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Characterization of the edaphic quality in agroecosystems managed by peasant families of Pirané, Formosa, Argentina

Caraterização da qualidade edáfica em agroecossistemas gerenciados por famílias de camponeses de Pirané, Formosa, Argentina

Caracterización de la calidad edáfica en agroecosistemas gestionados por familias campesinas de Pirané, Formosa, Argentina

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Abstract

Soil quality can be inherited, related to formation processes, and dynamic, especially due to those introduced by human activity. The objective of this research was to characterize the edaphic quality of four peasant agroecosystems through physical, chemical, biological indicators, and anthropogenic factors. This was proposed as a baseline for monitoring soil quality and for the implementation of technologies and practices for the promotion of the agroecological paradigm. The methodological perspective adopted was mixed. It was determined that the strongly acidic pH in the soil of AAA is the limiting chemical factor, while moderate salinity in TAG and TAD restricts plant nutrition. In the four agroecosystems, Colony Forming Units per gram of soil were quantified. These belonged to diazotrophic microorganisms, NH_4^+ and NO_2^- oxidizers, phosphorus solubilizers, cellulolytic fungi and total fungi. These populations are highly susceptible to edaphoclimatic conditions and anthropogenic influences, yet they play a pivotal role in natural biofertilization, natural biostimulation, biological control and natural bioremediation, which collectively facilitate the suppression of detrimental effects on these soils.

Keywords: Agroecology, Biofertilization, Bioremediation, Soil health, Soil microorganisms.

Resumo

A qualidade do solo pode ser herdada, em relação aos processos de formação e dinâmica, especialmente associados à atividade humana. O objetivo desta pesquisa foi caracterizar a qualidade do solo de quatro agroecossistemas camponeses por meio de indicadores físicos, químicos, biológicos e fatores antropogênicos. Isso foi proposto como uma linha de base para o monitoramento da qualidade do solo e para a implementação de tecnologias e práticas na promoção do paradigma agroecológico. A perspectiva metodológica foi mista. Foi determinado que o pH fortemente ácido no solo em AAA é um fator químico limitante, enquanto a salinidade moderada no ATH e no ATD restringe a nutrição das plantas. Nos quatro agroecossistemas foram quantificadas as Unidades Formadoras de Colônias por grama de solo, pertencentes a microrganismos diazotróficos, oxidantes de NH_4^+ e NO_2^-, solubilizadores de fósforo, fungos celulolíticos e fungos totais. Estas populações são muito sensíveis às condições edafoclimáticas e aos efeitos antropogênicos, mas contribuem para a biofertilização natural, para a bioestimulação natural, para o controle biológico natural e para a biorremediação natural, que, em conjunto, facilitam a supressão de efeitos prejudiciais nesses solos.

Palavras-chave: Agroecología, Biofertilização, Biorremediação, Microorganismos do solo, Saúde do solo.

Resumen

La calidad del suelo puede ser heredada, en relación con los procesos de formación y dinámica, especialmente debido a aquellos introducidos por la actividad humana. El objetivo de esta investigación consistió en caracterizar la calidad edáfica de cuatro agroecosistemas campesinos a través de indicadores físicos, químicos, biológicos y factores antropogénicos. Esto se planteó como línea de base para el monitoreo de la calidad del suelo y para la implementación de tecnologías y prácticas que promuevan el paradigma agroecológico. La perspectiva metodológica adoptada fue mixta. Se determinó que el pH fuertemente ácido en el suelo de AAA es el factor químico limitante, mientras que la salinidad moderada en ATH y ATD restringe la nutrición vegetal. En los cuatro agroecosistemas, se cuantificaron las Unidades Formadoras de Colonia por gramo de suelo, pertenecientes a microorganismos diazótrofos, oxidante de NH_4^+ y NO_2^-, solubilizadores de fósforo, hongos celulolíticos y hongos totales. Estas

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poblaciones son muy sensibles a las condiciones edafoclimáticas y a los efectos antropogénicos, pero contribuyen a la biofertilización natural, la bioestimulación natural, el control biológico natural y la biorremediación natural, que en conjunto, facilitan la supresión de efectos perjudiciales en estos suelos.

Palabras claves: Agroecología, Biofertilización, Biorremediación, Microorganismos edáficos, Salud del suelo.

INTRODUCTION

The soil is considered an “independent natural body with its own morphology, product of the joint action of climate, vegetation and living beings on a rock, during a certain period of time” (Ortiz-Silla, 2015, p. 53). Cantú *et al.* (2007) reveal that, until 1992, at the United Nations Conference on Environment and Development (UNCED) emphasized on the urgency of developing and applying methodologies to “determine the state of the environment and monitor changes that have occurred at the local, national, regional and global levels” (p. 173). These same authors highlight that the application of Chapter 40 of Agenda 21 led to the development and application of different indicators and indices, among which those related to determining soil quality. The concept of soil quality was defined, for the first time, by the Soil Science Society of America (Karlen *et al.*, 1997), which is evaluated with indicators. An indicator “is a variable that summarizes or simplifies relevant information, making a phenomenon or condition of interest perceptible and that quantifies, measures and communicates, in an understandable way, relevant information” (Cantu *et al.*, 2007, p. 174). In this sense, quantitative and qualitative indicators have been proposed for the evaluation of soil quality (Doran and Parkin, 1997; García; Ramirez; Sánchez, 2012; Grupo Operativo Leñosost, 2020).

Both soil quality and dynamic can be inherited. The first refers to the soil formation processes (long-term changes) and the second to the use and management of the soil by man (short and medium-term changes), which originated the concept of soil health, (Ortiz-Silla, 2015), which implies that the soil compromises its health or quality due to anthropogenic influence. The quality or health of the soil is evaluated by physical, chemical and biological indicators and their interactions; therefore, it is necessary to analyze them together (Afanador-Barajas *et al.*, 2020). However, only in recent times has it been suggested that soils contain an active biological component, which contributes to their sustainability (Moreira; Huising; Bignell, 2012) and allows it to be

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dimensioned as a 'living system' (Sánchez de Praguer *et al.,* 2007) vision that, "contributes to the health of the planet, the quality of food and the permanence of the soil over time" (Sánchez de Praguer *et al.,* 2012, p. 26). In response to this situation, the Initiative for the Conservation and Sustainable Use of Soil Biodiversity emerged, which emphasized the importance of long-term soil diversity evaluation and management. (FAO, 2020).

The World Soil Charter states that healthy soils are a basic prerequisite for meeting diverse needs for food, biomass (energy), fibre, fodder and other products, and for ensuring the provision of essential ecosystem services in all regions of the world (FAO, 2015). Nine planetary boundaries affect the security of the biosphere, and, therefore, the sustainability of agroecosystems and ecosystem services (Rockström *et al.*, 2009), of which five are related to food production, which are: climate change, land use change, biochemical fluxes of nitrogen (N) and phosphorus (P), the integrity of the biosphere and freshwater use (Salazar-Centeno; Jürgen; Marroquín, 2023). These realities require characterizing the edaphic quality of the agroecosystems managed by peasant families and providing guidelines for the promotion the agroecology paradigm. That is, to guarantee essential ecosystem services for maintaining the quality of life of human and the conservation of biodiversity (Kibblewhite; Ritz; Swift, 2007).

So far, in the province of Formosa, Argentina, the soil quality of peasant agroecosystems has not been characterized, which integrates physical, chemical, microbiological indicators, their interactions and the anthropogenic effect. For most biological indicators, there is little evidence available that directly relates the value of the indicator to productivity or the risk of negative environmental impact (Videla and Picone, 2017). In the Pampean region, studies have been conducted under different climatic conditions and agronomic management of soil quality with biological and/or physical, and/or chemical indicators (Baridón, 2015; De Luca; Salazar-Martínez; Pérez, 2018; Faggioli and Symanczik, 2018; Fernández *et al.,* 2018).

The objective of this work is to characterize the edaphic quality of peasant agroecosystems through a diagnosis using physical, chemical, and microbiological indicators and the anthropogenic influence in four agroecosystems, in the municipality of Villa Dos Trece, Pirané Sur, Formosa, Argentina.

MATERIALS AND METHODS

Location of the agroecosystems and study period

The study was conducted in four agroecosystems (one agroecological, one conventional and two in transition) during the period from August, 2018 to September, 2019 (Table 1). Agroecosystems are managed by peasant families that make up agricultural colonies, from the Jurisdiction of Villa Dos Trece – Pirané, located in lot 20 and Colonia km 210, province of Formosa, Argentina (Figure 1).

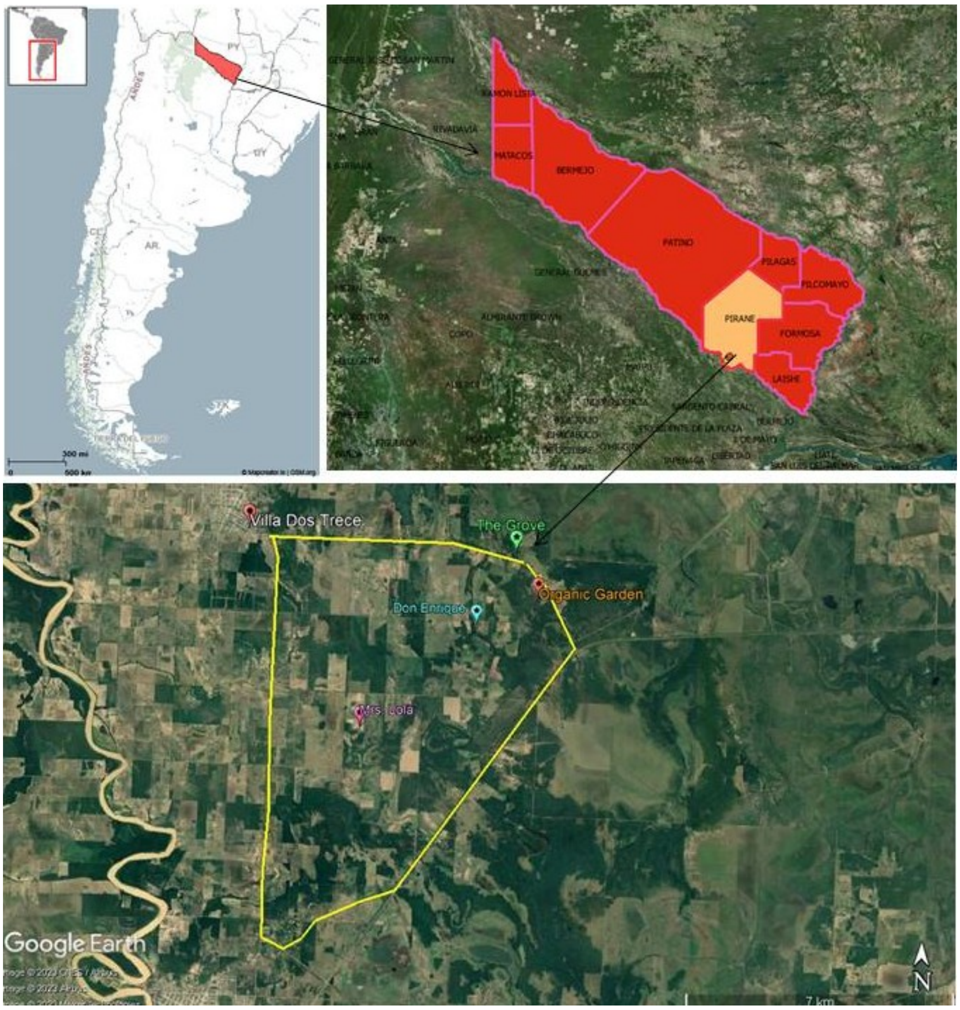

Figure 1. Location of agroecosystems, Jurisdiction Villa Dos Trece, Pirané, Formosa, Argentina.
Source: Platform Mapcreator, QGis 2.8.1 y Google Earth Pro 2023.

Pirané is located in the humid Chaco Ecoregion (Burkart *et al.*, 1999), and is divided into two productive zones, Pirané Sur and Pirané Norte. Pirané Sur has a total area of 3,136 km^2 and includes the towns of Palo Santo, El Colorado, Mayor Edmundo Villafañe and Villa Dos Trece (Schaller, 2013).

The climate is subtropical-subhumid, with rainfall between 600 and 1,200 mm annually. According to the physiographic map, it comprises the landscape unit called the Old Delta of the Bermejo River, which includes a plain of alluvial origin characterized by the alternation of albardons, floodable interfluves, plains dissected by paleochannels and paleovalleys with rambling channels. The sediments of this sector are mostly colloidal, composed of clay minerals and organic matter in different stages of degradation (Schulz; Rodríguez; Moretti, 2017).

Approach, scope, methodological design and selection criteria of agroecosystems

The methodological perspective adopted was mixed, with a quantitative approach, complemented by a qualitative approach that corresponds to a multiple case study (Yin, 2003). The scope of the quantitative approach is descriptive and correlational, with a non-experimental transectional design. The qualitative methodological perspective consisted of the combination of symbolic interactionism, whose method and technique were the individual semi-structured interview and the ethnographic approach, whose method and technique were participant observation, which contributed to the characterization of subsystems and management of agroecosystems, which was supported by a documentary analysis. The selection criteria for the four agroecosystems were based on those formulated by Mangione and Salazar-Centeno (2021). The agroecosystems were (Table 1): Agroecological Agroecosystem the Grove (AAG); Conventional Agroecosystem Don Enrique (CAD), Transition Agroecosystem Organic Garden (TAG); Transition Agroecosystem Mrs. Lola (TAM).

Soil sampling for physical and chemical indicators

Soil sampling in the subsystems with horticultural production was random. Homogenized samples were obtained for each agroecosystem at a depth of 0 to 15 cm (Mendoza-Corrales and Espinoza, 2017). Physical and chemical soil parameters were:

texture by the Bouyoucos method; pH (paste), potentiometric method; electrical conductivity in dS m^{-1} (EC) by conductimetry of the saturation extract (25ºC); percentage of total Nitrogen (tN%) by the Micro-Kjeldahl method; percentage of organic carbon (OC%) and percentage of organic matter (OM%) with the Walkley-Armstrong Black wet oxidation method; Nitrogen from nitrates (NO_3^-) in ppm by phenol-disulfonic acid colorimetry; available elemental Phosphorus in ppm (P) by the modified Bray-Kurtz method; Cation exchange capacity (CEC) method Washing of bases with 1N ammonium acetate pH 7.0 and evaluation of the retained nitrogen by the Kjeldahl method.

Table 1. Main characteristics of the studied agroecosystems (2018-2019).

Agroecosystems	**Productive approach**	**Coordinates**	**Surface (ha)**	**Subsystems and soil management**	
The Grove	Agroecological (AAG)	26°11´48.1”S 59°17´28.1”W	50	Orchard-fruit subsystem citrus fruits from non-grafted varieties	Vegetables under shade, with the incorporation of forest mulch. Citrus fruit forest with grass-covered soils
Don Enrique	Conventional (CAD)	26°12´49.7”S 59°18´04.1”W	52	Garden subsystem	Design in polyculture of vegetables, cleared land and natural management
Organic Garden	Transition (TAG)	26°12´50.5”S 59°17´31.7”W	25	Garden subsystem	Leafy vegetables under shade with organic matter mulch
Mrs. Lola	Transition (TAM)	26° 14´18.1”S 59°19´52.0”W	50	Garden subsystem	Leafy vegetables under shade. Polyculture of field vegetables, bare soils

Source: Mangione and Salazar-Centeno, 2021.

Soil sampling for quantification of functional groups of soil microorganisms

Sampling was random in the arable horizon Ap (0-15 cm) of the subsystems with horticultural production (vegetables under shade and in the field) (Table 1) and a soil sample of one kg was weighed and placed in a labeled nylon bag, kept in storage during transport and then in a refrigerator (Trejo *et al.*, 2020). The soil samples were placed in cardboard trays, under ambient conditions, up to a constant weight for processing. From each sample, 10g of dry soil were weighed and diluted in 90 ml of sterile water with 0.005% Tween (10^{-1} dilution) in a 250 ml Erlenmeyer flask. Subsequently, successive dilutions were made up to 10^{-8}, of which 1 ml was planted.

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The determination of diazotrophic bacteria was performed by the method of serial dilutions in triplicate (Döbereiner and Day, 1976). It was incubated at 30° C for 48 to 72 hours. The CFU g^{-1} of soil from ammonium-oxidizing bacteria (NH_4^+) and nitrite-oxidizing (NO_3^-) were obtained by sowing in specific broths. They were incubated for 30 days under continuous agitation in an ORBITAL SHEKER at 300 r.p.m. and were quantified using the most probable number technique (Alef and Nannipieri, 1995). The CFU g^{-1} of soil of phosphorus (P) solubilizing microorganisms were performed in triplicate in Petri dishes, with solid NBRIP medium (Nautiyal, 1999). The CFU g^{-1} of cellulolytic fungi soil was performed in broth with the addition of cellulose paper (Alef and Nannipieri, 1995), using the most probable number technique. It was incubated for 30 days under continuous agitation.

Total fungi CFU g^{-1} of soil were determined in serial dilutions of 10^{-3} to 10^{-5} in Petri dishes, in triplicate (Alef and Nannipieri, 1995). It was incubated at 28 +/- 2 ºC for 72 hours. After this period, the CFU g^{-1} of soil were determined with an optical microscope at 400x magnification, and the reproductive macro and microstructures were examined for identification.

Data analysis

In each agroecosystem, the CFU g^{-1} of soil of the functional groups were averaged and the general average of each functional group was calculated with its respective standard deviation to quantify the coefficient of variation in percentage (CV%). The fungi-bacteria ratio was selected as an indicator of the quality or health of the soil of the agroecosystems using the following formula:

$$\textit{fungi per bacteria ratio} = \frac{\textit{Total Fungi UFC } g^{-1} \textit{ of soil}}{\sum \textit{UFC } g^{-1} \textit{of soil diazotrophic } NH_4 \text{ and } NO_2 \textit{ oxidizing bacteria}}$$

The results of the physical and chemical edaphic variables of each agroecosystem are presented in a table and their interpretation is agroecological with the support of the documentary review.

RESULTS

Physical and chemical edaphic characteristics of agroecosystems

From an agronomic perspective, the pH of the AAG is strongly acidic (5.24) and is reflected in lower values of the CEC (14.7 meq. in 100 g of soil) and total nitrogen (0.22 %) so it is very likely that the number of cations in the exchange complex (organic and inorganic) with the soil solution is lower (Table 2). The pH of the CAD soil (7.37) typifies it as a very slightly alkaline soil because it exceeds the threshold of seven by 0.37 (Table 2). In these two agroecosystems, the salinity of their soils does not restrict the plant growth because the EC is 0.93 dS m^{-1} and 0.7 dS m^{-1} (Table 2). The soil of the TAG and TAM is moderately acidic and slightly acidic with a pH of 5.96 and 6.40, respectively (Table 2). These values are located in the optimal range of this chemical indicator so that nutrients are more available for productive plant biodiversity. The salinity of these soils is moderate with 2.62 dS m^{-1} y 2.67 dS m^{-1} (Table 2), which can restrict the growth and yield of cultivated plants.

The soils of the four agroecosystems belong to different Cartographic Units (CUs) (Table 3), but with a relatively homogeneous landscape so they share similar physical and chemical characteristics (Table 2 and 3). The predominant textural class is silty loam, are soils well supplied with soluble P, with a C/N ratio of the OM less than 10 (10C:1N), which is slow to decompose and very stable. Among the agronomic limitations of these high hills are the effective depth, acidity, alkalinity, water erosion and water retention.

Functional groups of edaphic microbes that participate in the biogeochemical nitrogen cycle

The functional groups of edaphic microorganisms that contribute to the BNC and that are very important for the nitrogen nutrition of the productive plant and auxiliary biodiversity in the four agroecosystems are illustrated in table 4. One of these functional groups is free-living diazotrophic bacteria (DB), whose colony-forming units per gram (CFU g^{-1}) of soil ranged between $3.5*10^6$ and $1.1*10^8$, which represented the largest amounts of CFU g^{-1} of soil, referring to the other functional groups, in each agroecosystem (Table 4). In this functional group, the greatest variability was determined with respect to its average (3.6E+07), whose coefficient of variation (CV) was estimated at 140 % (Table 4).

Table 2. Values of the chemical variables analyzed in each agroecosystem and their typical profile, Villa Dos Trece, Pirané, Argentina, 2019.

Agroecosystems	**pH**	**EC (dS m^{-1})**	**tN (%)**	**OC (%)**	**OM (%)**	**C/N**	**P (ppm)**	**CEC meq. in 100 g of soil**
Agroecological The Grove (AAG)	5.24	0.93	0.22	1.9	3.2	8.5	28	14.7
Range	Strongly acidic	Negligible salinity effect	Moderately provided		Well supplied	Good	Provided	Moderate
UC 22 Con. Pc Acuic Hapludol	6		0,270	2,68	Well supplied	10	70,1	Moderately high
Conventional Don Enrique (CAD)	7.37	0.70	0.39	2.7	4.6	6.9	24.5	19.4
Range	Neutral	Negligible salinity effect	Well supplied		Very well supplied	Good	Provided	High
UC 7 Con. Cb Acuic Argiudol	4.7		0,370	3,81	Well supplied	10	58.8	High
Transition Organic Garden (TAG)	5.96	2.62	0.25	1.7	2.9	6.7	206	16.9
Range	Moderately acidic	Restricted crop yield	Moderately provided		Moderately provided	Good	Provided	Moderate
UC 25 Con. Sa Entic Hapludol	5.9		0,228	2,06	Regularly supplied	9	40,3	Media
Transition Mrs. Lola (TAM)	6.40	2.67	0.45	2.3	4	5.2	217	15.7
Range	Slightly acidic maximum nutrient availability	Restricted crop yield	Very well supplied		Well supplied	Good	Provided	Moderate
UC 80 Aso. Pb Entic Hapludol	5.6		0,281	2.85	Well supplied	10	38.2	Moderately high

Source: Mangione, 2023.

In the AAG, managed by farmers Miguel and Paulo Gauliski; in the CAD, managed by Delia Caballero and Enrique Kemper; and in the TAM, managed by Lola Céspedes and Ernesto Bubrosky, the highest number CFU g^{-1} of soil were quantified with 1.5*10^{7}, 1.4*10^{7} and 1.1*10^{8}, respectively (Table 4). The minor CFU g^{-1} of soil were determined in the agroecosystem managed by Rosa Bustos and her children, with 3.5*10^{6}, so it is

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more likely that the process of biological fixation of atmospheric N_2 is less intense on the soil of the TAG.

Table 3. Composition of the Cartographic Units (CUs) of agroecosystems soils, series, location of the soils in the landscapes and productive limitations.

Agroecosystems	Cartographic unit (CU)	Composition, series and taxonomy	Location of soils in the landscape	Main limitations
Agroecological The Grove (AAG)	UC 22 Con. Pc	North Potrero Consociation, North Potrero Series, Acuic Hapludol	High hills	Effective depth, natural fertility, acidity, fragipan
Conventional Don Enrique (CAD)	UC 7 Con. CB	Coatí Consociation, Serie Coatí, Acuic Argiudol	High hills	Water erosion, acidity, alkalinity
Transition Organic Garden (TAG)	UC 25 Con. Sa	Saladillo Consociación, Saladillo Serie, Entic Hapludol	High hills	Acidity, water retention
Transition Mrs. Lola (TAM)	UC 80 Aso. Pb	XII Perín Association Perín Serie, Entic Hapludol	High hills	Effective depth, water erosion, acidity

Source: Schulz; Rodríguez; Moretti (2017).

Table 4. Colony forming units per gram (CFU g^{-1}) of soil functional groups of the edaphic microbiota that contribute to the biogeochemical cycles of Nitrogen (N), Phosphorus (P) and Carbon (C), and Fungi-bacterial ratio in four agroecosystems, Villa Dos Trece, Pirané, Argentina, 2019.

Agroecosystems	Functional groups that participate in biogeochemical cycles				
	Nitrogen			Phosphor	Carbon
	Diazotrophic	**NH_4^+ oxidants**	**NO_2- oxidants**	**Phosphorus solubilizers**	**cellulolytic fungi**
Agroecological The Grove (AAG)	1.50E+07	1.40E+05	1.40E+04	1.90E+06	1.20E+06
Conventional Don Enrique (CAD)	1.40E+07	7.00E+04	6.00E+03	1.90E+06	2.00E+06
Transition Organic Garden (TAG)	3.50E+06	1.10E+04	1.70E+04	9.00E+04	1.40E+06
Transition Mrs. Lola (TAM)	1.10E+08	1.40E+06	1.70E+04	1.50E+05	1.40E+05
Average	3.6E+07	4.1E+05	1.4E+04	1.0E+06	1.2E+06
DS	4.99E+07	6.65E+05	5.20E+03	1.03E+06	7.75E+05
CV (%)	140	164	38	102	65

Source: Authors.

The CFU g^{-1} of soil from NH_4^+ cation-oxidizing bacteria ranged between $1.1*10^4$ and $1.4*10^6$, whose average was quantified at $4.1*10^5$ with a CV of 164 % (Table 4), which

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represented the highest value of this dispersion measure. The highest CFU g^{-1} of soil were recorded on the TAM and AAG soils from NH_4^+ cation-oxidizing bacteria with $1.4*10^6$ and $1.4*10^5$, respectively. The CFU g^{-1} of soil of NO_2^- Anion Oxidizing Bacteria varied between $6*10^3$ and $1.7*10^4$, that represented the smallest amounts of CFU g^{-1} of soil with the lowest CV with 38 % (Table 4), which was attributed to the fact that the edaphoclimatic conditions and the management carried out by peasant families in the agroecosystems exert less influence on the reproduction of oxidant bacteria of the NO_2^-, so it is to be expected that the oxidation of the anion NO_2^- to the NO_3^- anion$^-$ would be very similar. The higher the coefficient of variation, the more marked the influence of soil and climatic conditions and the management of peasant families in their agroecosystems.

Functional groups of soil microbes that participate in the biogeochemical phosphorus cycle

The CFU g^{-1} of soil by microorganisms that belong to the P-solubilizing functional group various $9.0*10^4$ to $1.9*10^6$ (Table 4), whose general average was quantified at 1.0E+06 and its CV% at 102 %. The highest CFU g^{-1} of soil were quantified in the AAG and CAD soils floor with $1.9*10^6$, respectively. These results allow us to infer that the metabolic activity of these edaphic microorganisms may be more intense in these agroecosystems compared to that which occurs in the soils of TAG and TAM, which implies that the populations of this functional group are very sensitive to the edaphic-climatic conditions and to the management of the agroecosystem by peasant families.

Functional groups of edaphic microbes involved in the biogeochemical carbon cycle

The CFU g^{-1} of soil of cellulolytic fungi that participate in BCC ranged between $1.4*10^5$ to $2.0*10^6$, whose general average was estimated at $1.2*10^6$ with a CV of 65 % (Table 4), which only exceeds the CV of NO_2^- (CV= 38 %) anion-oxidizing bacteria. These results lead to infer that the populations of NO_2^- anion-oxidizing bacteria are more stable, followed by the populations of cellulolytic fungi. The soil of CAD will probably have greater metabolic activity of fungi capable of producing the enzyme complex to convert cellulose into glucose because in this agroecosystem the highest number of CFU g^1 of soil was quantified ($2.0*10^6$). Under this assumption, in TAM there is a lower capacity to convert cellulose into glucose because the CFU g^{-1} of soil are the lowest ($1.4*10^5$). These results, apparently, are contradictory, because the management implemented by the family of the first agroecosystem is conventional (CAD) and that of the second is in agroecological transition (TAM). The pH (7.37) of the CAD favors the enzymatic activity of this functional group referring to a soil slightly acidic, like the one cataloged by the TAM (6.4). To sum up, the management of the peasant families in their agroecosystem and the pH of the soil influence the ability to establish CFU g^{-1} of soil from cellulolytic fungi. Also, it is worth highlighting that the CFU g^{-1} of soil of cellulolytic fungi exceed the CFU g^{-1} from soil bacteria that oxidize ions NH_4^+ y NO_2^- (Table 4), whose averages obtain values of $1.2*10^6$, $4.1*10^5$ and $1.4*10^4$, respectively. The average CFU g^{-1} of soil of cellulolytic fungi is very similar to that of CFU g^{-1} of soil from the edaphic microbiota that is capable of solubilizing P ($1.0*10^6$ vs $1.2*10^6$).

Fungi-bacteria ratio as an indicator of soil quality or health

The average ratio of CFU g^{-1} of soil of total fungi to CFU g^{-1} of soil bacteria that fix atmospheric nitrogen (Diazotrophic) and nitrifying bacteria (Oxidizers NH_4^+ and NO_2^-) is 0.26 with a CV of 789 % (Table 5). This ratio ranged between 0.002 and 0.794 (Table 5), which means that fungi communities can represent from 2 to 79.9 % of the edaphic microbiota of these agroecosystems. The lowest value of the fungi-bacteria ratio was quantified in TAM, while the highest in TAG. Fungi accounted for 9.9 % and 14.9 % of CFU g^{-1} of soil in the AAG and CAD, respectively (Table 5) which are the agroecosystems with a better balance of the fungi-bacterial ratio.

Table 5. Ratio of total of the CFU g^{-1} soil of the fungi with the CFU g^{-1} of soil bacteria that participate in the biogeochemical nitrogen cycle (Diazotrophs + NH_4^+ oxidants + NO_2^- oxidants), in four agroecosystems, Villa Dos Trece, Pirané, Argentina, 2019.

Agroecosystems	**CFU g^{-1} soil**		**Ratio**
	Diazotrophic bacteria + NH_4+ oxidizing bacteria NO_2-oxidizing bacteria	Total soil fungi	Fungi/Bacteria
Agroecological The Grove (AAG)	1.52E+07	1.50E+06	0.099
Conventional Don Enrique (CAD)	1.41E+07	2.10E+06	0.149
Transition Organic Garden (TAG)	3.53E+06	2.80E+06	0.794
Transition Mrs. Lola (TAM)	1.11E+08	1.90E+05	0.002
Average	3.60E+07	1.6E+06	0.26
DS	5.05E+07	1.11E+06	0.36
CV (%)	140	67	789

Source: Authors.

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DISCUSSION

Physical and chemical edaphic characteristics of agroecosystems

According to the soil charter of the Argentine Republic, the strongly acidic pH of the soil is a limiting indicator for the nutrition of vegetables (Schulz; Rodríguez; Moretti, 2017). Therefore, liming is recommended in AAG, considering the cationic ratio for the selection of the Ca source (Jürgen-Pohlan; Salazar; Torrico*,* 2020; Marroquin-Agreda *et al*., 2023). In contrast, a pH between 6-7 is adequate for nutrients to beat reasonable levels of availability (Cremona and Enriquez, 2020). The moderate salinity of the soil of TAG and TAM reduces water and nutrients availability for plants through the drying effect it causes with the retention of water in the soil matrix, which does not allow plants to absorb it (Cremona and Enriquez, 2020), mainly during prolonged droughts in the province of Formosa as a consequence of climate change. These results affirm that the moderate salinity of the soils of TAG and TAM is the limiting factor for the growth and yield of the plants that make up the productive and auxiliary biodiversity, while the pH of the soil, in AAG, is the limiting factor for adequate nutrition of vegetables.

Peasant families have observed that the silt loam textural class favors the formation of superficial crusts, its aggregates are firm, break under moderate pressure, with good water retention and suitable for cultivation. The soils of these agroecosystems are located in a landscape of high hills with agronomic limitations (Table 3), so it is very important that the agroecological soil management contributes to their restoration and improvement. To counteract the negative aspects of these high hills from a physical point of view (effective depth, water retention and availability), chemical (acidity, alkalinity, salinity and nutrient availability) and degradation by water erosion, it is important that they are always well protected by fresh and/or living organic matter to stimulate the different trophic chains inside and outside the soil, increase OC, OM, CEC and the metabolic activity of the edaphic microbiota. This contributes to counteracting the planetary limits that affect the sustainability of agroecosystems and ecosystem services.

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Functional groups of edaphic microbes that participate in the biogeochemical nitrogen cycle

Andrade-Ochoa *et al*. (2015) state that the greatest participation of microorganisms occurs in the biogeochemical nitrogen cycle (BNC). Diazotrophic bacteria (DB) reduce or fix atmospheric bimolecular nitrogen (N_2) to make it assimilable by the productive plants and auxiliary biodiversity (Assimilation) in the form of the ammonium cation (NH_4^+) and perform the enzymatic digestion of NH_4^+, which degrades it to amino compounds (proteases, peptones and amino acids), a process known as ammonification or mineralization (Gaviria-Giraldo *et al*., 2018; Innovatione AgroFood Design, 2019). López (2022) found that DB adapted well to agroecological and conventional management of agroforestry systems with coffee, which was reflected in the highest values of CFU g^{-1} of soil. Beltrán-Pineda and Lizarazo-Forero (2013) state that the bacteria involved in atmospheric N_2 reduction reached higher populations because the physicochemical conditions of undisturbed and burned soils favor their abundance. This high plasticity of the DB to adapt to different agroecosystem management environments is the reason why they reached the largest populations in the four agroecosystems (Table 4). Clavijo *et al*. (2012) found that native DB correlates with organic matter, phosphorus (P) and soil pH, an association that was not always confirmed in this characterization of edaphic quality (Tables 2 and 3).

The results of the CFU g^{-1} of soil of diazotrophic bacteria and NH_4^+ oxidizing bacteria shows that the edaphoclimatic conditions and the management carried out by peasant families in each agroecosystem exert a very marked influence on the reproduction capacity of these bacteria. Therefore, it is to be expected that the amount of N_2 fixed and that of the NH_4^+ cation oxidation in the soil is very dissimilar in each agroecosystem. This deduction is based on the highest coefficients of variation (140 % and 164 %) with respect to the general average of each functional group (Table 4), so it is more likely that the biological fixation of atmospheric N_2 is less intense in the TAG soil, possibly due to a lower organic matter content (OM %) (Table 2). The OM % content of the TAG soil is classified as moderately supplied (2.9 %); while this chemical edaphic parameter in the soils of AAG, CAD and TAM is characterized as well supplied (3.2 %), very well supplied (4.6 %) and well supplied (4 %), respectively (Table 2). This influence of soil-climatic conditions and the management carried out by peasant families, in each agroecosystem, on the reproductive capacity of NO_2^- anion oxidizing bacteria is minor, so the oxidation of NO_2^- anion and NO_3^- anion are expected to be very similar.

The agroecological management of the TAG soil must encourage an increase in the percentage of its OM to favor the increase in CFU g^{-1} of soil of free-living diazotrophic microorganisms, which will be reflected in a lower dependence on synthetic nitrogenous and phosphorous fertilizers, reduced production costs and less environmental damage by mitigating the planetary limit related to the biochemical fluxes of N and P, which have surpassed the area of uncertainty or increasing risk (Rockström *et al*., 2009). On the contrary, the greatest number of CFU g^{-1} of soil of this functional group in the AAG, the CAD and the TAM favors a more dynamic enzymatic activity of the diazotrophic bacteria with greater metabolic activity, which mainly promotes ecosystem services of regulation and support so that productive plant biodiversity and auxiliary express better growth and development through better nitrogen nutrition; greater resistance to the onslaught of pests and diseases, and consequently a better ecosystem supply service (Food, medicines, fibers, wood, energy, biomass). López (2022) concludes that the functional roles of the genera of edaphic microorganisms are more related to supporting, regulating and cultural ecosystem services; and indirectly to the ecosystem supply service since the biomass that is characterized as yield (Food, fiber, wood, energy or firewood) is the result of good growth and development of the producers (plants), in which natural biofertilization, the natural biostimulation of vegetables and natural biological control agents for pests and pathogens intervene.

The study of microbial processes of nitrification and denitrification are essential to promote the productivity of agroecosystems and to care for the environment (water and air), whose purpose must maintain the balance of the fundamental elements for life (Turrini; Sbrana; Giovannetti, 2015).

In the TAM and AAG soil, NH_4^+oxidation is more likely to cause greater availability of the NO_2^- anion, which is absorbed by the productive plant and auxiliary biodiversity or oxidized by other bacteria. Conversely, in both agroecosystems, there may be greater NO_2^- leaching because the silt loam textural class soils (Table 3) are moderately permeable.

Functional groups of edaphic microbes that participate in the biogeochemical phosphorus cycle

Biogeochemical processes associated with the release of P into plant-available forms include solubilization of inorganic P and mineralization of organic P (Zou; Binkley; Caldwell, 1995). P-solubilizing edaphic microorganisms are a functional group that mainly include bacterial genera (free-living or in symbiosis with plants) compared to actinomycete and fungi genera, which have the capacity to solubilize mineral phosphates that have been fixed in soils and cannot be used by plants in their nutrition; therefore, its ecological role is essential (López, 2022). The main mechanism of action of the P solubilizing functional group is the decrease in the pH of the extracellular medium through the release of low molecular weight organic acids (Mantilla; Esquivel-Ávila; Negrete-Peña, 2011).

Presumably, the release of low molecular weight organic acids is more intense and active in AAG and CAD soils and consequently there is greater solubilization of P, fixed by edaphic minerals, so that this nutrient is more available to plants in the soil solution, which can reduce phosphorus fertilizer applications, production costs and promote environmentally friendly management of this nutrient, mainly in CAD. López (2022) highlights that this functional group with the ability to solubilize P is multifunctional due to its contribution mainly to the support and regulation ecosystem services that arise in agroecosystems and ecosystems, which promote the growth and development of productive plant and auxiliary biodiversity.

Functional groups of edaphic microbes that participate in the biogeochemical carbon cycle

The first stage of the carbon cycle consists of the reduction or fixation of CO_2 from the atmosphere through photosynthetic autotrophic organisms (plants, algae and cyanobacteria) and chemosynthetic autotrophic bacteria. In the second stage of this cycle, in agroecosystems and ecosystems, fresh organic matter from plant remains (straw, leaves, peels, fruits and roots *etc*.) is mineralized; whose main biopolymer (Linear Polysaccharides D-glucose) is cellulose (15 to 60 g per 100 g of dry matter). A complex of cellulolytic enzymes (C_1: exo-β-1,4-glucanase, C_x: endo-β-1,4-glucanase, and C_b: β-D-glucoside glucohydrolase E.C.3.2.1.21) present in a variety of bacteria, actinomycetes and fungi hydrolyzes this linear polysaccharide of D-glucose, which transforms it from cellobiose and cellotriose into the monosaccharide glucose, which is the main source of energy (C) for the growth of the edaphic microbiota (Frioni, 2006; Ovando-Chacón and Waliszewski, 2005). It is very likely that in the conventional agroecosystem (CAD) with greater metabolic activity of fungi capable of producing the enzyme complex to convert cellulose into glucose are attributed, according to Frioni (2006), to the application of synthetic nitrogen fertilizers, because the cellulolytic capacity of this functional group is stimulated and increases their populations. This same author points out that a pH close to neutrality favors the enzymatic activity of this functional group. López (2022) found that fungi that degrade organic matter are multifunctional because they can contribute to the solubilization of P, K and S, the production of hormones for plant growth, the natural biocontrol of pests and pathogens and the natural bioremediation of soils.

Fungi-bacteria ratio as an indicator of soil quality or health

From an ecological perspective, “soil quality” is its capacity to accept, store and recycle water, minerals and energy for the production of productive plant biodiversity, and the preservation of a healthy environment (Arshad and Coen, 1992). This concept is functional (Estrada-Herrera *et al*., 2017) and includes indicators that serve for the evaluation of the physical, chemical and biological characteristics of soils because they are related to each other, and actively participate in the production and stability of agroecosystems and are the foundation for their sustainability (Garcia; Ramirez; Sánchez, 2012). The fungi-bacteria ratio is a good indicator for the evaluation of soil quality or health due to its sensitivity to the reaction to agronomic management and edaphoclimatic conditions (Bobadilla, 2022; Fernández *et al*., 2018).

Bobadilla (2022), in a preliminary study of microbiota, in 11 agroecosystems with different management and edaphoclimatic conditions in Zamorano, Honduras, determined a range of the fungi-bacterial ratio from 0.004, in an intensive agroecosystem (0.4%), to 1.714, in an organic agroecosystem (171.4%). In agroecosystems, fungi are less abundant compared to bacteria (López, 2022; Salazar-Centeno *et al*., 2021), but they are larger in size and biomass (Mora-Delgado; Silva-Parra; Escobar-Escobar, 2019), whose participation in the decomposition of organic matter is appreciable because the majority of these communities live in dead organic matter (INIAP, 2002) and are capable of biodegrading cellulose (15 to 60%), hemicellulose (10 to 30%) and lignin (5 to 30%), which are the most abundant polymers in plants (Frioni, 2006). Both groups participate in the processes of mineralization of organic matter and solubilization, which release: N, P, potassium (K), calcium (Ca) and sulfur (S) (Perez-Perez *et al*., 2021; Ramos-Salazar *et al*., 2022).

The results of the fungi-bacteria ratio confirm that the reproductive capacity of both groups is very sensitive to agronomic management by the producing families and to the edaphoclimatic conditions. The lower fungi-bacterial ratio in the TAM is attributed to the fact that the soil of this agroecosystem remains without plant cover (Table 1), at its moderate salinity (2.67 dS m^{-1}), to a higher percentage of total nitrogen (tN%=0.45) in the soil, to a higher availability of P (217 ppm in 100 g of soil) and to a lower C/N ratio (5.2) of the OM (Tables 2 and 5), which restrict the reproductive capacity of edaphic fungi. Opposite to this situation, the TAG soil covered with a mulch of organic matter (Table 1), a moderately acidic pH (5.96), with medium salinity (2.62 dS m^{-1}), with a percentage of total nitrogen of 0.25 and with a P availability of 206 ppm in 100 g of soil promote greater production of CFU g^{-1} of soil of fungi (Tables 2 and 5).

The lower availability of P in AAG and CAD soils (28 and 24.5 ppm) combined with a very low salinity (less than 1 dS m^{-1}) may possibly cause the fungi-bacterial ratios to be 0.099 and 0.149, respectively (Tables 2 and 5). Another element that can contribute to this ratio is soil management, which is not intensive. In the first agroecosystem, in shade-grown vegetables, soil management integrates forest mulch and grass cover; In the second agroecosystem, vegetable polyculture was established on cleared soil with natural management (Table 1). This information makes it possible to conclude that the biological fixation processes of N_2, nitrification and the decomposition and

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mineralization of organic matter, and the solubilization of nutritional elements for productive plant and auxiliary biodiversity, in the AAG and CAD, are more balanced and can contribute to a more balanced natural nutrition.

In the four agroecosystems, the populations belonging to diazotrophic microorganisms, oxidant of NH_4^+ and NO_2^-, P solubilizers, cellulolytic fungi and total fungi, are multifunctional because they contribute to natural biofertilization, natural biostimulation, natural biological control and natural bioremediation of the soil, which encourage these soils to be suppressive, which are balanced soils and have the ability to regulate pests and edaphic pathogens (Calvo-Araya, 2021; Rossi, 2016). The condition of suppressive soils can be achieved more easily in AAG and CAD because the fungi-bacteria ratio is more balanced. For this purpose, in the four agroecosystems, it is *sine qua non* to implement technologies, practices and management systems for productive and auxiliary biodiversity, which promote the positive functionalities of the associated biodiversity. For which, the reference values, criteria and judgments of this baseline for quality and health monitoring of soils must be considered. Besides, the benefits of the agroecology paradigm should be exposed to the communities of the Villa Dos Trece municipality, Pirané Sur, Formosa, Argentina and society in general.

In the literature it is reported that these functional groups, in addition to contributing to natural biofertilization through their ability to fix N_2 from the atmosphere, oxidize the NH_4^+ and NO_2^-, to solubilize tricalcium phosphates (Clavijo *et al*., 2012) and to produce cellulolytic enzymes, they can synthesize metabolites or growth-regulating substances (auxins, gibberellins, cytokinins, ethylene and abscisic acid), which promote natural biostimulation (Hernández-Rodríguez *et al*., 2014; Pedraza *et al*., 2010); as well as the natural biocontrol of pests and edaphic pathogens (Clavijo *et al*., 2012) through different mechanisms of action (Competence for nutrients and space, induction of systemic plant resistance, production of antibiotics, siderophores, enzymes lithics and volatile and diffusible compounds).

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CONCLUSIONS

The reproduction of diazotrophic bacteria, NH_4^+ and NO_2^- oxidizing bacteria, and phosphorus-solubilizing microorganisms is more sensitive to the effects of edaphoclimatic conditions and the management practices carried out by peasant families in each agroecosystem. Therefore, these conditions can favor or disfavor the reproduction of fungi or bacteria, influencing the fungus-bacteria ratio. In contrast, populations of NO_2^- oxidizing bacteria are more stable, followed by populations of cellulolytic fungi.

CFU g^{-1} of soil were quantified for diazotrophic microorganisms, NH_4^+ and NO_2^- oxidizers, P solubilizers, cellulolytic fungi, and total fungi, whose populations contribute to natural biofertilization, biostimulation, biological control and bioremediation of soil. These functions facilities the development of soils that are suppressive, balanced, and capable of regulating edaphic pests and pathogens. This condition is more easily achieved in AAG and CAD due to the more balanced fungi-bacteria ratio.

In the four agroecosystems, it is essential to implement technologies, practices, and management systems that support productive and auxiliary biodiversity. These measures should promote the positive functionalities of associated biodiversity. To achieve this, the reference values, criteria, and judgments from this baseline must be considered for monitoring soil quality or health.

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