YIELD OF *Coffea arabica* GRAFTED ONTO *Coffea canephora* IN SOILS INFESTED WITH NEMATODES IN MEXICO

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ABSTRACT: The total of three consecutive years of fruit production was evaluated in six coffee cultivars (*Coffea arabica* L.) propagated by seed and grafted onto Robusta (*Coffea canephora* var. Robusta). The plantations were established at 640 m, 920 m, and 1340 m altitude in the central region of the Veracruz State, Mexico. The *coffea* plants were established in soils naturally infested with nematodes. Grafted plants had higher production than those propagated by seed. Fruit production was higher at 640 m and 920 m than at 1340 m for the two types of propagation. The cultivars Colombia Brote Café and Colombia Brote Verde had the highest fruit yield regardless of the propagation methods; in contrast, Pacamara, had the lowest. The grafted coffee plants that were planted at 1340 m had a yield reduction of 27% in comparison with those at 640 and 920 m. When the Costa Rica 95 variety was grafted, it achieved fruit yield similar to Colombia Brote Verde and Colombia Brote Café. Pacamara produced almost 28% more fruit when it was grafted onto Robusta.

Index terms: Variety x environment interaction, Robusta, coffee cherry production, *Coffea* environments.

PRODUÇÃO DE *Coffea arabica* ENXERTADAS EM *Coffea canephora* EM SOLOS INFESTADOS COM NEMATÓIDES EM MÉXICO

RESUMO: O total de três anos consecutivos de produção de frutos foi avaliado em seis cultivares de café (*Coffea arabica* L.) propagadas por sementes e enxertadas em Robusta (*Coffea canephora* var. Robusta). As plantações foram estabelecidas a 640 m, 920 m e 1340 m de altitude na região central do estado de Veracruz, no México. As plantas de café foram estabelecidas em solos naturalmente infestados com nematóides. Plantas enxertadas tiveram maior produção do que as propagadas por sementes. A produção de frutos foi maior em 640 m e 920 m do que em 1340 m para os dois tipos de propagação. As cultivares Colombia Brote Café e Colombia Brote Verde apresentaram maior produção de frutos, independentemente dos métodos de propagação. Em contraste, Pacamara, teve o menor. As plantas de café enxertadas que foram plantadas a 1340 m tiveram uma redução de rendimento de 27% em comparação com aquelas em 640 e 920 m. Quando a variedade Costa Rica 95 foi enxertada, obteve rendimento de frutos semelhante ao da Colômbia Brote Verde e Colômbia Brote Café. A Pacamara produziu quase 28% mais frutas quando foi enxertada no Robusta.

Termos para indexação: Coffea, interação variedade x ambiente, Robusta, produção de café cereja, ambientes para café

1 INTRODUCTION

Nematodes are worm-like invertebrate and unsegmented animals that attack coffee plantations around the world and severely reduce fruit production. In Mexico, coffee production has decreased significantly due to nematode infestations in cropland (MARBÁN-MENDOZA, 2009; LÓPEZ-LIMA et al., 2015). Rootstocks have been used to control nematode attack in coffee production fields (ZHANG & SCHMITT, 1995); they offer environmental advantages over the application of nematicides to the soil (VILLAIN et al., 2000). In Guatemala, hypocotyledonary grafting of the coffee tree has been carried out for more than 45 years (BERTRAND et al., 2001). One of the rootstock species most commonly used to control nematodes is *Coffea canephora* Pierre var. Robusta (ETIENNE et al., 2002). Most *C. canephora* rootstocks are propagated by seed, and this species is cross-pollinated (ETIENNE et al., 2002). If the rootstocks are not properly selected, they may only have 30-40% resistance to *Meloidogyne incognita* (BERTRAND et al., 2000). There are clonal rootstocks of Robusta like the cv. Nemaya (ETIENNE *et al*., 2002) that tolerate root damage from *Meloidogyne* and *Pratylenchus* or the cv. BP 534 (PRAWOTO & YULIASMARA, 2003) that is drought tolerant. However, commercial coffee production usually uses seedlings because of their low cost (ETIENNE et al., 2002). In Mexico, clonal rootstocks of Robusta are not used commercially, and they have not yet been certified or registered.

Generally, cultivars of *Coffea arabica* L. grafted on *C. canephora* have greater growth and coffee bean production over time on land with nematode infestation (FAHL et al., 2001, PRAWOTO & YULIASMARA, 2013). However, when the soil is free of nematodes, there are apparently no advantages to its use. REYES

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et al. (2016) evaluated one season of fruit yield from grafted coffee plants and contrasted them with the same cultivars with their own roots in a highland coffee zone at 1300 m. The seedlings had higher fruit yield than the grafted plants. However, certain scion/rootstock combinations can significantly improve coffee fruit production (PAIVA et al., 2012). The response to the use of Robusta rootstocks in coffee production zones at different altitudes in Mexico is unknown.

Positive effects on coffee fruit production were expected from rootstocks. Thus, the cumulative production over three years from six coffee cultivars propagated by seeds was compared to their production when grafted onto Robusta, in soils infested with nematodes in regions of different altitudes.

2 MATERIALS AND METHODS

The experimental material consisted of the *Coffea arabica* L. cultivars Colombia Brote Verde, Colombia Brote Café, Pacamara, Costa Rica 95, Garnica F5, and Aztec Gold obtained of seed germination as well as grafted onto *Coffea canephora* Pierre ex Froehner (Robusta coffee). The rootstocks were obtained from seeds of Robusta plants growing in Zentla county at 1000 m altitude that seemed vigorous and without any disease or insect attack.

Coffee plants were established in Zentla county, Veracruz, Mexico, in the community of Maromilla at 640 m altitude, with annual averages of rainfall of 1430 mm and temperature of 22°C, and in the community of Colonia Manuel González at 920 m altitude, with annual averages of rainfall of 1604 mm and temperature of 20°C. Another plantation was established in Huatusco county, Veracruz, at 1340 m altitude, with annual averages of rainfall of 1700 mm and temperature of 17°C. The plantations were established in September 1998 in lands infested with nematodes. During the experiment, the roots of the coffee plants were found to be infested with nematodes such as *Meloidogyne* spp., *Criconemella spp.*, *Helicotylenchus spp., Tylenchus spp.*, and *Paratylenchus* (BARRAGÁN, LÓPEZ & MARBAN-MENDOZA, 2000; MARBÁN-MENDOZA., 2009). These nematode species cause severe damage to *Coffea arabica* plantations in Veracruz, Mexico (ORISAJO & FADEMI, 2012).

Planting distance was 2.0 x 2.5 m between plants and between rows, respectively. Plots were shaded with trees of the *Inga* genus in an 8 x 8 m frame arrangement, 30 days after the coffee plants were planted. In all the plots in the first year of planting, 50 g of urea (46N) per plant was applied twice, once in March and once in September. In the second year, 100 g of 18N-46P was applied in the months indicated. In the third year, two more applications were made at the rate of 200 g per plant of 18N-46P. Weed control in the plantations was performed manually, and the plants were not pruned throughout the experiment.

The experiment was carried out in a split-split plot design (LÓPEZ & GONZÁLEZ, 2014). The three factors were altitude (Maromilla - 640 m, Colonia Manuel González - 920 m, and Huatusco - 1340 m), type of plant (grafted and seedling coffee trees), and cultivars (Colombia Brote Verde, Colombia Brote Café, Pacamara, Costa Rica 95, Garnica F5, and Aztec Gold). There were six replications and six plants per experimental unit.

For statistical analysis, the cumulative total of three consecutive years of coffee fruit production (2001-2003) was considered. The fresh fruit weight ($kg.plant^{-1}$) was determined in each of the six cultivars of grafted and seedling coffee plants established in the three different environments. Harvest was carried out between December and February in each of the three years. Means were compared by Fisher's LSD method at 5% (LÓPEZ & GONZÁLEZ, 2014). The statistical analysis was carried out by the Infostat software (DI RIENZO et al., 2016).

3 RESULTS AND DISCUSSION

The altitude, plant type, and variety factors were all significant ($P \leq 0.05$) for fruit production. Three interactions were also significant ($P \leq 0.05$): county × propagation method, environment × variety, and propagation × variety.

Altitude

At altitudes of 640 m (Maromilla) and 920 m (Col Manuel González), the coffee trees had greater fruit production than at 1340 m (Huatusco), irrespective of the type of propagation (Table 1), three years after been established. The lower temperatures in Huatusco may have affected this result. The annual average of Huatusco of 17°C was 3°C and 5°C less than the average annual temperatures reached in Maromilla and Colonia Manuel González, respectively. WAMATU et al. (2003) indicated that variations in fruit production between coffee cultivars with adequate crop practices are mainly influenced by the environment.

TABLE 1 - Coffee cherry production (Kg.pl^{-1}) for all plants over three consecutive years in three different environments: Maromilla (640 m), Col Manuel González (920 m), and Huatusco (1340 m).

Environment	Total fruit yield (Kg.pl^{-1})
Maromilla (640 m)	6.30 a*
Col. M.Glez, (920 m)	6.20 a
Huatusco (1340 m)	4.90 b

*Means with the same letters in the column are statistically similar (LSD, 0.05).

In the present study, the highest elevation site had the lowest fruit production. The optimum annual temperature for *C. arabica* is 18-21ºC, and in regions with an average annual temperature below 17-18ºC, growth is negatively affected (DAMATTA & COCHICHO, 2006). However, the highland areas where coffee is produced may gain suitability due to climate change (OVALLE-RIVERO et al., 2015). Therefore, more research and application of technology is necessary for coffee production in these zones.

Type of propagation

Rootstocks have been used in various horticultural species to increase fruit production (PALLIOTTI et al., 2018). In coffee, rootstocks have mainly been used for nematode control (BERTRAND et al., 2001), drought tolerance (PRAWOTO & YULIASMARA, 2003), and disease resistance/tolerance (CASTRO-CAICEDO et al., 2010). In the present study, the grafted coffee trees had higher fruit production in the three different altitudes (Table 2); the difference was nearly 39%. In other studies, increases in production were 89% and 151%, depending on the coffee scion/rootstock combination (FAHL et al., 2001).

Coffee scion plants grafted onto Robusta showed an increase in the number of stems and an increase of 52% in total leaf area. In addition, under drought conditions, grafted plants showed higher transpiration and higher stomatal conductance rates than non-grafted plants (FAHL et al., 2001). Then, grafted coffee plants could be an option in dry zones. In some studies, rootstocks negatively affected production of cherry coffee in high altitude areas (REYES et al., 2016), and the lack of adaptation of Robusta to low temperatures may be a determining factor since Robusta rootstocks are more efficient at 20-23°C. (BERTRAND et al., 2001). The selection of Robusta seeds from highly productive plants in highlands could generate rootstocks that would increase the initial production of *C. arabica*.

In the present study, seedlings and grafted plants initiate fruit yield at the first year of its establishment. Then, trying to avoid possible seedling juvenility effects on fruit production, the recording of the data initiated three years after plants were established.

Cultivars

Colombia Brote Café and Colombia Brote Verde had the highest cumulative production over three years, regardless of the type of propagation; in contrast, Pacamara had the lowest fruit yield (Table 3). Similar results were reported by LÓPEZ-GARCÍA et al. (2016) in cumulative fruit production over five years for seedling plants established at 800 m altitude. In that study, the Colombian cultivars Brote Café and Brote Verde were the most productive, and Pacamara was the least. In the coffee plant, a greater load of fruits per plant is associated with smaller grains (Vaast et al., 2006) of low dry weight (Vaast et al., 2005). Thus, Pacamara had the lowest fruit production in the present study, and in other works had the largest grain (LÓPEZ-GARCÍA et al., 2016). Sink-source relationships using rootstocks to improve coffee yield has not been deeply studied.

County x type of propagation interaction

In each cultivar, the highest production was in grafted plants that were established at 640 m and 920 m altitude, and the lowest in seedling plants at the three altitudes in which the plantations were established (Table 4). Across all the cultivars and altitudes, grafted coffees that were planted at 1340 m had a yield reduction of 27% in soil infested with nematodes. Thus, selection of rootstocks is necessary for production from grafted coffee trees in highlands. All the seedling plants had a yield reduction of 45% in relation to the grafted plants established at the 640 and 920 m altitude.

TABLE 2 - Fruit production in grafted and seedling plants (Kg.pl^{-1}) over three consecutive years.

Propagation	Total fruit yield (Kg.pl^{-1})
Grafting	7.20 a*
Seedling	4.40 b

*Means with the same letters in the column are statistically similar (LSD, 0.05).

TABLE 3 - Coffee fruit production (Kg.pl^{-1}) of six cultivars over three consecutive years.

Cultivar	Total fruit yield (Kg.pl^{-1})
Colombia BV.	6.90 a*
Colombia BC.	6.80 a
Costa Rica 95	6.00 b
Garnica	5.50 c
Pacamara	4.70 d
Oro Azteca	4.90 c

*Means with the same letters in the column are statistically similar (LSD, 0.05).

TABLE 4 - Fruit yield of the counties × type of propagation interaction (Kg.pl^{-1}).

Cultivar	Propagation	Total fruit yield (Kg.pl^{-1})
Maromilla	Grafting	7.90 a*
Colonia Manuel González	Grafting	8.00 a
Huatusco	Grafting	5.80 b
Maromilla	Seedling	4.70 bc
Colonia Manuel González	Seedling	4.40 c
Huatusco	Seedling	4.00 c

*Means with the same letters in the column are statistically similar (LSD, 0.05).

Nematode damage to the roots influenced this result. In the roots of the seedlings, a large number of nematodes were observed (BARRAGÁN, LÓPEZ & MARBAN-MENDOZA, 2000; MARBÁN-MENDOZA, 2009). The Robusta rootstocks currently in Mexico are not a solution to low yield and nematode damage in highlands. However, there are individuals of *C. canephora* that could be adapted to these zones (WEVERTON et al., 2016) can be used as rootstocks. Furthermore, nematode tolerant cultivars of *C. arabica* should be generated for high altitude areas (ANZUETO et al., 2001). In Brazil, 'Acaua', 'Catucai 785/15', 'Elpar 59' (BARBOSA et al., 2010), and progenies of MG 0179-3-R1-151 and MG 0185-2-R2-132 (SANTOS et al., 2018) exhibit individuals of *C. arabica* that are tolerant to nematodes of the *Meloidogyne* genus.

Environment x cultivar interaction

Elevation and cultivar were indicators of coffee yield. The Colombia Brote Café and Colombia Brote Verde cultivars achieved the highest cumulative yields at 920 m (Colonia Manuel González) (Table 5). However, these two cultivars decreased their yield by 33.5% when planted at 1340 m.

An absence of the environment × genotype interaction indicates that the genotypes are very stable (GARCÍA et al., 2015). This is a fact that was not verified in this study. For example, the yield performance of Costa Rica 95 was the same in the three different environments (Table 5). This is the first report in a refereed journal in which the genotype × environment interaction in the production of cherry coffee in Mexico has been quantified.

TABLE 5 - Fruit yield (Kg.pl^{-1}) for the environment × cultivar interaction.

Environment	Cultivar	Total fruit yield (Kg.pl^{-1})
Colonia Manuel González	Colombia BC	8.7 a*
Maromilla	Colombia BV	6.7 b
Maromilla	Colombia BC	6.3 bc
Colonia Manuel González	Colombia BV	8.0 ab
Maromilla	Costa Rica 95	6.5 bc
Maromilla	Garnica	6.2 bc
Maromilla	Pacamara	6.9 b
Maromilla	Oro Azteca	5.5 bcd
Colonia Manuel González	Costa Rica 95	5.7 bcd
Huatusco	Colombia BV	5.9 bcd
Col. M. Glez	Garnica	6.0 bcd
Huatusco	Costa Rica 95	5.9 bcd
Colonia Manuel González	Pacamara	4.3 cde
Huatusco	Garnica	4.5 cde
Huatusco	Colombia BC	5.2 de
Huatusco	Oro Azteca	5.1 de
Colonia Manuel González	Oro Azteca	4.4 cde
Huatusco	Pacamara	2.8 f

*Means with the same letters in the column are statistically similar (LSD, 0.05).

TABLE 6 - Type of propagation × cultivar interaction (Kg.pl^{-1}).

Propagation	Cultivar	Total fruit yield
Grafting	Colombia BC	8.70 a*
Grafting	Colombia BV	8.20 a
Grafting	Garnica	7.00 b
Grafting	Costa Rica 95	7.70 ab
Seedling	Colombia BV	5.60 c
Seedling	Colombia BC	4.70 cd
Seedling	Costa Rica 95	4.50 cd
Grafting	Oro Azteca	6.00 bc
Grafting	Pacamara	5.40 c
Seedling	Pacamara	3.90 d
Seedling	Garnica	4.00 d
Seedling	Oro Azteca	3.90 d

*Means with the same letters in the column are statistically similar (LSD, 0.05).

Future studies to manage nematode attack in coffee plantations may consider the use of rootstocks together with cover crops that suppress nematodes (WANG et al., 2002), application of bionematicides (BRAND et al., 2004), and specific nutrition management practices to confer nematode resistance to coffee plants (SANTANA-GOMES et al., 2013).

Type of propagation x cultivar interaction

All the cultivars produced more fruit when they were grafted (Table 6). Colombia Brote Café and Brote Verde had the highest production in the cumulative total of three years. Other studies showed that specific scion/rootstock combinations determine high yield (FAHL et al., 2001), even with a considerable number of nematodes in the soil (ZHANG & SCHMIDTT, 1995). Cultivars with low yields in the center of Veracruz, such as the Pacamara variety (LÓPEZ-GARCÍA et al., 2016), might have higher yields with the use of adequate rootstocks (ETIENNE et al., 2002; PRAWOTO & YULIASMARA, 2003); in the present study, Pacamara produced almost 28% more fruit when it was grafted onto Robusta.

4 CONCLUSIONS

The *Coffea arabica* cultivars studied, both grafted or planted as seedlings in areas with nematodes, had higher production at 640 m and 920 m altitude than at 1340 m.

The cultivars Colombia Brote Café, and Colombia Brote Verde grafted on Robusta are recommended for planting on soils naturally infested with nematodes at 920 m altitude, in the central region of Veracruz.

The Pacamara variety, characterized by larger sized coffee beans and low yield, is recommended for planting in lowland areas since it had better yields at 640 m than at 940 m and 1340 m.

This is the first report in a refereed journal where the genotype x environment interaction has been quantified in the cumulative total of three consecutive years of coffee fruit production in Mexico.

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