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Bamboo species, size, and soil water define the dynamics of available photosynthetic active solar radiation for intercrops in the Brazilian savanna biome

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ABSTRACT

Bamboo has many potential applications in agroforestry systems. This study evaluated the photosynthetic active solar radiation available (PAR) to intercrops in three bamboo species as a function of estimated soil water content in the Brazilian savanna biome (tropical savanna climate with dry winters and rainy summers). The study was conducted from 2019 to 2021 (three to five years after planting), with clumps spaced at 8 × 5 m. PAR was measured below the bamboo at 0900, 1200, and 1500 h in the central, in-row, and inter-row positions. The estimated soil water balance was used to define the water available in the soil, which was correlated with the fraction of available PAR. The lowest value for the available PAR fraction occurred at the end of the maximum soil water content, being lower than 0.20 for *Dendrocalamus asper* and *Dendrocalamus strictus* and 0.80 for *Guadua angustifolia*. *D. asper* and *D. strictus* showed an inverse response rate of 0.50% and 0.75%, respectively, in the change in the available PAR fraction for each percentage change in the estimated mean soil water content 60 days prior to the PAR measurement date. *G. angustifolia* did not show any significant effect because of the smaller size of the culms and clump. The available PAR was correlated with estimated soil water content and species rate response. This information can be used to plan the cutting of bamboo culms to maximize the amount of PAR based on intercrop demand.

Introduction

Bamboo has 1662 known species in 121 genera (Canavan et al., 2017), suggesting that there is considerable potential to expand its distribution in different regions of the world. Battisti et al. (2018) argued that 74% of the central-northern region of the Brazilian savanna is agro-climatically suitable for bamboo growing, using *Bambusa vulgaris* Schrad. ex J.C.Wendl. as a reference species. Bamboo can be used as a crop to recover degraded areas because of its high growth rate (Kleinhenz and Midmore, 2001), as its extensive root systems improve water conservation and avoid soil erosion (Canavan et al., 2017). Carbon sequestration is an additional benefit due to the high amount of biomass accumulated in the culms and soil (Sohel et al., 2015; Subbanna et al., 2021).

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Bamboo can be used for human food and renewable bio-based materials, such as structural material, composites, fibres and chemicals (Van Goethem et al., 2014; Rathour et al., 2022). When considering edible sprouts and craftsmanship, the time between planting and profit is approximately three years and ten years for construction. This makes it possible to use the available space for growing intercrops, using annual crops such as cassava, corn, rice, or common beans in the first three years, which increases the productivity of the area (Shanmughavel and Francis, 2001; Domiciano et al., 2020; Surki et al., 2020) and improves the carbon balance (Crous-Duran et al., 2019).

After the third year of growth, the potential for intercropping below bamboo is limited by the photosynthetic active solar radiation, and also by competition for water and nutrients (Kittur et al., 2016; Dupraz et al., 2018). The energy available to plants below the bamboo culms is the main driving factor for intercrop systems (Bazié et al., 2012; Kittur et al., 2016), and the intercrops can be defined based on the available photosynthetic active solar radiation (PAR). The PAR below bamboo is dependent on how the bamboo is cultivated, which is determined by four factors: 1) the bamboo species, which defines the plant structure and size (Rusch et al., 2019); 2) the planting space between clumps (Kittur et al., 2016); 3) any pruning of the bamboo culms to clear the clump (Mao et al., 2017; Durai and Long, 2019; Ziccardi et al., 2021); and 4) the weather dynamics in the growing region (Bazié et al., 2012; Dupraz et al., 2018; Andriyana et al., 2020; Mao et al., 2020). The Brazilian savanna biome includes a drier period from May to September, which changes the amount of green leaf area and, consequently, the PAR intercepted by the overstorey, although the trunks and branches of trees also affect interception (Pilau and Angelocci, 2015).

The evaluation of PAR in a managed bamboo forest could help verify the potential species to be grown as intercrops. The hypothesis tested in this study is that despite differences in PAR availability during the year due to differences in the available soil water affecting the leaf area, there is sufficient PAR for intercrops to be grown below bamboo. This study evaluated the photosynthetic active solar radiation availability and its dynamics as a function of soil water content based on the estimated water balance in a planted forest with three bamboo species, *Dendrocalamus asper* Backer ex K.Heyne, *Dendrocalamus strictus* Nees, and *Guadua angustifolia* Kunth in the Brazilian savanna biome.

Material and methods

Bamboo species

The bamboo species planted in this area are *D. asper*, *D. strictus, and G. angustifolia* (Supplementary material - Fig. S1). These species were selected because they are well-adapted to the climatic conditions of the area and because of their potential use (sprouts, civil construction, coal, and handicrafts) (Almeida et al., 2022). The general characteristics of the three species used in this study are as follows.

-*D. asper* is commonly known as giant or rough bamboo, with very large and dense clumping, reaching 20 m in height and 12 cm in diameter. It is native to Southeast Asia, preferring moist soil, and it is used as a building material, while its shoots are used as a vegetable (PFAF Plants for a Future, 2022).

-*D. strictus* is native to India and is cultivated in Southeast Asian countries. It has multiple uses, mainly as a raw material in paper mills, but also for construction and furniture, while the young shoots are used for food (Guadua Bamboo, 2022a). This species is a medium-sized bamboo with culms between 8 and 20 m tall and 2.5–8 cm in diameter.

-*G. angustifolia* is a tropical bamboo species native to South America, known as guadua, Colombian timber bamboo, and Colombian giant thorny bamboo. Culms can reach between 15 and 30 m in height, with a diameter of 7–18 cm. The main application is for construction owing to the strength of the culms (Guadua Bamboo, 2022b). In this study, the culms of *G. angustifolia* grew more slowly than the other two bamboo species.

Field experiment: climate, soil, and management

The field experiment was conducted in Goiânia, Goiás State, Brazil (lat −16° 35′ 45″, long −49° 17′ 35″, 730 m above sea level). Bamboo was planted in October 2016, using cuttings produced from the main stems of *D. asper* and *G. angustifolia,* and seed from *D. strictus*. The cuttings and seedlings were around of 40 cm height at planting. They were planted with a spacing of 8 m between rows and 5 m between clumps with a view to enabling an agroforestry system. The soil was prepared for planting using a disk plow twice, followed by the opening of the planting hole. No soil corrections or fertilizers were used as the area is dedicated to organic production. After planting, weed control was mechanical, using a tractor-driven brush cutter four times a year, leaving the straw on the soil. The leaves from bamboo pruning were also left to encourage nutrient recycling in the soil.

The bamboo culms were pruned at four (August/2020) and five (August/2021) years old. In August 2020, mature, old, and dry culms were removed, representing around 40% of the culms of *D. asper* and *D. strictus*. In August 2021, the oldest culms were pruned to clear the clumps, removing 49% and 52% of *D. asper* and *D. strictus*, respectively. The two species respectively had culm lengths of 12.6 and 9.2 m and diameters at breast height of 6.3 and 3.9 cm for the cut culms and 8.9 and 4.6 cm for the culms kept at the clump. There were 7.67 and 13.0 culms per clump, respectively, for *D. asper* and *D. strictus*. Only the dry culms of *G. angustifólia* were pruned due to their small size (culms with 3.0 m length, 3.2 cm diameter at breast height and 21.5 culms per clump).

The soil texture in the area was classified as sandy clay loam, with 58%, 12%, and 30% sand, silt, and clay content, respectively. The soil water table measured *in loco* was at approximately 100 cm depth. The soil water available to the crop was calculated based on the reference evapotranspiration (ETo), estimated using the Penman-Monteith approach (Pilau et al., 2012) using meteorological data obtained from a weather station 500 m from the experimental area, and the rainfall amount obtained in the experimental area. The soil water content was defined based on the estimated water balance developed by Thornthwaite and Mather (1955), considering the maximum water available in the soil to be 100 mm, where soil water content was estimated to characterize the water available to bamboo throughout the experimental period.

According to the Köppen classification, the region is classified as Aw, a tropical savanna climate with dry winters and rainy summers (Alvares et al., 2013). This region has been determined as being suitable for bamboo growth (Battisti et al., 2019). The air temperature had minimum and maximum values ranging from 5.85° to 41.1°C (Supplementary material - Fig. S2a), resulting in an average of 24.4 °C. The total shortwave solar radiation incidence had a mean value of 19.3 MJ m^{-2} day^{-1}, ranging from 4.22 to 31.9 MJ m^{-2} day^{-1} (Supplementary material - Fig. S2a). The rainfall during the experimental period (12 March 2019–17 November 2021) had an accumulated value of 3758 mm, with the monthly figures ranging from 0 to 557 mm (Supplementary material - Fig. S2b), while the reference evapotranspiration (ETo) ranged from 89 to 169 mm $month^{-1}$. The dry period occurred from April/May to September/October each year, with daily relative humidity ranging from 21.8% to 91.1%, with the lowest values occurring at the end of dry season (Supplementary material - Fig. S2b).

Photosynthetic active radiation measurement

The photosynthetic active radiation (PAR) was measured simultaneously below the canopy and outside the bamboo forest using two photosynthetically active solar radiation interception bars with 10 sensors (Model MQ-301 - Apogee Instruments), taking around 30 min to sample data across three bamboo species. No data were collected on cloudy days because of the variation in PAR inside and outside the

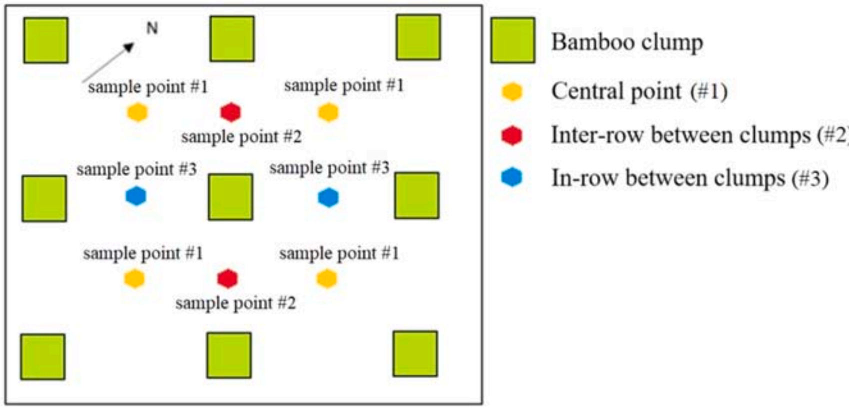

Fig. 1. Position of PAR measurement in relation to bamboo clump, defined as central point (sample point #1), inter-row between clumps (sample point #2) and in-row between clumps (sample point #3). The spacing between rows was eight meters and between clumps in the row was five meters.

bamboo forest. The sensor quantifies the total solar radiation available in the 400–700 nm wavelength range. The measurements were performed at eight points per species between nine bamboo clumps, evaluating the variability of PAR at the central (sample point #1), between inter-rows (sample point #2), and in-row (sample point #3) positions, with eight samples outside the bamboo forest to obtain PAR in full sun (Fig. 1). The measurements were performed at 0900, 1200 and 1500 h to evaluate the effect of solar position during the day. The measurements were conducted on 13 days between 12 March 2019 and 17 November 2021. PAR was sampled 312 times per species (8 points x 3 times a day x 13 days).

Data analysis

PAR was analyzed in terms of the fraction of available PAR obtained through the relationship between PAR measured below and outside the bamboo forest, and also included the total absolute available PAR. The averages between the position and time samples during the evaluation period were used. The rate of change in intercepted PAR was obtained from the inclination curve between the two measurements and correlated with the change in the mean estimated soil water content (described in Section 2.1) between sample dates, considering the mean values from 60, 30, and 15 days prior to the PAR sample date. Furthermore, available PAR was shown by the time of day through a box plot (percentiles 5, 10, 25, 50, 75, 90, and 95) for 13 daily samples, while the fraction of available PAR by position was analyzed considering the mean of the period with an intensity graph and box plot using point/time/species.

Results

Temporal dynamic: PAR x estimated soil water content

The three bamboo species showed marked variations in the available PAR fraction that followed variations in the estimated soil water content (Fig. 2). Higher PAR values were recorded after the dry period. During this period, occurring after July each year, the estimated soil water content decreased. *D. asper* had PAR values below the bamboo canopy of 0.94, 0.78, and 0.77 for October 2019, October 2020, and August 2021, respectively (Fig. 2a). The lowest value of available PAR occurred at the end of the period with the greatest estimated soil water content, leading to values below 0.20 for *D. asper* and *D. strictus* in May 2021 (Fig. 2a). *G. angustifolia* did not show changes in PAR in response to estimated soil water content in 2019; however, in 2020 and 2021, the available PAR decreased after the wet period, reaching 0.66 and 0.79 in June 2020 and May 2021, respectively (Fig. 2c). *G. angustifolia* grew more slowly than the other two species, probably due to soil type and the open sun conditions. Casual observations of *G. angustifolia* in the study area suggests than it grows better in shaded conditions.

The available PAR below the canopies of *D. strictus* and *D. asper* behaved similarly during the experimental period, but *D. strictus* had lower values and a quick reduction in the available PAR with the recovery of estimated soil water content (Fig. 2b). In March 2019, at the end of the wet season, the available PAR fraction was 0.22 and 0.71 for *D. strictus* and *D. asper*, respectively (Fig. 2a and b). In June 2020, the values were 0.39 and 0.23 for *D. asper* and *D. strictus*, respectively. The difference was lower from November 2020 to May 2021, due to a longer wet period that year, with an available PAR fraction of 0.18 and 0.13 for *D. asper* and *D. strictus*, respectively. In August 2021, rainfall reduced the available PAR fraction from 0.77 to 0.45 and from 0.56 to 0.31 for *D. asper* and *D. strictus*, respectively (Fig. 2a and b), resulting the patterns differing between 2019 and 2020.

The maximum available PAR ranged from 700 to 2000 μmol m^{-2} s^{-1} at midday in the open sun area (Fig. 2). The minimum available PAR below the bamboo canopy ranged from 140 to 400 μmol m^{-2} s^{-1} at midday during the period of maximum bamboo growth (the minimum available PAR fraction), and from 665 to 1900 μmol m^{-2} s^{-1} at midday during periods with a higher amount of leaf senescence for bamboo (the maximum available PAR fraction) for *D. asper*. For *D. strictus*, the minimum available PAR at midday below the bamboo canopy ranged from 105 to 665 μmol m^{-2} s^{-1} and the maximum from 665 to 1900 μmol m^{-2} s^{-1}. *G. angustifolia* had higher values of available PAR due to its smaller size, with PAR above the range of 490–1400 μmol m^{-2} s^{-1}.

The available PAR fraction below the bamboo canopy was dependent on leaf area, which was associated with the available soil water content in the region as calculated from the estimated soil water balance. This can be observed by the greater amount of green leaves on 12 March 2019 (Supplementary material - Fig. S3), when the estimated soil water content fraction was higher than 0.80. From April to September 2019, the dry period led to an estimated soil water content fraction below 0.50 (Fig. 2), with increased leaf senescence and almost no green leaves by 1 October 2019 (Supplementary material - Fig. S3). The bamboo culms were pruned to clear the clump in August 2021, removing around 50%, and a good recovery was observed due to the rainfall occurring in July and August (Supplementary material - Fig. S2), with plants having green leaves on 1 September 2021 (Supplementary material - Fig. S3).

Reduced soil water content led to an increase in the available PAR fraction and vice versa (Fig. 3). Individual plants showed different response rates to changes in the increase or reduction in the estimated soil water content and available PAR (Fig. 3). The best correlations between the available PAR fraction and the estimated mean soil water content for *D. asper* and *D. strictus* were obtained when using the

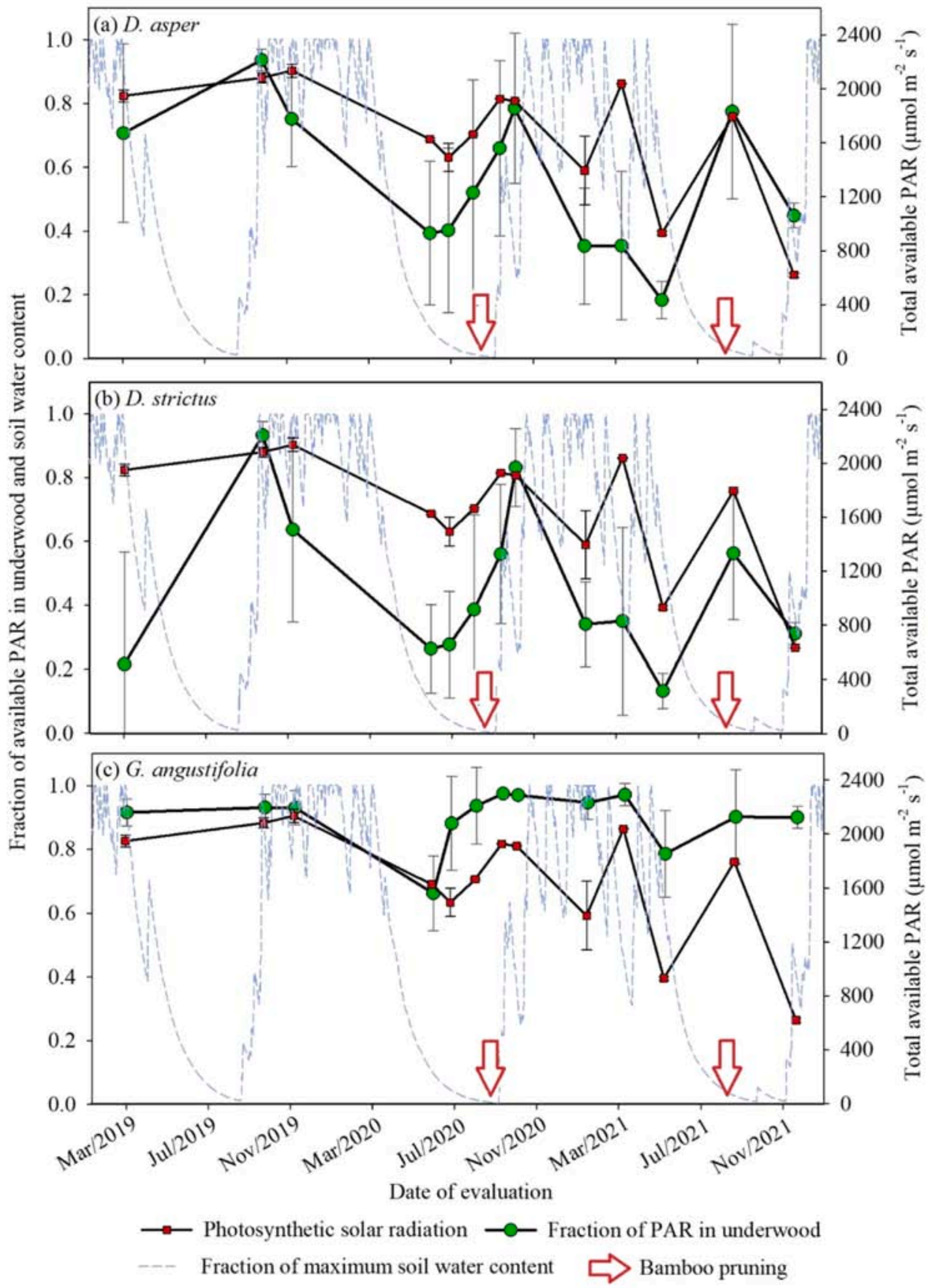

Fig. 2. Fraction of available photosynthetic active solar radiation (PAR) in the understorey in relation to the total PAR in the open sun area (green points), total PAR in the open sun area (red points) at 12 am, and fraction of maximum soil water content for *D. asper* (a), *D. strictus* (b) and *G. angustifolia* (c).

estimated mean soil water content from 60 days prior to the available PAR fraction measurement. Both species showed a significant correlation ($p < 0.01$) and r^2 above 0.50 between changes in estimated mean soil water content and changes in available PAR fraction (Figs. 3a and 3d).

The relationship between the changes in the estimated mean soil water content and the changes in the available PAR fraction represents the capacity of bamboo plants to respond to available soil water and induce leaf production or senescence when the soil water content increases or declines. *D. asper* showed a rate of 0.50% on the change in the available PAR fraction for each percent change in the estimated mean soil water content 60 days prior to the PAR measurement date (Fig. 3a), while *D. strictus* had a value of 0.75% (Fig. 3d). These values indicate that *D. strictus* had a faster response than *D. asper*, being an indirect capacity of bamboo growth that affected the available PAR for intercrops.

These relationships were weaker when considering the estimated mean soil water content 30 and 15 days prior to the PAR measurement sample date for *D. asper* and *D. strictus* (Figs. 3b, 3c, 3e, and 3 f). However, the relationship for *D. strictus* was statistically significant ($p < 0.05$) when considering mean soil water content 30 and 15 d prior to the PAR measurements (Figs. 3e and 3 f). *D. asper* did not show this correlation, indicating that it had a faster response rate (Figs. 3b and 3c). *G. angustifolia* did not show a significant correlation between changes in the estimated soil water content fraction and available PAR. This bamboo has smaller culms and clumps, leading to more energy being available at the points of measurement. However, green leaves responded the soil water content dynamics (Supplementary material - Fig. S3).

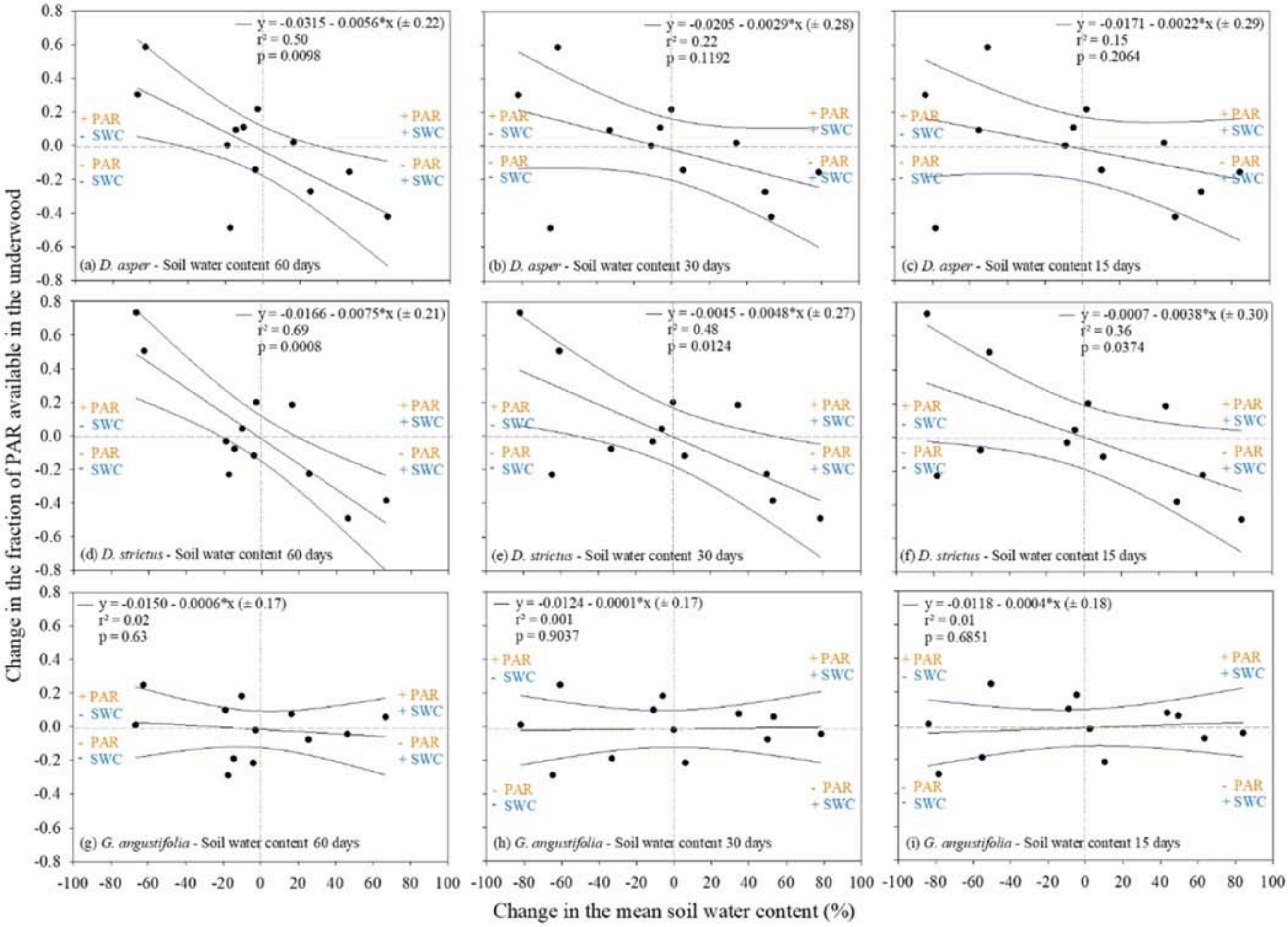

Fig. 3. Relationship between changes in the estimated mean soil water content 60 (a, d, and g), 30 (b, e, and h) and 15 days (c, f, and i) prior to the day of PAR measurement, and change in the fraction of PAR available in the understorey on current and previous sample dates for *D. asper* (a, b, and c), *D. strictus* (d, e, and f) and *G. angustifolia* (g, h, and i).

Diurnal variations in available PAR

The available fraction of PAR at 1200 for the three bamboo species were 0.55, 0.38, and 0.94 for *D. asper*, *D. strictus,* and *G. angustifolia*, respectively (Fig. 4). *D. strictus* showed a lower amount of energy when considering all three measurements, showing similar values of available PAR fraction below the bamboo canopy at 0900 and 1500, representing fractions of 0.68 and 0.73 of the mean fraction at 1200 h, respectively. More than half the samples had values below 0.24 at 0900 and 0.32 at 1500 h. *D. asper,* and *G. angustifolia* had higher values of the available PAR fraction at 0900 than at 1500 h (Fig. 4). *D. asper* had fractions of 0.89 and 0.58 for 0900 and 1500 h, respectively, in relation to the mean fraction at 1200. *G. angustifolia* had PAR fractions of 0.87 and 0.78 for 0900 and 1500 h, respectively, in relation to the mean fraction at 1200,

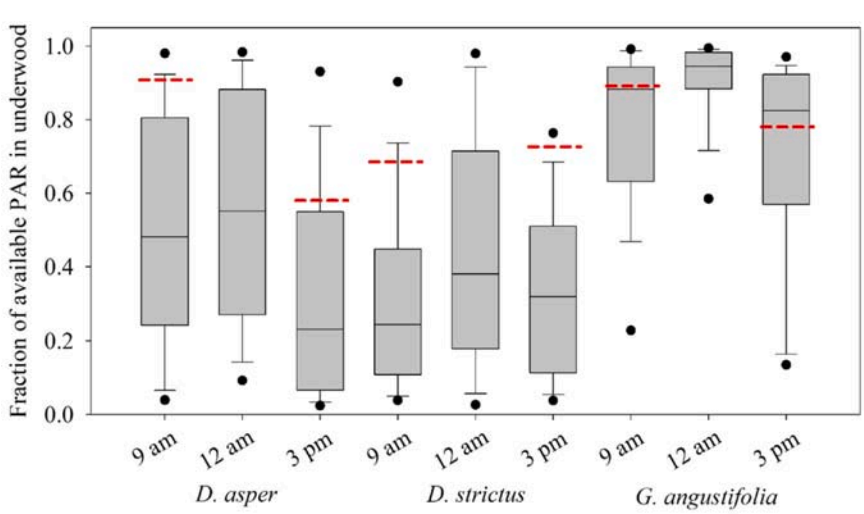

Fig. 4. Fraction of available photosynthetic active solar radiation (PAR) below the bamboo canopy in relation to the total PAR outside the bamboo forest and the fraction in relation to the mean value at 1200 h (red line) for *D. asper* (a), *D. strictus* (b) and *G. angustifolia* (c). The box plots indicate the percentile 5–95%, 10–90%, 25–75% and 50% for 104 evaluations (date × position).

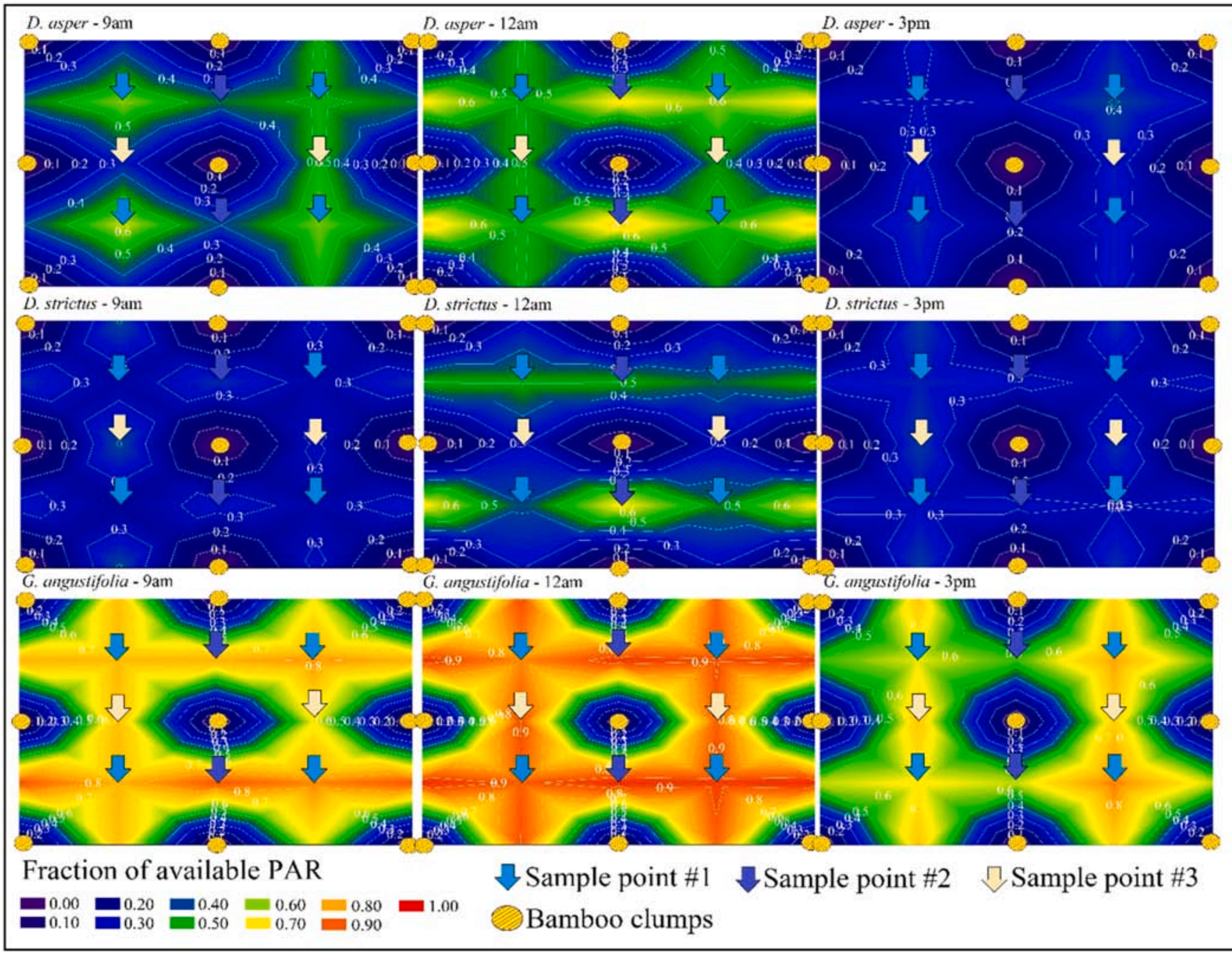

Fig. 5. Mean fraction of available photosynthetic active solar radiation (PAR) below bamboo canopy at o900, 1200 and 1500 h for *D. asper*, *D. strictus,* and *G. angustifolia*. The spacing between clumps was 8 m (x-axis) between planting rows and 5 m (y-axis) between clumps.

demonstrating that it was associated with a higher potential available energy than the other two bamboo species.

Available PAR by position

The PAR fraction available for intercropping varied due to the shading caused by varying amounts of green leaves on the bamboo culms (Fig. 5). At 1200, a higher PAR fraction was available at the central point, defined between the bamboo planting line and between plants (sample point #1) and in the line between plants (sample point # 2). *D. asper*, *D. strictus,* and *G. angustifolia* had PAR fractions above 0.50, 0.40 and 0.80, respectively (Fig. 5). These values were reduced to 0.40 and 0.20 for *D. asper* and *D. strictus*, respectively, at the planting line (sample point #3), while *G. angustifolia* maintained values above 0.80 for this position.

D. asper had PAR fractions between 0.30 and 0.60 at 0900 and between 0.30 and 0.40 at 1500 across the different positions, with lower values occurring at sample point #3 (Fig. 5). *D. strictus* had a similar pattern to *D. asper* at 0900 and 1500 h, with all sampling points showing a fraction of PAR ranging between 0.30 and 0.40. *G. angustifolia* had a higher fraction of PAR available, with values reaching 0.90 at sample points #1 and #2 at 0900, while at sample point #3, the value was reduced to 0.60 (Fig. 5). At 1500 h, *G. angustifolia* values were reduced to 0.50 and 0.80, with the greatest changes occurring at sample point #3.

The position, time of day, and period of the year led to variations in the PAR fraction available below the canopy of the bamboos (Fig. 6). *D. asper* had a percentile range of 25–75% for the PAR fraction between 0.06 and 0.96, where sample point #1 had higher values than sample points #2 and #3, except for sample point #3 at 1200 h. Sample points #1 and #3 for *D. strictus* showed higher values than sample point #2 at 1200, with percentile range of 25–75% between 0.23 and 0.88. At 0900 and 1500, the three positions had similar values with percentile 75% below 0.64 (Fig. 6). *G. ansgustifolia* had the highest PAR fraction available, with averages above 0.82 (sample point #2), 0.94 (sample point #2) and 0.60 (sample point #3) at 0900, 1200 and 1500 h (Fig. 6).

Discussion

The available water in the soil calculated from the estimated water balance was correlated with the amount of PAR below the canopy throughout the year. The response of bamboo to the water balance components and growth has been reported previously (Patra et al., 2022). The species used in the study showed different response rates to changes in intercepted PAR as a function of change in the soil water content. *D. strictus* had a higher value than *D. asper*. The different responses between species are likely associated with differences in water use efficiency in the various microenvironments (Ichihashi et al., 2015) and root development, which changes soil hydraulic properties (Patra et al., 2022),

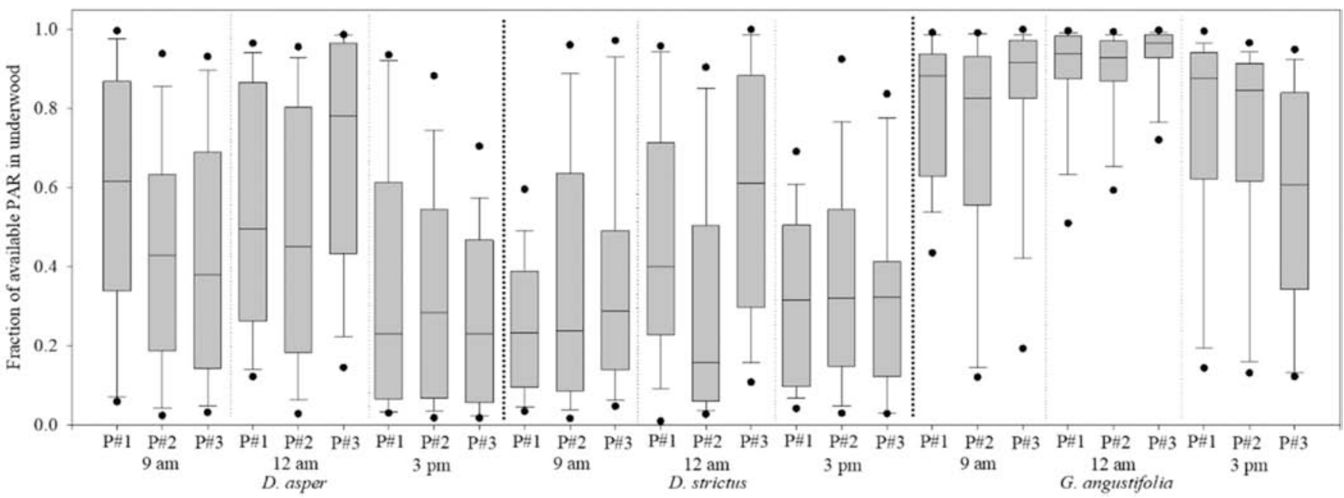

Fig. 6. Fraction of available photosynthetic active solar radiation (PAR) below the bamboo canopy in relation to the total value measured during the field study (13 dates) at 0900, 1200 and 1500 h, and sample points #1, #2 and #3 (see Fig. 1) for *D. asper*, *D. strictus,* and *G. angustifolia*. The box plots indicate the percentile 5–95%, 10–90%, 25–75%, and 50% for 52 samples for sample point #1 and 26 samples for sample point #2 and #3 (dates × replications).

soil water content (Shinohara and Otsuki, 2015), and physiological characteristics (Zhang et al., 2019).

The response of bamboo to soil water content can be used to define the time to harvest and the clearance of bamboo clumps. Mao et al. (2017) verified that cutting strategies could maximize the carbon stocks and yield in bamboo forests when there is an increase in the number of culm cuttings in 6- to 8-year-old bamboo and when all culms are removed at 8 years of age. A reduction in the number of culms reduces excessive shading during the wet season (Bazié et al., 2012), and reduces transpiration during the dry season (Zhang et al., 2019).

Crops adapted to shading can be included in *D. asper* and *D. strictus* forests; however, monitoring needs to be done to avoid reaching the lower limit in the amount of PAR needed for crops (Bazié et al., 2012; Nascimento et al., 2019). *G. angustifolia* responded differently to soil water content due to the plant's smaller size, and PAR levels below the canopy were higher. This higher PAR availability also occurs in the first years of bamboo growth, enabling the inclusion of crops in inter-rows (Nair et al., 2011). Given these findings, crops that require more energy, such as grains and grass, could be included in the systems during the wet season or dry season with irrigation (Bazié et al., 2012; Domiciano et al., 2020; Surki et al., 2020).

The sampling point affected the amount of PAR available below the bamboo canopy owing to the row direction in relation to the sun's trajectory. The rows were planted in a southeast-northwest direction, which led to more energy between clumps, even with 5 m spacing, than between rows at the clump position with 8 m of space. In this case, fruit trees could be planted between bamboo clumps. Surki et al. (2020) indicated that in an almond-cereal agroforestry system, PAR availability was affected by the position defined by the distance from the tree. At 2.5 m from the tree, wheat and barley had higher yields than with conventional sole cropping. Dupraz et al. (2018) evaluated the best row direction as a function of latitude to improve crop irradiance, with an east-west direction being found best for planting tree rows in alley-cropping agroforestry at low latitudes (25°).

Variations in planting design can determine the amount of energy reaching the crops, specifically the spacing between rows and plants (Kittur et al., 2016; Mao et al. 2017; Mao et al., 2020; Domiciano et al., 2020; Surki et al., 2020). This is the case of *D. strictus* and *D. asper,* where the use of wider spacing between rows (> 8 m), could increase the amount of below-canopy PAR (Figs. 2 and 6). At the same time, the planting direction need to be considered in order to make full use of the sun's trajectory (Dupraz et al., 2018). This would avoid a reduction in PAR that could limit intercrop yields (Surki et al., 2020).

Management of such systems need to consider both the species of bamboo and the crop species in the intercrop (Bazié et al., 2012). For example, with *D. strictus* and *D. asper* forest, crops need to be more adapted to shade, such as coffee. Zaro et al. (2023) observed a reduction of 1.4–2.5 °C in air temperature for coffee plants growing in an agroforestry mix with rubber trees in southern Brazil. In contrast, *G. angustifolia* can be grown with annual crops, such as rice and soybeans (Nair et al., 2011), and maize and cowpeas (Silva et al., 2015). Even in the wet season, there are high levels of PAR around bamboo clumps.

The success of bamboo agroforestry will depend on the correct selection of the intercrop in relation to the chosen bamboo species, planting spacing and direction, and estimated soil water dynamics. Studies in the Brazilian savanna biome have highlighted the following potential crops: rice and soybean in the first 2 years, followed by *Brachiaria* forage (Nair et al., 2011); maize and cowpeas (Silva et al., 2015); coffee (Jaramillo-Botero et al., 2007), and mixed exotic (*Mangifera indica* L.; *Hylocereus undatus*; *Persea americana*) and native (*Caryocar brasiliense; Syagrus oleracea; Euterpe oleracea; Plinia cauliflora; Spondias dulcis*; *Annona muricata*) fruit species of economic interest (Zardo and Henriques, 2011; Miccolis et al., 2019).

Conclusions

The water available in the soil affects the amount and dynamics of PAR available in the understorey of bamboo forests for *D. strictus* and *D. asper* by changing the amount of green leaf area. Additionally, these bamboo species show different rates of change in PAR availability as a function of changes in the estimated soil water content. Under *D. strictus* and *D. asper*, there are lower amounts of PAR during the wet season. This means that number of culms in each clump needs to be reduced in order to maintain sufficient PAR for understorey crops. The same applies during the dry season if irrigation is being used. For *D. strictus* and *D. asper,* spacing and row direction can be planned to maximize the amount of PAR. PAR is not a limiting factor for *G. angustifolia,* which showed a lower culm height, diameter and green leaf area than *D. strictus* and *D. asper*. This led to higher PAR levels, even during the wet season. Further studies are needed to analyze the interaction between soil water uptake by bamboo and potential understorey crops, especially during the dry season, when there may be competition for water amongst the bamboo and the intercrops.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bamboo.2023.100025.

References

Almeida, R.A., Battisti, R., Mesquita, M., Araújo, D.S., Estrella, P.F.J., 2022. Bamboo crops in consortia. Circular Técnica 1 – Rede Bambu Goiás. Dezembro 19.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalvez, J.D., de; Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Andriyana, Y., Thaler, P., Chiarawipa, R., Sopharat, J., 2020. On-farm effect of bamboo intercropping on soil water content and root distribution in rubber tree plantation. Forests, Trees and Livelihoods 29, 205–221. https://doi.org/10.1080/14728028.2020.1798818

Battisti, R., Casaroli, D., Alves Júnior, J., Evangelista, A.W.P., Mesquita, M., 2019. Agroclimatic zoning of bamboo as a support for crop farming in the central-north region of the Brazilian Savannah. Pesquisa Agropecuária Tropical 49, e52794. https://doi.org/10.1590/1983-40632019v4952794

Bazié, H.R., Bayala, J., Zombré, G., Sanou, J., Ilstedt, U., 2012. Separating competition-related factors limiting crop performance in an agroforestry parkland system in Burkina Faso. Agroforestry Systems 84, 377–388. https://doi.org/10.1007/s10457-012-9483-y

Canavan, S., Richardson, D.M., Visser, V., Le Roux, J.J., Vorontsova, M.S., Wilson, J.R.U., 2017. The global distribution of bamboos: assessing correlates of introduction and invasion. AoB PLANTS, 9:plw078. https://doi.org/10.1093/aobpla/plw078

Crous-Duran, J., Graves, A.R., Garcia-de-Jalón, S., Paulo, J.A., Tomé, M., Palma, J.H.N., 2019. Assessing food sustainable intensification potential of agroforestry using a carbon balance method. iForest - Biogeosciences and Forestry 12, 85–91. https://doi.org/10.3832/ifor2578-011

Domiciano, L.F., Pedreira, B.C., da Silva, N.M.F., Mombach, M.A., Chizzotti, F.H.M., Batista, E.D., Carvalho, P., Cabral, L.S., Pereira, D.H., Nascimento, H.L.B., 2020. Agroforestry systems: an alternative to intensify forage-based livestock in the Brazilian Amazon. Agroforestry Systems 94, 1839–1849. https://doi.org/10.1007/s10457-020-00499-1

Dupraz, C., Blitz-Frayret, C., Lecomte, I., Molto, Q., Reyesm, F., Gosme, M., 2018. Influence of latitude on the light availability for intercrops in an agroforestry alley-cropping system. Agroforestry Systems 92, 1019–1033. https://doi.org/10.1007/s10457-018-0214-x

Durai, J., Long, T.T., 2019. Manual for sustainable management of clumping bamboo forest. Technical report. International Bamboo and Rattan Organization (INBAR), Beijing 72 pg.

Guadua Bamboo. *Dendrocalamus strictus*. Accessed on March 2022a. Available from: https://www.guaduabamboo.com/blog/dendrocalamus-strictus#.

Guadua Bamboo. *Guadua angustifolia*. Accessed on March 2022b. Available from: https://www.guaduabamboo.com/blog/guadua-angustifolia.

Ichihashi, R., Komatsu, H., Kume, T., Onozawa, Y., Shinohara, Y., Tsuruta, K., Otsuki, K., 2015. Stand-scale transpiration of two Moso bamboo stands with different culm densities. Ecohydrology 8, 450–459. https://doi.org/10.1002/eco.1515

Jaramillo-Botero, C., Martinez, H.E.P., Santos, R.H.S., 2007. Characteristics of shade-grown coffee (Coffea arabica L.) in North of Latin America and Brazil: a comparative analysis. Coffee Science 1, 94–102.

Kittur, B.H., Sudhakara, K., Kumar, B.M., Kunhamu, T.K., Sureshkumar, P., 2016. Bamboo based agroforestry systems in Kerala, India: performance of turmeric (*Curcuma longa L.*) in the subcanopy of differentially spaced seven year-old bamboo stand. Agroforestry Systems 90, 237–250. https://doi.org/10.1007/s10457-015-9849-z

Kleinhenz, V., Midmore, D.J., 2001. Aspects of bamboo agronomy. Advances in Agronomy 74, 99–153. https://doi.org/10.1016/S0065-2113(01)74032-1

Mao, F., Du, H., Li, X., Ge, H., Cui, L., Zhou, G., 2020. Spatiotemporal dynamics of bamboo forest net primary productivity with climate variations in Southeast China. Ecological Indicators 116, 106505. https://doi.org/10.1016/j.ecolind.2020.106505

Mao, F., Zhou, G., Li, P., Du, H., Xu, X., Shi, Y., Mo, L., Zhou, Y., Tu, G., 2017. Optimizing selective cutting strategies for maximum carbon stocks and yield of Moso bamboo forest using BIOME-BGC model. Journal of Environmental Management 191, 126–135. https://doi.org/10.1016/j.jenvman.2017.01.016

Miccolis, A., Peneireiro, F., Vieira, D., Marques, H., Hoffmann, M., 2019. Restoration through agroforestry: options for reconciling livelihoods with conservation in the Cerrado and Caatinga biomes in Brazil. Experimental Agriculture 55, 208–225. https://doi.org/10.1017/S0014479717000138

Nascimento, H.L.B., do, Pedreira, B.C., Sollenberger, L.E., Pereira, D.H., Magalhães, C.A., de, S., Chizzotti, F.H.M., 2019. Physiological characteristics and forage accumulation of grazed Marandu palisade grass (Brachiaria brizantha) growing in monoculture and in silvopasture with Eucalyptus urograndis. Crop & Pasture Science 70, 384–394. https://doi.org/10.1071/CP18403

Nair, R.K.R., Tonucci, R.G., Garcia, R., Nair, V.D., 2011. Silvopasture and Carbon Sequestration with Special Reference to the Brazilian Savanna (Cerrado). In: Kumar, B., Nair, P. (Eds.), Carbon Sequestration Potential of Agroforestry Systems. Advances in Agroforestry, vol 8 Springer, Dordrecht. https://doi.org/10.1007/978-94-007-1630-8_8

Patra, S., Kaushal, R., Singh, D., Gadedjisso-Tossou, A., Durai, J., 2022. Surface soil hydraulic conductivity and macro-pore characteristics as affected by four bamboo species in North-Western Himalaya. India. Ecohydrology & Hydrobiology 22, 188–196. https://doi.org/10.1016/j.ecohyd.2021.08.012

PFAF (Plants for a Future). *Dendrocalamus asper* - (Schult.) Backer. Accessed on March 2022. Available from: https://pfaf.org/user/Plant.aspx?LatinName=Dendrocalamus+asper.

Pilau, F.G., Angelocci, L.R., 2015. Leaf area and solar radiation interception by orange tree top. Bragantia 74, 476–482. https://doi.org/10.1590/1678-4499.0130

Pilau, F.G., Battisti, R., Somavilla, L., Righi, E.Z., 2012. Performance of methods for estimating reference evapotranspiration in the municipalities of Frederico Westphalen and Palmeira das Missões, state of Rio Grande do Sul, Brazil. Ciência Rural 42, 283–290. https://doi.org/10.1590/S0103-84782012000200016

Rathour, R., Kumar, H., Prasad, K., Anerao, P., Kumar, M., Kapley, A., Pandey, A., Awasthi, M.K., Singh, L., 2022. Multifunctional applications of bamboo crop beyond environmental management: An Indian prospective. Bioengineered 13, 8893–8914. https://doi.org/10.1080/21655979.2022.2056689

Rusch, F., Ceolin, G.B., Hillig, É., 2019. Morphology, density and dimensions of bamboo fibers: A bibliographical compilation. Pesquisa Agropecuária Tropical 49, e55007. https://doi.org/10.1590/1983-40632019v4955007

Shanmughavel, P., Francis, K., 2001. Bioproductivity and nutrient cycling in bamboo and acacia plantation forests. Bioresource Technology 80, 45–48. https://doi.org/10.1016/S0960-8524(01)00060-8

Shinohara, Y., Otsuki, K., 2015. Comparisons of soil-water content between a Moso bamboo (Phyllostachys pubescens) forest and an evergreen broadleaved forest in western Japan. Plant Species Biology 30, 96–103. https://doi.org/10.1111/1442-1984.12076

Silva, Á.R., da, Collier, L.S., Flores, R.A., Santos, V.M., dos, Silva, L.L., da, Oliveira, V.A., Barbosa, J.M., 2015. Productive yield of cowpea and maize in single crop and mixtures in an agroforestry system. American-Eurasian Journal of Agricultural & Environmental Sciences 15, 85–92. https://doi.org/10.5829/idosi.aejaes.2015.15.1.12495

Sohel, M.S.I., Alamgir, M., Akhter, S., Rahman, M., 2015. Carbon storage in a bamboo (*Bambusa vulgaris*) plantation in the degraded tropical forests: Implications for policy development. Land Use Policy 49, 142–151. https://doi.org/10.1016/j.landusepol.2015.07.011

Subbanna, S., Viswanath, S., 2021. Above-ground biomass and carbon content in select bamboo species across humid and semiarid zones of Karnataka. In: Shit, P.K., Pourghasemi, H.R., Adhikary, P.P., Bhunia, G.S., Sati, V.P. (Eds.), Forest Resources Resilience and Conflicts 2021. Elsevier, India, pp. 153–163 Chapter 11. ISBN 9780128229316, https://doi.org/10.1016/B978-0-12-822931-6.00011-3.

Surki, A.A., Nazari, M., Fallah, S., Iranipour, R., Mousavi, A., 2020. The competitive effect of almond trees on light and nutrients absorption, crop growth rate, and the yield in almond–cereal agroforestry systems in semi-arid regions. Agroforestry Systems 94, 1111–1122. https://doi.org/10.1007/s10457-019-00469-2

Thornthwaite, C.W., Mather, J.R., 1955. The water balance publications in climatology (8) 1. Drexel Institute of Technology, Laboratory Climatology. Centerton, New Jersey, US, pp. 104.

Van Goethem, D., Potters, G., De Smedt, S., Gu, L., Samson, R., 2014. Seasonal, diurnal and vertical variation in photosynthetic parameters in *Phyllostachys humilis* bamboo plants. Photosynthesis research 120, 331–346. https://doi.org/10.1007/s11120-014-9992-9

Zaro, G.C., Caramori, P.H., Wrege, M.S., Caldana, N.F.S., Virgens Filho, J.S., Morais, H., Yada Junior, G.M., Caramori, D.C., 2023. Coffee crops adaptatition to climate change in agroforestry systems with rubber trees in southern Brazil. Scientia Agricola 80, e20210142. https://doi.org/10.1590/1678-992X-2021-0142

Zardo, R.N., Henriques, R.P.B., 2011. Growth and fruit production of the tree *Caryocar brasiliense* in the Cerrado of central Brazil. Agroforest Systems 82, 15–23. https://doi.org/10.1007/s10457-011-9380-9

Zhang, M., Chen, S., Jiang, H., Lin, Y., Zhang, J., Song, X., Zhou, G., 2019. Water-use characteristics and physiological response of Moso bamboo to flash droughts. Environmental Research and Public Health 16, 2174. https://doi.org/10.3390/ijerph16122174

Ziccardi, L.G., Graça, P.M.L.A., Figueiredo, E.O., Yanai, A.M., Fearnside, P.M., 2021. Community composition of tree and palm species following disturbance in a forest with bamboo in southwestern Amazonia, Brazil. Biotropica 53, 1328–1341. https://doi.org/10.1111/btp.12979