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Reduction of frost damage to coffee trees under agroforestry systems

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ABSTRACT

Frosts affect coffee production in Brazil, with effects on commodity prices around the world. Agroforestry systems are strategies to reduce the effects of frost on coffee trees. To date, this study has evaluated the largest number of tree species in coffee tree AFSs in Brazil in the same experiment. The objective was to identify tree species that can protect coffee trees against frost damage in agroforestry systems. The study was conducted in Londrina, Paraná, Brazil. Each treatment consisted of coffee trees associated with one of the following tree species: *Moringa oleifera*, *Croton floribundus*, *Trema micrantha, Gliricidia sepium*, *Senna macranthera*, *Heliocarpus popayanensis*, and *Mimosa scabrella, as* well as a control of coffee trees in monoculture. The experimental area was affected by frost that damaged the coffee plants fifteen months after planting. Immediately thereafter, the dendrometric characteristics of the trees were evaluated. After 30 days, the defoliation and mortality of the trees were evaluated. The phytometric characteristics of the coffee trees were evaluated 12 months after the frosts. Six of the seven tree species were evaluated for the first time for their ability to protect coffee trees against frost. Even at an early stage of development, *T. micrantha* and *H. popayanensis* provided increased protection of coffee trees, reducing the defoliation and mortality of coffee trees. The main protective factor was the canopy area of these species, which provided a high rate of tree cover. The development of coffee trees after frosts was favoured by the shading of the species, with the exception of *M. scabrella*. The AFSs with *T. micrantha* and *H. popayanensis* constitute an alternative that allows the mitigation of frost damage to coffee plants in regions prone to this climatic stress, reducing defoliation and mortality.

Key words: Intercropping; multifunctional trees; microclimate; shaded coffee trees; diversified systems.

1 INTRODUCTION

Climate change and global warming will lead to more frequent extreme events of cold, heat, drought, rain, wind, etc. (Intergovernmental Panel on Climate Change - IPCC, 2022), posing a major challenge for future coffee production in terms of grain supply and cultivation in traditional coffee-producing regions (Bunn et al., 2015; Ovalle-Rivera et al., 2015). It is estimated that by 2055, these changes will be responsible for a significant reduction in current coffee production areas, especially in medium-altitude regions (400–700 m altitude) (Sousa et al., 2019).

Frost is one of the most limiting climatic events for coffee production (Smith, 1985). Temperatures of -2 °C at the trunk and -3 °C at the leaf are sufficient to cause the death of leaves, branches, and young plants (Franco, 1960; Camargo; Salati, 1966), negatively impacting the production and economic yield of the crop (DaMatta; Ramalho, 2006). A large part of the coffee belt in Brazil, the world's largest producer and exporter of coffee, is located in frost-prone regions, in areas south of the 19th parallel and 44th meridian (Matiello et al., 2020). Hence, weather conditions in Brazil represent a real threat to the world coffee market, directly influencing coffee supply, prices, and price volatility.

Between the years 1870 and 2000, 21 severe frosts were recorded for coffee production, with most intervals between events equal to or less than six years (Pereira; Camargo; Camargo, 2008). The most recent frost was in July 2021, which affected much of the coffee-growing region in South and Southeast Brazil, leading to a 33.9% reduction in coffee exports, with negative effects on production in the following two years. The reduction in supply led to the highest price increase recorded in the last 10 years. The occurrence of frosts in Brazil is one of the factors that most negatively affects global coffee production (Organização Internacional do Café - OIC, 2021a; 2021b; 2021c).

Agroforestry systems (AFSs) are promising farming techniques that contribute to more sustainable agriculture by promoting carbon sequestration and providing a range of ecological services, such as water and soil conservation, maintenance of soil fertility, and conservation of biodiversity (Somarriba et al., 2013; Rosenstock et al., 2014; Blaser et al., 2018; Liu et al., 2018; Sousa et al., 2019; Zaro et al., 2020). In unfavourable climatic scenarios, AFSs are relevant for coffee production because they can mitigate adverse weather conditions, such as extremes of high and low temperatures, reducing abiotic stress and facilitating the performance of understory crops (Zomer et al., 2016; Blaser et al., 2018; Gomes et al., 2020; Koh et al., 2020). AFSs are very common in coffee growing in some Latin American countries, such as Colombia, Venezuela, Costa Rica, Panama, and Mexico, but are scarcely used in Brazil.

In low-temperature conditions, other trees can protect coffee trees by maintaining higher ambient temperatures through the interception and trapping of long-wave electromagnetic radiation emitted by their canopies. However, the magnitude of protection against intense cold can be influenced by several factors, such as the intensity, duration, and quantity of frosts; intrinsic variables of the coffee trees, such as age, nutrition, vigour, and health; characteristics of the tree species, such as size, architecture, and density of the canopy; and, finally, the type of management of the system, such as distribution of trees, spacing, pruning, etc. However, these variables and their interactions remain mostly unexplored.

In view of the many elements that influence and are influenced by AFSs and their potential to mitigate the damaging effects of adverse climatic events, studies of these systems have become essential for parameterizing the recommendations of tree species, according to their purposes for management of coffee production in different soil and climate regions. The aim of this study was to identify tree species that can protect coffee plants against frost damage in AFSs.

2 MATERIAL AND METHODS

2.1 Description of the experimental area and occurrence of frost

The experiment was conducted in Londrina, Paraná (23°21'27.8"S and 51°09'33.5"W, 574 m), in a typical Cfa climate (humid subtropical with hot summer, according to Koppen's classification). The average annual temperature is 21.1 ºC, with an average of 23.9 ºC in the hottest month (January) and 17 ºC in the coldest month (July), with the occurrence of weak frosts (-1 to -2 ºC) annually and moderate to strong (-2 to -4 ºC) occasionally, during autumn/winter (Caramori et al., 2000). The average annual precipitation is 1,632 mm; December, January, and February are the rainiest months, and June, July, and August are the driest. The soil is classified as "Red Dystrophic Latosol" (Santos et al., 2018).

Coffea arabica seedlings, cultivar IPR 98, with six pairs of leaves, were planted in April 2012 at a spacing of 0.60 × 2.50 m. After 20 days, the tree seedlings, 30 to 40 cm-high, were planted in the same rows as the coffee trees. The arrangement of trees in the area was in quincunx, with one tree in each interval of 11 coffee trees, equivalent to 555 trees and 6,111 trees per hectare in the treatments in Agroforestry Systems (AFSs) (Figure 1). The tree species were: *Moringa oleifera, Croton floribundus, Trema micrantha, Gliricidia sepium, Senna macranthera, Heliocarpus popayanensis*, and *Mimosa scabrella*. The pre-selection of these species was based on their adaptability to the soil and climate conditions of the region, their rapid growth characteristics, and their potential for firewood production, as a second commercially valuable product. The control was coffee trees in monoculture at the same spacing, corresponding to 6,666 plants per hectare.

The experimental design was in randomized blocks, with four repetitions in 19.80 × 22.50 m (plots). The evaluations were made in the centre of the plots, in a 10.00 × 10.20 m area (useful plot) (Figure 1). Fertilization, liming, and weed management were performed according to the technical recommendations for the crop, and there was no need for pest and disease management.

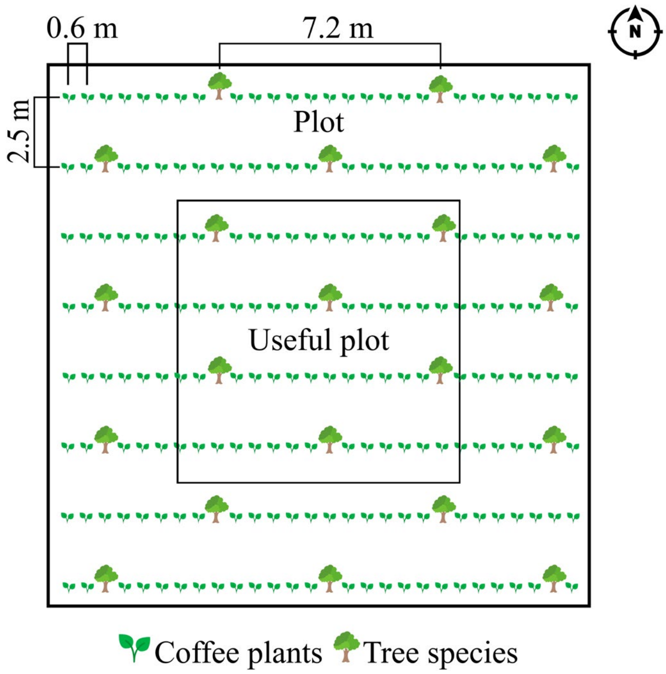

Figure 1: Arrangement of trees and coffee plants in the plots and useful plot in the treatments of agroforestry systems.

In July 2013, 15 months after planting, the minimum grass temperatures recorded at the weather station of IDR-Paraná, located 500 m from the experimental area, were: -5.4, -3.4, -0.6, 0.4 and 0.6 ºC, on days 24, 25, 26, 27 and 28, respectively. On all these days, frost formations of intensities strong to weak were observed. Monthly temperature extremes and the water balance data were also obtained from the same weather station.

2.2 Dendrometric characteristics of tree species

The dendrometric characteristics of the tree species were evaluated in the month when the frosts occurred (July 2013) and after nine months (April 2014), in six trees per repetition. The variables measured were: a) total height (m), measured from the base to the apex of the tree, with a tape measure; b) diameter of the stem at breast height (DBH) (cm), obtained by measuring the circumference (C) of the stem at 1.30 m from the ground, with a tape measure, where $DBH=C/\pi$; c) crown projection (CP) (m^2), which corresponds to the circular area, in the horizontal plane, covered by the vertical projection of the crown, obtained by the average of two opposite diameters (D) of the crown, measured with a tape measure, calculated by $CP=(\pi \times D^2)/4$ (Burger, 1939); d) tree crown cover index (ICA), which is the percentage of the areas occupied by the vertical projections of the crown in relation to the total area, calculated by *ICA=(PC×555)/10000×100* (Queiroz; Carvalho, 2019), where PC is the area of the projection of the crown of the tree, 555 is the number of trees per hectare, 10,000 is the area (m^2) corresponding to one hectare, and 100 is the conversion factor in percentage.

2.3 Defoliation damage and mortality of coffee trees

Coffee tree defoliation was evaluated 30 days after the occurrence of frost (August 2013), using a 0 to 5 scale corresponding to visual quantification of damage, where 0 = no damage; 1 ≅ 20% defoliation; 2 ≅ 40% defoliation; 3 ≅ 60% defoliation; 4 ≅ 80% defoliation, and 5 ≅ 100% defoliation. Fifty plants per repetition were evaluated.

The mortality of coffee plants was evaluated 30 days after the occurrence of frosts (August 2013), and plants with total absence of leaves and that did not sprout plagiotropic and/or orthotropic branches during the period were considered dead. Sixty-eight plants were evaluated per repetition. The total number of dead plants was transformed into percentages.

2.4 Phytometric characteristics of coffee trees

The phytometric characteristics of the coffee plants were evaluated 12 months after the frosts (July 2014) in surviving plants. The variables were: a) stem diameter at the base of the plant (cm), obtained by the average of two opposite diameters, measured with a pachymeter; b) total height (cm), measured from the base to the apex of the plant, with a tape measure; c) crown diameter (cm), obtained by the average of two opposite diameters of the crown at the base of the plant, measured with a tape measure. Eight plants were evaluated per repetition.

2.5 Statistical analyses

The data were submitted to variance analysis, and the means were compared using the Scott-Knott test ($p \leq 0.05$), using the Sisvar software. The dendrometric variables of the tree species were correlated with defoliation and mortality of coffee trees by Pearson's correlation coefficient, which measures the degree of linear association between two variables, using XLStat software. The variables of dendrometric characteristics of tree species, defoliation damage, and mortality of coffee trees and phytometric characteristics of coffee trees were subjected to principal component analysis using XLStat software.

3 RESULTS

3.1 Dendrometric characteristics of the tree species

When the frosts occurred in July 2013, *T. micrantha* was the species with the best development in all variables and stood out from the others in relation to the crown, with greater projection and incidence of tree cover (Table 1). *Heliocarpus popayanensis, M. Oleifera*, and *C. floribundus* exhibited an intermediate development. Finally, the species *G. sepium, S. Macranthera*, and *M. scabrella* had smaller aboveground dimensions. The trees were not yet in their full development because in the subsequent evaluation nine months later, the dimensions were larger, with *H. popayanenis* and *T. micrantha* standing out in relation to height, crown projection area, and tree crown cover index.

3.2 Defoliation damage and mortality of coffee trees

Defoliation and mortality were equivalent within the same treatment because they are interdependent variables (Table 2). Coffee trees under *T. micrantha* and *H. popayanensis* had the lowest defoliation and mortality rates, averaging 29 and 12%, respectively, indicating good protection of coffee trees against frost. This occurred because these species had a good canopy development (Table 1), intercepting the radiation emitted by the surface in the form of long-wave, which reduced energy loss and kept the environment warmer. In the other AFSs, on the contrary, high rates of defoliation and mortality occurred and did not differ from monoculture, with averages of 76 and 37%, respectively. The lower canopy development of *G. sepium* and *S. macranthera* (Table 1), or the intrinsic morphological aspects of the canopy, as observed for *M. oleifera,* which has a canopy with little leaf coverage, may have hindered the retention of warmer air in the environment due to the radiation emitted by the surface.

3.3 Phytometric characteristics of coffee trees

In the development of the coffee plants 12 months after the frost, there was less total height and canopy diameter in the plants under the *M. scabrella* AFS and in monoculture (Table 3). This probably occurred because these coffee plants suffered greatly from the frost and recovery was slower. In addition, this was one of the tree species with the smallest crown size, a condition that may also have hindered protection against the high temperatures recorded during the subsequent spring and summer (Figure 2). It should be noted that in the 12 months after the frosts, water deficit and minimum temperatures that could compromise the development of the coffee tree were not observed (Figure 2). The coffee plants in the other treatments developed well, especially in terms of plant height and canopy diameter, showing that the shade provided by most tree species favoured the recovery of the plants that survived the frosts.

3.4 Pearson Correlation

In the correlations between the variables, defoliation and mortality of the coffee plants had a strong positive correlation between them (Table 4), which means that the higher the level of defoliation, the greater the mortality of the plants, because both are direct morphological damages resulting from freezing.

Table 1: Dendrometric characteristics and cover index of tree species in AFSs in the month of frost occurrence (July 2013) and after nine months (April 2014). Londrina-PR.

Date evaluation	Tree species	Total height (m)*	Diameter of the stem at breast height (cm)	Crown projection (m^2)	Tree crown cover index (%)
July 2013	*Moringa oleifera*	4.26 a	7.20 a	5.94 b	32.97 b
	Croton floribundus	2.55 b	4.95 b	4.45 b	24.69 b
	Trema micrantha	3.75 a	7.10 a	11.46 a	63.58 a
	Gliricidia sepium	2.71 b	2.98 c	1.52 c	8.44 c
	Senna macranthera	2.73 b	4.08 b	2.69 c	14.96 c
	Heliocarpus popayanensis	3.68 a	7.90 a	6.37 b	35.35 b
	Mimosa scabrella	1.57 c	2.31 c	1.80 c	10.01 c
	CV (%)	20.09	20.52	32.88	32.90
April 2014	*Moringa oleifera*	4.83 b	9.64 c	8.62 b	47.86 b
	Croton floribundus	4.20 c	8.56 c	12.00 b	66.62 b
	Trema micrantha	5.87 a	11.42 b	23.11 a	128.25 a
	Gliricidia sepium	3.23 d	4.38 d	4.87 b	27.05 b
	Senna macranthera	4.48 c	8.04 c	10.56 b	58.59 b
	Heliocarpus popayanensis	5.74 a	14.48 a	19.36 a	107.44 a
	Mimosa scabrella	3.73 d	6.30 d	7.11 b	39.43 b
	CV (%)	11.48	15.43	26.36	26.36

*Means (± standard error) followed by the same letter in the column and season belong to the same similarity group by the Scott-Knott test ($p \leq 0.05$).

Table 2: Leaf defoliation and mortality of coffee trees in monoculture and AFSs, 30 days after the occurrence of frost (August 2013). Londrina-PR.

Treatment	Defoliation (%)*	Mortality (%)
Monoculture	90.40 b	42.65 b
Moringa oleifera	64.05 b	32.76 b
Croton floribundus	61.55 b	19.76 b
Trema micrantha	22.80 a	8.47 a
Gliricidia sepium	80.35 b	44.76 b
Senna macranthera	79.00 b	39.92 b
Heliocarpus popayanensis	35.95 a	15.73 a
Mimosa scabrella	79.95 b	40.73 b
CV (%)	26.45	16.78

*Means (± standard error) followed by the same letter in the column belong to the same similarity group by the Scott-Knott test ($p \leq 0.05$).

Correlations between damage from defoliation and mortality of coffee trees and dendrometric characteristics of tree species were strong and negative for crown projection area, diameter at breast height, and tree crown cover index, i.e., the larger these dimensions, the less frost damage to coffee trees (Table 4). It is important to emphasize that significant correlations do not necessarily show a cause and effect relationship, such as with diameter at breast height and coffee tree defoliation. There was no significant correlation between tree height and damage from defoliation and mortality of coffee trees.

Table 3: Phytometric characteristics of coffee trees in monoculture and in AFSs, 12 months after frost (July 2014). Londrina-PR.

Treatment	Total height (cm)*	Crown diameter (cm)	Stem diameter (cm)
Monoculture	64.91 b	56.13 b	2.49 b
Moringa oleifera	82.30 a	74.19 a	2.70 a
Croton floribundus	84.31 a	71.63 a	2.46 b
Trema micrantha	82.44 a	75.41 a	2.34 b
Gliricidia sepium	81.38 a	78.78 a	2.79 a
Senna macranthera	77.31 a	71.97 a	2.57 b
Heliocarpus popayanensis	80.63 a	75.38 a	2.48 b
Mimosa scabrella	73.09 a	63.00 b	2.62 a
CV (%)	17.60	9.66	5.02

*Means (± standard error) followed by the same letter in the column belong to the same similarity group by the Scott-Knott test ($p \leq 0.05$).

3.5 Principal component analysis

In the principal component analysis (PCA), the first two components (F1 and F2) explained 93.77% of the total variance (Table 5). F1 was positively correlated with the

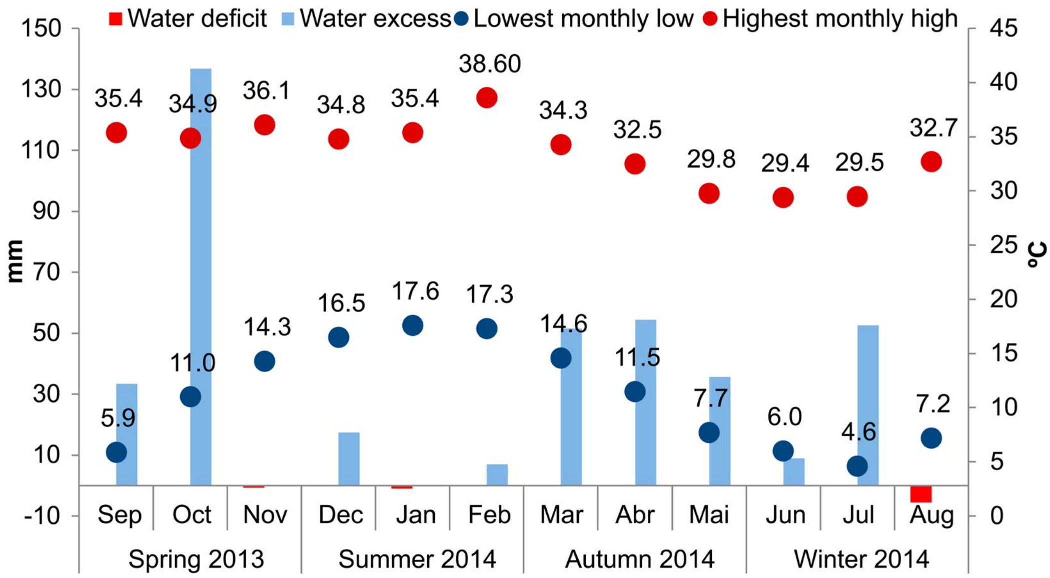

Figure 2: Highest monthly maximum temperature, lowest monthly minimum temperature and soil water balance between September 2013 and August 2014. Weather station of the IDR-Paraná. Londrina, Paraná, Brazil.

Table 4: Pearson's correlation coefficient between mortality and defoliation of coffee trees and dendrometric characteristics of tree species in AFSs after frost events, 2013. Londrina, PR.

	Variables	Defoliation	Mortality
Coffee trees	Defoliation	-	-
	Mortality	0.951*	-
Tree species	Total height	-0.700^{ns}	-0.571^{ns}
	Crown projection area	-0.951*	-0.892*
	Diameter at breast height to	-0.848*	-0.773*
	Tree crown cover index	-0.951*	-0.892*

*Significant correlation ($p \leq 0.05$);^{ns} not significant.

dendrometric variables of the tree species and with the height and canopy diameter of the coffee trees; it was negatively correlated with mortality and defoliation. F2 was positively correlated with tree stem diameter.

The PCA results reinforce that the larger canopy size and tree cover index observed for *T. micrantha* and *H. popayanensis* species located further to the right of the *Blipot* provided greater protection of coffee trees against frost, reducing defoliation and mortality, located to the left (Figure 3). In addition, these species subsequently favoured the development of coffee trees with respect to plant height and canopy diameter.

4 DISCUSSION

The area where coffee can be commercially produced is limited to the intertropical zone, between latitudes 25° N and 25° S, mainly because of temperature, since the plant is easily damaged by frost (Smith, 1985). Within this limit, the problem of frost occurs mainly in the higher latitudes, and the South and Southeast regions of Brazil are among the few affected by the phenomenon. For this reason, the literature on the subject is scarce and local.

Table 5: Eigenvalues between variables related to tree species and coffee trees and principal components in coffee trees in monoculture and in AFSs.

Variables		Principal components	
		F1	F2
Tree species [1]	H	0.88	0.44
	DBH	0.94	0.16
	CP	0.95	-0.21
	TCI	0.95	-0.21
Coffee trees [2]	DESF	-0.94	0.27
	MORT	-0.89	0.41
	H	0.81	0.48
	SD	-0.41	0.88
	CD	0.74	0.61
Variations (%)		72.48	21.29

[1]H - total height, DBH - diameter at breast height, CP - crown projection area, TCI - tree cover index. [2]DESF - defoliation, MORT - mortality, H - total height, SD - stem diameter, CD - crown diameter.

Despite the limited attention on the subject, the impact of frost on coffee production is great and can compromise the production chain, even at the global level, or even completely change the economic and social matrix of a region. This was the case of the 1975 frost in Paraná, which decimated the coffee crop overnight; until then, the crop was predominant in approximately 1.8 million hectares. In view of the problem and the need for mitigating measures, this study evaluated the largest number of tree species ever tested in a single experiment of coffee tree AFSs in Brazil. Of the seven species, six were evaluated for the first time with regard to their ability to reduce frost damage to coffee trees. The exception was *M. scabrella*, which had already been evaluated in coffee AFSs during a frost in 2002 and increased leaf temperature by 0.5 °C compared to the control (Leal et al., 2005).

Some studies show that AFSs minimize the effects of strong cooling by raising the minimum air temperature (Leal et al., 2005; Valentini et al., 2010; Moreira et al., 2018). However, these systems can present diverse combinations and structures between their components, and all the variables of each of these components should be considered, especially the morphological characteristics of the tree species, because the wrong choice can compromise technical aspects crucial to the viability of the system (Aguiar Junior et al., 2021).

When one of the objectives of an AFS is the protection of coffee trees against frost damage, the choice of the tree component should take into account the speed of development, especially of the crown, whose projection area is high and negatively correlated with the level of defoliation and mortality, i.e., the larger the diameter of the crown of the tree species, the greater the protection of the coffee trees against frost damage.

In addition to canopy projection, canopy conformation should be taken into consideration. Although *M. oleifera* and *C. floribundus* did not differ from *H. popayanensis* with respect to crown projection area, these species performed differently in protecting coffee trees against frost damage. The lower protection attributed to *M. oleifera* and *C. floribundus is* probably due to the fact that these species have less dense canopies (Carvalho, 2003; Lorenzi; Matos, 2021).

The relationship between the cover index of tree species was also high and negatively correlated with the level of defoliation and mortality of coffee trees. This correlation suggests that fast-growing species that provide more canopy cover early in the establishment of the system may be more successful in protecting coffee trees against frost damage. *T. micrantha* and *H. popayanensis,* responsible for the best level of protection of coffee trees, are pioneer species with rapid initial development (Lorenzi, 2020). These species were responsible for up to 55% reduction in defoliation and approximately 27% reduction in coffee tree mortality after frost. Young coffee trees are more susceptible to frost damage, and therefore, protection in the early stage of development is more important.

The adaptability of the tree species to the edaphoclimatic conditions is another highly relevant factor when defining the composition of the system. None of the tree species suffered severe damage from frost. Regardless of the species, only a few trees, located peripherally in the borders, had slight damage to their shoots, which did not interfere with their capacity for protection. Frost tolerance is an essential characteristic for tree species that will be part of AFSs in areas at risk of this climatic event.

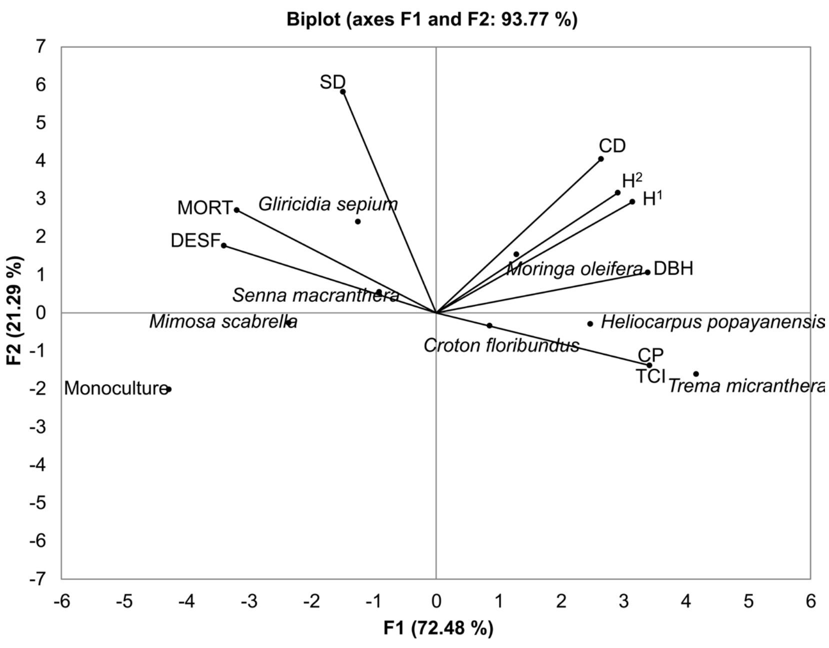

Figure 3: *Biplot of* principal components with the projection of variables related to tree species (H^1 - total height, DBH - diameter at breast height, CP - crown projection area, TCI - tree cover index) and coffee trees (DESF - defoliation, MORT - mortality, H^2 - total height, SD - stem diameter, CD - crown diameter) in monoculture and in AFSs.

For *T. micrantha* and *H. popayanensis*, frost tolerance gives these species the possibility of maintaining their protective potential even in conditions where successive frosts occur, as in July 2013, when this climatic event occurred on four consecutive days. It is noteworthy that the frost that hit during the experiment occurred approximately one year after its implementation and that the tree species were in the initial phase of development. For this reason, we cannot exclude the possibility of protection of coffee trees by other species in older systems.

The AFSs increase the minimum temperatures, which can vary according to several factors, such as the tree species and its morphological characteristics, the arrangement and quantity of specimens in the area, geographical location, and intensity and duration of the cold. In Minas Gerais, the minimum temperatures in coffee tree AFSs with *Acrocomia aculeata* were 0.9 to 1.1 ºC higher than those in monoculture coffee areas (Moreira et al., 2018). In Paraná, the coffee tree AFS with *M. scabrella* allowed an increase of 2.3 ℃ compared to monoculture. The tree systems of rubber and coconut trees in São Paulo minimized the effects of strong cooling, raising temperatures by up to 2 °C (Valentini et al., 2010).

Because of thermal inversion, the cold air from higher altitudes is drained to lower altitudes (Rolland, 2003; Kotikot; Onywere, 2015) and, for this reason, in frost episodes, the temperatures in the grass are lower than those recorded in meteorological shelters, with differences that can reach 9 ºC (Instituto de Desenvolvimento Rural do Paraná - IAPAR-EMATER, 2022). The temperatures recorded in shelter in the period when frost was observed in the experimental area ranged from 0.2 to 4.4 ºC. At the time, there were no meteorological stations in the treatments, but because of the formation of frost on the coffee trees, characterized by dew freezing and the phenomenon of thermal inversion, it can be inferred that the temperatures at the site were negative.

The adaptation of *C. arabica* to milder climates, with average temperatures between 16 and 23 ºC (Matielo et al., 2020), may explain the better development of the plants in most AFSs, since climatic factors play a fundamental role in the physiological processes of coffee (DaMatta; Ramalho, 2006). For each degree of temperature increase above 24 ºC, there is a 10% reduction in the photosynthetic rate (Matielo et al., 2020). Besides protecting coffee trees from damage by low temperatures, AFSs play an important role in reducing maximum air and soil temperatures, and also contribute to reducing wind speed and increasing relative humidity near coffee trees, which also favours a better microclimate (DaMatta; Ramalho, 2006; Morais et al., 2006; Oliosi et al., 2016; Ehrenbergerová; Šenfeldr; Habrová, 2017; Coltri et al., 2019).

5 CONCLUSIONS

AFSs affect the microclimatic dynamics of the environment, and the level of protection of coffee trees against frost damage depends on the tree species and especially on its morphological characteristics. *Trema micrantha* and *H. popayanensis* have a more effective protective effect against frost damage when coffee plants are young because the rapid growth of this two species. Therefore, AFSs with *T. micrantha* and *H. popayanensis* can be utilized in coffee production in regions prone to climatic stresses, such as sub-optimal temperatures, reducing defoliation and frost mortality of coffee trees in the early stage of development, when plants are more susceptible.

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7 AUTHORS' CONTRIBUTION

PHC and HM wrote the manuscript, PHC designed and performed the experiment, PHC and CSGK analyzed the data, PHC and HM co-wrote the paper, PHC supervised the research, PHC and CSGK conducted statistical analyses and HM, PHC and CSGK review and approval of the final version of the work.

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