Revista Mexicana de Ciencias Agrícolas
DOI: https://doi.org/10.29312/remexca.v14i5.3102

Article

Improvement of soil hydraulic properties in soybean cultivation through subsoiling

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Abstract

The preparation of the soil for soybean sowing in El Soconusco, Chiapas, is carried out intensively and under wet soil conditions, which causes the soil to compact and the 'plow floor' to be formed approximately 35 cm deep. 'The plow floor' reduces infiltration and its hydraulic conductivity at saturation. The rupture of the 'plow floor' by subsoiling increases infiltration and improves the hydraulic properties of the soil. Therefore, the objective of this work was to evaluate for three consecutive years (2017 to 2019) the infiltration in three soil management systems: subsoiling (SUB), fallowing (FAL) and harrowing (HAR). Soil samples were taken from 0-30 cm depth before applying the treatments to estimate their physical and hydraulic properties. Then, SUB, FAL and HAR were applied on an area of 1.5 ha, respectively. Each year the infiltration was measured three times by the double cylinder method for approximately 10 h. Rates of infiltration, accumulated infiltration and hydraulic conductivity at saturation were determined. The results confirmed higher rates of infiltration with subsoiling followed by harrowing, fallowing, respectively; likewise, the accumulated infiltration as the hydraulic conductivity at saturation showed the same behavior. The rupture of the 'plow floor' through subsoiling increased infiltration, hydraulic conductivity at saturation and yield components.

Keywords:

Soconusco, compaction, plow floor.

DOI: https://doi.org/10.29312/remexca.v14i5.3102

Introduction

In El Soconusco, Chiapas, for many years the preparation of the soil for soybean sowing has been intense and under wet soil conditions, this activity has included between one and seven passes of harrow before the 90s. Currently, these soils present varied levels of compaction that, as reported in the literature in this area (Van Ouwerkerk and Soane, 1994; Cabria and Culot, 1999; Alakukku *et al*., 2003; Ahmad *et al*., 2007), the repetitive passage of machinery compacts the soil, reduces the permeability and storage of moisture of the root profile of the crop (Comia *et al*., 1994; Van Wie *et al*., 2013).

Also, when the soil is loosened with the harrow, the sowing of soybeans follows, and if it immediately rains, a 'crust' forms which causes plugging of the surface and prevents the germination of the seed. When this happens, a second sowing is carried out and it generates more production costs. At the global level, soil compaction is interpreted as a form of physical degradation caused by the intensive use of agricultural machinery (Van Ouwerkerk and Soane, 1994; Kuiperd and van de Zande, 1994), this traffic produces a hard layer (plow floor) below the arable layer that reduces infiltration, hinders internal water movement, inhibits root growth and crop yields (Czarnes *et al*., 2000; Hagedorn and Bundt, 2002).

One way to increase infiltration is through subsoiling, the rupture of the 'plow floor' increases infiltration, internal movement of water, its redistribution, its storage capacity and root growth of the crop to explore greater volume of the rhizosphere (Lampurlanes *et al*., 2001; Sharma *et al*., 2004). Also, the rupture of the 'plow floor' leads to the structural improvement of the soil, since it allows the free exchange of flows towards the subsoil, increases gas exchange and reduces surface runoff (Bertolino *et al*., 2010).

In general, it is conceived that sustainability in agriculture is only possible through soil and water conservation. Under rainfed conditions, the care of water results in the sustainable improvement of production as long as its management is efficient. Hence the importance of knowing the content and dynamics of water in the soil for purposes of storage and conservation for crops, mainly for soybeans under rainfed conditions. The dynamics of water in the soil are affected by several factors that limit its use; among these, tillage systems under wet soil conditions and for prolonged periods (Alakukku *et al*., 2003).

During compaction, some physical characteristics of the soil such as reduction of porosity, it increases bulk density and limits the flow of water during its redistribution. Some studies on soil hydraulic variables recommend the development of theories, field measurements and the use of physico-mathematical models to understand the phenomenon of soil compression on its hydraulic properties (Horton *et al*., 1994).

Thus, the rupture of compaction improves the hydraulic properties of the soil, and for this reason, it is necessary to use physico-mathematical methods for the measurement and adjustment of this information that evidence the substantive improvement of this practice. Since infiltration is the only source of water entry and recharge in the soil, its knowledge leads to recommend subsoiling as a soil and water conservation measure, particularly for soybean cultivation under rainfed conditions (Klute and Dirksen, 1986; Cabria and Culot, 2000).

Repetitive tillage for soybean sowing in El Soconusco, Chiapas; revealed that these soils maintain medium to high compaction observable through soil profiles, which originated this research whose objective was to evaluate for three consecutive years the infiltration in three soil management systems and their hydraulic conductivity at saturation of a farm, in whose soil year after year soybeans are sown under the aforementioned conditions, as well as the improvement of crop yield.

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Materials and methods

Location of the study area

The experiment was located in the municipality of Tapachula, Chiapas; between coordinates 14° 45' north latitude and 92° 23' west longitude at an altitude of 16 m. The climate is warm subhumid, its average temperature was 28 ±1 °C and the average annual accumulated rainfall is 1 110 mm. The soil, based on its texture, is of the loamy type, the pH was 6.6 slightly acidic, and an organic matter content of 2.5%. The experimental period comprised three consecutive years and during the spring-summer (SS) production cycles 2017, 2018 and 2019.

Treatments and experimental design

The experiment consisted of three treatments of 1.5 ha (150 m long by 100 m wide) distributed as independent plots. Subsoiling (SUB) plus a pass of harrow and mechanized sowing, fallowing (FAL) plus one pass of harrow and mechanized sowing, and harrowing (HAR), two passes of harrow and mechanized sowing. Annually the preparation of the soil for sowing was done in the second half of June. The sowing dates were variable, July 10 in 2017, July 12 and 8 in 2018 and 2019, respectively.

The plant material was the soybean variety Huasteca 100 generated by the South Experimental Field of Tamaulipas, dependent on the National Institute of Forestry, Agricultural and Livestock Research (INIFAP, for its acronym in Spanish). This variety is a material of intermediate size and cycle. In relation to the infiltration of water into the soil, it is based on a whole theory described by physico-mathematical models that govern its behavior.

Preliminary studies

Through soil profiles opened in January 2017, the 'plow floor' was detected at approximately ±35 cm depth, which indicated a depth for the practice of subsoiling at 70 cm during the dry period (April). These profiles were observed within each treatment (three) for this purpose, from where at the beginning of the experimental cycle, soil samples were extracted at depths of 0-30 cm and their physical characteristics were determined.

From these, the parameters of initial moisture and the hydraulic conductivity at saturation were estimated for comparison after the experimental period (three years). These estimates were made based on their texture, using the software SPAW V. 6.02.75; whose moisture parameters were: volumetric moisture content at field capacity (Θ_{FC}), permanent wilting point (Θ_{PWP}), moisture content at saturation (Θs), infiltration rate (q_0), hydraulic conductivity at saturation (Ks) and their bulk density (BD).

Infiltration

The theory of water infiltration is briefly described, in this study this phenomenon was observed in the different soil management systems where soybeans have been grown for more than 40 consecutive years under rainfed conditions. In general terms, the phenomenon of infiltration is nothing more than the entry of water into the interior of the soil through its surface, physically in dry soil conditions and in this way, this phenomenon is governed by the potentials or matric and gravitational forces. However, as water enters the soil, it becomes moist and the matric potential disappears because the pores fill with water (saturated soil) and capillary forces cease; then, when this occurs, only the gravitational potential participates (Cabria and Culot, 1999).

The description of this phenomenon over time has been analyzed by some authors through mathematical expressions whose quasi-analytical approach reveals the dynamics of infiltration (Green and Ampt, 1911; Kostiakov, 1932; Swartzendruber, 1993; Horton, 1940; Holtan, 1961;

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Philip, 1957), but currently the physico-mathematical interpretation of these principles to determine other functions that best describe the phenomenon continues.

Among the authors cited, Philip (1957) deduced an expression for accumulated infiltration, I(t), which so far presents good results, since, from this equation truncated in the quadratic term, the coefficients by which the hydraulic conductivity at saturation (Ks) is estimated are deduced by Kutilek and Krejca (1987). In relation to the above antecedents, it is evident that the source of water entry into the soil is infiltration, since through it, the amount of water that enters the soil by its profile as a function of time is determined.

In this research work, the infiltration rate, q_0 (t), and the accumulated infiltration sheet, I(t), were measured. In relation to the flow of water (q_0), the subscript 0 refers to the entry of water by the surface of the soil, Z= 0. There are methods to measure infiltration such as that of double cylinder (concentric cylinders), whose information is adjusted by physico-mathematical models that allow analyzing its behavior.

Thus, the infiltration rate, q_0= dI/dt, (equation 1), is a magnitude (cm min^{-1}) whose behavior is a monotonic potential function that decreases rapidly over time (q_0) and approaches a constant value; that is, t= 0; when $q_0 \rightarrow \infty$ (equation 2); and when $t \rightarrow \infty$ q_0= constant; that is, in theory; q_0= Ks (hydraulic conductivity at saturation; cm min^{-1}); when $t \rightarrow \infty$ (equation 3).

Successively the infiltration of water in the soil is a variable of the volume of water that enters the soil per unit area over a given time, and is denoted as accumulated infiltration, I(t), which is expressed in linear units as a sheet accumulated in the soil as a function of time. This is a continuous ascending curve expressed by equation 4.

1).
$$q_0(t)=\frac{dI}{dt}$$

2).
$$\lim_{t \rightarrow 0} q_0(t) \rightarrow \infty$$

3).
$$\lim_{t \rightarrow \infty} q_0(t) \rightarrow Ks$$

4).
$$I(t)=\int_0^t q_0(t)\,dt$$

The infiltration rate, q_0(t)= dI/dt, as noted, decreases exponentially over time and approaches a constant value after a long infiltration time. Then, if $t \rightarrow \infty$, $q_0 \rightarrow$ Ks, such that the infiltration rate reaches a constant value and approaches the hydraulic conductivity at saturation, Ks (Chow *et al*., 1988). In general, infiltration measurements are widely used to estimate hydraulic conductivity at saturation (Ks), since this physical property of the soil is key to describing its hydraulic properties and the hydrological balance on the earth's surface (Campbell, 1985; Van Looy *et al*., 2002; Hillel, 2003; Lal and Shukla, 2004; Morbidelli *et al*., 2011).

In addition, its value is a fundamental parameter for the correct design of irrigation systems. Some soil properties, such as its texture, bulk density, initial moisture content, layers or strata in the soil profile, terrain slope, soil cover (harvest residues and stoniness), rainfall pattern and time influence the variability of infiltration (Smith *et al*., 2002). In the third stage of this research, two measurements of the infiltration were made within each treatment.

The infiltration rate, q_0(t) = dI/dt, whose behavior is similar to the equation of Kostyakov (1932), shows a graph for a long time of infiltration and experiences a magnitude that decreases exponentially, and when this value approaches the asymptote with the horizontal, this value is the basic infiltration (BI) of the particular soil. Likewise, the accumulated infiltration, I(t), is the sum of the infiltration in time and is represented by the equation of Philip (1957), reduced to the first three terms (equation 5), the same information that was subjected to its adjustment by equation

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6 (Kutílek and Krej#a, 1987). $I(t)= C_1t^{1/2} + C_2t + C_3t^{3/2} + C_4t^2 + C_mt^{m/2}$ 5). Where: C_1; C_2, C_3, C_m are parameters of the equation; and t is the time.

Kutilek and Krejca (1987) suggested the first three terms of the equation of Philip (1957), from their adjustment coefficients, the hydraulic conductivity at saturation (Ks) is estimated by equation 6. $Ks = (3C_1{*}C_3)^{1/2} + C^2$ 6). Where: C_1 estimates sorptivity, C_3, and C_2 are parameters of the equation. From the field information, infiltration and other hydraulic characteristics of the soil object of this investigation, the corresponding estimates and adjustments were made by the models indicated and processed by the software Curve Expert V. 2.6.

Results and discussion

Table 1 shows soil texture and moisture parameters in relation to the different soil management treatments. It was observed that, for the same soil based on its texture, after subsoiling (April 2017), these parameters and its bulk density showed only slight variation, denoted as initial values. On these results, other studies reported similar variability during the first year of observation and indicate that this is due to the heterogeneity of the soil (Kutilek and Nielsen, 1994).

Table 1. Parameters of soil moisture, bulk density, infiltration rate and hydraulic conductivity at saturation in three soil management systems: subsoiling, fallowing and passes of harrow, in soybean-producing soils in El Soconusco, Chiapas.

Soil texture	Hydraulic variables	Subsoiling		Fallowing		Harrowing	
		2017	2019	2017	2019	2017	2019
Loamy	Θ_{PWP} (%)	15.4	15.4	15.1	15.1	15.8	15.8
	Θ_{FC} (%)	28.2	28.2	27.7	27.7	28.9	28.9
	Θ_s (%)	40.8	40.8	39.5	39.5	39.4	39.4
	BD (g cm^{-3})	1.04	1.04	0.97	0.97	0.94	0.94
	q_0 (cm min^{-1})	0.027	0.06	0.011	0.044	0.019	0.033
	Ks (cm h^{-1})	1.27	2.34	1.32	2.1	1.57	2.22
	Δ of Ks (%)		184		159		141

$\Theta_{PWP=}$ is the volumetric moisture content at the permanent wilting point in percent; Θ_{FC}= is volumetric moisture content at field capacity in percent; $\#_S$= is the volumetric moisture content at saturation in percent; BD= is the bulk density of the soil; q_0= is the infiltration rate; #= increment; and Ks= is the hydraulic conductivity at saturation.

In Table 1, it is also shown that subsoiling, in relation to the other soil management systems (fallowing and passes of harrow) after three years, reported a significant change in the infiltration rate, whose value increased 184% with respect to its initial value. Likewise, the fallowing treatment, its infiltration rate experienced an increase with respect to its initial value of 159% and the treatment of passes of harrow increased 141% during this experimental period.

Although the results correspond to a medium-term period, it is inferred that, among the soil management systems evaluated, subsoiling shows that its practice promotes the increase of infiltration and other physical and hydraulic properties of the soil. This statement can be seen in (Figure 1), where the dynamics of the infiltration rate over time are shown. While (Figure 2) shows the accumulated infiltration in the observed time, where the highest value of the infiltrated sheet corresponds to subsoiling.

With respect to the accumulated infiltrated sheet, I(t), Figure 2 shows evidence of the impact of the subsoiling system on soybean-producing soils under rainfed conditions, since, in the short term under the soil management system evaluated, the accumulated infiltrated sheet, I(t), in the

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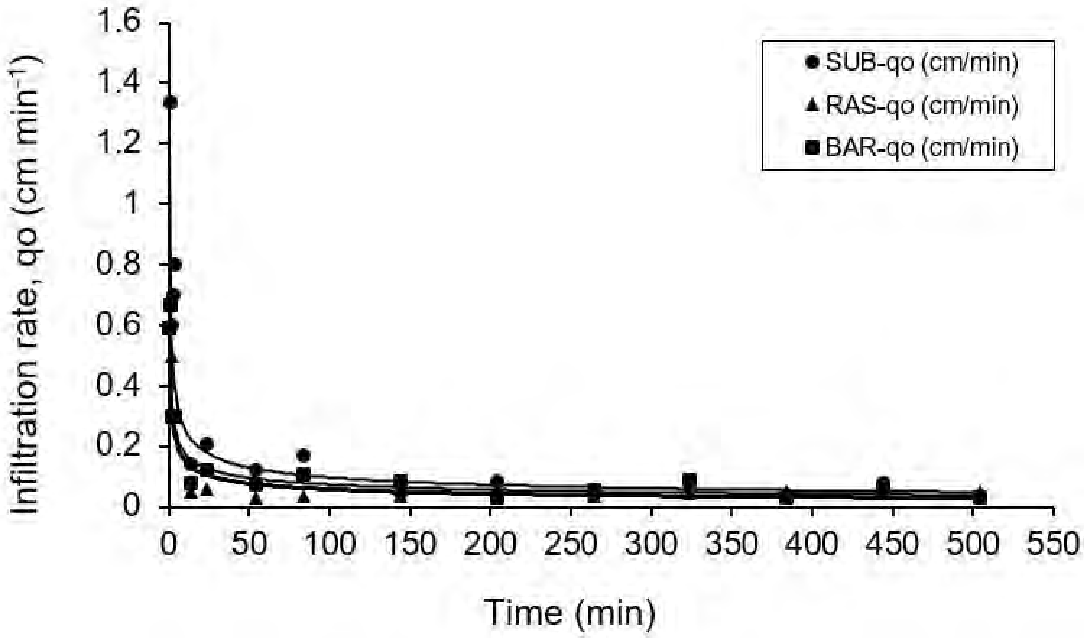
DOI: https://doi.org/10.29312/remexca.v14i5.3102

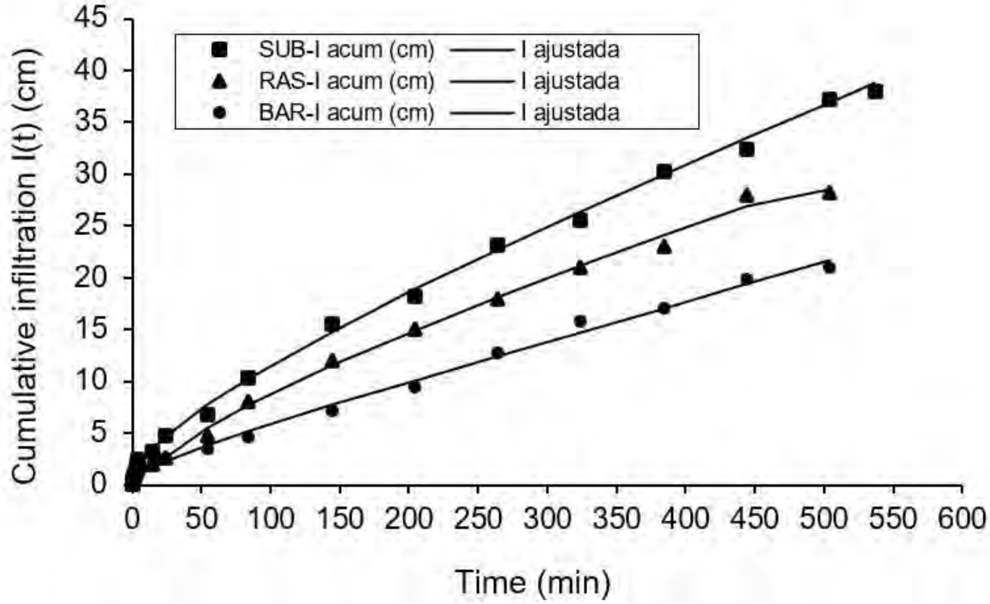
root profile of the crop was 38 cm, followed by the soil management systems of only passes of harrow and fallowing of the soil, whose accumulated infiltrated sheets were 28 cm and 21 cm, respectively, and for equal evaluation times of eight and a half hours in all soil management systems evaluated.

Figure 1. Average behavior of infiltration rates, q_0 (cm min^{-1}), in three soil management systems: subsoiling (SUB), fallowing (BAR) and passes of harrow (RAS), in soybean-producing soils of El Soconusco, Chiapas.



DOI: https://doi.org/10.29312/remexca.v14i5.3102

Figure 2. Average behavior of accumulated infiltration [I(t); cm], in three soil management systems: subsoiling (SUB), fallowing (BAR) and passes of harrow (RAS), in soybean-producing soils of El Soconusco, Chiapas.



Based on these results, the accumulated infiltration sheets revealed a potential advantage of the subsoiling system for soil management in the sustainable production of soybeans under rainfed conditions in Chiapas. Likewise, other advantages, in addition to the hydraulic properties, indicated contribute to improving the physical properties in compacted soils. Some studies in this area indicate that chisel subsoiling, as was the case in this research, produced an increase in infiltration rates (Álvarez *et al*., 2006; Soracco, 2009).

In the framework of similar investigations on subsoiling, statistical analyses did not report significant differences for the physical properties of the soil, in particular for bulk density; while the infiltration rate was highly significant over treatments without subsoiling (Solhjou and Niazi Ardekani, 2001).

In the same vein, Desale *et al*. (2012) reported high rates of infiltration, accumulated infiltration and greater moisture retention by subsoiling compared to traditional tillage. Also, effects attributable to subsoiling are highlighted, of which the following were reported: an increase in moisture content in the root zone of the crops due to the improvement associated with macroporosity and induction of higher infiltration rates and increased root redistribution in the soil profile (Mohanty *et al*., 2007; Zibilske and Bradfort, 2007).

Other studies highlight substantive advantages of subsoiling for the improvement of the infiltration and redistribution of water within the soil profile (Sushil *et al*., 2018), derived from infiltration, its hydraulic conductivity at saturation which contributes to the recharge of aquifers. In general, the effect of subsoiling on soils affected by repetitive tillage and for prolonged periods of time as occurs in El Soconusco, Chiapas, the present research revealed acceptable preliminary results for the improvement of infiltration and hydraulic conductivity at saturation.

In relation to the hydraulic conductivity at saturation, in Table 1, row 8, it was observed that the highest percentage of this variable in the medium term corresponded to subsoiling over the rest of the systems of management of soil cultivated consecutively with soybeans under rainfed conditions. Likewise, other studies indicate that the internal movement of water in the soil cannot

DOI: https://doi.org/10.29312/remexca.v14i5.3102

be detected from one cycle to another and this phenomenon is only observable through a soil profile after a long period of time (Klute and Dirksen, 1986; Cabria and Culot, 1999).

However, this research allowed us to observe that, in the short term (three years), subsoiling increased the hydraulic conductivity at saturation. Hereinafter, similar studies indicate that subsoiling in soybean cultivation experienced a superior advantage over conventional tillage, since this practice increases the rate of infiltration and water storage in the root profile of the crop, since this superior moisture condition minimizes the risk of water deficit and favors the productivity of the soybean production system under rainfed conditions (Heatherly and Spurlock, 2001; Wesley *et al*., 2001).

Yield and yield components based on subsoiling

The analysis of results in relation to soil management systems in this research, mainly subsoiling, this in the first place, showed clear evidence of its effect, since, in this system, greater water storage capacity in the root zone of the soybean crop under rainfed conditions was observed, based on an accumulated sheet higher than 38 cm, compared to the systems of soil fallowing and harrowing, respectively.

On the other hand, the impact of soil management systems on soybean yield and its agronomic variables of interest was analyzed. These results are presented in Table 2, whose analyses of variance of the years analyzed (2017, 2018 and 2019) and their subsequent separation of means (*p*# 0.05) revealed that the yield, number of pods, branches and internodes; subsoiling marked a superior trend over the other treatments. Nevertheless, in relation to the variables plant height and weight of 100 grains, subsoiling maintained a behavior similar to the other treatments (fallowing and harrowing).

Table 2. Response variables of soybeans under rainfed conditions as a function of three soil management systems in El Soconusco, Chiapas. SS cycles: 2017, 2018 and 2019.

Treatments	Yield (kg ha^{-1})	Plant height (cm)	No. of pods (units)	Weight of 100 grains (g)	No. of branches (units)	Internodes (units)
Subsoiling	2 634 a	76.6 a	85.3 a	17.5 a	5.8 a	13.7 a
Fallowing	1 873 b	71.1 a	50.8 b	18.9 a	3.4 b	12.6 a b
Harrowing	1 772 b	68.7 a	35.9 b	18.7 a	5.2 a	10.1 b

Means of response variables. Tukey (*p*# 0.05)

In summary, subsoiling in this research confirmed a substantial improvement for soil management in soybean cultivation under rainfed conditions, as it is an effective soil management system to break the plow layer, reduce bulk density and promote root expansion in the subsoil. It has also been shown to improve tillage operations for the improvement of rhizosphere, microbial diversity and water storage capacity in the soil (Desale *et al*., 2012). Likewise, subsoiling establishes ideal conditions for root development and retards the senescence of the plant; increases grain yield and makes it possible to increase population density in this crop (Mohanty *et al*., 2007; Zibilske and Bradfort, 2007).

Conclusions

It was determined that the rupture of the plow floor through subsoiling in soybean-producing soils of El Soconusco, Chiapas, in the short term, on the one hand, increased the infiltration rate and its hydraulic conductivity at saturation and on the other hand, increased the yield and its yield components.

DOI: https://doi.org/10.29312/remexca.v14i5.3102

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Revista Mexicana de Ciencias Agrícolas

DOI: https://doi.org/10.29312/remexca.v14i5.3102

Improvement of soil hydraulic properties in soybean cultivation through subsoiling

Journal Information
Journal ID (publisher-id): remexca
Title: Revista mexicana de ciencias agrícolas
Abbreviated Title: Rev. Mex. Cienc. Agríc
ISSN (print): 2007-0934
Publisher: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias

Article/Issue Information
Date received: 01 June 2023
Date accepted: 31 July 2023
Publication date: 01 August 2023
Publication date: July 2023
Volume: 14
Issue: 5
Pages: 074-085
DOI: 10.29312/remexca.v14i5.3102

Categories

Subject: Articles

Keywords:

Keywords:

Soconusco

compaction

plow floor

Counts

Figures: 2

Tables: 2

Equations: 4

References: 39

Pages: 12