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Article

Analysis of soil quality indicators and indices in Mexico

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Abstract

One strategy for evaluating soils is through quality indices that depend on specific indicators on the soils sampled, the type of crop and the management carried out. Indicators are measurable physical, chemical or biological variables that affect the capacity of the soil as they perform one or more of its functions. The objective of this research was to examine the methodological use of the different physical, chemical and biological properties of the soil used as quality indicators to determine soil quality indices in Mexico, through a bibliographic review carried out in 2022, for the period 2000-2021 through various search engines of scientific articles and keywords related to the subject, in order to generate a diagnosis and glimpse research opportunities. Greater attention should be paid to the study of soil quality in Mexico, based on technical and scientific information in regions and states where this information remains scarce. As a product of the bibliographic review, the following sets of indicators are proposed: texture, bulk density, aggregate stability, infiltration, penetration resistance, moisture retention curve and soil depth as physical indicators; organic matter, pH, total nitrogen, inorganic nitrogen, phosphorus, potassium, calcium and magnesium as chemical indicators; and microbial biomass carbon, soil respiration, earthworm density, dehydrogenase, #-glucosidase, urease, phosphatase and arbuscular mycorrhizal fungi as biological indicators, opting for a subset of indicators or a minimum data set to form a soil quality index.

Keywords:

physical-chemical-biological soil fertility, principal component analysis, soil properties.

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Introduction

Current pressures on soil are reaching critical limits, in particular, the expected increases in food, fiber and fuel production required to achieve food and energy security imply greater pressure on this non-renewable resource. In Mexico, the presence of 25 of the 32 soil units that appear in the World Reference Base for Soil Resources (WRB) is reported. Two of the most important problems at present, due to their extension, that affect these soils in Mexico are: the loss of surface soil due to water erosion (20 million hectares) and degradation due to decreased fertility (31.6 million hectares) (Álvarez-Arteaga *et al*., 2020); however, for several sectors of today's society, knowledge about this problem in many regions of the country is little and uncertain, which explains the low interest placed on this natural resource.

One strategy for assessing soil degradation is through soil quality indices (SQi), which depend on specific indicators related to the soils sampled, the type of crop and its management (Bedolla-Rivera *et al*., 2020). Indicators can be measurable physical, chemical and biological properties of the soil that affect the ability of the soil to perform one of its functions (Castillo-Valdez *et al*., 2021). Physical indicators are physical properties associated with the efficient use of water, nutrients and the use of agrochemicals; chemical indicators are related to the chemical conditions that affect soil-plant relationships, water quality, soil buffering capacity and the availability of nutrients for plants and other living beings and biological indicators are those organisms or processes developed by them, which, with their presence or abundance, indicate changes or states of certain properties or processes of the soil.

Indicators constitute a powerful tool for decision-making in land management and use at local, regional and global scales, through their integration, SQi are obtained, which are numerical variables that allow a more accurate and reliable assessment of soil quality using statistical methods such as the minimum data set (MDS) and principal component analysis (PCA) (Bedolla-Rivera *et al*., 2020). A vast number of physical, chemical and biological parameters have been included in soil quality studies around the world. Nevertheless, their integration into SQi is scarce, uncertain and still remains a pending task.

Based on this, the objective of this research was to examine the methodological use of the different physical, chemical and biological properties of the soil used as quality indicators to determine SQi in Mexico; through a bibliographic review using various search engines of scientific articles and keywords related to the subject, in order to generate a diagnosis and glimpse research opportunities.

Materials and methods

The literature search was performed in the following databases: ScienceDirect, Scopus, JSTOR, SciELO, Springer, Redalyc and Google Scholar. The review was conducted in both English and Spanish and included exclusively articles in scientific journals published between 2000 and 2021. The words used focused on the title and keywords related to soil fertility, quality and health in Mexico; they were: quality, soils, indicators, indices and Mexico. The final selection of the articles was based on the reading of the title, the analysis of the information present in the sections of abstract, methodology and conclusions in each of them, and finally, that it led to the theme raised in the objective.

Forty-three scientific articles were found with the above criteria. Subsequently, each of them was taken to a spreadsheet of the Excel® program, where a log was formed with the following sections: year, main author, state of the Mexican Republic, where the research was carried out, physical indicators, chemical indicators and biological soil indicators used, group of soils analyzed and type of SQi used. Based on this log, a diagnosis of the use of indicators and SQi in Mexico was generated.

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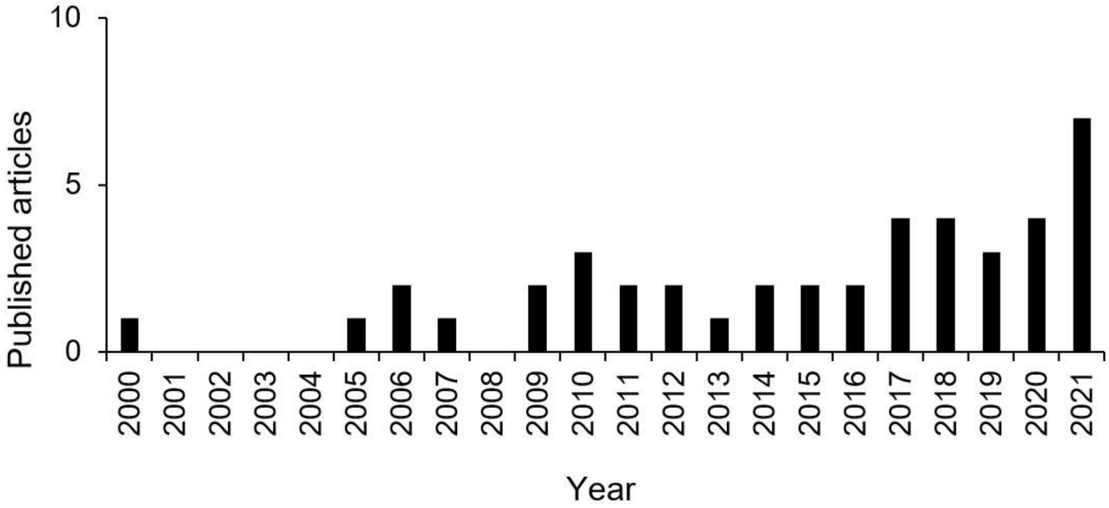
Results and discussion

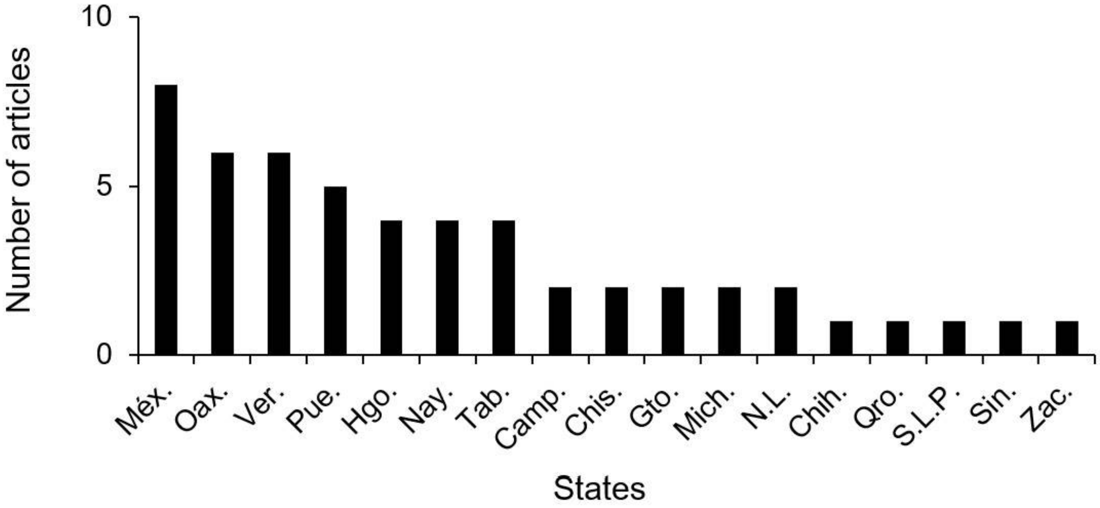
Forty-three scientific articles related to the methodological use of soil properties used as indicators of soil quality in Mexico were found. The number of articles per year varied from zero to seven on average and although there is no direct trend of increase in publications over time, it is visualized that, in the period from 2015 to 2021, 60.5% of scientific articles were published, compared to the period from 2000 to 2014 with only 39.5% of published articles (Figure 1).

Figure 1. Number of articles on soil quality in Mexico published in scientific journals.



With respect to the number of articles published by state, the State of Mexico concentrates the majority with eight; followed by Oaxaca and Veracruz with six; Puebla with five; Hidalgo, Nayarit and Tabasco with four; Campeche, Chiapas, Guanajuato, Michoacán and Nuevo León with two and Chihuahua, Querétaro, San Luis Potosí, Sinaloa and Zacatecas with one, respectively (Figure 2).

Figure 2. Distribution of the number of scientific articles on soil quality found by state in Mexico.



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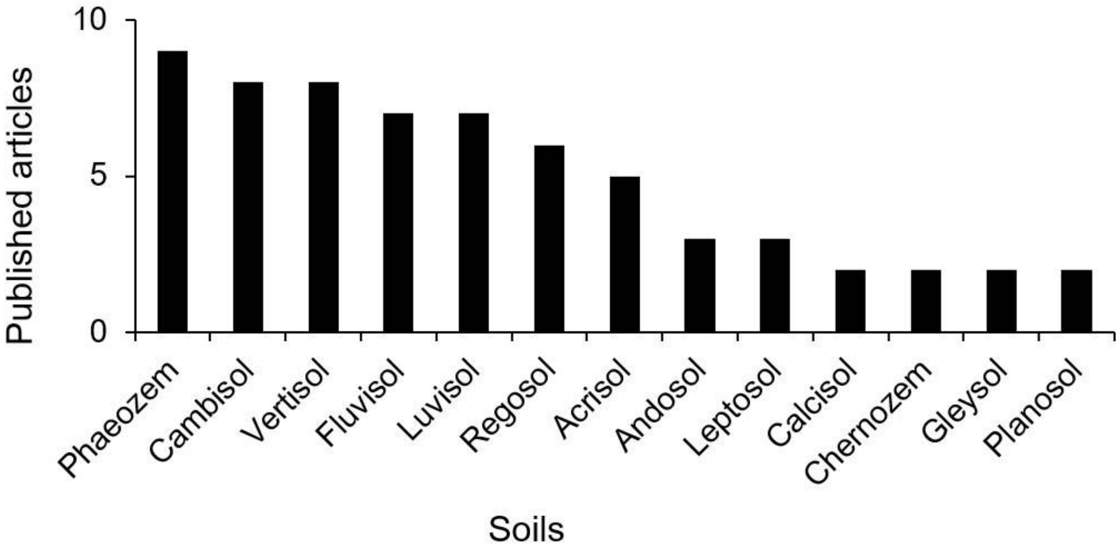
It is necessary to mention that there are regions where more studies on soil quality have been developed, Texcoco in the State of Mexico (Govaerts *et al*., 2006; Pajares-Moreno *et al*., 2010; Rodríguez-Serrano *et al*., 2016; Fonteyne *et al*., 2021), the Mixteca region in the state of Oaxaca (Estrada-Herrera *et al*., 2017; Santiago-Mejía *et al*., 2018; Fonteyne *et al*., 2021) and the central and mountain regions of Veracruz (Campos-Cascaredo *et al*., 2007; Fernández-Ojeda *et al*., 2016; de la Cruz-Elizondo and Fontalvo-Buelvas, 2019; Peña-Morales *et al*., 2021).

The analysis yielded information on several soil groups (WRB) studied in Mexico, with at least two articles per group (Figure 3). Some other groups studied were: Plinthosol, Solonchak, Leptosol, Planosol, Lixisol, Durisol, Solonetz and Technosol (Alcalá *et al*., 2009; Huerta *et al*., 2009; Pajares-Moreno *et al*., 2010; Alejo-Santiago *et al*., 2012; Fonteyne *et al*., 2021; Martínez-Rodríguez *et al*., 2021). Seven articles do not explicitly refer to any particular soil group (Prieto-Méndez *et al*., 2011, 2013; Rodríguez-Serrano *et al*., 2016; de la Cruz-Elizondo and Fontalvo-Buelvas, 2019; Murillo-Cuevas *et al*., 2019; Acevedo-Gómez *et al*., 2020; Peña *et al*., 2021) and Mollisol, Andisol, Ultisol, Inceptisol and Entisol soils under the nomenclature of the USDA Soil Taxonomy are reported in Govaerts *et al*. (2006), Campos-Cascaredo *et al*. (2007), Bautista-Cruz *et al*. (2012) and Chavarin-Pineda *et al*. (2021).

Figure 3. Groups of soils studied in relation to their quality in Mexico.



Physical indicators

When analyzing the frequency of study of physical indicators in scientific articles, it was found that the physical properties mostly chosen as physical indicators of soil quality are bulk density (Armida-Alcudia *et al*., 2005; Campos-Cascaredo *et al*., 2007; Bugarín *et al*., 2010; Prieto-Méndez *et al*., 2013; Murray *et al*., 2014; Zavala-Cruz *et al*., 2014; Fernández-Ojeda *et al*., 2016; Muñoz-Iniestra *et al*., 2017; Cantú-Silva *et al*., 2018; Santiago-Mejía *et al*., 2018; de la Cruz-Elizondo and Fontalvo-Buelvas, 2019; Álvarez-Arteaga *et al*., 2020; Chavarin-Pineda *et al*., 2021; Peña-Morales *et al*., 2021); texture (Prieto-Méndez *et al*., 2011; Zavala-Cruz *et al*., 2014; Muñoz-Iniestra *et al*., 2017; Cantú-Silva *et al*., 2018; Montaño-Arias *et al*., 2018; Santiago-Mejía *et al*., 2018; de la Cruz-Elizondo and Fontalvo Buelvas, 2019; López-Báez *et al*., 2019; Acevedo-Gómez *et al*., 2020; Álvarez-Arteaga *et al*., 2020; Bedolla-Rivera *et al*., 2020; Cruz-Flores *et al*., 2020; Peña-Morales *et al*., 2021).

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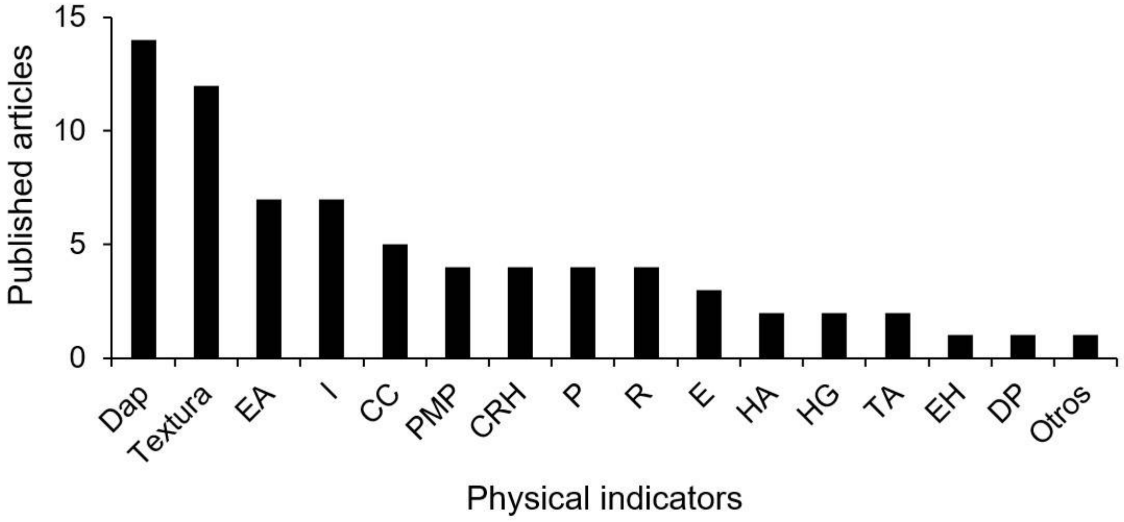
Aggregate stability (Sustaita-Rivera *et al*., 2000; Govaerts *et al*., 2006; Medina-Méndez *et al*., 2006; Prieto-Méndez *et al*., 2013; Hernández-González *et al*., 2018; Castillo-Valdez *et al*., 2021; Fonteyne *et al*., 2021) (Figure 4). These indicators are related to very important soil ecosystem services and ecological functions, as suggested by Bünemann *et al*. (2018).

Figure 4. Soil physical indicators frequently studied in Mexico. Dap= bulk density; EA= aggregate stability; I= infiltration; CC= field capacity; PMP= permanent wilting point; CRH= moisture retention curve; P= porosity; R= penetration resistance; E= structure, HA= usable moisture; HG= gravimetric moisture; TA= aggregate size; EH= thickness of horizons; and DP= pore diameter.



To measure the bulk density, the cylinder method is reported, for the texture the Bouyoucos hydrometer, aggregate stability through wet and dry sieving, infiltration by double cylinder, field capacity with a pressure pot, permanent wilting point with a pressure membrane, moisture retention curve at 33, 50, 150, 500, 1 000 and 1 500 kPa, total porosity using the bulk density and actual density value of 2.65 Mg m^{-3}, penetration resistance with the help of a dynamic penetrometer, usable moisture as the difference between field capacity and permanent wilting point and gravimetric moisture by weighing a sample of wet soil, drying it at 105 °C for 24 h to obtain the weight of dry soil.

With regard to the methods used for determining the physical indicators of the soil in order to assess its quality, it should be noted that indicators that limit root growth, seedling emergence, infiltration or movement of water within the soil profile should be considered and should be measured rather than derived. To integrate an MDS, texture (% sands, % silt and % clays), bulk density, aggregate stability, infiltration, penetration resistance, moisture retention curve and soil depth could be considered (Bünemann *et al*., 2018).

Chemical indicators

Soil organic carbon or organic matter is the soil property most commonly used as a chemical indicator (Sustaita-Rivera *et al*., 2000; Armida-Alcudia *et al*., 2005; Medina-Méndez *et al*., 2006; Bugarín *et al*., 2010; Uribe-Hernández *et al*., 2010; Prieto-Méndez *et al*., 2011; Alejo-Santiago *et al*., 2012; Murray *et al*., 2014; Zavala-Cruz *et al*., 2014; Cruz-Ruiz *et al*., 2015; Fernández-Ojeda *et al*., 2016; Estrada-Herrera *et al*., 2017; Hernández-Ordoñez *et al*., 2017; Muñoz-Iniestra *et al*., 2017; Rangel-Peraza *et al*., 2017; Cantú-Silva *et al*., 2018; Hernández-González *et al*., 2018; Santiago-Mejía *et al*., 2018; de la Cruz-Elizondo and Fontalvo Buelvas, 2019; López-Báez *et*

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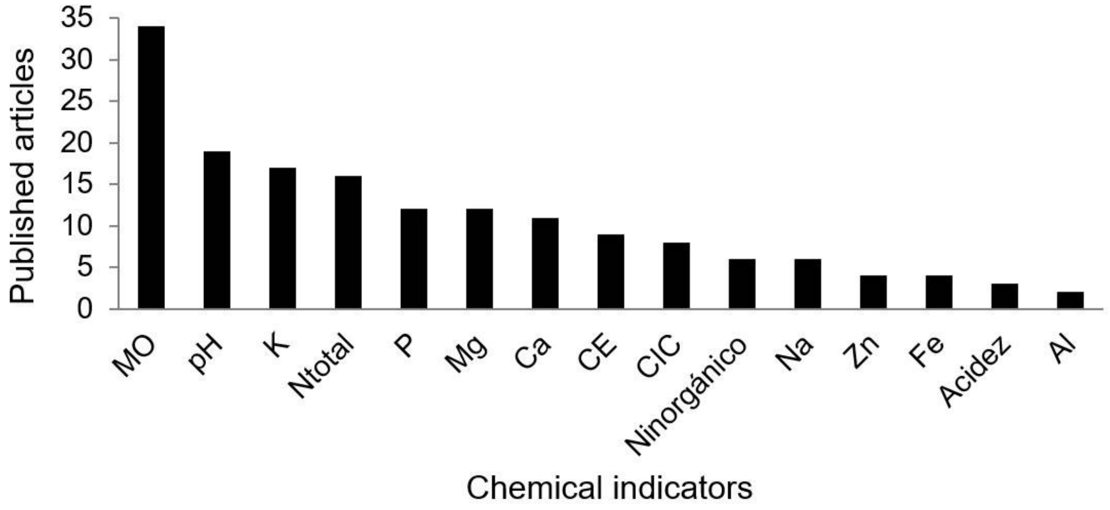
al., 2019; Acevedo-Gómez *et al*., 2020; Castillo-Valdez *et al*., 2021; Duché-García *et al*., 2021; Fonteyne *et al*., 2021; Martínez-Rodríguez *et al*., 2021; Peña-Morales *et al*., 2021).

It is followed by pH (Bugarín *et al*., 2010; Uribe-Hernández *et al*., 2010; Prieto-Méndez *et al*., 2011; Bautista-Cruz *et al*., 2012; Alejo-Santiago *et al*., 2012; Fernández-Ojeda *et al*., 2016; Estrada-Herrera *et al*., 2017; Muñoz-Iniestra *et al*., 2017; Rangel-Peraza *et al*., 2017; Yáñez-Díaz *et al*., 2018; de la Cruz-Elizondo and Fontalvo Buelvas, 2019; López-Báez *et al*., 2019; Acevedo-Gómez *et al*., 2020; Álvarez-Arteaga *et al*., 2020; Cruz-Flores *et al*., 2020; Castillo-Valdez *et al*., 2021; Fonteyne *et al*., 2021; Martínez-Rodríguez *et al*., 2021; Peña-Morales *et al*., 2021).

Interchangeable potassium (Govaerts *et al*., 2006; Prieto-Méndez *et al*., 2011; Alejo-Santiago *et al*., 2012; Zavala-Cruz *et al*., 2014; Palma-López *et al*., 2015; Fernández-Ojeda *et al*., 2016; Estrada-Herrera *et al*., 2017; Santiago-Mejía *et al*., 2018; López-Báez *et al*., 2019; Acevedo-Gómez *et al*., 2020; Álvarez-Arteaga *et al*., 2020; Cruz-Flores *et al*., 2020; Chavarin-Pineda *et al*., 2021; Duché-García *et al*., 2021; Fonteyne *et al*., 2021; Martínez-Rodríguez *et al*., 2021; Trejo *et al*., 2021), Kjeldahl nitrogen (Govaerts *et al*., 2006; Campos-Cascaredo *et al*., 2007; Pajares-Moreno *et al*., 2010, 2011; Prieto-Méndez *et al*., 2011; Cruz-Ruiz *et al*., 2015; Palma-López *et al*., 2015; Fernández-Ojeda *et al*., 2016; Hernández-Ordoñez *et al*., 2017; Muñoz-Iniestra *et al*., 2017; Hernández-González *et al*., 2018; Santiago-Mejía *et al*., 2018; Acevedo-Gómez *et al*., 2020; Álvarez-Arteaga *et al*., 2020; Chavarin-Pineda *et al*., 2021; Duché-García *et al*., 2021) and phosphorus (Alejo-Santiago *et al*., 2012; Bautista-Cruz *et al*., 2012; Palma-López *et al*., 2015; Fernández-Ojeda *et al*., 2016; Estrada-Herrera *et al*., 2017; Hernández-Ordoñez *et al*., 2017; López-Báez *et al*., 2019; Acevedo-Gómez *et al*., 2020; Álvarez-Arteaga *et al*., 2020; Castillo-Valdez *et al*., 2021; Martínez-Rodríguez *et al*., 2021; Trejo *et al*., 2021) (Figure 5).

Figure 5. Soil chemical indicators frequently studied in Mexico. MO= organic matter (organic carbon); pH= potential hydrogen; K= potassium, Ntotal= total nitrogen; P= phosphorus; Mg= magnesium; Ca= calcium; CE= electrical conductivity; CIC= cation exchange capacity; Ninorgánico= inorganic nitrogen; Na= sodium; Zn= zinc; Fe= iron; Al= aluminum.



To determine the organic carbon content, the articles report the Walkley-Black method and the organic matter content by multiplying the organic carbon by some factor: 1.724 or 2. The pH was determined in a suspension of soil:water: 1:1, 1:2 or 1:2.5, also using calcium chloride ($CaCl_2$) or potassium chloride (KCl) with the help of a potentiometer. K, Ca and Mg were determined in most articles using an extractor solution of ammonium acetate (1 N pH = 7). The total nitrogen was determined by the Kjeldahl or micro-Kjeldahl digestion procedure. For usable phosphorus, the procedures by Bray & Kurtz, Olsen and citric acid are reported.

Chemical indicators should describe soil-plant interactions, availability and mobility of nutrients, water for plants and other organisms. An MDS would be considering organic matter, pH, nitrogen, phosphorus and exchangeable bases (Bünemann *et al*., 2018).

Biological indicators

The biological properties that are most frequently used as indicators of soil quality were microbial biomass carbon (Armida-Alcudia *et al*., 2005; Campos-Cascaredo *et al*., 2007; Pajares-Moreno *et al*., 2010; Estrada-Herrera *et al*., 2017; Cruz-Flores *et al*., 2020); respiration (Pajares-Moreno *et al*., 2010; Rodríguez-Serrano *et al*., 2016; de la Cruz-Elizondo and Fontalvo-Buelvas, 2019; Bedolla-Rivera *et al*., 2020); earthworms (Huerta *et al*., 2009; de la Cruz-Elizondo and Fontalvo-Buelvas, 2019; Castillo-Valdez *et al*., 2021; Peña-Morales *et al*., 2021); enzymes involved in intracellular metabolism, nitrogen, carbon and phosphorus (Pajares-Moreno *et al*., 2010, 2011; Cruz-Ruiz *et al*., 2015; Cruz-Flores *et al*., 2020); soil mesofauna and macrofauna (Uribe-Hernández *et al*., 2010; Rodríguez-Serrano *et al*., 2016; Murillo-Cuevas *et al*., 2019) and arbuscular mycorrhizal fungi, bacteria and actinomycetes (Murillo-Cuevas *et al*., 2019; Cruz-Flores *et al*., 2020; Duché-García *et al*., 2021; Trejo *et al*., 2021).

To determine the microbial biomass carbon, fumigation-incubation methods are reported in the reviewed articles; for soil respiration, the closed chamber method is reported; for earthworms, the method of extraction of soil monoliths of dimensions of 25 cm x 25 cm x 30 cm depth is mentioned; enzymes through various methodologies, as described by Pajares-Moreno *et al*. (2010); mesofauna and macrofauna by the Berlese funnel, this methodology is described in detail in Rodríguez-Serrano *et al*. (2016) and the quantification of fungi, bacteria and actinomycetes in different culture media, as described in Murillo-Cuevas *et al*. (2019); Duché-García *et al*. (2021). An MDS would be considering microbial biomass carbon, soil respiration, earthworm density, enzymes: dehydrogenase, #-glucosidase, urease and phosphatase, and arbuscular mycorrhizal fungi (Bünemann *et al*., 2018).

Indices used

Most of the articles reviewed use a set of physical, chemical or biological properties as quality indicators, using the value or content of said property, comparing it with previously established or reported intervals, as described in Yáñez-Díaz *et al*. (2018) and Martínez-Rodríguez *et al*. (2021). Other authors (Prieto-Méndez *et al*., 2013; Estrada-Herrera *et al*., 2017; Muñoz-Iniestra *et al*., 2017; Hernández-González *et al*., 2018; Duché-García *et al*., 2021) employ equations to normalize the values of soil properties used as indicators.

$$V_I=\frac{I_m-I_{min}}{I_{max}-I_{min}} \quad 1)$$

$$V_I=1-\frac{I_m-I_{min}}{I_{max}-I_{min}} \quad 2)$$

Where: V_I: normalized value of the indicator (linear); I_m= experimental value of the soil property considered as an indicator; I_{min}= minimum value of the soil property considered as an indicator; I_{max}= maximum value of the soil property considered as an indicator.

Equation (1) is applied to those quality indicators where high values are desirable (e.g., organic carbon) and equation (2) to those where low values are suitable (e.g., bulk density). PCA is reported by several authors as useful in defining SQi (Govaerts *et al*., 2006; Campos-Cascaredo *et al*., 2007; Bautista-Cruz *et al*., 2012; Rangel-Peraza *et al*., 2017; Cruz-Flores *et al*., 2020; Bedolla-Rivera *et al*., 2020; Castillo-Valdez *et al*., 2021; Chavarin-Pineda *et al*., 2021; Duché-García *et al*., 2021; Fonteyne *et al*., 2021; Martínez-Rodríguez *et al*., 2021).

For the formation of an MDS through quality indicators, the principal components that explain at least a significant part of the variability (80%) with an eigenvalue >1 are chosen. The indicators with the highest weights have the greatest influence on soil quality within each principal component, for this case only indicators within the range of 10% are considered: SQI_c-0.1*SQI_c. Where: SQI_c= weight of the soil quality indicator with the highest weight within the principal component.

When more than one quality indicator is retained in the different principal components with the above rule, a redundancy analysis is performed using a Pearson correlation. If there is a significant correlation, the indicator with more weight is retained, otherwise both indicators are retained. After normalizing the retained quality indicators through any of equations 1-9, the SQi are generated through equations 10 and 11 (Bedolla-Rivera *et al*., 2020; Martínez-Rodríguez *et al*., 2021):

$$V_l=\frac{I_m}{I_{max}} \quad 3); \qquad V_{nl}=\frac{1}{\left\{1+\left(\frac{I_m}{\bar{I}}\right)^{-2.5}\right\}} \quad 4); \qquad f(x)_l=\begin{cases} 0.1, & x\leq L \\ 0.1+0.9\times\frac{x-L}{U-L}, & L\leq x\leq U \\ 1, & x\geq U \end{cases} \quad 5)$$

$$V_l=\frac{I_{min}}{I_m} \quad 6); \qquad V_{nl}=\frac{1}{\left\{1+\left(\frac{I_m}{\bar{I}}\right)^{2.5}\right\}} \quad 7); \qquad f(x)_l=\begin{cases} 1, & x\leq L \\ 1-0.9\times\frac{x-L}{U-L}, & L\leq x\leq U \\ 0.1, & x\geq U \end{cases} \quad 8)$$

$$f(x)=\begin{cases} 0.1, & x<L,\ \ x>U \\ 0.1+0.9\times\frac{x-L}{U-L}, & L\leq x<L_1 \\ 1-0.9\times\frac{x-L}{U-L}, & U_1\leq x<U \\ 1, & L_1\leq x<U_1 \end{cases} \quad 9)$$

Where: V_{nl}, f(x)$_l$= normalized value of the indicator (nonlinear and linear, respectively); equations 3-5= a higher value of the indicator is better; equations 6-8= a lower value of the indicator is better; equation 9= optimal value; #: average value of the indicator in the study area; L= lower threshold; U= upper threshold; L_1 and U_1= value of the indicator for a lower and upper baseline.

$$íCS_A=\sum_{i=1}^{n} S_i/n \quad 10)$$

$$íCS_{PA}=\sum_{i=1}^{n} W_i\times S_i \quad 11)$$

Where: SQi_A; SQi_{AW}= soil quality index (additive and additive weighted, respectively); S_i= normalized soil quality indicator; n= number of soil quality indicators in the MDS; W_i= weighting obtained by dividing the percentage of variance explained by the principal component by the percentage of variance accumulated by the retained principal components.

From the situation described above, it follows the need for greater efforts to generate knowledge about soil quality since information is scarce and the existing one is concentrated only in some regions of the country for some groups of soils. To address this situation in Mexico, it is necessary to develop indicators and indices of soil quality and health based on physical, chemical, biological properties based on technical and scientific information in the short (2022-2024), medium (2025-2030) and long term (beyond 2030).

Conclusions

Greater attention should be paid to the study of soil quality indicators and indices in Mexico. This attention should be focused at the state or regional level or on soil groups where information is not available. The following is proposed: texture, bulk density, aggregate stability, infiltration, penetration resistance, moisture retention curve and soil depth as physical indicators; organic matter, pH, total nitrogen, inorganic nitrogen, phosphorus, potassium, calcium and magnesium as chemical indicators; and microbial biomass carbon, soil respiration, earthworm density, dehydrogenase, #-glucosidase, urease, phosphatase and arbuscular mycorrhizal fungi as biological indicators.

From the set of physical, chemical and biological indicators, a subset of these should be chosen or reduced to a minimum data set to form a soil quality index.

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