Microbial biomass and earthworms as indicators of soil quality under contrasting management practices in small-scale dairy systems

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ABSTRACT

Objetive: To determine soil quality under two contrasting agricultural management practices, based on microbial biomass and earthworm density, as compared to untilled control soils in two seasons (dry and wet), in different production units of small-scale milk production systems.

Methodology: The work was conducted in ten production units in the municipality of Aculco, Estado de México, Mexico. We analyzed physical, chemical, and biological soil indicators (microbial biomass and earthworm density). We conducted an ANOVA with a 3×2 factorial arrangement (three systems [maize, grassland, and control] and two seasons [dry and wet]).

Results: Values for all quality indicators in maize-cultivated soils were low, but increased in the wet season. Parameters in pasture-cultivated soils were similar to control soils.

Implications: These results determine the conditions of the soils used in milk production systems.

Conclusions: Some of the parameters assessed can be used as indicators of soil degradation and to strengthen other indicators which lead to an improved assessment of these systems' sustainability.

Key words: Agricultural management practice, Soil quality, Small-scale milk production systems.

INTRODUCTION

In the context of agricultural production, small-scale dairy systems (SSDS) play an important role worldwide as an option to relieve poverty and improve quality of life in rural environments (McDermott *et al.*, 2010). These systems comprise production units with small farming land areas and herds of 3 to 35 cows (plus their replacements). They basically depend on family workforce and sell milk as a source of income. SSDS should have a long-term sustainability in order to last and fulfill the important role that they
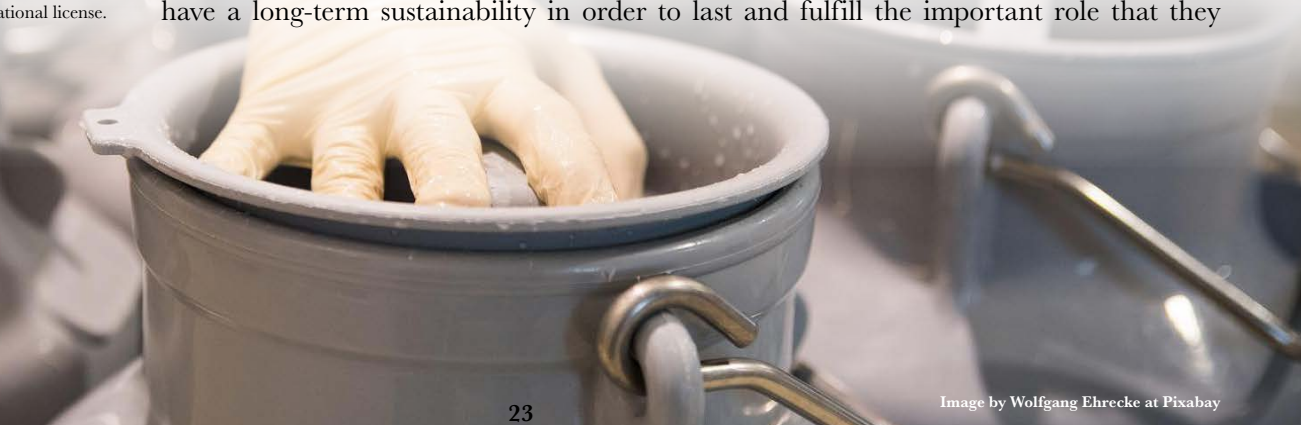
play within communities (Fadul-Pacheco *et al.*, 2013). Consequently, Mexico and the rest of the world have posed the need to reconcile the preservation of natural resources with agricultural production in small-scale dairy systems, particularly as a result of the importance of nutrient management in agricultural activities, which has a direct impact on soil quality (Gourley *et al.*, 2012).

Soil is a living, heterogeneous, and dynamic system that includes physical, chemical, and biological components, as well as their interactions. Each soil function includes or is the result of the interaction of its different physical, chemical, and biological properties, which can serve as quality indicators, as long as they can be measured qualitatively or quantitatively and propose an idea about soil functioning (Navarrete *et al.*, 2011). When assessing soil quality, different management systems can be compared in order to determine their respective effects on edaphic quality. Likewise, taking measurements in the same area throughout time can help to monitor soil quality trends—which are determined by soil use and management—, to compare problem areas within a piece of land with non-problem areas, and to compare measured values with edaphic benchmarks or with the natural ecosystem (Lemaire *et al.*, 2014). Soil quality indicators are seen as measuring tools that must provide information about properties, processes, and their characteristics (Pascual-Córdova *et al.*, 2017).

Soil deterioration is a natural process that can be reverted by adding pastures, which can restore some aspects of soil fertility (organic matter and biological properties), but it can also lead to content decline of several edaphic nutrients. This deterioration is difficult to perceive, because crops cultivated on a previously pastured soil usually present a better growth. Pasture requires nitrogenous and phosphorous fertilization, which allows the soil to recover the macronutrients removed during production (Abbona *et al.*, 2016). Determining the prevailing condition of soil in the SSDS of the municipality of Aculco, Estado de México, Mexico, will help to lay the foundations to improve management practices that increase the ecosystem's sustainability.

The objective of this study was to determine the quality of two soils under contrasting agricultural management practices, as compared to a control soil, using microbial biomass and earthworm density as indicators. The study was carried out during the dry and rainy seasons in ten different small-scale milk production units.

MATERIALS AND METHODS
Study area
The work was done in the municipality of Aculco, Estado de México, Mexico. The municipality is located at an average altitude of 2,440 m; the climate is warm sub-humid, with summer rains reaching a 700-1,000 mm precipitation (INAFED, 2015).

Production units and agricultural management
The work was carried out in ten production units. The selection criterion was at least 10 uninterrupted years of managing 1-2 ha plots where maize and pasture for cutting were cultivated together.

The agronomic management of the plots starts in February and March (plowing (fallowing), harrowing, and irrigation), followed by sowing in April. A first and a second weedings are carried out one and two months after sowing, respectively. These activities are mechanized through the use of tractors, plows, disc harrows, seeders, and croppers. Maize plots only receive a first irrigation, which allows farmers to sow in April, before the rainy season begins. The crops of choice are white maize, due to its better yield, and native maize, which is selected by producers themselves. Improved or open-pollinated varieties are also used (Aculco, Niebla, and Aspros).

Plots where grassland is cultivated have limited access to irrigation: they are only watered every four weeks, during the dry season. Grasslands are sown with different kinds of grasses, among which ryegrass (*Lolium multiflorum* L.) and white clover (*Trifolium repens* L.) are the dominant species. Traditionally, grasslands in the study area are managed based on a cut and carry system.

Unmodified zones in each farm were selected as control areas. Their soils had not been disturbed for at least 40 years and therefore were rich in native plants.

Soil sampling

One soil sample per production unit was taken each season: between February and March for the dry season and between June and July for the rainy season. Since the plots were irregular, each plot was divided into four subplots, where a stratified random sampling was conducted. A compound sample made up of 10 subsamples was collected in each subplot, adding up to four compound samples per plot.

Samples were taken at a depth of 0-20 cm and subsequently transported to the soil laboratory of the Instituto de Ciencias Agropecuarias y Rurales (ICAR), where they were dried at room temperature in the shade (18±2 °C), grinded, homogenized, and sieved through a 2-mm sieve.

Physical, chemical, and biological soil analyses

Based on the Mexican Official Standard NOM-021-RECNAT-2000, the total nitrogen content (NT) was determined using the Kjeldahl method, and the organic matter (OM) and total organic carbon (TOC) content with the Walkley-Black method. Gravimetry was used to determine moisture content, the graduated cylinder method was used to establish bulk density, and an electronic potentiometer was used to record the pH.

Determination of microbial biomass

The fumigation-incubation method (Jenkinson *et al.*, 2004) —the quantification of the CO_2 produced by soil samples— was used to determine the soil's microbial biomass carbon (MBC).

Determination of earthworm population

Earthworm population was determined following the Anderson and Ingram method (1993). The sampled monoliths were manually examined to collect earthworms and place them in glass jars with a 4% formaldehyde solution (Brito-Vega *et al.*, 2006).

Statistical analysis

The experimental design was a 3×2 factorial arrangement that considered the three systems (maize, grassland, and control) and both seasons (dry and rainy). The results were subjected to a variance analysis according to the following model (Kaps and Lamberson, 2004):

$$Y=\mu+M_i+E_j+M^*E_{ji}+R_k+e_{ijkl}$$

Where: μ: mean value; $M=$effect of the system ($i=1, 2, 3$); E: effect by season ($j=1, 2$); R: repetitions (producers) ($k=1,\ldots, 10$); $e=$residual term. When differences were found between treatments, the Tukey's median comparison test ($p \leq 0.05$) was applied. We used the MINITAB 14 statistical software.

RESULTS AND DISCUSSION

Figures 1 and 2 show the climate variables —precipitation, temperature, and evaporation— registered during the year when the study was conducted.

During the dry season, only 11 mm of rainfall were recorded, while total evaporation (TEv) in February and March reached 119.1 and 127.3 mm, respectively, with maximum
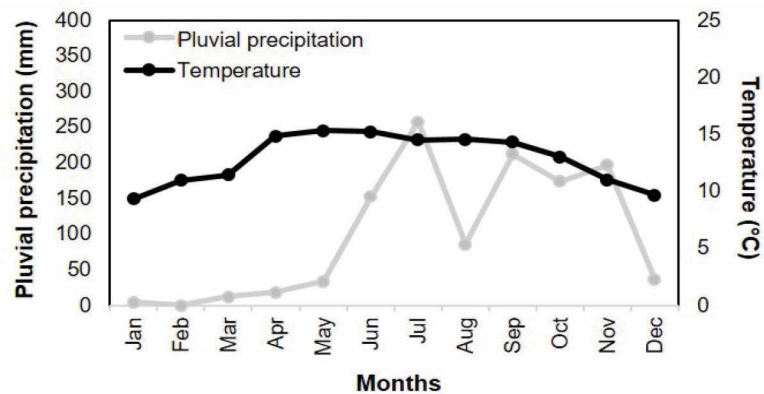

Figure 1. Pluvial precipitation and temperature in the municipality of Aculco, Estado de México, Mexico, during the development of the study.
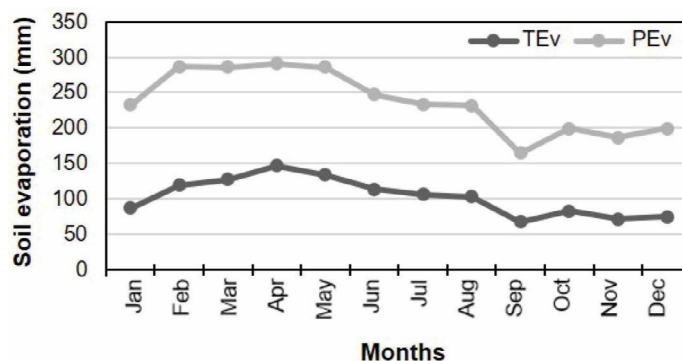

Figure 2. Soil total (TEv) and potential evaporation (PEv) in the production units.

average temperatures of 23.4 °C and 21.5 °C. Minimum average temperatures in February (with frost) and March were around 0 °C; during the rainy season (June and July), an average of 204.7 mm of rainfall was recorded, with approximate evaporation rates of 133 and 127 mm, maximum average temperatures of 22 °C, and minimum average temperatures over 8 °C.

The results for total evapotranspiration (TEv) and potential evaporation (PEv) obtained in this work are similar to those reported by Vacher *et al.* (1994), who assessed water balance in different plots during winter and found that TEv and PEv results were higher than in other seasons, which they related to the low temperatures recorded in this period. Soil evaporation is also related to the amount of vegetation cover, the soil surface moisturing before sowing, and the soil type (Castaño *et al.*, 2012; López-Báez *et al.*, 2018). During the rainy season, the vegetation cover does not eliminate evaporation —it can only reduce it. In fact, the thickness of this cover is a key factor in the drastic diminishing of evaporation (Kemper *et al.*, 1994).

Table 1 shows the results for the chemical and biological indicators found in the soil under different management practices and in different seasons.

pH

The pH of the studied soils is classified as moderate to strongly acidic (NOM-021-RECNAT-2000, 2002). The highest pH values were found in the control soils and no differences were recorded among seasons (dry, 5.91; rainy, 5.98). The lowest pH value was found in the maize plots (4.80). In 236 plots used to grow maize, López-Báez *et al.* (2019) reported pH values of 5.2 for 52% of soils, while the rest presented values lower than 5. The authors attributed these results to the soils' limited capacity to retain cations, resulting from their sandy texture and low organic matter content. In addition to their low capacity to store easily available K, Mg, and Ca, these cations are unprotected against the lixiviation process during the rainy season (Arcila-Pulgarín and Farfán-Valencia, 2010). Besides, soils can also be affected by agricultural practices (*e.g.*, the type of plow, the use of agrochemicals and of manure, and crop residue management), all of which is reflected on the acidification of plots in which maize is constantly grown.

Organic matter (OM)

The soil's OM presented significant differences ($p \leq 0.05$) between the different management practices and seasons. The soils cultivated with maize during the dry season had the highest concentration of organic matter; however, this value is classified as poor (NOM-21-RECNAT-2000, 2002), mainly because soils cultivated with maize are more prone to sediment and OM loss, as a consequence of their scarce vegetable cover at the beginning of their cultivation cycle (Fadul-Pacheco *et al.*, 2013). However, the amount of dry matter in the soil cultivated with maize increased during the rainy season, given the thicker vegetable cover on the soils. Meanwhile, the highest OM value was observed in the control soil during the rainy season. The results obtained in this work are similar to those reported by Wang *et al.* (2004), who mention that, after several years of annual crops, OM content diminishes because frequent farming affects OM inventories in the soil.

Table 1. Chemical and biological indicators of soils in the production units.

Soil parameter	pH			Total nitrogen (g kg^{-1})		
Soil system	DS	RS	Mean	DS	RS	Mean
Maize	4.80	5.30	5.05 b	0.8	1.9	1.35 c
Pasture	5.90	5.64	5.77 a	2.3	3.6	2.95 b
Control	5.91	5.78	5.84 a	2.6	3.1	2.85 a
Mean	5.53 b	5.57 a		1.9 a	2.86 b	
SEM Management	0.05*			0.01*		
SEM Season	0.04*			0.01*		
SEM Interaction	0.03*			0.02*		
Soil parameter	Organic matter (g kg^{-1})			Total organic carbon (g kg^{-1})		
Soil system	DS	RS	Mean	DS	RS	Mean
Maize	5.2	9.6	7.40 b	3.0	5.6	4.30 c
Pasture	7.8	2.9	5.35 c	4.5	7.5	6.00 b
Control	9.3	16.8	13.05 a	5.4	9.7	7.55 a
Mean	7.43 a	9.76 b		4.3 b	7.6 a	
SEM Management	0.02*			0.01*		
SEM Season	0.02*			0.01*		
SEM Interaction						
Soil parameter	Carbon of microbial biomass in soil (mg C-CO$_2$ kg^{-1} dry soil)					
Soil system	DS		RS		Mean	
Maize	57.25		63.84		60.54 c	
Pasture	120.29		134.38		127.33 b	
Control	119.62		140.03		129.82 a	
Mean	99.05 b		112.75 a			
SEM Management	1.35*					
SEM Season	1.11*					
SEM Interaction	1.91*					

*: Significant (p≤0.05). Different letters in each mean column and file indicate significant differences (p≤0.05). DS: dry season; RS: rainy season; SEM: standard error of the mean.

Total organic carbon (TOC)

TOC in the control soils during the rainy season is higher than in the dry season and in the case of the other two management practices. The amount of TOC in grassland soils is significantly different during the dry and rainy seasons. Magdoff and Weil (2004) report that grazing lands and grasslands improve soil TOC contents, which leads to an enhanced retention of organic-matter-related nutrients, better water relations, and an improved general functioning of soils.

The results found in this work for TOC in maize plots during the dry season are similar to those recorded by Salinas-García *et al.* (2002), who reported a direct relation between TOC and pluvial precipitation, with a lower TOC content during low precipitation periods. These results match the findings of Zinn *et al.* (2005), who found that soil TOC diminishes in intensive land-use systems with single-crop farming.

Microbial biomass carbon (MBC)

MBC in control soils during the dry season was no different from MBC in soils managed with grasslands, during the same season. Both managements showed an increase in MBC during the rainy season. Likewise, both had higher MBC values than soils used to grow maize. The results found in this work match those reported by Sparling *et al.* (1992), who found that MBC faced a 54-50 % reduction in the first 20 cm of soil cultivated with maize, as compared with soils used for the permanent cultivation of grassland. This is directly attributed to the quality of the OM added to the soil and to climate-related variations. Similarly, soil MBC is sensitive to changes brought about by tillage, crop rotation, and organic fertilizer usage, which have a positive effect on TOC and CSBM (Estrada-Herrera *et al.*, 2017). Low MBC values can be caused by a reduced C and N availability in the OM, resulting from an accelerated mineralization and the lixiviation of nutrients. These processes are favored by the destruction of soil aggregates due to frequent farming (Chaplot *et al.*, 2005).

Table 2 shows the results for the physical parameters of soil, which were significantly different (p≤0.05) between managements and seasons.

Bulk density (BD)

Control soils showed the lowest BD values (0.81 and 0.84 g/cm^3, respectively), which remained the same for both seasons. These data are similar to those recorded by Sánchez-Vera *et al.* (2003), who reported lower BD values in virgin forest soils than in soils with

Table 2. Physical indicators of the soils in the production units.

Soil parameter	Humidity (g kg^{-1})			Bulk density (g cm^{-3})		
Soil system	**DS**	**RS**	**Mean**	**DS**	**RS**	**Mean**
Maize	0.3	39.2	19.75 c	1.09	1.14	1.11 a
Pasture	0.4	52.7	26.55 b	0.96	1.07	1.01 b
Control	0.4	63.2	31.80 a	0.81	0.84	0.82 c
Mean	0.36 b	51.7 a		0.95 b	1.01 a	
SEM Management	0.10*			0.01*		
SEM Season	0.08*			0.01*		
SEM Interaction	0.14			0.02		

Soil parameter	Earthworm density (Number m^{-2})		
Soil system	**DS**	**RS**	**Mean**
Maize	5	11	8.0 c
Pasture	78	110	94.0 b
Control	7	16	11.5 a
Mean	30 b	45.66 a	
SEM Management	1.54*		
SEM Season	1.39*		
SEM Interaction	2.31		

*: Significant (p≤0.05). Different letters in each mean column and file indicate significant differences (p≤0.05). DS: dry season; RS: rainy season; SEM: standard error of the mean.

annual crops or grasslands, which they attributed to the fact that most soils with an undisturbed vegetation cover maintain an optimal BD.

These results show that farming has a high impact on changes in the distribution of primary particles and microaggregates in soils. Some authors have reported that, after seven or eight years of planting grassland, the physical properties of the soil are almost restored to their pre-modification levels (Sánchez-Vera *et al.*, 2003).

Earthworm density

Earthworm density showed higher values during the rainy season than the dry season; likewise, the values were higher in soils cultivated with grassland than in those cultivated with maize and control soils ($p \leq 0.05$). Domínguez *et al.* (2009) consider that an adequate earthworm density ranges from 100 to 500 individuals per m^2, and up to 2,000 individuals per m^2 in some temperate grasses. Earthworms are acknowledged as important indicators of soil health and environmental sustainability, since they play a key role in the improvement of soil fertility. A lower population of individuals per m^2 —which matches the data recorded in this work— was reported by Brito-Vega (2006), who mentions that farming the land tends to reduce earthworm population throughout time.

CONCLUSIONS

The alteration of soil quality by management practices influences the productivity and sustainability of the system through its impact on soil particle and microaggregate distribution, the depth of organic matter in the soil, microbial activity, earthworm density, and nutrient dynamics and availability. Meanwhile, crop rotation benefits soils, particularly when grasslands are sown after several years of being cultivated with maize.

Some of the parameters found in this work can be used as indicators of soil degradation and strengthen other parameters, in order to enhance the assessment of the sustainability of these systems.

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