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PLANT PROTECTION
Article

Potential of new *Coffea arabica* cultivars for renewal of *Meloidogyne paranaensis* infested crop

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ABSTRACT: *Meloidogyne paranaensis* is one of the most damaging species of root-knot nematode to coffee trees. The development of resistant cultivars is crucial to the continuity of cultivation in infested areas. Thus, the aims of this study were to assess the performance of F6:7 progenies derived from the Amphillo germplasm in an infested area and to validate the new *Coffea arabica* MGS Vereda and MGS Guaiçara cultivars. The Catuaí Amarelo IAC 62 cultivar was used as the susceptible standard, and IPR 100 as the resistance standard. The experiment was conducted in 2018 using a randomized complete block design with four replications and 15 plants per plot. Resistance related and agronomic traits were assessed over four years. The lowest population of *M. paranaensis* was observed in progenies 88, 44B, and 105 from MGS Guaiçara, MGS Vereda, and IPR 100 cultivars, respectively. The progenies with the lowest population of *M. paranaensis*, although resistant, were not productive. The new MGS Vereda cultivar stood out in terms of yield and early fruit ripening, with the highest proportion of cherry fruit at harvest and a low incidence of peaberry grain. The results suggest MGS Vereda cultivar's potential for the renewal of coffee cultivations occurs in a rainfed system according to the environmental conditions of the experiment.

Key words: resistance, root-knot nematode, coffee.

INTRODUCTION

Meloidogyne spp. root-knot nematodes (RKN) are a serious problem for coffee growing in several producing regions of the world, as they cause major economic impacts on the coffee industry (Villain et al. 2018). RKNs are sedentary and obligate biotrophic endoparasitic nematodes that penetrate the roots and benefit from the host plant's nutrients for their development and reproduction (Esmenjaud 2021). Among the RKN species, *Meloidogyne paranaensis*, as described by Carneiro et al. (1996) in the state of Paraná, Brazil, causes reduction in the leaf content of phosphorus, potassium, manganese, and iron, as well as in the rate of photosynthesis (Goulart et al. 2019). The reduction in photosynthetic efficiency causes physiological disturbances in the coffee plant, with an increase in the nematode population and metabolic damage (Casey 2022)[1], culminating in losses to plant production.

Given all the physiological and metabolic damage caused by *M. paranaensis* to coffee trees, it is of the utmost importance to consider the perennial condition of the crop and better understand the risks of planting susceptible cultivars in infested areas (Phani et al. 2021, Salgado and Terra 2021). In the cultivation of *Coffea arabica* in Brazil, the presence of *Meloidogyne*

[1] Casey, A. (2022). The interactions of root-knot nematodes and coffee. Thesis, University of Leeds.

exigua and *M. paranaensis* indicates the need for nematode containment measures and the development of technologies that make coffee cultivation viable (Terra et al. 2019, Villain et al. 2018, Salgado and Terra 2021).

The plant's genetic resistance is the ideal alternative for managing nematodes, especially considering the financial and environmental costs of applying nematicides. Coffee plant breeding programs exploit natural variability, especially natural resistance to RKN in *Coffea* sp. germplasm. Currently, for growing *C. arabica*, Brazilian coffee growers have two main resistant and commercially available cultivars: IPR 100 and IPR 106 (Sera et al. 2007, Holderbaum et al. 2021, Fatobene et al. 2022); and two *Coffea canephora* rootstocks: Apoatã IAC 2258 (Dias et al. 2008) and IAC Herculândia (Guerreiro Filho et al. 2023). Among them, the ones most used by Brazilian producers are *C. arabica* cultivar IPR 100 and *C. canephora* rootstock Apoatã IAC 2258.

The other cultivars need further study and an increase in seed production to meet demand, including the newest cultivars, namely MGS Guaiçara and MGS Vereda, which were developed recently and are not commercially available, despite their potential in terms of genetic resistance and other agronomic characteristics, which still need to be tested in infested areas in various regions. These two cultivars originated in the 1970s from being crossed with one of the genitors derived from Amphillo germplasm of *C. arabica* from Ethiopia, which is kept at the Empresa de Pesquisa Agropecuária de Minas Gerais (EPAMIG) germplasm bank.

Therefore, this study was carried out to analyze the productive performance of progenies and cultivars originating from crossing Amphilo germplasm (2-161 or 2-474) with the Catuaí Amarelo IAC 62 cultivar, which presents genetic resistance to *M. paranaensis*, and to validate the new MGS Vereda and MGS Guaiçara cultivars in infested fields. Preliminary results are encouraging, as there are promising progenies that could become cultivars with a few adjustments. Additionally, one of the recently developed cultivars has shown potential for inclusion in coffee plantations in infested areas. It is important to mention that this long-term experiment was set up in an area highly infested by a proven aggressive population of *M. paranaensis* (Santos, M. F. A. et al. 2018, Shigueoka et al. 2022), where the coffee trees were evaluated using nematological and reproductive variables.

MATERIALS AND METHODS

Description of the experiment

Progenies of *C. arabica* in the $F_{6:7}$ generation (Table 1) and the cultivars MGS Vereda and Guaiçara, resulting from the cross between the Catuaí Vermelho coffee tree group and the wild germplasm Amphillo, were selected from the $F_{4:5}$ generation by Salgado et al. (2014) using the genealogical method, from plants registered as MG 0179 pl.1 R1, MG 0179 pl.3 R1, and MG 0185pl.1 R2 in the coffee germplasm selection of EPAMIG. The first generations of these progenies were obtained in 1970 by researchers from the now-defunct Brazilian Coffee Institute and later sent to various research institutions, including EPAMIG (Peres et al. 2017).

Table 1. Identification (ID) and genealogy of *Coffea arabica* L. progenies in the F6:7 generation evaluated in areas infested by *Meloidogyne paranaensis*.

ID	Progenies	Origin
87A	MG 0179-1-R1-16-6-III – 2-1-II	CV. × Amphillo MR 2-161
87B	MG 0179-1-R1-16-6-III – 2-7-II	CV. × Amphillo MR 2-161
88	MG 0179-1-R1-E1: 16-5-III – 22-1-I	CV. × Amphillo MR 2-161
20A	MG 0179-1-R1-16-6-I – 10-2-II	CV. × Amphillo MR 2-161
40	MG 0179-3-R1-28-4-I – 5-3-IV	CV. × Amphillo MR 2-161
44B	MG 0185-2-R2-29-2-I – 11-2-I	CV. × Amphillo MR 2-474
105	MG 0179-1-R1-E2: 16-5-III – 23-5-II	CV. × Amphillo MR 2-161

CV: Catuaí Vermelho.

The experiment was set up in January 2018 in the planting spacing of 3 m inter rows and 0.60 m in the rows, at 812 m altitude, 20°25'28.7" latitude and 46°1'10.5" longitude, with average annual temperature and rainfall between 2019 and 2023 of 21°C and 1,640 mm, respectively, in clay-textured soil and flat topography. We used a randomized complete block design with four replications and 15 plants per plot. The cultivar Catuaí Amarelo IAC 62 was used as the susceptible control and cultivar IPR 100 as the resistant control.

The experiment was set up in an area infested with *M. paranaensis* population Est P1 (Santos, M. F. A. et al. 2018). The identification of this nematode was based on the esterase phenotype (Carneiro and Almeida 2001).

Assessments

Biotest

Soil samples were collected from the rhizosphere of the coffee plant at three equidistant points in each plot for conducting the biotest with tomato plants (bioindicators) 18 months after planting the experiment. In a greenhouse, the soil samples were distributed in 500-mL cups, in which tomato seedlings of the Santa Clara cultivar were planted for the biological indicator test of the *M. paranaensis* population in the soil of the plots. The biotest evaluation was performed by quantifying eggs and second-stage juveniles (J2) of *M. paranaensis* in the roots of tomato plants 60 days after planting. The populations of eggs and second-stage juveniles (J2) of *M. paranaensis* per gram of root was quantified in triplicates under an inverted objective biological microscope using a counting slide, after the extraction was conducted as described by Hussey and Barker (1973) and modified by Boneti and Ferraz (1981).

Population of *Meloidogyne paranaensis* in coffee trees

The population of *M. paranaensis* was assessed between the months of October and November in the years 2019, 2020, 2022 and 2023, using samples of roots taken at the depth of 0–40 cm on both sides of coffee trees, perpendicular to the planting line. The population of eggs and second-stage juveniles (J2) of *M. paranaensis* per gram of root (NGR) was quantified in triplicates under an inverted objective biological microscope using a counting slide, after the extraction was conducted as described by Hussey and Barker (1973) and modified by Boneti and Ferraz (1981).

Classification of resistance levels

Equation 1 (Gonçalves and Ferraz 1987) was used to classify the resistance levels of the progenies, according to the modified Fassuliotis (1985) criteria:

$$\text{Host susceptibility index (HIS)} = (\text{NGR of the treatment} / \text{NGR of the susceptible standard}) \times 100 \quad (1)$$

The criteria correspond to:

- 0 to 1%: highly resistant (HR);
- 1.1 to 10%: resistant (R);
- 10.1 to 25%: moderately resistant (MR);
- 25.1 to 50%: moderately susceptible (MS);
- 50.1 to 75%: susceptible (S);
- 75.1 to 100%: highly susceptible (HS).

Production variables

The yield of the coffee trees in 2020, 2021, 2022 and 2023 (harvesting at 251, 218, 223 and 242 days after flowering, respectively) was calculated through the total harvest of the fruits of each plot, with subsequent weighing in kg of coffee per total harvest, followed by conversion to bags per ha^{-1} of processed coffee, according to the yield of each coffee tree.

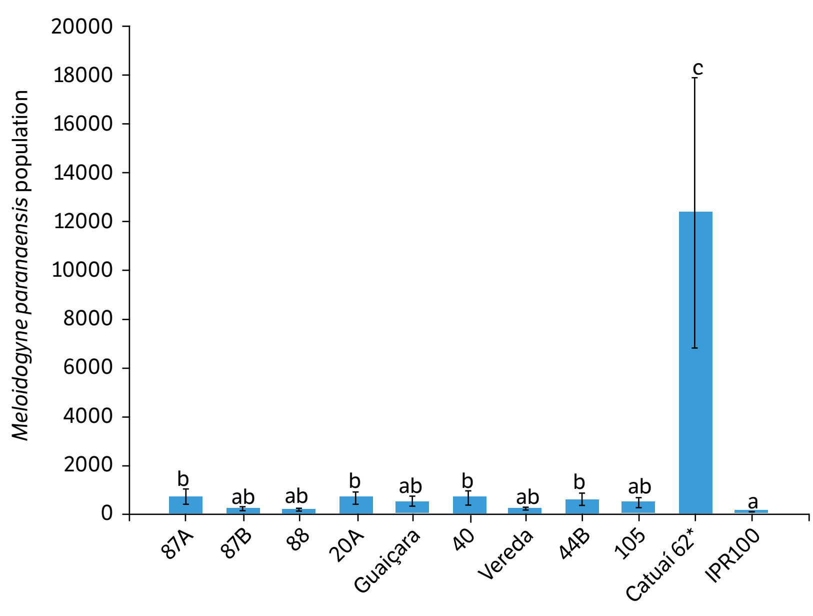
At harvest, a random sample of approximately 300 mL of fruit from each plot was classified by the percentage of cherry and floating grain, according to Antunes Filho and Carvalho's (1954) methodology. The percentage of sieves measuring 17 and above was assessed on a 300-g sample of green coffee using a set of sieves (17/64 to 19/64), according to Brasil's (2003) method. The peaberry percentage was calculated after processing the coffee using a 300-gram sample and a set of sieves (8 to 13), in which the material retained in each sieve was weighed (Brasil 2003).

Statistical analysis

The data on the population of *M. paranaensis* in the roots was tested using the generalized linear model with negative binomial distribution (GLM-NB), and the model was adjusted using the DHARMa package (Hartig 2022). The means were compared using the Tukey's test at 5% probability using the means package (Lenth 2023). The data for the agronomic variables were subjected to the Shapiro-Wilk normality test, and those that did not meet the normality assumptions were transformed into log(x). Analysis of variance was carried out, and the means of the treatments were compared using the Scott-Knott's test at 5%. All the analyses were carried out using the statistical program RStudio version 4.3.1 (R Core Team 2023).

RESULTS

The populations of *M. paranaensis* per gram of tomato roots, evaluated by means of the biotest cultivated in soil from the rhizosphere of the coffee plant, were significantly different from each other (Fig. 1). The Catuaí Amarelo IAC 62 cultivar presented a higher number of eggs and J2/gram of root in the biotest when compared to the progenies and resistant cultivars evaluated.

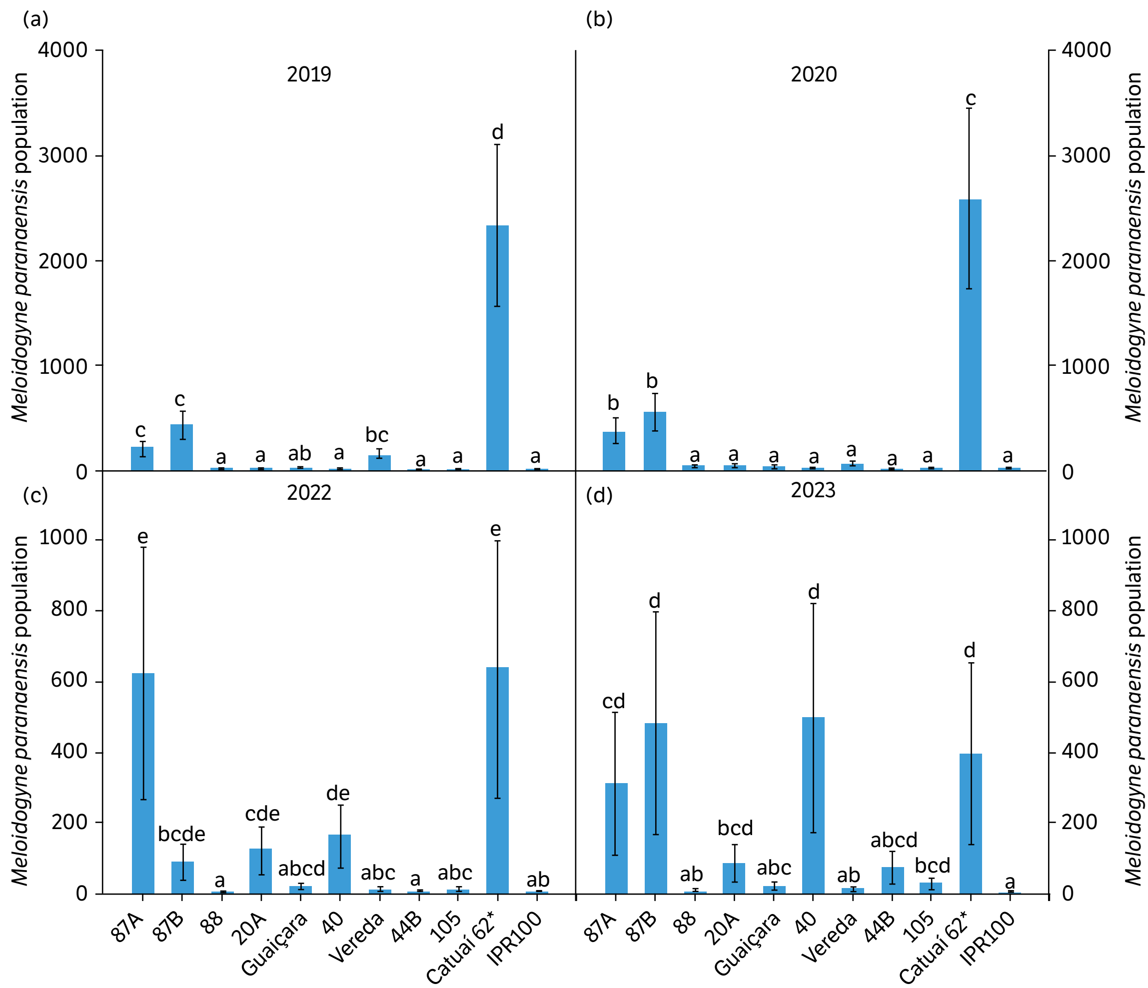


*Catuaí Amarelo IAC 62.

Figure 1. Population of *Meloidogyne paranaensis* in relation to the number of eggs and second-stage juveniles (J2) per gram of root in the tomato bioindicators plant, 18 months after planting.

During the four years of assessment, coffee trees of progeny 88, and the MGS Guaiçara cultivar, MGS Vereda cultivar and resistant control maintained a low population of nematodes in their roots statistically different from the susceptible control, Catuaí Amarelo IAC 62. Considering separately the nematode population for each year, progenies 88, 20A, 40, 44 B, 105 and cultivars MGS Guaiçara and IPR 100 had low averages of eggs and J2/gram of root of *M. paranaensis* in 2019 (Fig.

2a). In 2020, the Catuaí Amarelo IAC 62 cultivar stood out again with the largest population, followed by progenies 87 B and 87 A (Fig. 2b). The population averages of the other progenies and cultivars were lower and statistically equal to the resistant IPR 100 cultivar. In 2022, the *M. paranaensis* population remained low in progenies 88, 44B, 105 and in MGS Guaiçara and MGS Vereda (Fig. 2c). Lastly, in 2023, progeny 88, MGS Guaiçara and MGS Vereda and resistant control presented lower populations than the other coffee trees. There was reduction in the *M. paranaensis* population in the roots of the Catuaí Amarelo IAC 62 cultivar in the last years of the assessment (Fig. 2d).



*Catuaí Amarelo IAC 62.

Figure 2. Population of *Meloidogyne paranaensis* in relation to the number of eggs and second-stage juveniles (J2) per gram of root in progenies and new cultivars of *Coffea arabica* in (a) 2019, (b) 2020, (c) 2022, and (d) 2023, in a naturally infested area.

Progenies 88, 44B, 105, and MGS Guaiçara stood out for having the lowest values of *M. paranaensis* population in the average of the years of assessment, as was also observed for cultivar MGS Vereda and resistant control IPR 100 (Table 2). As for HSI, an indicator of genetic resistance to nematodes, progenies 88, 20A, 44B, 105 and cultivars MGS Guaiçara and MGS Vereda were resistant. Progenies 40 and 87 A were classified as moderately resistant and progeny 87B was classified as moderately susceptible.

On average, over the four years of evaluation, progenies considered resistant showed low yield compared to resistant cultivar MGS Vereda and resistant control IPR 100. In 2023, all the coffee trees were equally productive, except susceptible control Catuaí Amarelo IAC 62 (Table 3).

Table 2. Average population of eggs and second-stage juveniles-J2 per gram of coffee root (NGR); host susceptibility index (HSI); resistance levels (RL) of *Coffea arabica* progenies in an area naturally infested by *Meloidogyne paranaensis**.

Coffee trees	NGR (average)	HSI%	RL
87A	333.68 bcd	23.4	MR
87B	458.35 cd	32.4	MS
88	22.43 a	1.5	R
20A	69.16 ab	4.9	R
MGS Guaiçara	33.09 a	2.2	R
40	248.8 bc	17.6	MR
MGS Vereda	70.60 ab	4.9	R
44B	29.81 a	2.0	R
105	30.16 a	2.1	R
IPR 100	17.50 a	1.2	R
Catuaí 62**	1,416.3 d	100	HS

*Averages followed by the same lowercase letter in the columns do not differ statistically according to the Tukey's test ($p < 0.05$); NGR: average of the years 2019, 2020, 2022 and 2023; RL according to the criteria of Fassuliotis (1985); **Catuaí Amarelo IAC 62.

Table 3. Yield, in bags per hectare (bg/ha^{-1}), from cultivars and progenies assessed in 2020, 2021, 2022, 2023, and averages of the years of evaluation in rainfed areas infested by *Meloidogyne paranaensis*[I].

Coffee trees	2020	2021	2022*	2023*	Average
87 A	17.30 b	14.51 c	11.09 a	21.29 a	16.05 c
87 B	27.26 a	19.62 b	14.66 a	26.78 a	22.08 b
88	21.47 b	19.34 b	12.03 a	22.96 a	18.95 c
20 A	20.12 b	23.14 b	12.52 a	18.40 a	18.55 c
MGS Guaiçara**	25.19 a	22.91 b	15.94 a	26.20 a	22.56 b
40	14.05 b	18.78 b	8.79 a	16.83 a	14.61 c
MGS Vereda**	26.52 a	40.37 a	28.61 a	29.10 a	31.15 a
44 B	18.35 b	25.27 b	11.51 a	28.10 a	20.81 b
105	16.99 b	18.63 b	14.63 a	24.47 a	18.68 c
Catuaí 62***	14.97 b	5.32 c	4.33 a	8.08 b	8.17 d
IPR 100**	36.57 a	25.07 b	18.70 a	27.62 a	26.99 a
CV (%)	37.56	31.35	25.24	16.11	27.02

[I]Averages followed by the same lowercase letter in the columns do not differ statistically according to the Scott-Knott's test ($p < 0.05$); *data transformed into log(x); **resistant cultivars; ***Catuaí Amarelo IAC 62; CV: coefficient of variation.

MGS Vereda was the most productive over the average of the four harvests, as was resistant control 'IPR 100', presenting a reasonable average for commercial standards through this production system. This demonstrates the technological potential of the MGS Vereda cultivar and validates its performance as a resistant cultivar. The MGS Guaiçara cultivar had an average yield equal to IPR 100 in all years of evaluation, with no significant difference from the MGS Vereda cultivar in 2020, 2022 and 2023.

Among the most productive cultivars, MGS Vereda stood out due to its high proportion of cherry fruit at harvest, while IPR 100, due to its late ripening cycle, produced the lowest percentage of cherry fruit, except in the 2023 harvest, when both cultivars had the same amount of fruit at this stage of ripeness (Table 4). Progenies 87 A, 20 A, 40 and 105 presented cherry fruit percentages that were statistically the same as those of MGS Vereda.

Significant differences were observed in the floating grain percentage during the assessment period. Except for progeny 40, all other coffee trees produced a low floating grain percentage, which indicates that they do not have problems in pollination and fertilization. By comparing the results over the course of the assessments, we noticed that, in the 2023 harvest, even the progenies and cultivars increased in average floating grain percentage (Table 5).

Table 4. Percentage of cherry fruit from cultivars and progenies assessed in 2020, 2021, 2022, 2023 and averages of the years of evaluation in rainfed areas infested by *Meloidogyne paranaensis*[I].

Coffee trees	2020	2021	2022*	2023*	Average
87 A	67.75 a	71.88 a	66.25 a	48.53 a	63.56 a
87 B	41.25 b	30.15 c	63.50 a	47.00 a	45.46 b
88	37.00 c	31.71 c	76.50 a	43.25 a	47.05 b
20 A	54.00 b	56.88 c	64.00 a	49.45 a	56.16 a
MGS Guaiçara**	50.25 b	49.25 c	66.75 a	23.70 b	47.48 b
40	45.25 b	47.34 c	80.50 a	62.90 a	59.01 a
MGS Vereda**	69.50 a	70.96 a	72.25 a	43.90 a	64.10 a
44 B	55.75 b	52.95 c	67.50 a	25.32 b	50.42 b
105	74.75 a	77.83 a	60.25 a	26.72 b	59.91 a
Catuaí 62***	34.00 c	29.01 c	85.25 a	54.60 a	50.64 b
IPR 100**	14.00 d	10.90 d	31.00 b	46.27 a	25.54 c
CV (%)	15.29	22.02	20.84	29.06	14.97

[I]Averages followed by the same lowercase letter in the columns do not differ statistically according to the Scott-Knott's test ($p < 0.05$); *data transformed into log(x); **resistant cultivars; ***Catuaí Amarelo IAC 62; CV: coefficient of variation.

Table 5. Floating grain percentage of the cultivars and progenies from the assessments in 2020, 2021, 2022, 2023 and averages of the years of evaluation in a rainfed area infested by *Meloidogyne paranaensis*[I].

Coffee trees	2020	2021	2022*	2023*	Average
87 A	1.50 a	1.50 a	7.00 a	16.25 a	6.56 a
87 B	3.25 b	3.50 a	6.00 a	20.00 b	8.18 a
88	2.00 a	2.50 a	1.75 a	13.50 a	4.93 a
20 A	3.50 b	2.50 a	5.00 a	13.50 a	6.12 a
MGS Guaiçara**	2.25 a	3.00 a	4.75 a	23.75 b	8.43 a
40	20.25 c	12.50 c	23.50 c	35.25 b	22.87 b
MGS Vereda**	1.00 a	1.00 a	6.50 a	7.00 a	3.87 a
44 B	1.75 a	2.00 a	3.00 a	23.25 b	7.50 a
105	1.50 a	2.50 a	6.75 a	24.25 b	8.75 a
Catuaí 62***	5.00 b	5.00 a	3.00 a	25.25 b	9.56 a
IPR 100**	2.00 a	2.00 a	13.25 b	11.75 a	7.31 a
CV (%)	17.58	30.51	37.79	23.05	17.52

[I]Averages followed by the same lowercase letter in the columns do not differ statistically according to the Scott-Knott's test ($p < 0.05$); *data transformed into log(x); **resistant cultivars; ***Catuaí Amarelo IAC 62; CV: coefficient of variation.

According to grain size, as verified by the percentage of grains retained in sieve 17 and above, there were significant differences ($p < 0.05$) in both the individual harvests and the average over the assessed period. We observed that progeny 40 and MGS Guaiçara and Catuaí Amarelo IAC 62 had the highest percentage of larger seeds retained in the sieves numbered 17 and above. The other progenies and the MGS Vereda cultivar, which was productive during the assessment period, did not stand out in this regard (Table 6).

As for the percentage of peaberry, there were significant differences ($p < 0.05$) between the coffee trees in the assessment years and in the average for the period. Except for three progenies, 87A, 87B and 88, all the other coffee trees showed a low percentage of peaberry, in line with commercial standards even in an area infested by *M. paranaensis* (Table 7).

Table 6. Percentage of grains retained in sieve 17 and above of the cultivars and progenies assessed in 2020, 2022, and 2023, and averages of the years of evaluation in rainfed areas infested by *Meloidogyne paranaensis*[1].

Coffee trees	2020	2022	2023*	Average
87A	52.79 a	42.06 b	24.52 b	39.79 b
87B	42.53 b	41.00 b	22.41 b	35.31 b
88	33.81 b	30.45 b	27.50 a	30.59 c
20A	38.15 b	38.57 b	21.57 b	32.76 b
MGS Guaiçara**	62.24 a	46.16 a	35.56 a	47.99 a
40	60.98 a	51.34 a	38.78 a	50.37 a
MGS Vereda**	37.95 b	34.58 b	16.33 c	29.62 c
44B	24.01 c	31.89 b	12.96 c	22.95 c
105	23.30 c	35.36 b	15.30 c	24.65 c
Catuaí 62***	66.94 a	57.35 a	47.75 a	57.35 a
IPR 100**	59.28 a	40.07 b	20.86 b	40.07 b
CV (%)	17.73	17.36	10.39	15.85

[1]Averages followed by the same lowercase letter in the columns do not differ statistically according to the Scott-Knott's test ($p < 0.05$); *data transformed into log(x); **resistant cultivars; ***Catuaí Amarelo IAC 62; CV: coefficient of variation.

Table 7. Peaberry percentage of the cultivars and progenies assessed in 2020, 2022, and 2023, and averages of the years of evaluation in rainfed areas infested by *Meloidogyne paranaensis*[1].

Coffee trees	2020*	2022	2023	Average *
87A	19.83 a	22.23 a	25.14 a	22.40 a
87B	29.12 a	25.48 a	27.10 a	27.23 a
88	18.01 a	19.78 a	21.54 b	19.78 a
20A	16.16 b	13.06 b	14.02 c	14.41 b
MGS Guaiçara**	14.44 b	15.52 b	16.59 c	15.52 b
40	13.41 b	16.95 b	20.38 b	16.91 b
MGS Vereda**	15.48 b	12.48 b	14.41 c	14.12 b
44B	14.35 b	10.98 b	13.22 c	12.85 b
105	20.82 a	13.19 b	15.75 c	16.58 b
Catuaí 62***	11.71 b	13.19 b	13.93 c	12.94 b
IPR 100**	11.09 b	16.24 b	18.81 c	15.38 b
CV (%)	10.50	18.81	19.91	6.78

!Averages followed by the same lowercase letter in the columns do not differ statistically according to the Scott-Knott's test ($p < 0.05$); *data transformed into log(x); **resistant cultivars; ***Catuaí Amarelo IAC 62; CV: coefficient of variation.

DISCUSSION

The population of nematodes with parasitic capacity was lower in the roots of the tomato plants used as bioindicators, except when using soil from the Catuaí Amarelo IAC 62 cultivar plot. This biotest result indicates a high population of the nematode in the rhizosphere of the susceptible cultivar in the experimental area, which reached an average of over 1,416.3 specimens per gram of root. During the assessment period, the number of roots available in the Catuaí Amarelo IAC 62 cultivar was drastically reduced with the increase in the nematode population. This caused intense depletion and mortality of the root system, confirming the susceptibility of this cultivar to *M. paranaensis*, in concurrence with Azevedo et al. (2022) and Santos et al. (2018). In fact, susceptible plants present chlorosis and leaf fall, reduction in growth and, consequently, in production, which can culminate in plant death (Terra et al. 2019, Machado et al. 2023), due to the destruction of the root system, especially the finer roots that are responsible for absorbing water and nutrients (Peres et al. 2017). The population from this experimental area has a high reproductive capacity as verified by M. F. A. Santos et al. (2018) and Shigueoka et. al. (2022), who identified that isolate 2291 had a higher reproductive capacity, being one of the few isolates that multiplied in the resistant IPR 106 cultivar, which is why this population is of great interest in coffee breeding programs.

Among the coffee genotypes, the highest nematode populations occurred in progenies 87A, 87B and 40, which had over 248 specimens per gram of roots, which shows the susceptibility of these progenies. According to Greco and Inserra (2024), highly resistant coffee trees can withstand up to 10% of the reproduction observed in susceptible coffee trees, which was not the case with said progenies. This confirms the HSI indices, in which these progenies (87 and 40) were not classified as resistant. Only 87B had yields equal to IPR 100 (resistant cultivar) throughout the years of assessment, which indicates tolerance to *M. paranaensis*, since 87B had a high nematode population and good yields, just as 87A had yields equal to 'IPR 100' in 2022 and 2023. Tolerance is defined as the reaction of a plant that allows the infestation and good reproduction of nematodes, but still provides satisfactory yields (Greco and Inserra 2024).

In all years, the population of *M. paranaensis* was lower in progeny 88 and in MGS Guaiçara, MGS Vereda and IPR 100 cultivars, indicating the effectiveness of these coffee trees in reducing the population of *M. paranaensis* in the experimental area. In progenies 88, 44B and 105, the low population of the nematode confirms the result of the HSI, in which these progenies were classified as resistant to *M. paranaensis*.

The resistance of the MGS Vereda cultivar and its performance in the area infested by *M. paranaensis* validates the genealogical selection process carried out on previous progenies in an infested area (Salgado et al. 2014). Under controlled greenhouse conditions, several studies have shown the resistance of the cultivars MGS Vereda and MGS Guaiçara to progenies (Peres et al. 2017, Santos, M. F. A. et al. 2018, Alves et al. 2019, Rezende et al. 2019, Pasqualotto et al. 2020) and in naturally infested areas under field conditions (Salgado et al. 2014, Pasqualotto et al. 2015, Santos, H. F. et al. 2018), which culminated in the registration of these cultivars (Salgado et al. 2022), corroborating the results obtained in this study. Although registered as resistant to *M. paranaensis*, cultivars MGS Guaiçara and MGS Vereda (Salgado et al. 2022) showed multiple resistance to *Meloidogyne* spp., according to Peres et al. (2017) in a study on resistance to M. incognita. M. F. A. Santos et al. (2018) studied the previous generation of the MGS Guaiçara cultivar and observed its resistance against seven populations of *M. paranaensis* in the progeny derived from the Amphillo MR2-161 germplasm (E1 16-5 III), with a low segregation rate (2.4%), indicating the potential of advancing generations.

The MGS Vereda cultivar proved to be productive, outperforming IPR 100 cultivar by 4.16 bags/ha. On the other hand, the MGS Guaiçara cultivar was less productive than IPR 100. In addition to the productive potential, we observed early ripening of the fruits of MGS Vereda cultivar. Another important characteristic observed in the MGS Vereda cultivar was the number of peaberry, with a percentage below the tolerance limit. All the other progenies and cultivars presented less than 10% floating grain (Table 5), which is considered satisfactory, according to Carvalho et al. (2017).

It is worth noting that all the progenies and cultivars had a higher percentage of cherry fruit than the IPR 100 cultivar, confirming the late ripening cycle of this cultivar (Sera et al. 2017) and highlighting the early to medium ripening cycle of the other ones. The MGS Vereda cultivar, in addition to showing resistance to *M. paranaensis* (Table 2) and similar yield to the IPR 100 cultivar, had approximately 70% of its fruit in the cherry stage at harvest time in the first few years, while 'IPR 100' had 12% (Table 4), and in the last two years MGS Vereda was superior or statistically equal to 'IPR 100'. The MGS Vereda cultivar showed promising results and could be an excellent alternative for producers with delayed harvest in areas infested by *M. paranaensis*, as it is early maturing and currently only arabica coffee IPR 100 (Sera et al. 2017) and IPR 106 (Sera et al. 2020) cultivars are resistant to this nematode.

As regards the floating grain percentage, the increase in 2023 is possibly due to very adverse weather conditions, such as a water deficit, damaging the physiology of the coffee trees and preventing the beans from filling at the right time. In this study, there was reduction of 68% in rainfall during the grain-filling phase of 2023, compared to February 2022.

The MGS Guaiçara cultivar, which in this study had yields equal to 'IPR 100' in all the assessed years, performed well in the infested area under rainfed farming. Another important characteristic of 'MGS Guaiçara' is the percentage of grains retained in sieve 17 and above, which, along with progeny 40 and Catuaí Amarelo IAC 62, stood out with the highest percentages of retained grains. Carvalho et al. (2006) found 51.88 and 45.11% in sieve 17 and above in coffee trees from generations prior to progeny 40 and the MGS Guaiçara cultivar. High percentages of coarse beans showed a greater potential for adding value when marketing coffee, which is a favorable characteristic for producers (Nadaleti et al. 2018).

From 2022 onwards, we believe that the shade over the experiment, due to the tall Mahogany (*Swietenia macrophylla*) planted around the experimental area, affected the production and ripening of the coffee trees. Most of the coffee trees had the same percentage of cherry fruit as IPR 100. In addition to ripening, we believe that the increased shade caused by the trees prevented the progenies and cultivars from fully expressing their productive potential. The influence of shade on coffee production was verified by Jaramillo-Botero et al. (2010) from the third year onwards, and the effects of shade became more pronounced after high-yield harvests.

Environmental factors influenced the roots of the nematode population over time, such as the temperature and humidity conditions in the rhizosphere of the plants. This reinforces the need to assess the genetic resistance of plants over a longer period of time in order to factor it into population dynamics. It is important to mention the difficulty of obtaining perennial crop plants that are resistant to this aggressive nematode and that have good agronomic characteristics, since no cultivar is planted solely due to its genetic resistance.

This study confirmed how susceptible Catuaí Amarelo IAC 62 is to *M. paranaensis*, as it is highly productive, has a high sieve rate, and is widely used by producers, and therefore should be avoided in infested areas. In another study conducted in an area in the state of Paraná, Brazil, infested with *M. paranaensis* and *M. incognita*, a drastic reduction in yield and vegetative vigor was observed six years after planting, along with a 44.66% mortality rate of Catuaí Vermelho IAC 81 plants seven years after planting (Sera et al. 2020).

The two new cultivars used in this study for comparison with the progenies MGS Vereda and MGS Guaiçara resistant to *M. paranaensis* confirmed their height, long internodes and early ripening cycle. These characteristics do not directly affect yield. On the other hand, tall plants with long internodes are more tolerant to cold and frost. In coffee breeding programs, these progenies and new cultivars will be very useful for crossbreeding, generating variability and seeking genetic gains in yield and plant height reduction, as well as possible clonal exploitation and use as rootstocks. In addition, these cultivars are novel, as they were recently registered (Salgado et al. 2022), and are worth analyzing to monitor their agronomic performance, especially considering infested areas under irrigated and rainfed conditions.

Given the occurrence of *M. paranaensis* in various coffee-growing regions and the intrinsic characteristics of coffee production to meet the demands of producers and consumers, genetic breeding programs must continually develop cultivars resistant to the nematode and accumulate information to validate the use of such technology. Although no cultivar is perfect, they can present similar levels of resistance and yield and have different ripening cycles, for example, which is a useful characteristic for growers when scheduling harvests.

CONCLUSION

The progenies 88, 20A, 44B and 105 showed resistance to *M. paranaensis*, but their low yield restricts practical application. This study was the first to confirm MGS Vereda as resistant to *M. paranaensis* in an infested area, and this cultivar stood out in terms of yield and early ripening cycle, an important technological advantage.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Luz, S. R. O. T., Salgado, S. M. L., Andrade, V. T. and Carvalho, G. R.; **Methodology:** Luz, S. R. O. T., Salgado, S. M. L., Andrade, V. T., Botelho, C. E. and Carvalho, G. R.; **Formal Analysis:** Salgado, S. M. L., Luz, S. R.

O. T. and Teixeira, L. P.; **Data Curation:** Luz, S. R. O. T., Fatobene, B. J. R., Salgado, S. M. L., Andrade, V. T. and Teixeira, L. P.; **Writing – Original Draft:** Luz, S. R. O. T., Salgado, S. M. L., Teixeira, L. P. and Andrade, V. T.; **Writing – Review & Editing:** Teixeira, L. P., Marques, E. R., Salgado, S. M. L., Fatobene, B. J. R. and Andrade, V. T.; **Visualization:** Carvalho, G. R.; **Supervision:** Salgado, S. M. L.; **Project Administration:** Salgado, S. M. L.; **Funding Acquisition: S**algado, S. M. L. and Carvalho, G. R.; **Final approval:** Salgado, S. M. L.

DATA AVAILABILITY STATEMENT

Data will be made available upon request.

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