Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

The role of microbial fertilizers in diversified cropping systems

El papel de los fertilizantes microbianos bajo un sistema de cultivo diversificado

Tania Romero-Figueiras[1], Pablo Andrés-Meza[1*], Joaquín Murguía-González[1], Alejandro Espinosa-Calderón[2], Octavio Maldonado-Saavedra[3], Otto Raúl Leyva-Ovalle[1]

[1]Universidad Veracruzana. Facultad de Ciencias Biológicas y Agropecuarias. Región Orizaba – Córdoba. Camino Peñuela-Amatlán s/n, CP. 94945. Municipio de Amatlán de los Reyes, Veracruz. México.
[2]Comisión Intersecretarial de Bioseguridad de los Organismos Genéticamente Modificados. Avenida Insurgentes Sur, 1582, Colonia Crédito Constructor, Benito Juárez, CP. 03940. Ciudad de México, México.
[3]Universidad Tecnológica del Centro de Veracruz. Avenida Universidad, 350, Carretera Federal Cuitláhuac-La Tinaja, Localidad Dos Caminos, CP. 94910. Cuitláhuac, Veracruz. México.
*Autor de correspondencia: pandres@uv.mx

Scientific article

Received: february 08, 2024
Accepted: june 14, 2024

ABSTRACT. Agroforestry systems combine fruit trees with crops, providing environmental and productive benefits. This study investigated the impact of a combined application of arbuscular mycorrhizal fungi (AMF), *Rhizobium*, and mineral fertilization levels on the agronomic and physiological characteristics of maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.) intercropped with peach (*Prunus persica*), Persian lime (*Citrus latifolia* Tan.), and litchi (*Litchi chinensis*). The study also examined changes in the physical, chemical, and microbiological properties of the soil. An agroforestry system was established during the fall-winter agricultural cycle of 2020 in the community of Campo Grande, municipality of Ixtaczoquitlan, Veracruz, Mexico. The treatment with *Rhizophagus irregularis* + *Rhizobium etli* (2) + 50% mineral fertilization produced the greatest increases in plant height: 68.5±8.6 cm (Persian lemon), 105.3±11.0 cm (peach) and 6.8±4.5 cm (lychee). It also produced the highest grain yield in corn (5 653.7 kg ha^{-1}) intercropped with beans (995.1 kg ha^{-1}). At the end of the first productive cycle, the soil pH decreased from moderately acidic (5.7) to acidic (4.9). On the other hand, the organic matter increased from 1.71 to 2.76%. There was an increase in the number of bacteria (55.0 x 10^{6} to 68.0 x 10^{6} CFU g^{-1} soil), fungi (73.55 x 10^{2} to 511.7 x 10^{2} CFU g^{-1} soil) and actinomycetes (48.61 x 10^{5} to 53.19 x 10^{5} CFU g^{-1} soil). The establishment of diversified agricultural systems in combination with microbial consortia promotes crop productivity and improves the physical, chemical, and microbiological properties of the soil.
Key words: Milpa system, fruit trees, soil health, microbial consortia, productivity.

RESUMEN. Los sistemas agroforestales combinan árboles frutales con cultivos agrícolas, brindando beneficios ambientales y productivos. Este estudio determinó el efecto de la aplicación combinada de hongos micorrícicos arbusculares (HMA), *Rhizobium* y niveles de fertilización mineral sobre las características agronómicas y fisiológicas del maíz (*Zea mays* L.) y frijol (*Phaseolus vulgaris* L.) intercalados con durazno (*Prunus persica*), limón persa (*Citrus latifolia* Tan.) y lichi (*Litchi chinensis*), así como algunos cambios en las propiedades físicas, químicas y microbiológicas del suelo. Se estableció un sistema agroforestal durante el ciclo agrícola otoño-invierno de 2020 en la comunidad de Campo Grande, municipio de Ixtaczoquitlán, Veracruz, México. El tratamiento con *Rhizophagus irregularis* + *Rhizobium etli* (2) + 50% de fertilización mineral produjo los mayores aumentos en la altura de las plantas: 68.5±8.6 cm (limón persa), 105.3±11.0 cm (durazno) y 6.8±4.5 cm (lichi). Además, produjo el mayor rendimiento de grano en maíz (5 653.7 kg ha^{-1}) intercalado con frijol (995.1 kg ha^{-1}). Al final del primer ciclo productivo, el pH del suelo disminuyó de moderadamente ácido (5.7) a ácido (4.9). Por el contrario, la materia orgánica aumentó de 1.71 a 2.76%. Hubo un aumento en la cantidad de bacterias (55.0 x 10^{6} a 68.0 x 10^{6} UFC g^{-1} de suelo), hongos (73.55 x 10^{2} a 511.7 x 10^{2} UFC g^{-1} de suelo) y actinomicetos (48.61 x 10^{5} a 53.19 x 10^{5} UFC g^{-1} de suelo). El establecimiento de sistemas agrícolas diversificados en combinación con consorcios microbianos promueve la productividad de los cultivos y mejora las propiedades físicas, químicas y microbiológicas del suelo.
Palabras clave: Sistema milpa, árboles frutales, salud del suelo, consorcios microbianos, productividad.

Como citar: Romero-Figueiras T, Andrés-Meza P, Murguía-González J, Espinosa-Calderón A, Maldonado-Saavedra O, Leyva-Ovalle OR (2024) The role of microbial fertilizers in diversified cropping systems. Ecosistemas y Recursos Agropecuarios 11(3): e4007. DOI: 10.19136/era.a11n3.4007.

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

INTRODUCTION

In recent decades, crop yields have increased significantly due to crop breeding and technological advances because of the Green Revolution (Hedden 2003, Yang *et al*. 2020). However, this increase in agricultural production has been associated with the degradation of agroecosystems in terms of reduced biodiversity, soil and water pollution, loss of organic matter, increased incidence of pests and diseases with greater resistance to pesticides, and low resilience of agroecosystems (Jiao *et al*. 2011, Jones *et al.* 2012, Marcos-Pérez *et al*. 2023). It is therefore clear that a combination of productivity and sustainability is required through innovative approaches (Naudin *et al.* 2015). This can be achieved through the design and management of cropping systems that consider the principles for greater resilience to climate change and that simultaneously contribute to soil recovery and biodiversity conservation (Fargione *et al.* 2018, Jahan *et al.* 2022).

Agroforestry is highlighted for its positive effects on soil quality (Guillot *et al.* 2021). It consists of establishing rows of trees on at least 10% of agricultural land to obtain wood, firewood, or other products, in association with agricultural species or livestock (Montagnini and Nair 2004). This agronomic strategy allows farmers to increase their income and land productivity in space and time through the production of basic crops (Tsonkova *et al.* 2012, Wolz and DeLucia 2018). The importance of this form of vegetation management has added new dimensions to food security and poverty alleviation, by creating additional income, reducing inequality, and social inclusion.

Another production form of used in traditional agricultural systems is intercropping or companion cropping, which involves planting two or more species in space and time (Brooker *et al.* 2015). Different types of intercropping systems have been proposed (Burgess *et al.* 2022, Almagro *et al.* 2023) report improvement in soil structure, water and nutrient availability for plants, land productivity, among others. The most common combination in this practice is cereal-legume (Layek *et al.* 2018), however, several authors have reported other interactions such as maize-tomato (Chen *et al.* 2023), broccoli-broad bean (Marcos-Pérez *et al.* 2023). In Mexico and some South American countries, agroforestry systems and the design of intercropped maize in fruit trees, hereinafter referred to as MIAF, have been implemented to meet their basic needs with the production of maize and beans as strategic elements for the food security of rural families (Cadena *et al.* 2018, Regalado *et al.* 2020). The MIAF agricultural system has represented an excellent productive option on sloping soils. Particularly under this system, crops are used that do not compete for physical spaces, nutrients, water, and radiation, among others (Dou *et al*. 2022).

Agroforestry systems are important for their economic and environmental benefits (Schroth *et al.* 2004). However, the stable development of these complex agricultural

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

systems is limited by the availability of water and nutrients in the soil (Gao *et al.* 2016, Dou *et al*. 2022). Additionally, it has been reported that, under nitrogen-limiting conditions, soil microorganisms decompose more organic matter, resulting in higher greenhouse gas emissions (GHG) (Moorhead and Sinsabaugh 2006, Wang *et al.* 2014). In this sense, it is still necessary to add knowledge on sustainable forms of fertilization in the discipline of diversified crops.

Furthermore, the complementary use of microorganisms and nutrients in intercropping systems, such as the MIAF system, can be an economically viable alternative for soil fertilization and regeneration (Lai *et al*. 2022). When applied to soil in the MIAF system, microbial consortia can fix nitrogen from the air, activate soil nutrients, improve plant nutritional status, and produce active substances to stimulate plant growth as growth promoters (Jia *et al*. 2020). Several studies have revealed the changes in soil microbiological characteristics caused by the association or intercropping between different crops (Guillot *et al*. 2019, Yang *et al*. 2020, Deng *et al*. 2022, Judson *et al*. 2023). However, changes in the soil microbial community and their effect on intercropped maize in fruit trees are scarce. Our hypothesis is that the MIAF system can improve crop yield and promote fruit tree growth by increasing microbial associations in the soil and improving nutrient uptake. In general, the MIAF system is expected to improve the physical, chemical, and biological properties of the soil. Therefore, the objective of this study was to determine the effect of arbuscular mycorrhizal fungi (AMF), *Rhizobium* and fertilization levels on the agronomic characteristics of maize and beans intercropped in fruit trees, as well as the effect of the MIAF agricultural system on the physical, chemical, and biological properties of the soil.

MATERIALS AND METHODS

The research was conducted under seasonal conditions in the community of Campo Grande, municipality of Ixtaczoquitlán, Veracruz, Mexico (Figure 1), located at 18° 49' 16" N, 97° 01' 15" W, and 823 m above sea level. The soil where the trial was established is of the luvisol type, with a slope of 27%. The climate is warm and humid *Am* b(i')g (García 2004), with an annual total precipitation of 2035.5 mm. During the research period, the average daily temperature was 23.2 °C and the average daily relative humidity was 88.1%. The average daily maximum temperature was over 28 °C, in July. The coldest month of the period was November.

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

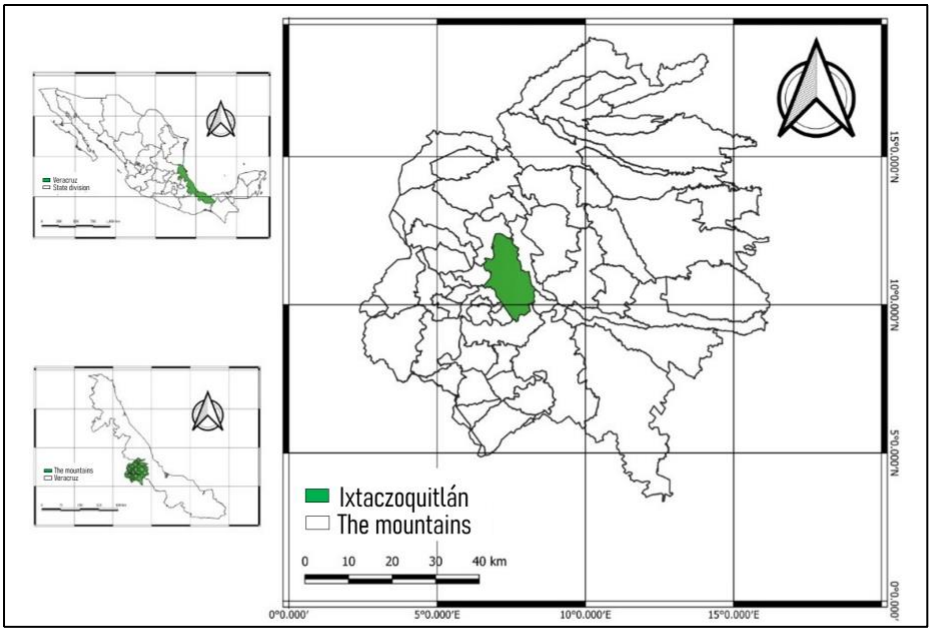

Figure 1. Location of the study area.

Establishment of the MIAF plot and plant material

A maize-intercropped-with-fruit-trees agricultural system was established in December 2020. The initial design involved tracing level curves perpendicular to the slope of the land for planting the fruit trees, which were planted in a layout of 1.0 m spacing between trees and 7.8 m between rows. Thirty fruit trees were planted on each level curve, 10 of each species: peach (*Prunus persica* L. Batsch), Persian lime (*Citrus latifolia* Tan.) and lychee (*Litchi chinensis* Sonn), with a spacing of 2.0 m between species (Figure 2). On each side strip of the fruit trees, two furrows of maize (*Zea mays* L.) were sown alternating with two furrows of beans (*Phaseolus vulgaris* L.), with a spring-summer 2021 cycle. In both crops, the spacing between furrows was 0.80 m. The spacing between plants was 0.6 m for maize and 0.3 m for beans. The first furrow of maize or beans is 2.3 m from the trunk of the fruit tree on both sides of the row. The plant density for maize cultivation was 10 416 plants ha^{-1}. The plant density for bean cultivation was 20 833 plants ha^{-1}. The total area of the land where the system was established was 0.09 hectares.

Microbiological Inoculants

The inoculants used were: *Rhizophagus irregularis* and a mycorrhizal consortium (composed of 13 AMF genera, including *Glomus dimorphicum*, *Rhizophagus fasciculatus*, and *Funneliformis mosseae*) [250 propagules g^{-1}] and two strains of *Rhizobium etli* [9 x 10^7 CFU g^{-1} soil], from the company BioFábrica Siglo XXI. Inoculation was carried out directly to the seed with 50 g of inoculant per kilogram of seed. Carboxymethylcellulose was used as an adhesive.

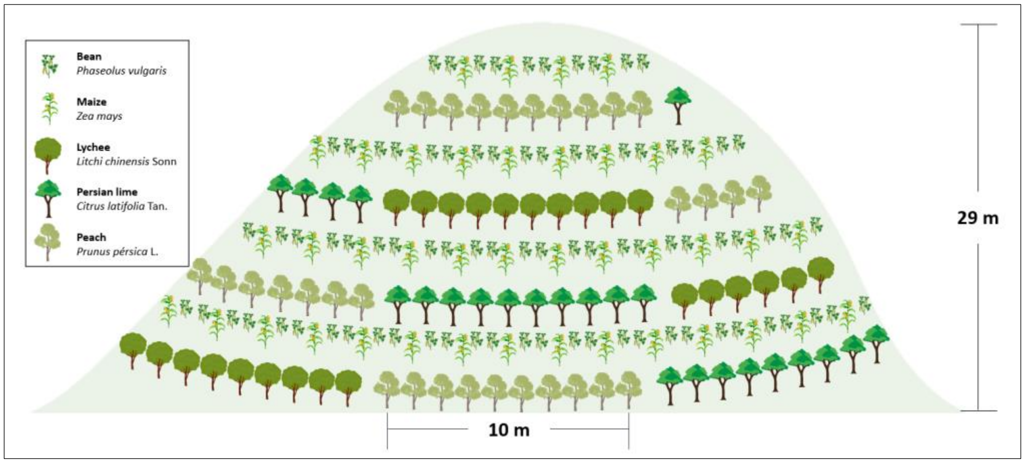

Figure 2. Distribution of crops in the experimental plot.

Experimental design

To investigate the effect of the combination of the studied microorganisms and chemical fertilization on seasonal crops, a completely randomized block experimental design with three replications was used (Table 1). In total, four combinations were involved in this experiment. The blocking factor was applied based on the slope of the land to prevent the transfer of microorganisms between the experimental plots. The slope of the land can generate water and soil movement, which could accidentally transport microorganisms from one treatment to another, affecting the integrity of the experiment's results.

Table 1. Description of the treatments applied to the maize and bean crop intercropped with fruit trees.

Treatment applied	Inoculant
T1	Consortium AMF + *Rhizobium etli* (1) + 50% de MF
T2	Consortium AMF + *Rhizobium etli* (2) + 50% de MF
T3	*Rhizophagus irregularis* + *Rhizobium etli* (1) + 50% de MF
T4	*Rhizophagus irregularis* + *Rhizobium etli* (2) + 50% de MF
T5	100% de MF (negative control)
T6	0% de MF (absolute control)

AMF: arbuscular mycorrhizal fungi, MF: mineral fertilization.

Agronomic management

Mineral fertilization for maize and bean was carried out with the formula 70 N - 60 P - 00 K and 35 N - 35 P - 00 K, respectively. At 15 days after planting (DAP) of maize, one-third of N and all the P_2O_5 were applied, subsequently, 30 DAP, the remaining two-thirds of N were applied, while for bean, all the fertilizer was applied at 15 DAP. Fertilization in the fruit trees was carried out with the formula 20 N - 10 P - 20 K.

Data recording

Maize Cultivation

Leaf area index (LAI m^2 m^{-2}) was determined by measuring the length and width of all leaves on 5 randomly selected plants. The LAI was calculated using equation (Wang *et al.* 2023):

$$\text{LAI} = A * PD/10000$$

Where: LAI = leaf area index (m^2 m^{-2}), A=total leaf area (m^2), PD= planting density (plants ha^{-1}).

Fresh biomass (g $plant^{-1}$) was determined by weighing the different plant organs separately on a digital balance with a precision of 0.01 g. Subsequently, dry biomass (g $plant^{-1}$) was calculated by placing the fresh organs in a drying oven at 65 °C, with forced air circulation, until a constant drying weight was reached.

The corn grain yield was recorded in kg ha^{-1}, using equation:

$$Corn\ grain\ yield\ (\text{kg h}^{-1}) = (TFW * DM * PG * CF)/8600$$

Where: TFW= total field weight harvested in the experimental unit, DM= percentage of dry matter of a sample of grain from five ears, EG= estimated grain percentage of five ears, CF= conversion factor to obtain grain yield per hectare, 8600 = is a constant to estimate grain yield at a commercial moisture of 14% (Tadeo *et al*. 2014).

To measure the symbiosis between the microorganisms and the corn crop, the percentage of root colonization was determined using the triphenyltetrazolium chloride (TTC) staining technique (Phillips and Hayman 1970). The AMF spores from the samples were extracted from the soil using the wet decanting and sieving method proposed by Gerdemann and Nicolson (1963). The quantification of spores was performed by direct counting (low density) according to INVAM (2019).

Bean Cultivation

Leaf area index (LAI m^2 m^{-2}) was calculated by measuring the length (from the petiole to the apex of the leaf) and width (widest point of the leaf) of all leaflets of randomly selected plants. LAI was calculated using equation 1 (Wang *et al*. 2023). Fresh and dry biomass (g $plant^{-1}$) was obtained using the same procedure employed for maize cultivation.

The bean grain yield was recorded in kg ha^{-1}, using equation:

$$Bean\ grain\ yield\ (\text{kg h}^{-1}) = ((NV * NG)/1{,}000\ g) * PD$$

Where: NV= number of pods, NG= number of grains, PD= planting density (plants ha^{-1}).

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

To assess the symbiosis between the microorganisms and the bean crop, the number of nodules present on the roots of 5 bean plants was counted visually. Additionally, the length and diameter of the taproot were measured using a graduated ruler. Root volume (mL) was determined by inserting the root into a graduated cylinder filled with water and recording the volume of water displaced.

Fruit trees

In the fruit trees, the initial height (cm) at the beginning of the experiment and the final height (cm) at the end of the annual crop production cycle were recorded. The height increment was calculated as the difference between the final height (cm) and the initial height (cm).

Soil quality

Soil samples were collected before the experiment was established (agricultural cycle 2020) and after the first production cycle (agricultural cycle 2021). Sampling was carried out according to the topography of the land at a depth of 0-40 cm. The sampled soil was homogenized to avoid edge effects and a composite sample was obtained. The physical, chemical, and microbiological parameters (Table 2) were determined according to the NOM-021-RECNAT-2000 standard, which establishes the specifications for soil fertility, salinity, and classification.

Table 2. Physical, chemical, and microbiological parameters of the study area.

Indicators	Units	Methods
Texture	-	Bouyoucos hydrometer
Bulk density	g cm^{-3}	Waxed lump
pH	-	Electrometric in water
Electrical conductivity	Sdm^{-1}	Conductivity meter
Carbonates	%	Volumetric titration
CEC	cmol Kg^{-1}	Ammonium acetate
Total nitrogen	%	Micro Kjeldahl
Assimilable P	mg kg^{-1}	Bray and Kurtz 1
K	mg kg^{-1}	Ammonium acetate
Ca	mg kg^{-1}	Ammonium acetate
Na	mg kg^{-1}	Ammonium acetate
Mg	mg kg^{-1}	Ammonium acetate
Fe	mg kg^{-1}	DTPA and EDTA
Cu	mg kg^{-1}	DTPA and EDTA
Zn	mg kg^{-1}	DTPA and EDTA
Mn	mg kg^{-1}	DTPA and EDTA
B	mg kg^{-1}	Azometina-h
Organic matter	%	Walkley and Black
Bateria	CFU g^{-1} soil	Plate count
Fungi	CFU g^{-1} soil	Plate count
Actinomycetes	CFU g^{-1} soil	Plate count

CFU: colony formin units, CEC : cation exchange capacity, DTPA : diethylenetriaminepentaacetic acid, EDTA: ethylenediaminetetraacetic acid.

Statistical analysis

All variables were subjected to a test of normality and homoscedasticity of variances using the Shapiro-Wilk and Bartlett tests (Castillo 2007). The data were analyzed using an analysis of variance (ANOVA) and a means comparison test using Tukey's HSD (P ≤ 0.05). The data were analysed using the STATGRAPHICS® Plus 5.0 statistical software.

RESULTS

Effect of microorganisms and mineral fertilization on corn and bean crops

Treatment T3 exhibited the highest yield (5 653.6 ± 310.2 kg ha^{-1}), followed by T4 (4 698.6 ± 470.3 kg ha^{-1}) and T5 (5 230.7 ± 807.7 kg ha^{-1}). Treatments T1 and T2 with HMA consortium had lower yields (3 865.6 ± 651.2 kg ha^{-1} and 4 000.4 ± 106.6 kg ha^{-1}, respectively). The absolute control, which received no treatment, had the lowest yield (2 779.6 ± 149.1 kg ha^{-1}) (Figure 3a).

The highest IAF was observed in treatments T4 (5.4 m^2 m^{-2}) and T5 (5.8 m^2 m^{-2}) (Figure 3b). Treatment T5 (505.7 ± 42.1) produced the highest fresh root biomass. Dry root biomass did not show significant differences among treatments. However, treatments T3, T4, and T5 had the highest dry root biomass values (Figure 3c). Treatments T4 and T5 generated higher fresh and dry aerial biomass, with statistical significance (Figure 3d).

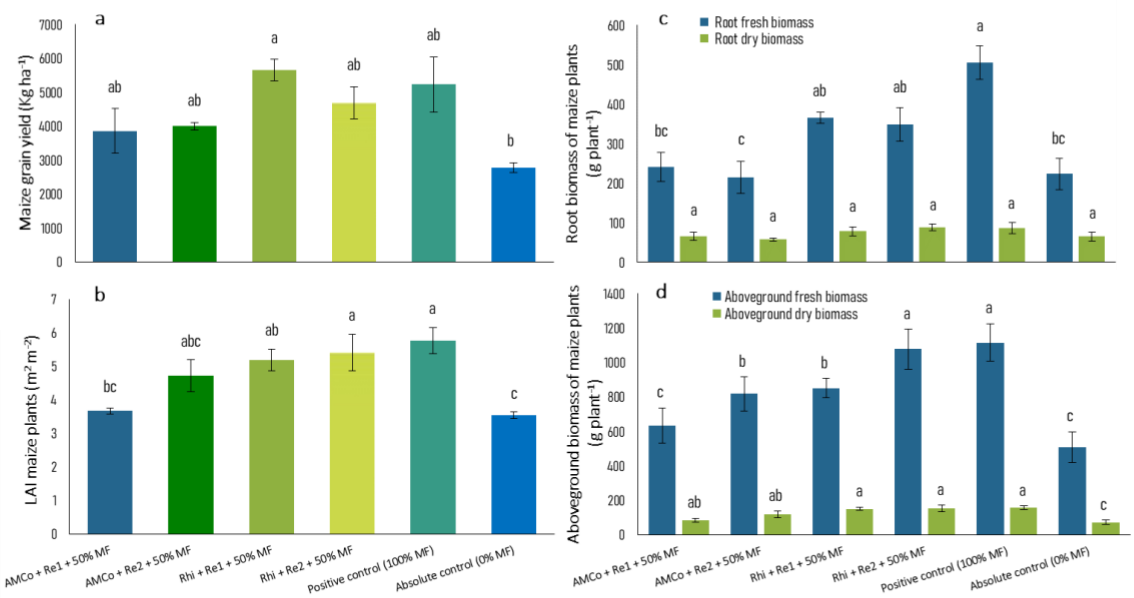

Figure 3. Effect of microorganisms and mineral fertilization on maize cultivation: a) grain yield, b) leaf area index, c) fresh and dry root biomass, d) fresh and dry aerial biomass, AMCo: arbuscular mycorrhizal consortium, Rhi: *Rhizophagus irregularis*, Re1: *Rhizobium etli* strain 1, Re2: *Rhizobium etli* strain 2, and MF: mineral fertilization. The vertical lines in the bars represent standard errors. Different letters indicate significant differences between the different treatments in the Tukey's multiple comparisons test.

Regarding the number of HMA spores, these were detected in all treatments. Treatments T3 and T4 had the highest quantities, with 377 ± 21.2 and 322 ± 39.2 spores per 50 g^{-1} soil, respectively ($p \leq 0.05$). Treatments T1, T2, T5, and T6 did not show significant differences between each other in the number of spores (Figure 4a). The colonization percentage was also higher in treatments T3 (55%) and T4 (60%) (Figure 4b).

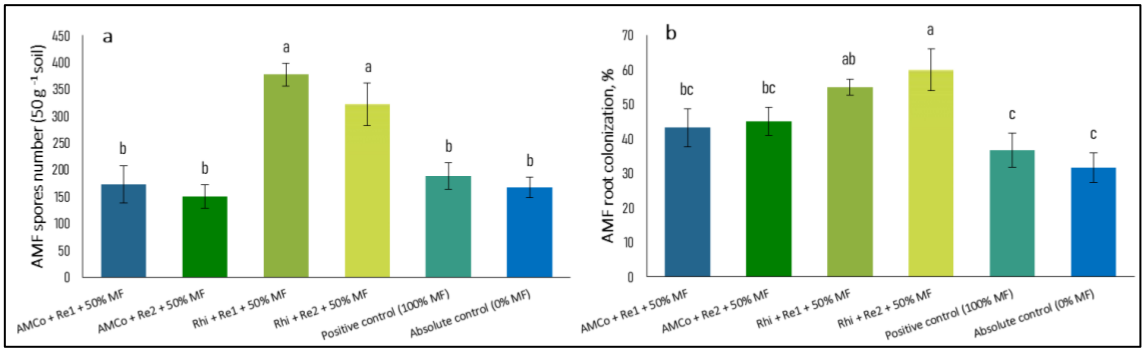

Figure 4. Effect of microorganisms and mineral fertilization on maize cultivation: a) number of spores in soil, b) percentage of colonization, AMCo: arbuscular mycorrhizal consortium, Rhi: *Rhizophagus irregularis*, Re1: *Rhizobium etli* strain 1, Re2: *Rhizobium etli* strain 2, and MF: mineral fertilization. The vertical lines in the bars represent standard errors. Different letters indicate significant differences between the different treatments in the Tukey's multiple comparisons test.

In the bean crop, treatment T4 (1 123.8 ± 129.8 kg ha^{-1}) achieved the highest grain yield (Figure 5a), slightly higher than the overall experiment average (918.9 kg ha^{-1}). Regarding the leaf area index (LAI) values at 75 days after planting (DAP), no statistically significant differences were observed. However, treatments T3 (1.27 m^2 m^{-2}) and T5 (1.19 m^2 m^{-2}) presented the highest LAI values (Figure 5b).

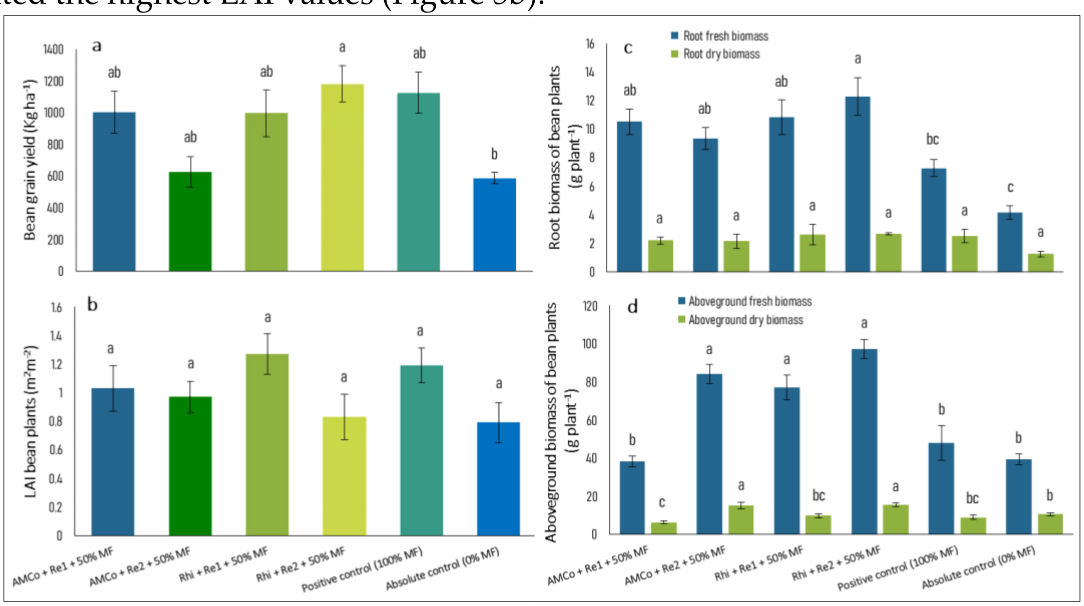

Figure 5. Effect of microorganisms and mineral fertilization on the bean crop: a) bean grain yield, b) leaf area index, c) fresh and dry root biomass, and d) fresh and dry aerial biomass, AMCo: arbuscular mycorrhizal consortium, Rhi: *Rhizophagus irregularis*, Re1: *Rhizobium etli* strain 1, Re2: *Rhizobium etli* strain 2, and MF: mineral fertilization. The vertical lines in the bars represent standard errors. Different letters indicate significant differences between the different treatments in the Tukey's multiple comparisons test.

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

In the bean crop, the generation of fresh root biomass was higher in treatment T4 (12.1 g plant^{-1}). No significant differences were observed in dry root biomass among the evaluated treatments; however, treatment T4 obtained the highest value, like fresh root biomass (Figure 5c). Fresh aerial biomass in treatments T3, T4, and T5 was statistically superior to that of the other treatments (Figure 5d).

In the cultivation of native variety beans, root characterization did not show significant differences in root length (Figure 6a). Treatments T3 and T4 had the plants with the highest LAI (Figure 6b). Root volume was higher in treatment T1, followed by treatments T2, T3, and T4 (Figure 6c). Similarly, the number of nodules in bean plants was statistically higher in treatments with beneficial microorganisms (T1, T2, T3, and T4) (Figure 6d).

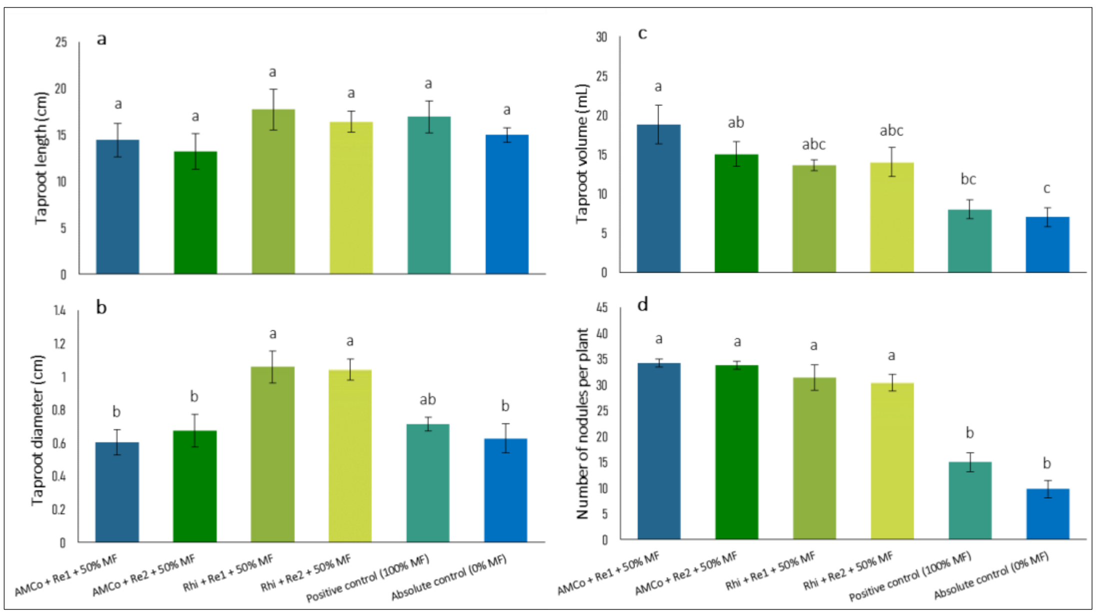

Figure 6. Effect of microorganisms and mineral fertilization on bean cultivation: a) length of the taproot, b) diameter of the taproot, c) volume of the taproot, d) number of nodules per plant, AMCo: arbuscular mycorrhizal consortium, Rhi: *Rhizophagus irregularis*, Re1: *Rhizobium etli* strain 1, Re2: *Rhizobium etli* strain 2, and MF: mineral fertilization. The vertical lines in the bars represent standard errors. Different letters indicate significant differences between the different treatments in the Tukey's multiple comparisons test.

Effect of intercropping on fruit trees

Figure 7 shows the average height increments (m) during the research period. The addition of different combinations of microorganisms and mineral fertilization in annual crops promoted significant changes in tree development, with statistically superior results observed in treatments T3, T4, and T5. Treatment T4 had a positive effect on lemon tree growth, with height increments of 68.5 ± 8.6 cm. Compared to other fruit trees, lychee tree showed low adaptability to the soil and climate conditions of the area.

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

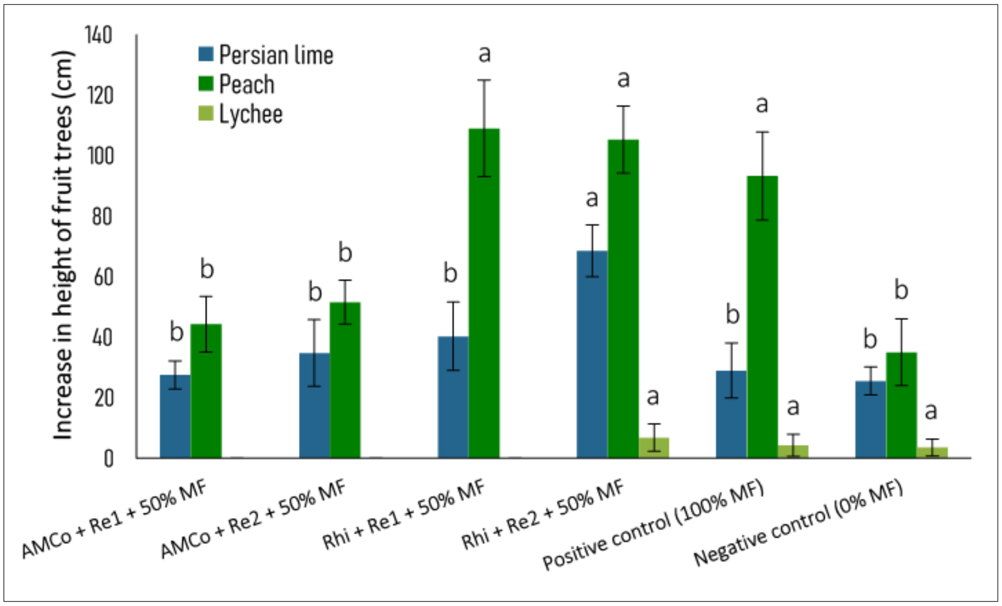

Figure 7. Effect of treatments on height increase of fruit trees (Lychee, Persian Lemon, Peach). AMCo: arbuscular mycorrhizal consortium, Rhi: *Rhizophagus irregularis*, Re1: *Rhizobium etli* strain 1, Re2: *Rhizobium etli* strain 2, and MF: mineral fertilization. The vertical lines in the bars represent standard errors. Different letters indicate significant differences between the different treatments in the Tukey's multiple comparisons test.

Effect of intercropping on fruit trees

Figure 7 shows the average height increments (m) during the research period. The addition of different combinations of microorganisms and mineral fertilization in annual crops promoted significant changes in tree development, with statistically superior results observed in treatments T3, T4, and T5. Treatment T4 had a positive effect on lemon tree growth, with height increments of 68.5 ± 8.6 cm. Compared to other fruit trees, lychee tree showed low adaptability to the soil and climate conditions of the area.

Evaluation of the MIAF agroforestry system on soil properties

To assess the impact of the MIAF agroforestry system on soil properties, various soil parameters were measured. The soil in the study area is a luvisol with a clayey texture (Table 3). The bulk density of the soil decreased slightly from 1.78 g cm^{-3} at the beginning of the experiment to 1.58 g cm^{-3} at the end of the production cycle. The soil was found to be free of carbonates (0.13%) and salts (0.023 Sdm^{-1}). Electrical conductivity (EC) values increased from 0.02 to 0.04 dSm^{-1}. The Cation Exchange Capacity (CEC) also showed an increase from 13.70 to 15.38 cmol kg^{-1}. Organic matter (OM) increased from 1.71 to 2.76%; similarly, total nitrogen (Nt) increased from 0.08 to 0.13%. In terms of macro and micronutrients, the MIAF agroforestry system promoted increases in the content of N, P, K, B, Cu, Fe, Mn, and Zn at the study site (Table 3).

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

Table 3. Results of the physical, chemical, and biological characterization of the soil, before establishing the MIAF plot and at the end of the first production cycle.

Indicators	Pre-production cycle	Production cycle	Units
Texture	Arcilla	Arcilla	-
Bulk density	1.78	1.58	g cm^{-3}
pH	5.70	4.90	-
Electrical conductivity	0.02	0.04	Sdm^{-1}
Carbonates	0.13	0.13	%
CEC	13.70	15.38	cmol Kg^{-1}
Total nitrogen	0.08	0.13	%
Assimilable P	0.78	1.08	mg kg^{-1}
K	37.05	56.94	mg kg^{-1}
Ca	1 998.40	2 003.40	mg kg^{-1}
Na	119.93	147.74	mg kg^{-1}
Mg	9.89	10.35	mg kg^{-1}
Fe	19.10	66.60	mg kg^{-1}
Cu	0.30	1.22	mg kg^{-1}
Zn	0.15	0.53	mg kg^{-1}
Mn	5.50	17.29	mg kg^{-1}
B	0.29	0.73	mg kg^{-1}
Organic matter	1.71	2.76	%
Bateria	55.0 x 10^6	68.0 x 10^6	CFU g^{-1} soil
Fungi	73.55 x 10^2	511.7 x 10^2	CFU g^{-1} soil
Actinomycetes	48.61 x 10^5	53.19 x 10^5	CFU g^{-1} soil

CFU: colony forming units, CEC: Cation exchange capacity.

At the end of the first production cycle, changes were observed in the quantity of microorganisms present in the soil of the MIAF agricultural system (Table 3). The fungal population increased from 73.55 x 10^2 to 511.7 x 10^2 colony-forming units per gram of soil (CFU g^{-1} soil), while bacteria increased from 55.0 x 10^6 to 68.0 x 10^6 g^{-1} soil. Actinomycetes experienced an increase from 48.61 x 10^5 to 53.19 x 10^5 g^{-1} soil. While bacteria are the most abundant microorganisms in the soil in terms of the number of individuals, fungi, due to their larger size, represent around 70% of the total microbial biomass, playing a fundamental role in the functioning of the ecosystem.

DISCUSSION

The association between mycorrhizal fungi and rhizobacteria is likely the most widespread beneficial relationship between plants and microorganisms. This ecological interaction is crucial for the ecosystem. Its potential to improve agricultural productivity and reduce environmental impact makes it a valuable tool for sustainable agriculture (Hidalgo and Ramos 2019, García *et al*. 2012).

In staple crops, such as cereals and legumes, the use of biofertilizers has yielded satisfactory results in many tropical regions (Reyes *et al*. 2018). Inoculating seeds with beneficial microorganisms promote the speed of nutrient uptake by plants through a direct effect on the roots (Aguirre-Medina and Velasco-Zebadúa 1994). This allows for improved soil fertility, promotes biodiversity, and reduces dependence on synthetic fertilizers.

The use of HMA and *Rhizobium etli* inoculants supplemented with 50% mineral fertilization in maize and bean crops on hillslope luvisol soils resulted in yields comparable to those obtained with 100% mineral fertilization. This effect can be attributed to the characteristics of arbuscular mycorrhizal fungi (AMF) species such as *Rhizophagus irregularis*, which are characterized by being intraradical colonizers with long extraradical hyphae (Jansa *et al*. 2007, Thonar *et al*. 2011). These features allow AMF to effectively absorb nutrients from the soil and deliver them to plants. On the other hand, the symbiotic association between *Rhizobium* bacteria and legumes involves the formation of nodules, where the concentration of O_2 is regulated by leghemoglobin. The supply of carbon compounds occurs inside the nodules, which allows the bacteria to avoid competition with other microorganisms (Osorio-Vega 2009). This mutually beneficial relationship helps legumes fix nitrogen from the atmosphere, making nitrogen available to the plants.

The relationship between the number of spores in the soil and crop yield is complex, being affected by the type of crop, climatic conditions, and management practices. In the case of cultivated soils, the average number of spores is 1 000 spores 100 g^{-1} soil (Aguilar *et al*. 2016). This study found particularly low numbers of spores. However, Cavigelli *et al*. (2005) found a lower number of spores in soils with a heavier texture, such as the soil in this study. It is important to note that organic farming has not been shown to necessarily result in many numbers of arbuscular mycorrhizal fungal spores (Gosling *et al*. 2010). However, Morton *et al*. (1993) found a positive correlation between the number of spores and the percentage of mycorrhizal colonization in a study with different plant species.

Treatments containing beneficial microorganisms and reduced mineral fertilizer had a positive effect on leaf area index (LAI) and biomass production. While LAI and biomass are influenced by a range of factors, beneficial microorganisms represent a valuable tool that can be used to improve crop management and increase productivity. This suggests that even with reduced fertilizer application, beneficial microbes can enhance plant growth and yield.

In general, Persian lime and peach showed greater adaptability to the soil and climatic conditions. Rivera *et al*. (2020) demonstrated that intercropping inoculated with mycorrhizal fungi had positive effects on the main crops (fruit trees). These

Ecosist. Recur. Agropec. 11(3): e4007, 2024
https://doi.org/10.19136/era.a11n3.4007

microorganisms are highly efficient in promoting crop growth, and this promotion may depend on the fungal species and soil characteristics. The correct choice of tree species can contribute to limiting competition and promoting complementarity due to the temporal and spatial separation of nutrient uptake with the crops (O'Connor *et al.* 2024).

Concerning soil quality, the results obtained in this study reinforce what has been described by various authors (Schroth *et al*. 2004, Wolz and DeLucia 2018, Guillot *et al*. 2019, Morugán-Coronado *et al*. 2020, Yang *et al*. 2020, Barros-Rodríguez *et al*. 2021, Almagro *et al*. 2023, Quandt *et al*. 2023). These authors argue that the combination of intercropping in fruit trees, perennials, and conservation tillage could have beneficial effects on the physical, chemical, and biological attributes of the soil. These attributes are indicators of soil structure recovery and improvements in water and nutrient availability for plants. This is important because in mountainous areas, agroforestry can be a more sustainable way to produce food, products, and services than monoculture agriculture (Duchene *et al*. 2017). In general, the establishment of the MIAF agricultural system allowed for increases in soil quality indicators.

According to Dominati *et al*. (2010), physical indicators are related to "inherent quality" which is influenced by soil age and past climates. In contrast, most chemical and all biological indicators can be associated with "dynamic quality" which is highly sensitive to land use and soil management (Gianfreda and Ruggiero 2006).

The use of living wall technology constructed with fruit trees and zero soil tillage practices led to a decrease in bulk density. Stine and Weil (2002) suggest that bulk density is influenced by the balance between solid particles and pore space, which is itself largely determined by soil organic matter content. High bulk density can restrict plant root growth, potentially leading to aeration stress (Stepniewski *et al*. 1994), lower soil temperature, altered biological processes (Brussaard and Van Faassen 1994), increased denitrification (Linn and Doran 1984), and loss of mycorrhizal fungi (Ellis 1998). Conversely, the increase in the CEC value suggests a greater capacity for storing nutrient cations. Soil CEC is primarily influenced by organic matter and clay minerals (Bourg and Sposito 2011).

This study observed an increase in both macro and micronutrients within the soil. Morugán-Coronado *et al*. (2020) similarly reported positive effects on nitrogen and other soil quality indicators in the presence of alley cropping and conservation tillage practices. This synergy is attributed to improved soil physical properties, enhanced water conservation, and reduced CO_2 emissions (Simoes *et al*. 2014, Almagro *et al*. 2016). These findings can explain the observed increase in soil organic matter and microbiota in this experiment. Organic matter originates from microbial decomposition and transformation of plant residues and root exudates (Guo *et al*. 2020). Several studies have shown that the composition of dissolved organic matter in soil is primarily derived from plant litter leachates and rhizodeposits released through root exudates, secretions, and the shedding of fine roots during growth, alongside organic compounds from mycorrhizal turnover (Canarini *et al*. 2019, Shen *et al*. 2023, Zheng *et al*. 2024). Microbial communities play a crucial role in improving soil structure and chemical properties, ultimately supporting plant growth. They therefore serve as strong indicators of soil health (Sahu *et al*. 2019). Furthermore, soil organisms exemplify the cause-and-effect chain linking land management decisions with productivity and the overall health of plants and animals (Doran and Zeiss 2000).

One noteworthy indicator from the analysis is the acidic soil pH. In Mexico, acidic soils are typically found in tropical and temperate forest regions. These regions cover an area close to 14 million hectares, with the state of Veracruz having the largest expanse of such soils (Castellanos 2014). However, the acidic pH could also be attributed to the mineralization of organic matter, where NH_4 (ammonium) is produced as a final product of decomposition. This NH_4 contributes to soil acidification (Molina 1999). Another potential mechanism within agricultural systems involves the production of CO_2 through respiration processes. This CO_2 forms carbonic acid (H_2CO_3), which can combine with cations in the soil. The resulting reaction products are then leached from the soil profile, promoting acidic conditions (Valencia 1998).

CONCLUSIONS

This study underlines the potential of fostering mutually beneficial interactions between plants and microorganisms to achieve sustainable and productive agriculture. Intercropping with fruit trees demonstrably improves soil quality. This practice has been shown to enhance the physical, chemical, and biological properties, leading to improved soil structure, water availability, and nutrient retention. Further research is necessary to optimise management practices for specific crops and soil conditions, while also addressing challenges such as acidic pH.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Sembrando Vida producers' group for the facilities granted for the realization of this research work. Special thanks to Mr. Miguel Federico Monterrosas Baez for his cooperation with the experimental module.

CONFLICTO DE INTERÉS

The authors have no financial or non-financial interests that could influence the research presented in this manuscript.

LITERATURE CITED

Aguilar W, Arce P, Galiano F, Torres T (2016) Aislamiento de esporas y evaluación de métodos de inoculación en la producción de micorrizas en cultivos trampa. Tecnología en Marcha 29(3): 5-14. https://doi.org/10.18845/tm.v29i7.2700.

Aguirre-Medina J, Velasco-Zebadúa E (1994) Componentes morfológicos y fisiológicos del rendimiento de *Leucaena leucocephala* al inocularse con micorriza VA y/o *Rhizobium loti*. Agricultura Técnica en México 20 (1): 43-54.

Almagro M, De Vente J, Boix-Fayos C, García-Franco N, Melgares de Aguilar J, González D, Solé-Benet A, Martínez-Mena M (2016) Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems. Mitigation and Adaptation Strategies for Global Change 21(7): 1029-1043. https://doi.org/10.1007/s11027-013-9535-2.

Almagro P, Díaz-Pereira E, Boix-Fayos C, Sánchez-Navarro V, Zornoza R, Martínez-Mena M (2023) Crop diversification effects on soil organic carbon and nitrogen storage and stabilization is mediated by soil management practices in semiarid woody crops. Soil and Tillage Research 233: 105815. https://doi.org/10.1016/j.still.2023.105815.

Barros-Rodríguez A, Rangseekaew P, Lasudee K, Pathom-Aree W, Manzanera M (2021) Impacts of agriculture on the environment and soil microbial biodiversity. Plants 10(11): 1–10. https://doi.org/10.3390/plants10112325.

Bourg I, Sposito G (2011) Molecular dynamics simulations of the electrical double layer on smectite surfaces contacting concentrated mixed electrolyte (NaCl-$CaCl_2$) solutions. Journal of Colloid and Interface Science 360(2): 701-715.

Brooker R, Bennett A, Cong W, Daniell T, George T, Hallett P, Hawes C, Iannetta P, Jones H, Karley A, Li L, Mckenzie B, Pakeman R, Paterson E, Schöb C, Shen J, Squire G, Watson C, Zhang C, and White P (2015) Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. New Phytologist 206(1): 107-117. https://doi.org/10.1111/nph.13132.

Brussaard L, van Faassen H (1994) Effects of compaction on soil biota and soil biological processes. In: Soane B, van Ouwerkerk C (eds) Soil compaction in crop production. Elsevier. U.K. pp. 215-235.

Burgess A, Correa M, Parkes B (2022) The deployment of intercropping and agroforestry as adaptation to climate change. Crop and Environment 1(2): 145-160. https://doi.org/10.1016/j.crope.2022.05.001.

Cadena P, Camas R, López W, López H, González J (2018) El MIAF, una alternativa viable para laderas en áreas marginadas del sureste de México: caso de estudio en Chiapas. Revista Mexicana de Ciencias Agrícolas 9(7): 1351-1361. https://doi.org/10.29312/remexca.v9i7.1670.

Canarini A, Kaiser C, Merchant A, Richter A, Wanek W (2019) Root exudation of primary metabolites: Mechanisms and their roles in plant responses to environmental stimuli. Frontiers in Plant Science 10:157. https://doi.org/10.3389/fpls.2019.00157.

Castellanos J (2014) Manejo y corrección de la acidez de los suelos. Hojas Técnicas de Fertilab. https://www.intagri.com/articulos/suelos/manejo-y-correccion-de-acidez-de-suelo. Data consulted: February 7, 2024.

Castillo L (2007) Introducción al SAS para Windows. 1ra Edición. Universidad Autónoma Chapingo. Estado de México, México. 295p.

Cavigelli M, Lengnick L, Buyer J, Fravel D, Handoo Z, McCarty G, Millner P, Sikora L, Wright S, Vinyard B, Rabenhorst M (2005) Landscape level variation in soil resources and microbial properties in a no-till corn field. Applied Soil Ecology 29: 99-123. https://doi.org/10.1016/j.apsoil.2004.12.007.

Chen N, Li X, Shi H, Zhang Y, Hu Q, Sun Y, Ma H, Wang B (2023) Quantifying interspecies competition for water in tomato–corn intercropping system using an improved evapotranspiration model considering radiation interception by neighboring plants in two-dimensional profile. Scientia Horticulturae 310: 111751. https://doi.org/10.1016/j.scienta.2022.111751.

Deng P, Fan W, Wang H, Ti J, Xu X (2022) Chinese Torreya agroforestry alters the rhizosphere soil bacterial communities and potential functions. Applied Soil Ecology 177: 104504. https://doi.org/10.1016/j.apsoil.2022.104504.

Dominati E, Patterson M, Mackay A (2010) A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics 69(9): 1858–1868. https://doi.org/10.1016/j.ecolecon.2010.05.002.

Doran J, Zeiss M (2000) Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15: 3-11. https://doi.org/10.1016/S0929-1393(00)00067-6.

Dou X, Wang R, Zhou X, Gao F, Yu Y, Li C, Zheng C (2022) Soil water, nutrient distribution and use efficiencies under different water and fertilizer coupling in an apple–maize alley cropping system in the Loess Plateau, China. Soil and Tillage Research 218: 105308. https://doi.org/10.1016/j.still.2021.105308.

Duchene O, Vian J, Celette F (2017) Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review. Agriculture, Ecosystems and Environment 240: 148-161. https://doi.org/10.1016/j.agee.2017.02.019.

Ellis F (1998) Household strategies and rural livelihood diversification. The Journal of Development Studies 35(1): 1-38. https://doi.org/10.1080/00220389808422553.

Fargione J, Bassett S, Boucher T, Bridgham S. Conant R, Cook-Patton S, Ellis P, Falcucci A, Fourqurean J, Gopalakrishna T, Gu H, Henderson B, Hurteau M, Kroeger K, Kroeger T, Lark T, Leavitt S, Lomax G, McDonald R, Griscom B (2018) Natural climate solutions for the United States. Science Advances 4(11): 1-15. https://doi.org/10.1126/sciadv.aat1869.

Gao F, Wang R, Xu H (2016) Effects of water and fertilizer coupling on soil moisture content and distribution in apple and maize intercropping system in the loess region of western Shanxi Province. Soil and Water Conservation 14 (04): 94-104. https://doi.org/10.13287/j.1001-9332.201608.021.

García E (2004) Modificaciones al sistema de clasificación climática de Köppen. 5ta Edición. Instituto de geografía–UNAM. México. 91p.

García J, Mendoza A, Mayek N (2012) Efecto de *Azospirillum brasilense* en el rendimiento del maíz en el norte de Tamaulipas, México. Universidad y Ciencia 28(1): 79-84. https://doi.org/10.19136/era.a28n1.35.

Gerdemann J, Nicolson T (1963) Spores of mycorrhizal Endogone species extracted from soil by wet sieving and decanting. Transactions of the British Mycological Society 46(2), 235–244. https://doi.org/10.1016/S0007-1536(63)80079-0.

Gianfreda L, Ruggiero P (2006) Enzyme activities in soil. In: Nannipieri P, Smalla K (eds) Nucleic acids and proteins in soil. Vol 8. Springer. Berlin. pp 257–311. https://doi.org/10.1007/3-540-29449-X_12.

Gosling P, Ozaki A, Jones J, Turner M, Rayns F, Bending G (2010) Organic management of tilled agricultural soils results in a rapid increase in colonisation potential and spore populations of arbuscular mycorrhizal fungi. Agriculture, Ecosystems anf Environment 139 (1-2): 273-279. https://doi.org/10.1016/j.agee.2010.08.013.

Guillot E, Bertrand I, Rumpel C, Gomez C, Arnal D, Abadie J, Hinsinger P (2021) Spatial heterogeneity of soil quality within a Mediterranean alley cropping agroforestry system: Comparison with a monocropping system. European Journal of Soil Biology 105: 103330. https://doi.org/10.1016/j.ejsobi.2021.103330.

Guillot E, Hinsinger P, Dufour L, Roy J, Bertrand I (2019) With or without trees: Resistance and resilience of soil microbial communities to drought and heat stress in a Mediterranean agroforestry system. Soil Biology and Biochemistry 129: 122-135. https://doi.org/10.1016/j.soilbio.2018.11.011.

Guo Z, Wang Y, Wan Z, Zuo Y, He L, Li D, Yuan F, Wang N, Liu J, Song Y, Song C, Xu X (2020) Soil dissolved organic carbon in terrestrial ecosystems: Global budget, spatial distribution and controls. Global Ecology and Biogeography 29(12): 2159-2175. https://doi.org/10.1111/geb.13186.

Hedden P (2003) The genes of the Green Revolution. Trends in Genetics 19(1): 5-9. https://doi.org/10.1016/S0168-9525(02)00009-4.

Hidalgo J, Ramos C (2019) Coinoculation of *Rhizophagus irregularis* and *Rhizobium sp*. in *Phaseolus vulgaris* L. var. canary (Fabaceae) "canary bean". Arnaldoa 26(3): 991-1006. http://doi.org/10.22497/arnaldoa.263.26309.

INVAM (2019) International culture collection of vesicular arbuscular mycorrhizal fungi. https://invam.wvu.edu/home. Data consulted: December 1, 2023.

Jahan H, Rahman M, Islam M, Rezwan-Al-Ramim A, Tuhin M, Hossain M (2022) Adoption of agroforestry practices in Bangladesh as a climate change mitigation option: Investment, drivers, and SWOT analysis perspectives. Environmental Challenges 7: 100509. https://doi.org/10.1016/j.envc.2022.100509.

Jansa J, Smith F, Smith S (2007) ¿Are there benefits of simultaneous root colonization by different arbuscular mycorrhizal fungi? New Phytologist 177(3): 779-789. https://doi.org/10.1111/j.1469-8137.2007.02294.x.

Jia T, Yao Y, Guo T, Wang R, Chai B (2020) Effects of plant and soil characteristics on phyllosphere and rhizosphere fungal communities during plant development in a copper tailings dam. Frontiers in Microbiology 11:556002. https://doi.org/10.3389/fmicb.2020.556002.

Jiao H, Chen Y, Lin X, Liu R (2011) Diversity of arbuscular mycorrhizal fungi in greenhouse soils continuously planted to watermelon in North China. Mycorrhiza 21: 681-688. https://doi.org/10.1007/s00572-011-0377-z.

Jones A, Panagos P, Barcelo S, Bouraoui F, Bosco C, Dewitte O, Gardi C, Erhard M, Hervás J, Hiederer R, Jeffery S, Lükewille A, Marmo L, Montanarella L, Olazabal C, Petersen J, Penizek V, Strassburger T, Toth G, Van Den E, Van L, Verheijen F, Viestova E, Yigini Y (2012) The state of soil in Europe: A contribution of the JRC to the European Environment Agency's Environment State and Outlook Report-SOER 2010. Publications Office of the European. Union. Luxembourg, Luxembourg. https://doi.org/10.2788/77361.

Judson J, Holden J, Chapman P, Galdos M (2023) Trees, hedges, agroforestry and microbial diversity. In: Blagodatskaya J (eds) Encyclopedia of Soils in the Environment 469-479. Elsevier. Unites States. https://doi.org/10.1016/B978-0-12-822974-3.00165-8.

Lai H, Gao F, Su H, Zheng P, Li Y, Yao H (2022) Nitrogen distribution and soil microbial community characteristics in a legume–cereal intercropping system: A review. Agronomy 12(8). https://doi.org/10.3390/agronomy12081900.

Layek J, Das A, Mitran T, Remote N, Centre S, Meena R (2018) Legumes for soil health and sustainable management. In: Swaroop R, Das A, Singh G, Lal R (eds) Legumes for soil health and sustainable management. Springer. Singapore. pp. 1-539. https://doi.org/10.1007/978-981-13-0253-4.

Linn D, Doran J (1984) Efecto del espacio poroso lleno de agua sobre la producción de dióxido de carbono y óxido nitroso en suelos labrados y sin labrar. Revista de la Sociedad de Ciencias del Suelo de América 48: 1267-1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x.

Marcos-Pérez M, Sánchez-Navarro V, Zornoza R (2023) Intercropping systems between broccoli and fava bean can enhance overall crop production and improve soil fertility. Scientia Horticulturae 312. https://doi.org/10.1016/j.scienta.2023.111834.

Molina E (1999) La acidez y encalado de suelos. 1ra Edición. Editorial International Plant Nutrition Institute. Quito, Ecuador. 42p. https://doi.org/10.13140/2.1.3888.9281.

Montagnini F, Nair P (2004) Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agroforestry Systems 61-62: 281-295. https://doi.org/10.1023/B:AGFO.0000029005.92691.79.

Moorhead D, Sinsabaugh R (2006) A theoretical model of litter decay and microbial interaction. Ecological Monographs 76(2): 151-174. https://doi.org/10.1890/0012-9615(2006)076[0151:ATMOLD]2.0.CO;2.

Morton J, Bentivenga S, Wheeler W (1993) Germplasm in the international collection of arbuscular and vesicular-arbuscular mycorrhizal fungi INVAM and procedures for culture development documentation and storage. Mycotaxon 48: 491-528.

Morugán-Coronado A, Linares C, Gómez-López M, Faz Á, Zornoza R (2020) The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. Agricultural Systems 178: 102736. https://doi.org/10.1016/j.agsy.2019.102736.

Naudin K, Husson O, Scopel E, Auzoux S, Giner S, Giller K (2015) PRACT (Prototyping Rotation and Association with Cover crop and no Till)-a tool for designing conservation agriculture systems. European Journal of Agronomy 69: 21-31. https://doi.org/10.1016/j.eja.2015.05.003.

DOF (2002) Norma Oficial Mexicana NOM-021-RECNAT-2000 Que establece las especificaciones de fertilidad, salinidad y clasificación de suelos. Estudios, muestro y análisis. http://www.ordenjuridico.gob.mx/Documentos/Federal/wo69255.pdf. Data consulted: December 1, 2023.

O'Connor C, Zeller B, Choma C, Delbende F, Manouvrier E, Desmyttére H, Siah A, Waterlot C, Sitraka A (2024) Early share of 15N-labelled fertilizer between trees and crop in young temperate alley-cropping system. European Journal of Agronomy 152: 127013. https://doi.org/10.1016/j.eja.2023.127013.

Osorio-Vega N (2009) Microorganismos del suelo y su efecto sobre la disponibilidad y absorción de nutrientes por las plantas. In: Marín S, Arcilla J (eds) Segundo seminario regional. Materia orgánica, biología del suelo y productividad agrícola.

Comité Regional Eje Cafetero. Sociedad Colombiana de la Ciencia del Suelos. Colombia. pp. 43-71. https://doi.org/10.38141/10791/0003_3.
Phillips J, Hayman D (1970) Improved procedures for clearing roots and vesicular-arbuscular fungi for rapid assessment of the infection. Transactions of the British Mycological Society 55: 158-161.
Quandt A, Neufeldt H, Gorman K (2023) Climate change adaptation through agroforestry: opportunities and gaps. Current Opinion in Environmental Sustainability 60: 101244. https://doi.org/10.1016/j.cosust.2022.101244.
Regalado J, Castellanos A, Pérez N, Méndez J, Hernández E (2020) Modelo asociativo y de organización para transferir la tecnología milpa intercalada en árboles frutales (MIAF). Estudios sociales. Revista de Alimentación Contemporánea y Desarrollo Regional 30(56): e20983. https://doi.org/10.24836/es.v30i56.983.
Reyes L, Ernesto C, Jiménez A, Graciano M, Montiel C, Galdámez J, Martíenez A, Alonso J, Cabrera M, Aguilar F, Martínez J (2018) Biofertilización y fertilización química en maíz (Zea mays l.) en Villaflores, Chiapas, México. Siembra 5(1): 26-37.
Rivera E, Martín A, Simó G, Pedro J, García R, Tamayo A, Bustamante G, González C, Ramírez P, Ruiz M, Ojeda Q, Hernández J (2020) Bases y beneficios del manejo conjunto de Canavalia ensiformis e inoculantes micorrízicos en la producción agropecuaria. Anales de la Academia de Ciencias de Cuba 12(1): e1104.
Sahu P, Singh D, Prabha R, Meena K, Abhilash P (2019) Connecting microbial capabilities with the soil and plant health: Options for agricultural sustainability. Ecological Indicators 105: 601-612. https://doi.org/10.1016/j.ecolind.2018.05.084.
Schroth G, Fonseca G, Harvey C, Vasconcelos H, Gascon C, Izac A (2004) Introduction: The role of agroforestry in biodiversity conservation in tropical landscapes. Island Press, Washington DC, EE. UU. 1–12.
Shen L, Wang X, Liu T, Wei W, Zhang S, Keyhani A, Li L, Zhang W (2023) Border row effects on the distribution of root and soil resources in maize–soybean strip intercropping systems. Soil and Tillage Research 233: 105812. https://doi.org/10.1016/j.still.2023.105812.
Simoes M, Belo A, Pinto-Cruz C, Pinheiro A (2014) Natural vegetation management to conserve biodiversity and soil water in olive orchards. Spanish Journal of Agricultural Research 12(3): 633-643. https://doi.org/10.5424/sjar/2014123-5255.
Stepniewski W, Glinski J, Ball B (1994) Chapter 8 - Effects of Compaction on Soil Aeration Properties. In: Soane BD, van Ouwerkerk C (eds) Soil compaction in crop production. Vol. 11. Elsevier. Unites States. pp. 167-189. https://doi.org/10.1016/B978-0-444-88286-8.50016-7.
Stine M, Weil R (2002) The relationship between soil quality and crop productivity across three tillage systems in South Central Honduras. American Journal of Alternative Agriculture 17(1): 2-8. https://doi.org/10.1079/ajaa200201.

Tadeo M, Espinosa A, Turrent A, Zamudio B, Valdivia R, Andrés P (2014) Productividad de grano de cuatro híbridos trilineales de maíz en versión androesteril y fértil. Agronomía Mesoamericana 25(1): 45-52. https://www.scielo.sa.cr/scielo.php?script=sci_arttext&pid=S1659-13212014000100005. Accessed April 30, 2024.

Thonar C, Schnepf A, Frossard E, Roose T, Jansa J (2011) Traits related to differences in function among three arbuscular mycorrhizal fungi. Plant Soil 339(1): 231-245. https://doi.org/10.1007/s11104-010-0571-3.

Tsonkova P, Böhm C, Quinkenstein A, Freese D (2012) Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: a review. Agroforestry Systems 85(1): 133-152. https://doi.org/10.1007/s10457-012-9494-8.

Valencia G (1998) Manual de nutrición y fertilización del café. Instituto de la Potasa y el Fósforo. https://books.google.com.mx/books?id=F4z2cQAACAAJ. Data consulted: February 1, 2024

Wang Y, Chen B, Wieder W, Leite M, Medlyn B, Rasmussen M, Smith M, Agusto F, Hoffman F, Luo Y (2014) Oscillatory behavior of two nonlinear microbial models of soil carbon decomposition. Biogeosciences 11(7): 1817-1831. https://doi.org/10.5194/bg-11-1817-2014.

Wang Y, Huang D, Sun K, Shen H, Xing X, Liu X, Ma X (2023) Multiobjective optimization of regional irrigation and nitrogen schedules by using the CERES-Maize model with crop parameters determined from the remotely sensed leaf area index. Agricultural Water Management 286: 108386. https://doi.org/10.1016/j.agwat.2023.108386.

Wolz K, DeLucia E (2018) Alley cropping: Global patterns of species composition and function. Agriculture, Ecosystems and Environment 252: 61-68. https://doi.org/10.1016/j.agee.2017.10.005.

Yang T, Siddique K, Liu K (2020) Cropping systems in agriculture and their impact on soil health-A review. Global Ecology and Conservation 23: e01118. https://doi.org/10.1016/j.gecco.2020.e01118.

Zheng J, Wang X, Sun Y, Wang Y, Sha H, He X, Sun X (2024) Natural and anthropogenic dissolved organic matter in landfill leachate: Composition, transformation, and their coexistence characteristics. Journal of Hazardous Materials 465. https://doi.org/10.1016/j.jhazmat.2023.133081.