands and mixed stands. **New Forests**, Dordrecht, v.44, p.863-79, 2013. *https://doi.org/10.1007/s11056-013-9376-6*

PEZZOPANE, J. R.M.; BOSI, C.; BRUNETTI, H.B.; ALMEIDA, R.G.; LAURA, V.A.; OLIVEIRA, C.C.; MULLER, M.D. Basal area as a strategic indicator for forest component management in silvopastoral systems: insights from long-term experiments. **Agroforestry Systems**, Dordrecht, v.98, p.2013-25, 2024. *https://doi.org/10.1007/s10457-024-01038-y*

R CORE TEAM. **R**: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2021. Disponível em: *https://www.R-project.org/*. Acesso em: 10 abr. 2022.

12

Fruit. Crop. Sci. J. 2025; v.1: e-054

RÉJOU-MÉCHAIN, M.; TANGUY, A.; PIPONIOT, C.; CHAVE, J.; HÉRAULT, B. Biomass: an R package for estimating above-ground biomass and its uncertainty in tropical forests. **Methods in Ecology and Evolution**, Hoboken, v.8, n.9, p.1163-7, 2017. *https://doi.org/10.1111/2041-210X.12753*

ROMAN, M.; BRESSAN, D.A.; DURLO, M.A. Variáveis morfométricas e relações interdimensionais para *Cordia trichotoma* (Vell.) Arráb. ex Steud. **Ciência Florestal**, Santa Maria, v.19, n.4, p.473-80, 2009. *https://doi.org/10.5902/19805098901*

SANTOS, J.C.; ALVES, R.M.; CHAVES, S.F.S. Desempenho econômico-financeiro de sistema agroflorestal na região de Tomé Açu, Pará. **Agrotrópica**, Itabuna, v.32, n.3, p.197-206, 2020. *http://doi.org/10.21757/0103-3816-2020v32n3p197-206*

SORANSO, D.R.; VIDAURRE, G.B.; OLIVEIRA, J.T.S.; TOMAZELLO FILHO, M.; SILVA, J.G.M.; ARANTES, M.D.C. Variabilidade física e anatômica da madeira de *Khaya ivorensis* A. Chev.em diferentes espaçamentos de plantio. **Scientia Forestalis**, Piracicaba, v.44, n.110, p.519-26, 2016. *https://doi.org/10.18671/scifor.v44n110.24*

THERNEAU, T. **A package for survival analysis in R. R package.** Version 3.2-10, 2021. Disponível em: *https://CRAN.R-project.org/package=survival*. Acesso em: 10 aug. 2023.

TORRALBA, M.; FAGERHOLM, N.; BURGESS, P.J.; MORENO, G.; PLIENINGER, T. Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. **Agriculture, Ecosystems & Environment**, Amsterdam, v.230, p.150-61, 2016. *https://doi.org/10.1016/j.agee.2016.06.002*

UTOMO, B.; PRAWOTO, A.A.; BONNET, S.; BANGVIWAT, A.; GHEEWALA, S.H. Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia. **Journal of Cleaner Production**, Oxford, v.134, p.583-91, 2016. *https://doi.org/10.1016/j.jclepro.2015.08.102*

VASHUM, K.T.; JAYAKUMAR, S. Soil organic carbon status and sustainability of slash-and-burn cultivation in India. **Journal of Sustainable Forestry**, Binghamton, v.35, n.8, p.591-603, 2016. *https://doi.org/10.1080/10549811.2016.1236278*

VERZIGNASSI, J.R.; POLTRONIERI, L.S.; BENCHIMOL, R.L. Mancha-alvo em mogno-africano no Brasil. **Summa Phytopathologica**, São Paulo, v.35, p.70-1, 2009. *https://doi.org/10.1590/S0100-54052009000100015*

WARNASOORIYA, W. M. R. S. K.; SIVANANTHAWERL, T. Growth performance and carbon accumulation of Khaya (*Khaya senegalensis*) in Sri Lanka. **Tropical Agricultural Research**, Peradeniya, v.27, n.3, 2016. *https://doi.org/10.4038/tar.v27i3.8204*

Fruit. Crop. Sci. J. 2025; v.1: e-054

13