Article

Updating the soil mapping of the State of Mexico: a planning tool

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Abstract

The soil is a very important natural body for the development of crops and plant species, because it provides support to the roots of plants, it also provides nutrients for their development and production, depending on the type of soil and its properties. Knowing and quantifying soils is necessary to plan agricultural, livestock, forestry, urban, mining and conservation activities. The objectives of this work were: 1) to update the 1:50 000 soil mapping per municipality in the State of Mexico; and 2) quantify the surface of the soils and know their location to identify areas of productive reconversion. The cartography was generated with the digitization of the 1:50 000 scale soil charts, with a geographic information system (GIS), its database was generated: primary soils, secondary soils, physical phase, chemical phase and texture; this database was updated to the 2015 WRB soils version. The soils with the largest and most productive areas are: Andosols with 479 908 ha, Pheozems with 472 718 ha, Vertisols with 241 485 ha and Cambisols with 196 047 ha. These predominate in the municipalities of Aculco, Toluca, Acambay, Jilotepec, Axapusco, Ixtlahuaca and Almoloya de Juárez.

Keywords: digital cartography, municipality, soils, update.

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Introduction

The word 'soil' has several meanings and is derived from the Latin word *solum* which means soil. In its traditional meaning, soil is the natural environment for the development of terrestrial plants, whether or not it has discernible horizons (Soil Survey Staff, 2014; IUSS Working Group WRB, 2015).

Soils, naturally, have five main functions: 1) to support the growth of higher plants, mainly by providing a medium for the roots and supply of nutrients that are essential for all plants; 2) control the fate of water in the hydrological system; 3) as a recycling system; 4) provide a habitat for countless living organisms such as small mammals, reptiles, tiny insects, and a diversity of microscopic cells; and 5) the soil plays an important role as an engineering environment (Brady and Weil, 1999; Porta *et al*., 2003; Soil Survey Staff, 2014).

The modern and most widely used soil taxonomic systems are soil taxonomy (TS) and the world reference base of soil resources (WRB), which classify soils using diagnostic horizons, properties and materials (Bockheim and Gennadiyev, 2000; Spaargaren, 2000; Wilding, 2000; IUSS Working Group WRB, 2007; Soil Survey Staff, 2014; IUSS Working Group WRB, 2015).

The TS consists of six categories: order, suborder, large group, subgroup, family, and series. The first version was published in 1960, which consisted of 10 orders. The 1999 version is modified and consists of 12 orders, which include Andosols and Gelisols, which are preserved until the 2014 version (Soil Survey Staff, 1960; Soil Survey Staff, 1998; Soil Survey Staff, 2014). The WRB classification consists of two categories: unit and subunit. This began its publication in 1970 with 26 units and 104 subunits, the 1988 version with 28 units and 153 subunits, the 1998 version with 30 units and 533 subunits, the 2006 and 2015 version consist of 32 units and the subunits can be all possible combinations (FAO-UNESCO, 1970; FAO, 1988; FAO-ISRIC y SICS, 1998; IUSS Working Group WRB, 2006; IUSS Working Group WRB, 2015).

Soil studies emerged in the United States of America in the early 1820s and are based on the Russian school, where they start from a concept and a geological basis, which over time changes to a pedological concept of soils (Brevik and Hartemink, 2013). The researchers who conducted studies and mapped the soils had a geologically based formation (Brevik, 2009; Brevik, 2010), therefore these early maps were essentially maps of surface geology (Brevik and Hartemink, 2010).

Digital mapping has many advantages to improve, automate and update soil studies, such as: a) consistent mapping; b) rapid update of soil surveys; c) cost and time reduction; d) continuity of knowledge; and e) digital products (Zhu *et al*., 2001; McBratney *et al*., 2003; Hengl and Rossieter, 2003; Behrens and Scholten, 2006; Kozlova and Konyushkova, 2009).

Currently, studies to generate soil mapping are based on predictions and property-based modeling. This is due to the time-consuming and expensive application of soil survey methodologies for the preparation of Edaphological cartography. Among these studies, those by Behrens *et al*. (2010a; 2010b) who propose to generate soil maps based on the elevation of the terrain. Brevik and Hartemink (2013) mention that the soil maps generated with soil studies are important, because they provide valuable information about the maps and the time when they were prepared.

Rosas *et al*. (2015) conclude that the use of more environmental variables results in an increase in the accuracy of soil map prediction models. For their part, Jafari *et al*. (2014) apply prediction models for the digital mapping of large soil groups. Finally, Shi *et al*. (2009) mention that the knowledge of soils derived from studies carried out by soil science scientists is a guide for the development and planning of agricultural activities, they conclude that digital soil mapping is important for the generation and cartography of soil maps.

In the case of Mexico, Ortiz *et al*. (1994) make an adaptation of the 1988, FAO version to the soils of Mexico, where they make changes to the units that disappear from the country's soil maps (FAO, 1988). In addition, SEMARNAP (1996) established the foundations and adaptations of the soil units. For its part, the National Institute of Geography and Information Statistics (INEGI) carried out soil studies at the national level at three scales: 1:1 million covering 100% of the country, 1:250 000 covering 75% of the country and 1:50 000 covers 35% of the national territory (INEGI, 1974; 1988a; 1988b).

The State of Mexico is covered by the 1:50 000 Edaphological cartography, hence the need to generate an updated database arises. The sectors involved in planning demand updated digital information, by municipality, information that is the basis for the planning and ordering of urban, agricultural, livestock, forestry, mining and fishing activities (INEGI, 2015). Due to the relevance and demand of this information, in the present investigation, the following objectives were proposed: 1) update the soil mapping 1:50 000 per municipality of the State of Mexico; and 2) quantify the surface of the soils and know their location to identify the areas of productive reconversion.

Materials and methods

Location of area of study

The State of Mexico is located from 18° 22' 14" to 20° 17' 22" north latitude and from 98° 35' 35" to 100° 36' 19" west longitude and has a surface area of 2 324 422 ha. It borders with the states of Hidalgo and Querétaro to the North, Puebla and Tlaxcala to the East, Morelos and Guerrero to the South and Michoacán to the West (INEGI, 2015). The climates that occur in the state are: temperate, semi-cold, warm, semi-warm and cold. The annual mean temperature fluctuates from 6 to 28 °C, the annual precipitation ranges from 600 to 1 800 mm, the height above sea level ranges from 340 to 5 100 m (INEGI, 1999; García, 2004). The dominant soils are: Andosol, Pheozem, Vertisol, Regosol and Arenosol (Sotelo *et al*., 2010). The State of Mexico is made up of 125 municipalities (Figure 1), for which soils were described (INEGI, 2015).

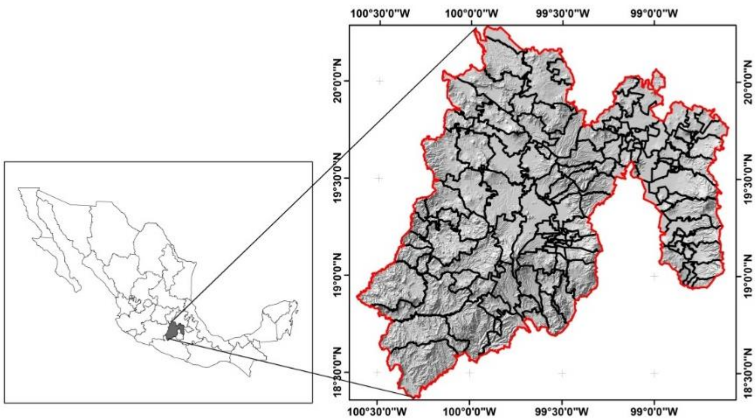

Figure 1. Location of the State of Mexico and municipalities that comprise it.

Methodology

The Edaphological information from INEGI, scale 1:50 000 (INEGI, 1974) was used. 43 letters covering the State were digitized with Arcinfo version 6.0 (ESRI, 1992). The delimitations of polygons and databases generated were: primary soils, secondary soils, physical phase, texture, chemical phase and soil depth. Field trips were carried out to verify and update the Soil Units, through drillings and description of soil profiles, in the groups that had doubts regarding the type of soil present; the profiles were geographically located and sampled (FAO, 2009). The soil samples were sent to the laboratory to perform the analyzes that the WRB uses to classify soils; these data were the basis for classifying and updating the soils. The classification was carried out with the WRB 2015 (IUSS Working Group WRB, 2015). The updating of the soils, its database and the generation of the maps by municipality was carried out with ArcGIS version 9.3 (ESRI, 2010).

Results and discussion

The State of Mexico has 11 soil units, which are: Andosol, Pheozem, Regosol, Vertisol, Cambisol, Leptosol, Luvisol, Acrisol, Solonchak, Fluvisol and Gleysol (Sotelo *et al*., 2011. In this work, the classification of the Planosols and Histosols corresponded to Vertisols and Pheozem respectively. The most productive soils in the state are: Pheozems, Vertisols and Cambisols, due to the physical and chemical properties that present, as average texture, organic matter> 3%, slope less than 10% and without physical phases in most cases Its surface is presented by municipalities and the state distribution is described (Figure 2 and Table 1).

Pheozems distribution

The State of Mexico has 472 718 ha and represents 20.34% of the state surface. Pheozems have potential for most crops and plant species, although climatic conditions limit their adaptation and development. They have potential for species such as corn, wheat, beans, potatoes, carrots, barley, oats, triticale, peas, broad beans, avocados, peaches, plums, raspberries, alfalfa and grasslands

(SIAP, 2019). The municipalities with the largest area are: Aculco, Toluca, Axapusco, Acambay and Jilotepec. Due to the surface area of these soils, it can be said that these municipalities have the greatest productive potential for species that adapt to their climatic conditions (Table 1).

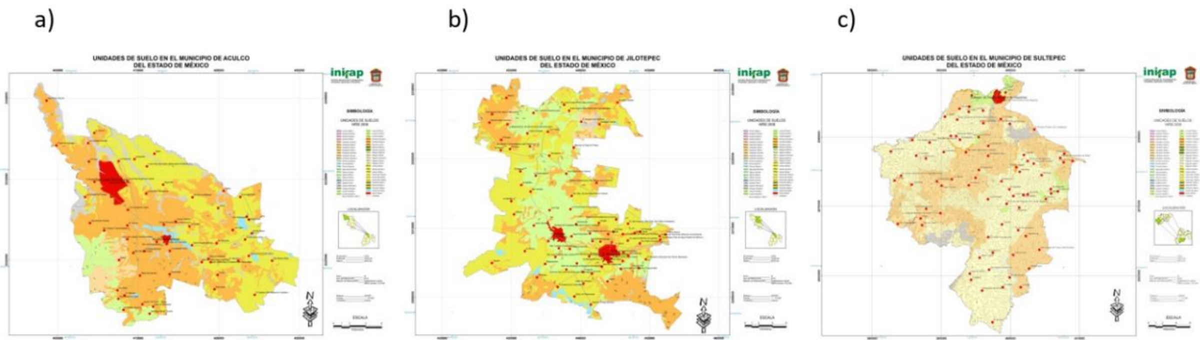

Figure 2. Municipalities with the largest area of Pheozem in a) Aculco, Vertisol; in b) Jilotepec; and Cambisol in c) Sultepec.

Table 1. Municipalities with the largest area of Pheozem, Vertisol and Cambisol.

Municipality	Pheozem (ha)	Municipality	Vertisol (ha)	Municipality	Cambisol (ha)
Aculco	21 654	Jilotepec	23 808	Sultepec	21 446
Toluca	21 475	Almoloya de Juárez	22 587	Zacualpan	15 889
Axapusco	20 250	Ixtlahuaca	20 428	Texcoco	15 123
Acambay	18 856	Aculco	15 294	Temascaltepec	14 276
Jilotepec	15 928	Acambay	14 718	San Simón de Guerrero	8 964
Hueypoxtla	15 465	Jocotitlan	13 476	Amatepec	8 803
Zumpango	14 773	San Felipe del Progreso	13 467	Ixtapaluca	8 517
Chapa de Mota	14 613	Temascalcingo	10 527	Almoloya de Alquisiras	6 908
Atlacomulco	12 831	Polotitlán	10 316	Tejupilco	6 540
Almoloya de Juarez	12 509	Jiquipilco	9 686	Texcaltitlán	6 155
Luvianos	11 713	Tepotzotlán	8 417	Otzoloapan	5 961
Temascalcingo	11 370	Atlacomulco	8 227	Otumba	5 094

Vertisols distribution

The state has 241 485 ha and represents 10.39% of the state's surface. They are located in the central and northern part of the state. They have potential for species such as corn, wheat, beans, triticale, barley, oats, peas, broad beans, alfalfa and grasslands (SIAP, 2019). The municipalities with the largest area are: Jilotepec, Almoloya de Juárez, Ixtlahuaca, Aculco, Acambay and Jocotitlán. These soils are very productive at the state level, although they need irrigation to exploit their full productive potential (Table 1).

Cambisols distribution

The state has 196 047 ha and covers 8.43% of the state surface. They are fertile soils with very good productive potential for plant species that adapt to the climatic conditions of the municipalities, mainly for species such as corn, wheat, beans, potatoes, carrots, barley, oats, peas, broad beans, avocado, peaches, plums, raspberry, alfalfa and grasslands (SIAP, 2019). The municipalities with the largest area are: Sultepec, Zacualpan, Texcoco, Temascaltepec and San Simón de Guerrero (Table 1).

Andosols, Regosols and Luvisols are the next in importance and surface area. They are less fertile, high Al content, medium to coarse textures, slopes >12%, organic matter <2% and acidic pH in the three soils (Figure 3 and Table 2).

a) b) c)

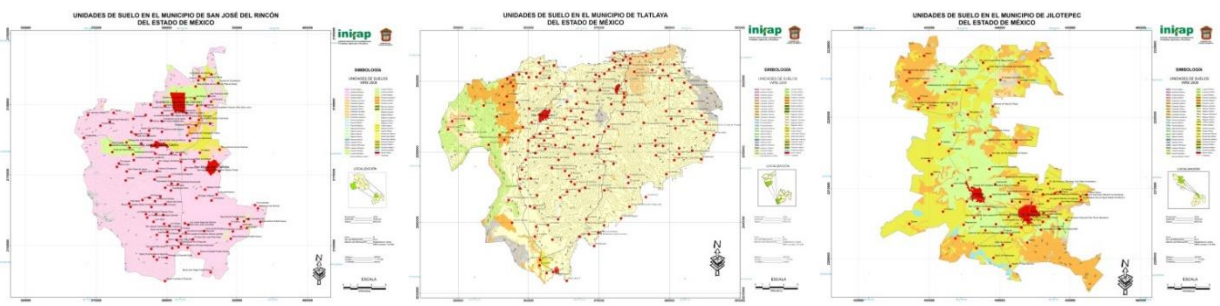

Figure 3. Municipalities with the largest Andosol area in a) San José del Rincón, Regosol; in b) Tlatlaya and Luvisol; and in c) Jilotepec.

Table 2. Municipalities with the largest surface area of Andosol, Regosol and Luvisol.

Municipality	Andosol (ha)	Municipality	Regosol (ha)	Municipality	Luvisol (ha)
San José del Rincón	43 244	Tlatlaya	60 889	Jilotepec	15 853
Villa de Allende	29 083	Tejupilco	42 253	Nicolas Romero	11 309
Ocuilan	21 974	Amatepec	41 099	Villa del Carbón	10 679
Amanalco	21 616	Sultepec	30 825	Acambay	9 876
Temascaltepec	21 314	Luvianos	29 716	Almoloya de Alquisiras	6 334
Valle de Bravo	19 885	Juchitepec	7 396	Tlatlaya	6 157
Zinacantepec	18 867	Atlautla	6 362	Morelos	6 056
Villa Victoria	18 031	Amecameca	5 907	San Felipe del Progreso	5 818
Donato Guerra	15 832	Zacualpan	5 643	Coatepec Harinas	5 753
Tenango del Valle	13 668	Ixtapaluca	2 728	Jiquipilco	5 565
Coatepec Harinas	13 108	Tepetlaoxtoc	2 679	Chapa de Mota	5 181
Tianguistenco	12 610	Ayapango	2 519	Otzoloapan	3 799

Andosols distribution

The State of Mexico has 479 908 ha, covers the largest area and represents 20.65% of the state. They are located in the mountainous parts of the Neovolcanic Axis, Sierra Madre del Sur and in the northern mountains of the state. They are soils of forestry and agricultural vocation. The species that have productive potential in these soils are corn, peas, potatoes, broad beans, carrots, avocados, peaches, plums and raspberries (SIAP, 2019). The municipalities with the largest area are: San José del Rincón, Villa de Allende, Ocuilan, Amanalco, Temascaltepec and Valle de Bravo (Table 2).

Regosols distribution

The state has 265 683 ha and represents 11.43% of the state surface. They have potential for species such as corn, wheat, beans, potatoes, barley, oats, peas, broad beans, avocados, peaches, plums, raspberries, and mangoes (SIAP, 2019). The municipalities with the largest surface area are: Tlatlaya, Tejupilco, Amatepec, Sultepec and Luvianos. These have the largest surface area in the southern part of the State of Mexico, where the predominant climate is tropical (Table 2).

Luvisols distribution

The State of Mexico has 146 905 ha and covers 6.32% of the state surface. They have forestry potential and for fruit trees such as peach, guava, coffee and avocado (SIAP, 2019). The municipalities with the largest area are: Jilotepec, Nicolas Romero, Villa del Carbon, Acambay and Almoloya de Alquisiras (Table 2).

Acrisols, Fluvisols and Leptosols are not very productive, with a forestry vocation, for the production of vegetables and for mining activities. Fluvisols are poorly developed and flat soils; Acrisols are mountain soils with medium texture and acid pH, Leptosols are thin soils 5 to 20 cm, slope> 20 and <2% organic matter, their vocation is mining and forestry (Table 3 and Figure 4).

Table 3. Municipalities with the largest surface area of Acrisol, Fluvisol and Leptosol.

Municipality	Acrisol (ha)	Municipality	Fluvisol (ha)	Municipality	Leptosol (ha)
Luvianos	11 597	Chalco	7 362	Zumpahuacan	14 094
Valle de Bravo	10 108	Amecameca	5 804	Luvianos	11 797
Villa Victoria	4 385	Ixtlahuaca	4 972	Malinalco	9 669
Temascaltepec	3 992	Tlalmanalco	1 021	Tepetlaoxtoc	7 623
Ixtapan del Oro	3 931	Temamatla	938	Tejupilco	7 552
Tejupilco	3 671	Cocotitlán	892	Santo Tomás	5 762
Malinalco	1 757	Jocotitlan	719	Otumba	4 753
Donato Guerra	1 704	Atlautla	530	Ocuilan	4 432
El Oro	1 481	Tenango del Valle	472	Tonatico	3 978
Villa de Allende	1 318	Luvianos	429	Amatepec	3 887
San Simon de Guerrero	704	Zacualpan	330	Tlalnepantla de Baz	3 868
Ocuilan	609	Morelos	315	Temascalcingo	3 823

a) b) c)

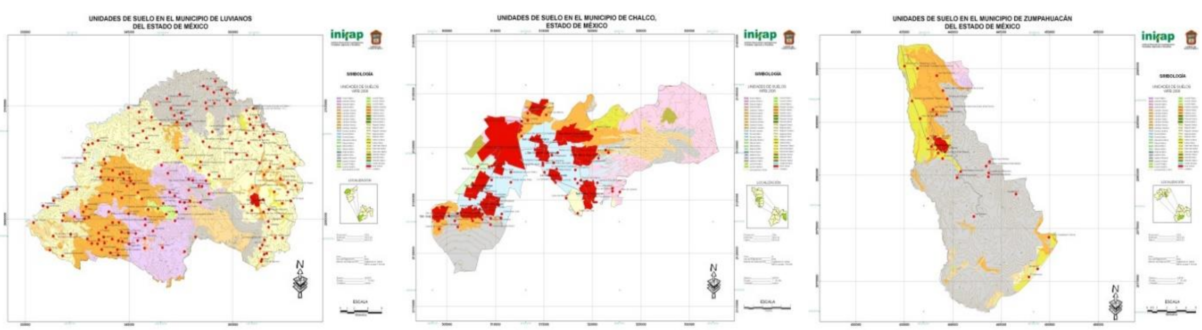

Figure 4. Municipalities with the largest Acrisol surface in a) Luvianos, Fluvisol; in b) Chalco and Leptosol; and in c) Zumpahuacan.

Acrisols distribution

The State of Mexico has 46 968 ha and covers 2.02% of the state surface. Acrisols are young, mountain soils and low fertility, if proper fertilization and conservation management is carried out, some species such as avocado, guava, coffee and peach can be planted (SIAP, 2019). The municipalities with the largest Acrisols area are: Luvianos, Valle de Bravo, Villa Victoria, Temascaltepec and Ixtapan del Oro (Table 3).

Fluvisols distribution

The state has 25 216 ha and represents 1.08% of the state. They have high natural fertility, because they have medium texture, they are deep, organic matter content is medium, flat and the crops that adapt to the present climatic conditions are developed; they are located on the banks of rivers, lakes and lagoons. The municipalities with the largest area are: Chalco, Amecameca, Ixtlahuaca, Tlalmanalco and Temamatla (Table 3).

Leptosols distribution

The state has 174 968 ha and covers 7.53% of the state’s surface. The potential of Leptosols is forestry, livestock, recreational and mining; the Rendzico and Umbric subunits have potential for crops such as corn, beans, wheat, barley, oats and rice in the state (SIAP, 2019). The municipalities with the largest surface area are: Zumpahuacan, Luvianos, Malinalco, Tepetlaoxtoc and Tejupilco. In these soils, a quarry is exploited and other minerals that the mining industry demands are extracted (Table 3).

The least productive soils that occur in the state are Solonchaks and Gleysols, due to their high salinity, sodicity, thick textures and irregular slopes, they are soils with little surface and very localized, where only salty grass grows in the case of the former (Table 4 and Figure 5).

Table 4. Municipalities with the largest area of Solonchak and Gleysol.

Municipality	Solonchak (ha)	Municipality	Gleysol (ha)
Texcoco	7 069	Valle de Chalco Solidaridad	1 345
Nezahualcoyotl	5 937	Chalco	542
Ecatepec de Morelos	5 685	Temascalcingo	212
Atenco	5 126	El Oro	182
Tecamac	2 878	Chapa de Mota	166
Chimalhuacan	2 585	Teoloyucan	95
Valle de Chalco Solidaridad	2 554	Zumpango	84
Zumpango	1 856	Jilotepec	57
Nextlalpan	1 679		
Tultitlan	773		
La paz	753		
Tezoyuca	445		

a) b)

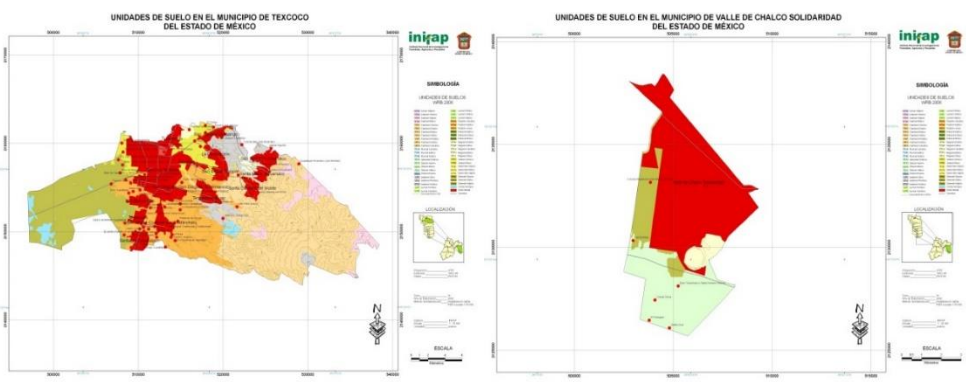

Figure 5. Municipalities with the largest area of Solonchak in a) Texcoco and Gleysol; and in b) Valle de Chalco Solidaridad.

Solonchaks distribution

The State of Mexico is covered by 39 290 ha and represents 1.69% of the state surface. These soils present characteristics of high salinity, electrical conductivity and pH, which is why it is very difficult to grow crops; the potential is for salty grass and for salt exploitation in areas where salinity is very high. The municipalities with these soils are: Texcoco, Nezahualcóyotl, Ecatepec de Morelos and Atenco (Table 4).

Gleysol distribution

The surface in the State of Mexico is 2 765 ha and it only represents 0.12% of the state's soils. They have a low natural fertility and their vocation is forestry; only a few species can be sown with proper fertilization management. The main municipalities with Gleysols are: Valle de Chalco Solidaridad, Chalco, Temascalcingo and El Oro (Table 4).

Soil information is necessary, because the data is crucial in land use planning, management, environmental studies, erosion studies, conservation and modeling studies, which simulate crop growth and estimate yield in advance (Nachtergaele *et al*., 2000; Adhikari *et al*., 2014; Jafari *et al*., 2014). There are very few soil studies and the scales of representation are between 5 and 25 million. FAO has soil studies at the continental level with scales of 1:25 million, 1:15 million and 1:5 million (FAO, 1993; FAO, 1996; FAO, 2008).

Soil surveys in the United States of America are scale 1:7.5 to 1:15 million (Soil Survey Staff, 1998). In this sense, Brevik and Hartemink (2013) use taxonomy and determine that the dominant soils in the USA are: Molisol, Alfisol, Entisol, Inceptisol, Aridisol, Ultisol and Vertisol; furthermore, Lytle (2000); USDA (2000); VanEngelen (2000) conducted soil studies and designed a database (NASIS), which facilitated the acquisition, management and location of soils.

At the international level, studies similar to those of this research have been carried out, such as those of the International Center for Reference Information on Soils (CIIRS), where a database with the world's soil information was designed to publicize the studies of soils, which are carried out in different countries (ISRIC, 2000). For their part, Adhikari *et al*. (2014) elaborate a national soil map of Denmark, which was based on the FAO-UNESCO legend, using digital soil mapping techniques, with observations of soil profiles and environmental data. This information is the basis for the planning, management, conservation and evaluation of the country's environmental impact studies.

In the case of Mexico, there are the INEGI soil studies with the scales 1:1 000 000, 1:250 000 and 1:50 000 (INEGI, 1970; INEGI, 1974) in this regard, the INEGI does not have digital cartography of no scale; for this reason, the results of this work are very important, since they present the digital cartography scale 1:50 000, where the dominant soils are Andosol, Pheozem, Vertisol, Regosol and Cambisol. For its part, the Ministry of the Environment and Natural Resources (SEMARNAT) establishes the bases for conducting and updating soil studies in Mexico (SEMARNAT, 1999).

At the national level, 18 units are reported (INEGI, 1974), of which 11 occur throughout the State of Mexico, the dominant soils being: Andosol, Pheozem, Regosol, Vertisol and Cambisol, which are also the most productive. Sotelo *et al*. (2010); Sotelo *et al*. (2011) carried out the updating of the soils of the State of Mexico at a scale of 1:50 000, at the level of the Rural Development District (DDR), highlighting that the soil is one of the main natural resources, on which forests are sustained. and food production. In addition, they indicate that having up-to-date information on the type of soil and its distribution facilitates the planning and classification of agricultural activities. Brevik and Hartemink (2013) mention that in the United States of America soil maps began to be generated at the beginning of the twentieth century, as a need to know the management and conservation of this resource.

Due to the soils present in the municipalities of the State of Mexico, it is recommended that the crop or species to be established be selected, taking into account the climatic conditions and the purpose of production, whether it is for self-consumption or commercial. It is not recommended to establish urban areas in municipalities that have fertile soils and with little slope. There are types of soils that have a vocation for mining exploitation and urban development, such as Leptosols. Urban developments in municipalities must be implemented on these soils and prohibit the construction of subdivisions on soils with agricultural vocation such as: Pheozem, Cambisols, Vertisols and Andosols.

Finally, the information generated is a fundamental tool in the planning of agricultural activities in the municipalities of the State of Mexico, due to the detail of the information, which is at the municipality level. The municipalities of the State of Mexico, with this study, know the types of soils they have and the surface they cover, therefore, they know if the vocation of their soils is: agricultural, livestock, forestry, urban or mining and consequently they can implement better municipal development plans.

Conclusions

The soils with the largest surface area in the State of Mexico are: Andosol (20.65%), Pheozem (20.34%), Regosol (11.43%), Vertisol (10.39%), Cambisol (8.43%), Leptosol (7.53%), Luvisol (6.32%), Acrisol (2.02%), Solonchak (1.69%), Fluvisol (1.08%) and Gleysol (0.12%). The best soils for agriculture and food production worldwide due to their physical and chemical properties and that dominate in the State of Mexico are: Pheozems with 472 718 ha, Vertisols with 241 485, Cambisols with 196 047 and Andosols with 479 908 ha. The Pheozem are presented in Aculco, Toluca, Axapusco, Acambay and Jilotepec, while the Vertisols stand out in Jilotepec, Almoloya de Juárez, Ixtlahuaca, Aculco and Acambay.

Cambisols have a greater surface area in the municipalities of Sultepec, Zacualpan, Texcoco, Temascaltepec and San Simon de Guerrero, while Andosols stand out in San José del Rincón, Villa de Allende, Ocuilan, Amanalco and Temascaltepec. The municipalities of the State of Mexico that have excellent soils, for the production of annual crops and perennial fruit trees depending on the present climate, are Aculco, Toluca, Jilotepec, Almoloya de Juárez, Ixtlahuaca, Sultepec, Zacualpan, Texcoco, Villa de Allende and Temascaltepec.

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