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Inter-row cover crops influencing the development of conilon coffee

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Abstract

The use of forage as a cover crop is an alternative for the sustainable management of conilon coffee (*Coffea canephora* Pierre ex Froehner) crops. The objective of this study was to evaluate the herbage accumulation and nutritive value of forages used as cover crops and their effect on the productivity and physiology of conilon coffee plants. The inter-row management assessed were 1- Congo grass [*Urochloa ruziziensis* (R. Germ. & C.M. Evrard) Crins], 2- Mombaça guineagrass [*Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs], 3- Marandu palisadegrass [*Urochloa brizantha* (Hochst. ex A.Rich.) R.D.Webster], 4- weeds, 5- weeding and herbicide application. The experiment was conducted in 2020 and 2021 using a randomized block design (split-plot) with four replications and a plot size of 24 m^2. Herbage accumulation of Congo grass, Mombaça guineagrass and Marandu palisadegrass (1.12 to 3.81 t/ha) were higher than weeds (0.18 to 1.95 t/ha) in seven periods evaluated. Mombaça guineagrass had the highest average herbage accumulation (1.47 to 3.81 t/ha). The forage cover crops did not differ among themselves for dry matter concentration, crude protein and *C:N* ratio in three periods evaluated. The inter-rows management with cover crops did not reduce productivity, grain/fruit ratio, grain size, vegetative vigour and physiology of the coffee plants compared to the management with weeding and herbicide in 2021. In 2022, they stagnated or reduced productivity by up to 49%, with changes in plant physiology. Adjustments in the management of cover crops are needed for the development of competitive and sustainable coffee crops.

Introduction

Coffee (*Coffea* spp.) is one of the most popular and consumed beverages in the world and an important export agricultural product in many Asian, African and Latin American countries (Mishra, 2019). The two species of greatest economic importance are arabica coffee (*C. arabica*) and conilon or robusta coffee (*C. canephora*). The conilon or robusta coffee plants are produced in tropical regions, usually in places with altitudes below 1000 m, and responsible for 36% of world production (Campuzano-Duque *et al.*, 2021). Brazil is the second largest producer of conilon coffee in the world, with the state of Espírito Santo (ES) being the main producer in the country, responsible for about 64% of production, with an expanding market (CONAB, 2022).

The largest part of Brazilian coffee is produced in monoculture crops without an inter-row vegetation cover of the coffee plants. The use of monoculture has led to the depletion of agricultural soils, changing the dynamics of soil organic matter and water availability, reducing agricultural productivity and intensifying soil erosion (Cardoso *et al.*, 2012; Melloni *et al.*, 2013; Franco Junior *et al.*, 2018). Most Brazilian coffee growers use herbicides to control weeds in the inter-row of coffee plants (Melloni *et al.*, 2013). Herbicides applied on exposed soil are easily carried away and can contaminate surface waters (Islam *et al.*, 2018). The uptake of herbicides by farmers is growing due to falling herbicide prices coupled with steadily rising wage rates (Haggbladea *et al.*, 2017). However, Carvalho *et al.* (2014) reported that herbicides caused phytotoxicity in coffee seedlings, delayed vegetative growth, and impaired the development of arbuscular mycorrhizal fungi in the soil, beneficial for nutrient absorption. Recent research reports have also indicated the presence of herbicide residues in leaves and processed coffee grains (Schrübbers *et al.*, 2016; John and Liu, 2018).

Cover crops can minimize the application of herbicides and soil degradation under crops (Cardoso *et al.*, 2012; Melloni *et al.*, 2013). However, the cover crop must be harvested periodically, avoiding competition for water and nutrients that can alter physiological processes and reduce the productivity of the main crop (Ragassi *et al.*, 2013; Franco Junior *et al.*, 2018; Ronchi and DaMatta, 2019; Medic and Baez Veja, 2021). The choice of the species used as cover crops in the inter-row of coffee plants influences productivity, although it still lacks conclusive scientific information.

Warm-season perennial grasses have the potential to be used as cover crops due to the superior biomass accumulation and adaption to different edaphic and climatic conditions (Ragassi *et al.*, 2013; Grzyb *et al.*, 2020; Medic and Boaz Vega, 2021). In addition, warm-season perennial grasses can be used as forage in crop-livestock systems (Jose and Dollinger, 2019). Dávila-Solarte *et al.* (2019) observed that growing coffee plantations in intercropping with lambs is economically viable and offers agronomic and environmental benefits. However, types of management influence the development and nutritional value of forage cover crops (Terra *et al.*, 2020; Costa *et al.*, 2021), as well as the edaphoclimatic conditions (Garay *et al.*, 2017; Costa *et al.*, 2021), lacking studies on their viability in integrated systems in tropical environments.

This research evaluated the herbage accumulation and nutritive value of forages used as cover crops and their effect on productivity, grain size and physiology of conilon coffee plants.

Materials and methods

Characterization of the area

The research was conducted in a commercial plantation of conilon coffee in Rio Bananal – ES, Brazil (latitude 19°15′58″ S, longitude 40°19′60″ W, altitude of 75 m) from April 2020 to June 2022. The climate in the region is Aw, according to the Köppen classification (Alvares *et al.*, 2013), with annual precipitation of 1217 mm and an average temperature of 24.2°C with a rainy period between October and March (Fig. 1). The soil has a clayey texture, with 47% of sand, 7% of silt, and 46% of clay.

The coffee seedlings were planted in March 2018 after subsoiling the planting rows at a depth of 0.60 m with a bulldozer. The spacing was 2.5 m × 1.2 m (3333 plants/ha) with localized drip irrigation. A soil sample was collected in January 2020 between the rows of coffee plants for soil fertility diagnosis (Table 1).

The inter-row management were: 1- Congo grass, 2- Mombaça guineagrass, 3- Marandu palisadegrass, 4- weeds [*Andropogon bicornis* L., *Lantana camara* L., *Cnidoscolus urens* (L.) Arthur, *Solanum Americanum* Miller, *Baccharis dracunculifolia* DC., *Ipomoea* sp., *Vernonia tweediana* (Baker) H.Rob., *Cenchrus echinatus* L., *Euphorbia heterophylla* L., *Cyperus rotundus L.*], 5- weeding and application of 200 l/ha of glyphosate herbicide, at a concentration of 10 ml/l (1%). Congo grass, Mombaça guineagrass and Marandu palisadegrass were planted in April 2020 without organic and mineral fertilizers to correct soil fertility, which is naturally acidic (Table 1). Before planting, weeds were eliminated with a hoe, and the herbicide glyphosate was applied in the coffee plants inter-row. Plots (9.0 m^2 on each side) were seeded with a manual seeder (Krupp Metal 13AZ, Araricá, Brazil) using the row spacing of 0.5 m and plant spacing within the row of 0.25 m for Congo grass and Marandu palisadegrass, and the row spacing of 0.55 m and plant spacing within the row of 0.35 m for Mombaça guineagrass. Weeds emerged naturally in the area.

The experimental plots had dimensions of 4.0 × 6.0 m (width × length), with five coffee plants and the inter-row on both sides. Each line of coffee plants had a single clone (genotype: P1, LB1, A1, P1), and the inter-row management was distributed side by side with every five coffee plants (6.0 m). Each coffee plant line represented a block, in a total of four blocks, and the coffee plants present in the rows between the blocks represented a border plant (coffee plants not evaluated).

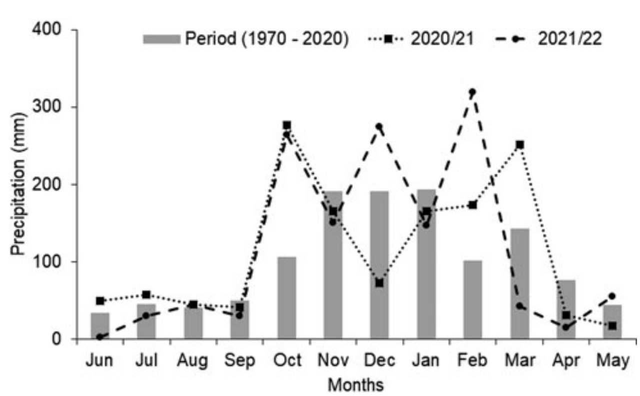

Figure 1. Average monthly precipitation of the period (1970 to 2020) and of the agricultural year 2020/21 and 2021/22 in Rio Bananal, Brazil, using data from National Water Agency of Brazil (2022).

Herbage accumulation of cover crops

An area of 1 m^2 was harvested manually using a 0.2 m stubble height and used to estimate herbage accumulation, following the method adapted from Leite *et al.* (2021). Two samples were collected per plot when the forage reached 0.5 m (Costa *et al.*, 2021), totalling seven sampling events from January 2021 to June 2022. Herbage accumulation was measured in the field with a portable digital scale in seven periods (harvests) from January 2021 to June 2022. The samples were dried in an oven with forced ventilation at 60°C until constant mass was measured with a digital bench scale (AOAC, 2012).

Forages nutritive value

Dried samples from three harvests, July 2021, December 2021, and June 2022, were ground in a Thomas-Willey mill and passed through a 1 mm sieve, adapted from Dias *et al.* (2020) and Leite *et al.* (2021). A subsample was dried at 135°C for two hours to determine the definitive dry matter concentration used to calculate dry matter concentration (AOAC, 2012).

Crude protein was analysed by the Kjeldhal method, and the ether extract was analysed by adapting Garay *et al.* (2017). The total carbon was calculated by the muffle method according to do Carmo and Silva (2012) and used to calculate carbon:nitrogen (C:N) ratio.

Productivity of conilon coffee plants and grain size

Conilon coffee clones productivity was measured in May 2021 and May 2022, analysing the three central plants of the plots containing five coffee plants each, when 80% of the fruits were ripe, i.e. with a reddish colouration of the exocarp (Ronchi and DaMatta, 2019; Mulindwa *et al.*, 2021). The fruits were harvested manually and measured volumetrically with a 20-l graduated bucket.

Samples with 2.0 l of coffee fruits were placed in perforated bags and dried to 12% humidity on a suspended and covered terrace. The dried fruits were peeled, and the grains were weighed to

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Table 1. Chemical attributes of the soil collected in the 0–0.2 m layer on the inter-row of the conilon coffee plants before planting the cover crops

pH	P	K	Ca	Mg	Na	Al	CEC	OM	AS	BS
H_2O			kg/ha				Cmolc/kg		%	
4.3	10	146	361	97	8	162	6.2	2.2	38.9	23.8

Analysis methodology: Teixeira *et al.* (2017). P, phosphorus; Na, sodium; K, potassium; Ca, calcium; Mg, magnesium; Al, aluminium; CEC, cation exchange capacity; OM, organic matter; AS, aluminium saturation; BS, base saturation.

calculate the grain/fruit ratio. The grain/fruit ratio was obtained by the ratio between the mass of processed grains and the initial volume of ripe fruits and used to calculate the mass productivity of grains per area (Franco Junior *et al.*, 2018; Pereira *et al.*, 2022), i.e. in bags (60 kg) per hectare. The size of the processed grains was measured using a set of sieves with holes ranging from 16/64″ (6.35 mm) to 8/64″ (3.175 mm), according to the Official Brazilian Classification (Brasil, 2003) and grouped into three classes, being ⩾15/64″, 13–14/64″ and ⩽12/64″.

Evaluation of the vegetative vigour of coffee plants

The vegetative vigour of coffee plants was measured in July 2021 and June 2022 using the normalized difference vegetation index (NDVI), acquired by the GreenSeeker portable meter (Trimble, Sunnyvale, USA), adapted from Martello *et al.* (2022). The apparatus was positioned at a height of 1.5 m above and parallel to the ground. The reading was performed at 0.5 m of linear distance from the coffee plants. Readings were taken on the three central plants of the plot on both sides of the planting row between 9:00 and 10:00 h (GMT, BRS, 3 h day), adapted from Quartezani *et al.* (2018). After activating the sensor, the reading occurs every 0.1 s, generating between 30 and 40 measurements per reading.

Physiological indices of coffee plants

Fluorescence indices of coffee plant leaves were collected in July 2021 and June 2022 with a Multiplex 330 optical fluorescence sensor (Force-A, Orsay, France), with six sources of light excitation, being ultraviolet (UV, 375 nm), blue (B, 450 nm), green (G, 515 nm) and red (R, 635 nm). The detection of fluorescence emitted by chlorophyll occurs in the red (RF) and far red (FRF) spectrum and was used to estimate the nitrogen balance index (NBI-G and NBI-R), chlorophyll (SFR-G and SFR-R), anthocyanin (ANT-RG and ANT-RB) and flavonoids (FLAV), adapted from Agati *et al.* (2013) and Abdallah *et al.* (2018).

Readings were taken on the three central plants of the plot on both sides of the planting row, between 9:00 and 10:00 h (GMT, BRS, 3 h day), adapted from Quartezani *et al.* (2018). The device was positioned at a height of 1.5 m above and parallel to the ground, directed towards the top of the coffee plants, from top to bottom, at an angle of 45° and a linear distance of 0.5 m.

Statistical design

The experiment was installed in a split-plot design (inter-row management [$n = 5$] and periods [n = 7, 3 or 2]) with four randomized blocks (replications), according to Eqn (1):

$$Y_{ijk} = \mu + \alpha_i + \eta_{k(i)} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{k(ij)} \quad (1)$$

where Y_{ijk} is the response variable, μ is a mean, α_i is the effect of the whole-plot, $\eta_{k(i)}$ is the whole-plot error, β_j is the effect of the split-plot, $(\alpha\beta)_{ij}$ is the interaction between factors, and $\varepsilon_{k(ij)}$ is the split-plot error.

Data were submitted for analysis of variance using the F test ($P > 0.05$) and comparison of means using the Tukey test ($P > 0.05$) in the R Core Team (2017) software. The interaction between the factors of inter-row management and period was considered significant for the productivity of conilon coffee plants with $P < 0.1$ due to the seasonality of the data in both periods, which agreed with field observations and with Megerssa *et al.* (2012) and Tanimonure and Naziri (2021).

Results

Herbage accumulation and nutritive value of cover crops

Herbage accumulation showed a significant interaction between inter-row management and periods ($P < 0.001$). The herbage accumulation of Congo grass, Mombaça guineagrass and Marandu palisadegrass (1.12 to 3.81 t/ha) were higher than the weeds (0.18 to 1.95 t/ha) in the evaluated periods, except for

Table 2. Herbage accumulation (t/ha) of cover crops in the inter-row of conilon coffee plants in the evaluated periods

Cover crops	28 Jan 2021	13 Jul 2021	18 Oct 2021	24 Nov 2021	17 Dec 2021	19 Jan 2022	18 Jun 2022
Congo grass	2.00 ± 0.29	0.76 ± 0.11	1.50 ± 0.15	3.06 ± 0.25	3.08 ± 0.14	3.40 ± 0.11	1.01 ± 0.32
Mombaça guineagrass	2.96 ± 0.26	1.47 ± 0.18	1.60 ± 0.06	3.61 ± 0.26	3.81 ± 0.11	3.68 ± 0.09	2.82 ± 0.20
Marandu palisadegrass	1.50 ± 0.30	1.12 ± 0.10	1.68 ± 0.04	3.25 ± 0.12	3.22 ± 0.11	3.46 ± 0.14	1.77 ± 0.16
Weeds	0.21 ± 0.05	0.18 ± 0.05	0.28 ± 0.16	1.23 ± 0.21	0.83 ± 0.48	1.95 ± 0.07	0.67 ± 0.13
HSD cover crops	0.69						
HSD period	0.76						

Mean ± standard error. HSD, honestly significant difference (Tukey's test, $P = 0.05$).

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Table 3. Dry matter concentration (DM), crude protein (CP) and carbon:nitrogen ratio (*C:N*) of cover crops in the inter-row of conilon coffee plants

Cover crop	DM (%)	CP (%)	*C:N*
13 July 2021			
Congo grass	31.2 ± 1.0	11.7 ± 0.6	24:1 ± 1.4
Mombaça guineagrass	26.3 ± 0.7	11.3 ± 0.3	24:1 ± 0.9
Marandu palisadegrass	29.4 ± 1.5	12.0 ± 0.2	23:1 ± 0.5
Mean	29.0 ± 0.9	11.7 ± 0.3	24:1 ± 0.6
17 December 2021			
Congo grass	25.8 ± 0.7	5.5 ± 0.1	53:1 ± 0.8
Mombaça guineagrass	23.7 ± 0.3	5.2 ± 0.1	55:1 ± 0.9
Marandu palisadegrass	24.9 ± 0.7	5.5 ± 0.1	53:1 ± 0.9
Mean	24.8 ± 0.5	5.4 ± 0.1	54:1 ± 0.6
18 June 2022			
Congo grass	22.2 ± 1.5	4.7 ± 0.3	60:1 ± 4.9
Mombaça guineagrass	20.9 ± 0.5	4.7 ± 0.1	61:1 ± 1.6
Marandu palisadegrass	21.3 ± 0.9	4.9 ± 0.4	62:1 ± 6.7
Mean	21.5 ± 0.7	4.7 ± 0.2	61:1 ± 3.0
HSD cover crops	7.3	2.1	6.7
HSD period	2.5	1.1	2.1

Mean ± standard error. HSD, honestly significant difference (Tukey's test, $P = 0.05$).

Congo grass on 13 July 2021 and 18 June 2022, not statistically different from the weeds (Table 2). Mombaça guineagrass presented an average herbage accumulation 29.5% higher than the other forages cover crops (1.47 to 3.81 t/ha), differing statistically from at least one of them on 28 January 2021, 13 July 2021, 24 November 2021, 17 December 2021, and 18 June 2022. The herbage accumulation of cover crops (2.32 t/ha) was 89% higher in the rainy season (October to March) compared to the dry season (1.23 t/ha).

Dry matter ($P = 0.969$), crude protein ($P = 0.931$), and *C:N* ratio ($P = 0.427$) showed no significant interaction between inter-row management and periods that were evaluated separately. Congo grass, Mombaça guineagrass and Marandu palisadegrass did not differ statistically from each other for dry matter ($P = 0.437$), crude protein ($P = 0.615$), and *C:N* ratio ($P = 0.419$) in the three evaluations performed (Table 3). However, dry matter concentration ($P < 0.001$), crude protein ($P < 0.001$), and *C:N* ratio ($P < 0.001$) differed statistically between periods. Dry matter concentration and crude protein contents decreased with the increase in the number of cuts, from 13 July 2021 (29.0 and 11.7%) to 18 June 2022 (21.5 and 10.5%), while the *C:N* ratio increased (24:1 to 61:1).

Productivity of conilon coffee plants and grain quality

Productivity ($P = 0.092$), grain/fruit ratio ($P = 0.855$), and grain size classes ⩾15/64″ ($P = 0.560$), 13–14/64″ ($P = 0.827$) and ⩽12/64″ ($P = 0.119$) showed no significant interaction between inter-row management and periods. Inter-row management differs statistically for conilon coffee productivity for the two years average ($P = 0.002$), with weeding and herbicide application showing higher productivity with 125.7 bags/ha (7545 kg/ha). The inter-row management with Congo grass, Mombaça guineagrass and Marandu palisadegrass obtained the lowest values, ranging from 96.0 to 82.0 bags/ha (5761 to 4922 kg/ha). However, the results demonstrated a variation in productivity between 2021 and 2022, indicating a tendency towards statistical significance of the interaction between inter-row management and period ($P < 0.1$). In 2021, inter-row management did not differ statistically for conilon coffee productivity, ranging from 102.0 to 115.2 bags/ha (6120 to 6912 kg/ha). Nevertheless, in 2022, the inter-row management with weeding and herbicide application showed higher productivity with 149.5 bags/ha (8970 kg/ha), while the inter-row management with Congo grass, Mombaça guineagrass and Marandu palisadegrass obtained the lowest values, ranging from 56.3 to 84 bags/ha (3378 to 5040 kg/ha). The inter-row management with weeding and herbicide application showed a 47% increase in the productivity of conilon coffee plants in 2022 compared to 2021, while the inter-row management with Congo grass, Marandu palisadegrass and weeds productivity did not vary statistically, and the inter-row management with Mombaça guineagrass showed a 48% reduction in productivity.

Inter-row management did not differ statistically ($P = 0.358$) for grain/fruit ratio in 2021 and 2022, ranging from 0.14 to 0.15 and from 0.17 to 0.20 kg/l, respectively (Table 4). The same also occurred for the grain size classes ⩾15/64″, 13–14/64″, and ⩽12/64″, ranging from 71.4 to 84.9%, 13.9 to 24.8%, and 1.2 to 7.0%, respectively. The grain/fruit ratio increased by 29% in 2022 (0.18 kg/l) compared to 2021 (0.14 kg/l). The grain size classes of conilon coffee ⩾15/64″ ($P = 0.270$), 13–14/64″ ($P = 0.162$), and ⩽12/64″ ($P = 0.296$) did not differ statistically between 2021 and 2022.

Vegetative vigour and physiological indices of coffee plants

The vegetation index per normalized difference ($P = 0.280$), chlorophyll index (SFR-G [$P = 0.359$] and SFR-R [$P = 0.468$]), nitrogen balance index (NBI-G [$P = 0.870$] and NBI-R [$P = 0.922$]), anthocyanin (ANTH-RB [$P = 0.221$]) and flavonoids ($P = 0.187$) showed no significant interaction between inter-row management and periods while the anthocyanin (ANTH-RG [$P = 0.014$]) showed the opposite.

The vegetation index per normalized difference ($P = 0.509$ and $P < 0.001$), chlorophyll index (SFR-G [$P = 0.113$ and $P < 0.001$] and SFR-R [$P = 0.109$ and $P = 0.085$]), nitrogen balance index (NBI-G [$P = 0.675$ and $P < 0.001$] and NBI-R [$P = 0.423$ and $P < 0.001$]), anthocyanin (ANTH-RB [$P = 0.415$ and $P < 0.001$]) and flavonoids ($P = 0.724$ and $P < 0.001$) showed no significant interaction for inter-row management but showed a significant effect for periods (Table 5). The inter-row management did not differ statistically for the vegetation index per normalized difference and physiological indices in 2021 and 2022, except for the anthocyanin index (ANT-RG) in 2022, with the highest values for inter-row management with cover crops (0.03 to 0.06) and the lowest for inter-row management with weeding and herbicide application (0.02).

In 2022, the inter-row management presented a vegetation index per normalized difference lower than in 2021 (0.79 *vs.* 0.83). The same occurred for the chlorophyll index (SFR-G [0.91 *vs.* 3.20]) and flavonoids (FLAV [0.79 *vs.* 1.20]), with the opposite occurring for the nitrogen balance index (NBI-G [0.18 *vs.* 0.10] and NBI-R [0.59 *vs.* 0.19]) and anthocyanin (ANTH-RG [0.04 *vs.* −0.33] and ANTH-RB [1.79 *vs.* −0. 64]).

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Table 4. Productivity, grain/fruit ratio and grain size classes of conilon coffee plants in the inter-row management with cover crops and with weeding and herbicide application

Inter-row management	Productivity bags/ha	Grain/fruit ratio kg/litre	⩾15/64″ %	13–14/64″ %	⩽12/64″ %
2021					
Congo grass	107 ± 11	0.15 ± 0.01	72.0 ± 2.9	24.6 ± 2.7	3.4 ± 0.9
Mombaça guineagrass	108 ± 6	0.14 ± 0.01	76.4 ± 5.7	21.2 ± 4.9	2.4 ± 0.9
Marandu palisadegrass	108 ± 7	0.15 ± 0.01	75.6 ± 4.2	22.0 ± 3.8	2.4 ± 0.5
Weeds	115 ± 7	0.15 ± 0.01	72.9 ± 5.1	24.8 ± 4.1	2.3 ± 1.0
Weeding and herbicide	102 ± 9	0.14 ± 0.01	75.1 ± 6.0	22.7 ± 5.2	2.2 ± 1.1
Mean	108 ± 3	0.14 ± 0.01	74.4 ± 4.4	23.1 ± 3.8	2.5 ± 0.8
2022					
Congo grass	66 ± 18	0.18 ± 0.01	72.1 ± 8.2	23.4 ± 8.2	4.5 ± 0.3
Mombaça guineagrass	56 ± 18	0.17 ± 0.01	71.3 ± 11.6	21.7 ± 8.0	7.0 ± 3.9
Marandu palisadegrass	84 ± 24	0.20 ± 0.01	80.5 ± 6.1	17.6 ± 6.1	1.8 ± 0.2
Weeds	97 ± 27	0.19 ± 0.01	80.7 ± 6.1	17.4 ± 6.0	1.9 ± 0.4
Weeding and herbicide	149 ± 10	0.18 ± 0.01	84.9 ± 4.4	13.9 ± 4.1	1.2 ± 0.3
Mean	90 ± 11	0.18 ± 0.01	77.9 ± 3.3	18.8 ± 2.8	3.3 ± 0.9
HSD management	58.20	0.03	18.1	13.4	6.5
HSD period	52.82	0.03	14.5	13.7	3.3

Mean ± standard error. HSD, honestly significant difference (Tukey's test, $P = 0.05$). Bags = 60 kg of processed grains (12% moisture and peeled).

Table 5. Normalized difference vegetation index (NDVI), chlorophyll (SFR-G and SFR-R), nitrogen balance (NBI-G and NBI-R), anthocyanin (ANT-RG and ANT-RB) and flavonoids (FLAV) of conilon coffee plants in the inter-row management with cover crops and with weeding and herbicide application

Inter-row management	NDVI	SFR-G	SFR-R	NBI-G	NBI-R	ANT-RG	ANT-RB	FLAV
2021								
Congo grass	0.84 ± 0.01	3.27 ± 0.13	3.12 ± 0.12	0.10 ± 0.01	0.19 ± 0.02	−0.33 ± 0.01	−0.65 ± 0.01	1.23 ± 0.06
Mombaça guineagrass	0.82 ± 0.01	2.93 ± 0.12	2.75 ± 0.14	0.09 ± 0.01	0.18 ± 0.02	−0.34 ± 0.01	−0.62 ± 0.01	1.20 ± 0.07
Marandu palisadegrass	0.84 ± 0.01	3.32 ± 0.18	3.12 ± 0.17	0.09 ± 0.01	0.19 ± 0.01	−0.33 ± 0.01	−0.64 ± 0.01	1.24 ± 0.05
Weeds	0.82 ± 0.01	3.34 ± 0.19	3.15 ± 0.17	0.10 ± 0.01	0.20 ± 0.02	−0.33 ± 0.01	−0.64 ± 0.01	1.20 ± 0.04
Weeding and herbicide	0.80 ± 0.02	3.12 ± 0.16	2.91 ± 0.15	0.11 ± 0.01	0.22 ± 0.02	−0.33 ± 0.01	−0.63 ± 0.01	1.14 ± 0.04
Mean	0.83 ± 0.01	3.20 ± 0.07	3.01 ± 0.07	0.10 ± 0.01	0.19 ± 0.01	−0.33 ± 0.01	−0.64 ± 0.01	1.20 ± 0.02
2022								
Congo grass	0.79 ± 0.02	0.92 ± 0.08	3.20 ± 0.18	0.19 ± 0.04	0.65 ± 0.13	0.04 ± 0.01	1.81 ± 0.06	0.76 ± 0.10
Mombaça guineagrass	0.76 ± 0.04	0.87 ± 0.03	2.97 ± 0.12	0.17 ± 0.04	0.53 ± 0.14	0.06 ± 0.01	1.73 ± 0.04	0.84 ± 0.08
Marandu palisadegrass	0.79 ± 0.01	0.93 ± 0.04	3.24 ± 0.10	0.20 ± 0.05	0.66 ± 0.19	0.04 ± 0.01	1.79 ± 0.03	0.78 ± 0.10
Weeds	0.79 ± 0.01	0.88 ± 0.03	3.08 ± 0.10	0.17 ± 0.03	0.58 ± 0.11	0.03 ± 0.01	1.81 ± 0.01	0.76 ± 0.09
Weeding and herbicide	0.81 ± 0.01	0.96 ± 0.04	3.32 ± 0.10	0.17 ± 0.03	0.56 ± 0.09	0.02 ± 0.01	1.81 ± 0.02	0.82 ± 0.07
Mean	0.79 ± 0.01	0.91 ± 0.02	3.16 ± 0.06	0.18 ± 0.02	0.59 ± 0.06	0.04 ± 0.01	1.79 ± 0.02	0.79 ± 0.04
HSD management	0.08	0.38	0.52	0.16	0.16	0.03	0.16	0.14
HSD period	0.04	0.32	0.39	0.07	0.27	0.02	0.07	0.10

Mean ± standard error. HSD, honestly significant difference (Tukey's test, $P = 0.05$).

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Discussion

Herbage accumulation and nutritive value of cover crops

Congo grass, Mombaça guineagrass and Marandu palisadegrass produced greater herbage accumulation than the weeds. The lower herbage accumulation of weeds was due to the residual effect of two years of herbicides use in the soil, applied before the installation of the experiment, eliminating weeds originating from seeds in the soil, reducing the potential of the soil seeds bank (Beckie *et al*., 2019). Mombaça guineagrass was the cover crop with higher herbage accumulation, related to genetic factors and its adaptability to tropical climate regions (Dias *et al*., 2020; Costa *et al*., 2021). A greater Mombaça guineagrass forage accumulation can occur in conditions of greater soil fertility and irrigation, while species of the genus *Urochloa* are more adapted to soils with low fertility and periods of water deficit (Costa *et al*., 2021).

The herbage accumulation of cover crops was higher in the rainy season compared to the dry season. It occurs due to climatic oscillations that occur in a year (Fig. 1), as the reduction of precipitation, temperature and photoperiod in the dry season, fundamental for photosynthesis, which decreases the growth of forage plants, resulting in the seasonality of production (Xia *et al*., 2017; Terra *et al*., 2020). In periods with lower water availability, plants assign more carbon to the root system than to the shoots as an adaptive response, reducing the production of new tillers (Maia *et al*., 2014; Xia *et al*., 2017). Furthermore, weeds have a lower range of herbage accumulation between periods, indicating phenotypic plasticity in the tropical environment (Terra *et al*., 2020).

The low natural soil fertility (Table 1) resulted in no statistical difference in dry matter concentration, crude protein and *C:N* ratio between forage cover crops, preventing mainly the Mombaça guineagrass from expressing its nutritional potential (Costa *et al*., 2021). Another factor that minimized differences between forage cover crops was the rest period between cuts that, when increased, reduces the nutritional value of forages (Terra *et al*., 2020; Costa *et al*., 2021). For the coffee producer, increasing the number of forage plants represents an increase in the cost of production. However, for crop-livestock integration systems, this adjustment is necessary and may improve economic viability (Dávila-Solarte *et al*., 2019). This nutritional limitation of cover crops stimulates root growth towards the coffee rows, generating competition for water and nutrients with the coffee plants (Partelli *et al*., 2010; Ronchi and DaMatta, 2019).

Climatic conditions throughout the year and plant age affect the nutritive value of forage cover crops (Garay *et al*., 2017; Maia *et al*., 2014). Dry matter concentration decreased over time due to higher water content in the leaf tissue, a result of rainfall above the historical average, with 1345 and 1375 mm/year in 2020/21 and 2021/22, respectively (Fig. 1), in agreement with Serrano *et al*. (2016). Crude protein values found in Congo grass, Mombaça guineagrass and Marandu palisadegrass (11.3 to 12.0%) on 17 March 2021 corroborate the value obtained by Oliveira *et al*. (2020) for forages of the genus *Urochloa*, ranging from 9.2 to 12.2%. However, the values found on 17 December 2021 and 18 June 2022 were lower, ranging from 4.7 to 5.4%. Garay *et al*. (2017) also found a reduction in crude protein values with increasing regrowth age for different forages and fluctuations throughout the year, from 14.1% in the rainy season to 7.6% in the dry season. The lowest crude protein values are also related to the low availability of nutrients in the soil (Table 1), in agreement with Leite *et al*. (2021). Increasing forage age decreased the crude protein concentration due to the reduction in the leaf: stem ratio, in agreement with Maia *et al*. (2014), reaching concentrations lower than the minimum considered (7%) when intake by ruminants could be suppressed (Lazzarini *et al*., 2009).

The *C:N* ratio increased from 13 July 2021 to 18 June 2022. Cavalli *et al*. (2018) found a *C:N* ratio for *Brachiaria* (syn. *Urochloa*) residues ranging from 32:1 to 56:1. Dias *et al*. (2020) found *C:N* ratio values of Mombaça guineagrass ranging from 29:1 to 37:1. The *C:N* ratio of residues added to the soil influences decomposition and the relationship between mineralization and nitrogen immobilization by microbial biomass (Grzyb *et al*., 2020). Straw with a low *C:N* ratio decompose quickly, reducing the mulch persistence time on the soil surface (Cavalli *et al*., 2018). However, if the *C:N* ratio of plant residues is greater than 25:1, the amount of mineralized nitrogen is not enough to meet the demand of microorganisms, which start to immobilize the mineral nitrogen available in the soil, compromising nitrogen nutrition of crops (Grzyb *et al*., 2020; Watthier *et al*., 2020). In tropical regions, decomposition is favoured by environmental conditions, and therefore covers with a *C:N* ratio greater than 25:1 is favourable, that is, more stable and with a longer time of permanence in the soil (Cavalli *et al*., 2018).

Productivity of conilon coffee plants and grain quality

The initial growth of cover crops was in 2021 with the superficial and localized root system, not causing competition for water and nutrients with the coffee plants, so coffee productivity did not differ statistically between the inter-row management with cover crops in relation to weeding and herbicide application. Partelli *et al*. (2010) also observed that the cover crops did not disturb the vegetative growth and nutrient concentrations in the leaves of the conilon coffee plants. In 2022, coffee productivity in inter-row management with weeding and herbicide application increased by 47% compared to 2021, while the inter-row management with cover crops stagnated or reduced by up to 48%.

Increased productivity of conilon coffee was expected in 2022 compared to 2021 due to greater rooting and vegetative development of plants, with elongation of orthotropic and plagiotropic branches, with a substantial number of internodes and flower buds, resulting in a higher production of coffee fruits (Ronchi and DaMatta, 2019; Colodetti *et al*., 2020). This stagnation or reduction in coffee productivity in inter-row management with cover crops in 2022 was due to root development and ability to compete for water and nutrients with coffee plants, in agreement with Franco Junior *et al*. (2018). Less competition occurred in inter-row management with weeds, while inter-row management with forages resulted in lower productivity due to herbage accumulation in the period. It is important to emphasize that the productivity of the coffee plants found for the inter-row management in the two years was higher than the highest national average productivity of conilon coffee in Brazil reached in 2022 with 46.2 bags/ha (2772 kg/ha) (CONAB, 2022).

Coffee spp. are perennial plants sensitive to competition for water and nutrients exerted by weeds (Ragassi *et al*., 2013). This competition have negative effects on coffee plant growth and crop productivity (Ragassi *et al*., 2013; Franco Junior *et al*., 2018). The critical period of competition takes place from flowering to fruiting, which comprises in southeastern Brazil from September to March, corresponding to the rainy season (Ronchi and DaMatta, 2019). This period was the phase of greatest growth

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of cover crops (Table 2), which favoured competition with coffee plants (Franco Junior *et al.*, 2018; Ronchi and DaMatta, 2019). The effect of the competition is conditioned by the vigour of cover crops, which can be minimized with a higher frequency of harvesting, especially in the rainy season. Although cover crops reduce the presence of weeds, in case of abundant growth, this positive effect will be eliminated by the competition generated by the cover crops themselves (Melloni *et al.*, 2013; Beckie *et al.*, 2019; Grzyb *et al.*, 2020). In this case, cover crops can play the role of weeds. Therefore, it is necessary, especially in the period from flowering to fruiting, the proper management of cover crops, such as reducing the strip (width) with cover crops, increasing planting spacing and frequency of mowing or using a greater intensity of grazing in agropastoral systems (Ragassi *et al.*, 2013; Dávila-Solarte *et al.*, 2019). An agropastoral system allows the addition of value, diversification of economic activity, and better use of natural resources and inputs (Jose and Dollinger, 2019).

The inter-rows management did not influence the grain/fruit ratio and grain size in 2021 and 2022. Mulindwa *et al.* (2021) also did not observe the effect of environmental variations on the grain size of *Coffea canephora*. Although the inter-row management did not differ statistically for grain size between 2021 and 2022, there was an increase in the average grain/fruit ratio in 2022 compared to 2021 (0.18 *vs.* 0.14 kg/l). These results demonstrated the absence of the effect of the cover crops competition, not influencing the grain/fruit ratio and grain size of the conilon coffee plants, which would be more related to climate and genotype characteristics (Fialho *et al.*, 2022).

Vegetative vigour and physiological indices of coffee plants

The absence of statistical difference for the vegetation index per normalized difference and physiological indices in 2021 can be explained by the high vigour and productivity of coffee plants of the inter-row management in relation to the national average (CONAB, 2022), indicating a lack of competition with cover crops in 2021. In 2022, inter-row management with weeding and herbicide application had the lowest anthocyanin content (ANT-RB), differing statistically from inter-row management with Mombaça guineagrass, which indicated a result of cover crop competition for water and nutrients. More stressed plants, whether due to toxicity, competition for water, nutrients or light, tend to produce higher levels of secondary compounds, such as anthocyanin (Quartezani *et al.*, 2018). The effect of competition was evident in the productivity data of coffee plants in 2022 (Table 4), which could be economically compensated in an agropastoral system (Dávila-Solarte *et al.*, 2019).

Anthocyanins have functions related to antioxidants, acting in protection against the effects of sunlight, defence mechanisms and biological functions (Agati *et al.*, 2013; Quartezani *et al.*, 2018). This protection against photoinhibition is important for regions with a tropical climate, as in the case of this work. Changes in vegetation during growth result in a differentiation of fluorescence, which allows the use of spectral sensors for monitoring vegetation and the detection of physiological changes in plants (Abdallah *et al.*, 2018). Quartezani *et al.* (2018) also observed differences in the physiological indices measured with a Multiplex sensor in conilon coffee seedlings associated with different types of organic matter used in the substrate to produce seedlings.

The reduction in the average for vegetation and chlorophyll indices in 2022 compared to 2021 is related to the lower capacity to produce photoassimilates by coffee plants intercropped with cover crops (Colodetti *et al.*, 2020), also resulting in lower average productivity (Table 4). Martello *et al.* (2022) observed relationships between NDVI and coffee productivity. Inter-row management with weeding and herbicide application reduced of chlorophyll in 2022 due to the depletion of coffee plants when they reach high levels of productivity (Pereira *et al.*, 2022), that is, reducing the pigments of the leaves and redirecting the metabolites to the formation of grains (Colodetti *et al.*, 2020). Often, plant depletion is observed only in the following year's productivity, creating biennial productivity cycles (Ronchi and DaMatta, 2019; Pereira *et al.*, 2022). The increase in nitrogen balance indices in 2022 was related to the effect of coffee competition for water and nutrients in inter-row management with cover crops, with the need for coffee plants to translocate nitrogen to leaf tissues (Colodetti *et al.*, 2020) and the greater need for microorganisms to decompose residues with a higher *C:N* ratio (Dias *et al.*, 2020; Watthier *et al.*, 2020), making coffee plants more efficient.

Conclusions

The productivity of forage plants was higher weeds in the evaluated periods, being a viable option for conservation management in coffee plantations. Among the forages, Mombaça guineagrass presented the highest average productivity, being more advantageous for soil cover and use in the crop-livestock system. Cover crops did not cause a reduction in productivity, grain/fruit ratio, grain size, vegetative vigour, and physiological indices of the coffee plants in 2021. However, in 2022, there was a reduction of 16 to 49% in productivity, with changes in vegetative vigour and physiological indices, indicating the need for adjustments in management for the development of a competitive and sustainable coffee culture.

Authors' contributions

G. S. de Souza and I. R. Pretti conceived and designed the study. L.C.L. Coelho, G.R. Sarnaglia, and J. Elias conducted data gathering. L.C.L. Coelho and E. C. de Oliveira performed statistical analyses. G. S. de Souza, L. L. Bitencourt, L. L. Pereira wrote the article. R. F. de Almeida and S. da S. Berilli revised it critically for intellectual content.

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References

Abdallah FB, Philippe W and Goffart JP (2018) Comparison of optical indicators for potato crop nitrogen status assessment including novel approaches based on leaf fluorescence and flavonoid content. *Journal of Plant Nutrition* **41**, 2705–2728.

Agati G, D'Onofrio C, Ducci E, Cuzzola A, Remorini D, Tuccio L, Lazzini F and Mattii G (2013) Potential of a multiparametric optical sensor for determining *in situ* the maturity components of red and white vitis vinifera wine grapes. *Journal of Agricultural and Food Chemistry* **61**, 12211–12218.

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM and Sparovek G (2013) Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* **22**, 711–728.

Association of Official Agricultural Chemists – AOAC (2012) *Official Methods of Analysis of AOAC International*, 19th Edn. Arlington, VA: AOAC International. Available at http://www.aoac.org

Beckie HJ, Ashworth MB and Flower KC (2019) Herbicide resistance management: recent developments and trends. *Plants* **8**, 161.

BRASIL (2003) Instrução Normativa n° 8, de 11 de junho de 2003. *Diário Oficial da União* 1, 4-6. Available at https://pesquisa.in.gov.br/imprensa/servlet/INPDFViewer?jornal=1&pagina=4&data=13/06/2003&captchafield=firstAccess

Campuzano-Duque LF, Herrera JC, Ged C and Blair MW (2021) Bases for the establishment of Robusta Coffee (*Coffea canephora*) as a new crop for Colombia. *Agronomy* **11**, 2550.

Cardoso DP, Silva MLN, de Carvalho GJ, de Freitas DAF and Avanzi JC (2012) Plantas de cobertura no controle das perdas de solo, água e nutrientes por erosão hídrica. *Revista Brasileira de Engenharia Agrícola e Ambiental* **16**, 632–638.

Carvalho FP, Souza BP, França AC, Ferreira EA, Franco MHR, Kasuya MCM and Ferreira FA (2014) Glyphosate drift affects arbuscular mycorrhizal association in coffee. *Planta Daninha* **32**, 783–789.

Cavalli E, Lange A, Cavalli C and Behling M (2018) Decomposition and release of nutrients from crop residues on soybean-maize cropping systems. *Revista Brasileira de Ciências Agrárias* **13**, e5527.

Colodetti TV, Rodrigues WN, Brinate SVB, Martins LD, Cavatte PC and Tomaz MA (2020) The management of orthotropic stems modulates the photosynthetic performance and biomass allocation of productive plants of Arabica coffee. *Revista Ceres* **67**, 454–463.

Companhia Nacional de Abastecimento – CONAB (2022) *Acompanhamento da safra brasileira de café – safra 2022*. Brasília: CONAB, 2022. 65 p.

Costa NdL, Jank L, Magalhães JA, Bendahan AB, Rodrigues BHN and Santos FdS (2021) Forage productivity and chemical composition of *Panicum maximum* cv. Mombaça under defoliations intensities and frequencies. Research, *Society and Development* **10**, e42910817494.

Dávila-Solarte P, Sanginés-García L, Amezcua T and Solano L (2019) Productive performance and economic evaluation of sheep grazing on weeds in coffee plantations compared to pastures with or without supplementation. *Agroforestry System* **97**, 175–183.

Dias MdC, Costa KdP, Severiano EdC, Bilego UO, Furtini Neto AE, Almeida DP, Brand SC and Vilela L (2020) Brachiaria and Panicum maximum in an integrated crop–livestock system and a second-crop maize system in succession with soybean. *The Journal of Agricultural Science* **158**, 206–217.

do Carmo DL and Silva CA (2012) Métodos de quantificação de carbono e matéria orgânica em resíduos orgânicos. *Revista Brasileira de Ciência do Solo* **36**, 1211–1220.

Fialho GS, da Fonseca AFA, Ferrão MAG, Ferrão RG, Olivoto T, Nardino M, dos Reis EF and Sakiyamo NS (2022) Conilon coffee outturn index: a precise alternative for estimating grain yield. *Acta Scientiarum Agronomy* **44**, e54249.

Franco Junior KS, Terra ABC, Teruel TR, Mantovani JR and Florentino LA (2018) Effect of cover crops and bioactivators in coffee production and chemical properties of soil. *Coffee Science* **13**, 559–567. Available at http://www.coffeescience.ufla.br/index.php/Coffeescience/article/view/1516

Garay JR, Joaquin Cancino S, Zárate Fortuna P, Ibarra Hinojosa MA, Martínez González JC, González Dávila RP and Cienfuegos Rivas EG (2017) Dry matter accumulation and crude protein concentration in Brachiaria spp. cultivars in the humid tropics of Ecuador. *Tropical Grasslands* **5**, 66–76.

Grzyb A, Wolna-Maruwka A and Niewiadomska A (2020) Environmental factors affecting the mineralization of crop residues. *Agronomy* **10**, 1951.

Haggbladea S, Mintenb B, Prayc C, Reardona T and Zilberman D (2017) The herbicide revolution in developing countries: patterns, causes, and implications. *The European Journal of Development Research* **29**, 533–559.

Islam F, Wang J, Farooq MA, Khan MSS, Xu L, Zhu J, Zhao M, Muños S, Li QX and Zhou W (2018) Potential impact of the herbicide 2,4-dichlorophenoxyacetic acid on human and ecosystems. *Environment International* **111**, 332–351.

John J and Liu H (2018) Glyphosate monitoring in water, foods and urine reveals an association between urinary glyphosate and tea drinking: a pilot study. *Journal of Environmental Health Engineering* **7**, 2.

Jose S and Dollinger J (2019) Silvopasture: a sustainable livestock production system. *Agroforestry System* **93**, 1–9.

Lazzarini I, Detmann E, Sampaio CB, Paulino MF, Valadares Filho SC, Souza MA and Oliveira FA (2009) Intake and digestibility in cattle fed low-quality tropical forage and supplemented with nitrogenous compounds. *Revista Brasileira de Zootecnia* **38**, 2021–2030. Available at https://goo.gl/s3WvxN

Leite RG, Cardoso AD, Fonseca NVB, Silva MLC, Tedeschi LO, Delevatti LMD, Ruggieri AC and Reis RA (2021) Effects of nitrogen fertilization on protein and carbohydrate fractions of Marandu palisadegrass. *Scientific Reports* **11**, 14786.

Maia G, Pinho Costa K, Costa Severiano E, Epifanio P, Neto J, Ribeiro M, Fernandes P, Guimarães Silva J and Gonçalves W (2014) Yield and chemical composition of *Brachiaria* forage grasses in the offseason after corn harvest. *American Journal of Plant Sciences* **5**, 933–941.

Martello M, Molin JP, Bazame HC, Tavares TR and Maldaner LF (2022) Use of active sensors in coffee cultivation for monitoring crop yield. *Agronomy* **12**, 2118.

Medic A and Baez Vega CB (2021) Benefits of cover cropping systems in walnut orchards as sustainable agricultural practice. *Journal of Sustainability and Climate Change* **1**, 5. Available at https://digitalcommons.humboldt.edu/sustainability/vol1/iss1/5/

Megerssa B, Welde Michael G and Teshome D (2012) Knowledge and attitude of small holder coffee producing farmers to coffee quality. *Ethiopian Journal of Applied Science and Technology* **3**, 31–44. Available at https://ejhs.ju.edu.et/index.php/ejast/article/view/864

Melloni R, Belleze G, Pinto AMS, Dias AdP, Silve EM, Melloni EGP, Alvarenga MIN and de Alcântara EN (2013) Métodos de controle de plantas daninhas e seus impactos na qualidade microbiana de solo sob cafeeiro. *Revista Brasileira de Ciência do Solo* **37**, 66–75.

Mishra MK (2019) Genetic resources and breeding of coffee (coffea spp.). In Al-Khayri J, Jain S and Johnson D (eds), *Advances in Plant Breeding Strategies: Nut and Beverage Crops*. Cham, Switzerland: Springer, pp. 475–515.

Mulindwa J, Kaaya AN, Muganga L, Paga M, Musoli P, Sseremba G, Wagoire WW and Bitalo DN (2021) Cup quality profiles of Robusta coffee wilt disease resistant varieties grown in three agro-ecologies in Uganda. *Journal of the Science of Food and Agriculture* **102**, 1225–1232.

National Water Agency of Brazil (2022) HIDROWEB. Available at https://www.snirh.gov.br/hidroweb/serieshistoricas (Accessed 11 February 2022).

Oliveira S, Costa KA, Severiano E, da Silva A, Dias M, Oliveira G and Costa JV (2020) Performance of grain sorghum and forage of the genus *Brachiaria* in integrated agricultural production systems. *Agronomy* **10**, 1714.

Partelli FL, Duarte H, Freitas SdP and Espindola JAA (2010) Aspectos fitossociológicos e manejo de plantas espontâneas utilizando espécies de cobertura em cafeeiro Conilon orgânico. *Semina: Ciências Agrárias* **31**, 605–617.

Pereira CTM, Sera GH, Sera T, Shigueoka LH, Carducci FC, Dias da Silva JBG and Telles TS (2022) Arabica coffee yields and profitability improved by reducing the spacing within the rows. *Agronomy Journal* **114**, 1220–1228.

Quartezani WZ, Sales RAD, Berilli SDS, Pletsch TA, Rodrigues WP, Campostrini E and Mantoanelli E (2018) Effect of different sources of organic matter added to the substrate on physiological parameters of clonal plants of conilon coffee. *Australian Journal of Crop Science* **12**, 1328–1334.

R Core Team (2017) *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. Available at https://www.r-project.org/ (Accessed 12 February 2023).

Ragassi CF, Pedrosa AW and Favarin JL (2013) Aspectos positivos e riscos no consórcio cafeeiro e braquiária. *Visão Agrícola* **12**, 29–32.

Ronchi CP and DaMatta FM (2019) Physiological aspects of conilon coffee. In Ferrão RG, da Fonseca AFA, Ferrão MAG and De Muner LH (eds), *Conilon Coffee*, 3rd Edn. Vitória, ES: Incaper. cap.5, pp. 111–143.

Schrübbers LC, Masís-Mora M, Rojas EC, Valverde BE, Christensen JH and Cedergreen N (2016) Analysis of glyphosate and aminomethylphosphonic acid in leaves from Coffea arabica using high performance liquid chromatography with quadrupole mass spectrometry detection. *Talanta* **146**, 609–620.

Serrano J, Shahidian S and Marques da Silva J (2016) Calibration of Grass Master II to estimate green and dry matter yield in Mediterranean pastures: effect of pasture moisture content. *Crop and Pasture Science* **67**, 780–791.

Tanimonure VA and Naziri D (2021) Impact of climate adaptation strategies on the net farm revenue of underutilised indigenous vegetables' (UIVs) production in Southwest Nigeria. *Resources, Environment and Sustainability* **5**, 100029.

Teixeira PC, Donagemma GK, Fontana A and Teixeira WG (2017) *Manual de métodos de análise de solo*, 3rd Edn. Brasília: Embrapa, 573 p.

Terra S, Gimenes FMA, Giacomini AA, Gerdes L, Manço MX, de Mattos WT and Batista K (2020) Seasonal alteration in sward height of Marandu palisade grass (*Brachiaria brizantha*) pastures managed by continuous grazing interferes with forage production. *Crop and Pasture Science* **71**, 285–293.

Watthier M, Antonio NP, Gomes JA, Rocha SBF and Santos RHS (2020) Decomposition of green manure with different grass: legume ratios. *Archives of Agronomy and Soil Science* **66**, 913–924.

Xia J, Yuan W, Wang YP and Zhang Q (2017) Adaptive carbon allocation by plants enhances the terrestrial carbon sink. *Scientific Reports* **7**, 3341.

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