GENETIC AND INDUCED PROPERTIES OF MOLLISOLS OF THE NORTHERN "PAMPA", ARGENTINA

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ABSTRACT

GENETIC AND INDUCED PROPERTIES OF MOLLISOLS OF THE NORTHERN "PAMPA", ARGENTINA

By

Jose Luis Panigatti

The Mollisols of the northern pampa, Argentina, have developed in loess pampeano, a fine calcareous material of volcanic and dust origin. They developed under the influence of tall grasses and some legume vegetation, and a warm temperate climate with alternating moist and dry periods, on nearly level topography with well drained conditions. The loess deposition at 9 m and above occurred during the equivalent stage of Wisconsinan glaciation, Farmdalian substage in U.S.A., and in recent time that may extend to the present.

The three soil series studied are Mollisols of fine, mixed, thermic families with different degrees of profile maturity, that increase with the position in the microrelief from convex to concave areas. Typic Argiudolls are the result of soil forming processes in upper or convex areas, while Typic Argialboll are the soils in concave positions. Due to the microclimate associated with the microrelief, more clay formation and clay movement occurs in the soils occupying the lower positions in the landscape. In Castellanos and Lehmann series, the A2 and B&A horizons respectively, were part of former B horizons that are now more leached than in Rafaela.

As a result of the partial volcanic origin, weathering and movement, the clay composition in all profiles is: illite, that has a tendency to increase in quantity or crystallinity toward the surface; allophane and vermiculite increasing with depth; and kaolinite, which is present in low amounts throughout. Quartz and feldspars are present in clay fractions of all horizons in every profile.

Due to their origin and genesis these Mollisols have a high natural fertility level that remains high in spite of the common soil management practiced in the area in the last 50 years. Macro and micromorphological studies complement some former field studies and laboratory analyses, which give evidences of the deterioration of soil physical properties due to different management systems.

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Jose Luis Panigatti

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The northern pampa area (in central-east Argentina) has an extensive flat topography on which predominate Mollisols developed in loess, under grass vegetation and a temperate subhumid climate (with four alternating dry and moist periods per year). They have an undetermined age. Some of the soils there have been under cultivation for nearly 100 years, and in spite of their high fertility, they have not been studied intensively. Only in the last 10 years have some works considered their productivity, which is not always as high as might be expected due to climatic conditions and induced soil properties. A few general studies included the northern pampa, in which some soil characteristics were pointed out, but there is a lack of research on genesis of Mollisols and properties of loess in the area. Early soil mineralogical investigations considered the sand fraction (a minor component) and there are not data available concerning the silt and clay fractions in loess and soil profiles.

The objectives of this study were: a) to discuss the genesis of the Mollisols of the northern pampa, b) relate their morphology and properties with soil forming factors and soil development processes, c) determine how these soils have evolved under different management treatments, and d) classify them at the soil type level.

PART I

MOLLISOLS OF THE NORTHERN "PAMPA", ARGENTINA:

1. GENESIS AND MORPHOLOGY

The Argentina "pampa" is an extensive natural region that occupies more than 500,000 km^2 in the central-eastern part of the country. Its boundaires are between 31 and 39° S latitude and between 57 and 65° W of Greenwich. The city of Rafaela is in the center of the area studied and the sampling site is described in another paper of the senior author (40).

The northern part of the pampa in Santa Fe province is between 31 and 33° S (Figure 1). Figure 2 shows the computed Rafaela climatic data from 1908-1966 (37).

Climatic classification of Rafaela using Thornthwaite and Mather water balance method (63) is:

PET (1)	Ih (2)	Ia (3)	Im (4)	Sc (5)
958 mm	0.00	5.89	-3.53	40.29

(1) Potential Evapotranspiration; (2) Humidity index; (3) Aridity index; (4) Moisture index; (5) Summer concentration of Thermal Efficiency.

Climatic formula is: $C_1\ B'_3\ d\ a'$

This formula indicates that Rafaela is in an area classified as: Dry subhumid climatic type (C_1), its thermal efficiency is third mesothermal (B'_3). The seasonal variation of effective moisture is characterized by zero water surplus (d) and the summer concentration of thermal efficiency is that of a full megathermal climate (a').

Rafaela has two periods of water deficit, one from December to February (summer) and the other, of lesser intensity, from July to September. Two periods of water recharge in the soil characterize the

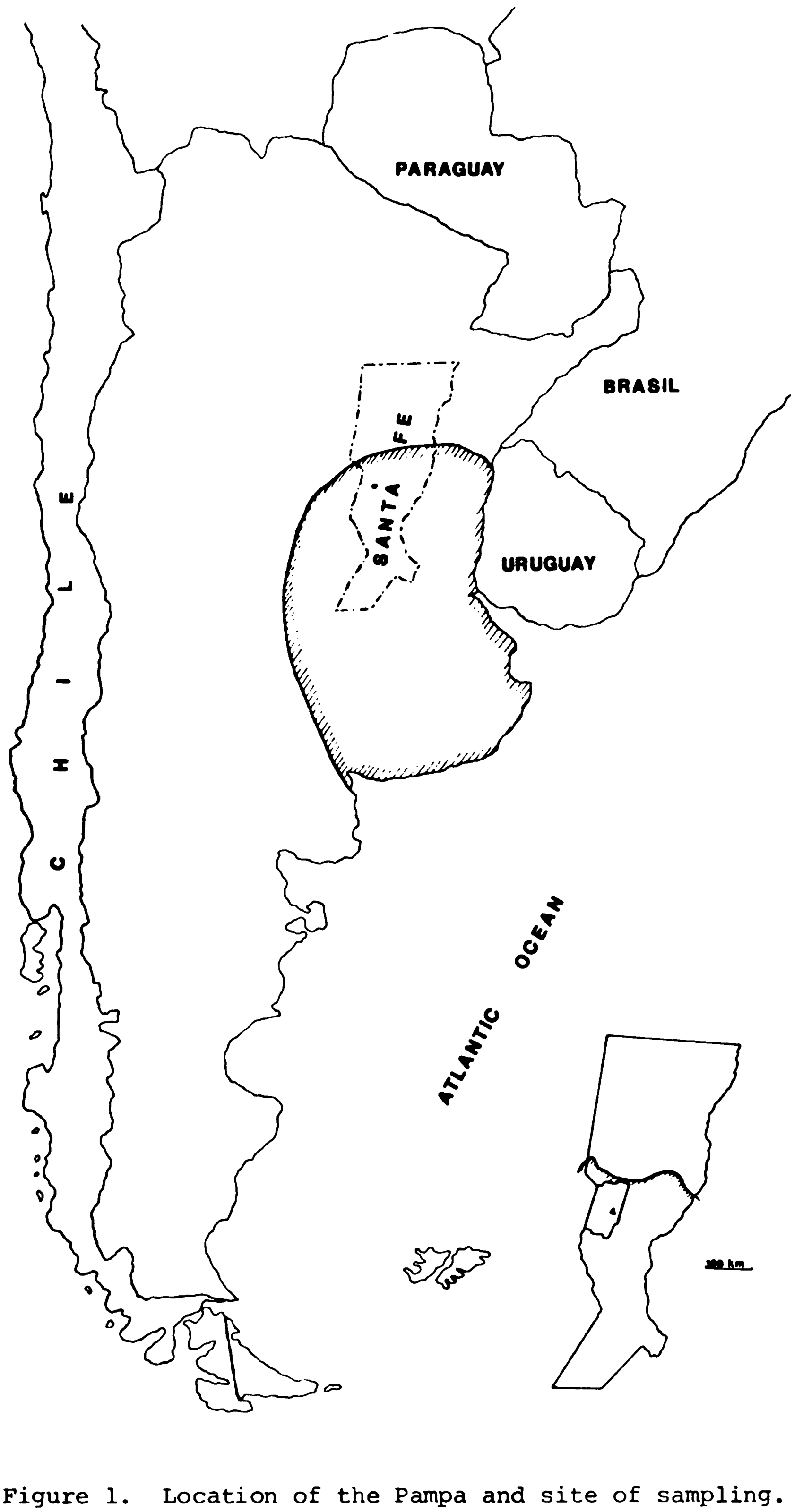

Figure 1. Location of the Pampa and site of sampling.

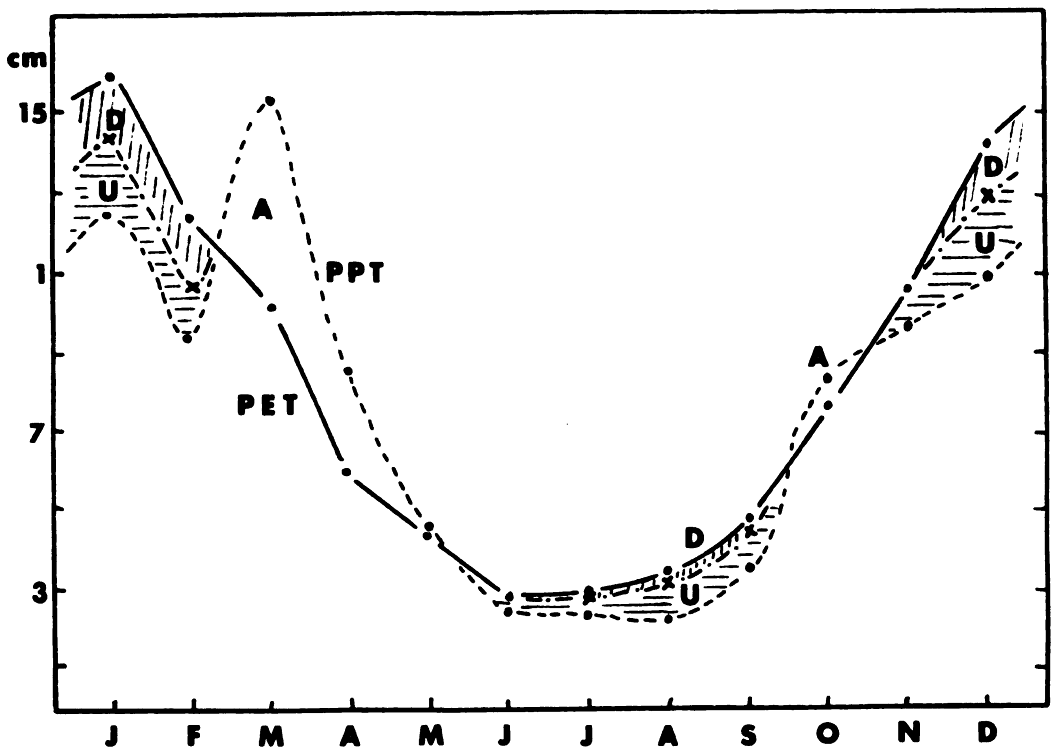

Figure 2. Water balance diagram for Rafaela. PPT, Precipitation; PET, Potential evapotranspiration; A, Water accumulation; D, Water deficit and U, Soil moisture utilization.

area; they are March-April and, with smaller values, October (spring).

Wind action is important for the intensification of evapotranspiration in the area (37). The deteriorated soil structure (52) due to agricultural management has a great influence on water balance and microclimate, reducing infiltration and enhancing drouthiness. Finally, one striking situation that characterizes the climate is irregularity, not only among seasons but also annually. Periods of drought occur, alternating with periods of excess of water more often here than farther south in the pampa.

The boundaries of the pampa are discussed by Frenguelli (23). He mentions the lack of a precise boundary in central Santa Fe area, where the soil samples were collected. He called the unit Cordobense-santafesino Monte, characterized by a transitional zone between the pampa in the south with steppe vegetation, and the bosque in the north. The area has patches of forest, particularly concentrated near the rivers, creeks and poorly drained areas, while grasses are extensive in between. Actually the northern boundary of the pampa must be moved toward the north due to reduction of forest, uniformity of soil management and also based on general soil maps that show Mollisols in the central Santa Fe province. With Skylab images there is no doubt that drawing a new boundary leaves Rafaela in the pampa. The boundary from 30° 40' at Parana River must go west to central Santa Fe and then to the northwest to 29° 50' and follow the Altos de Chipion in Cordoba to continue south and west with former boundaries.

The common grasses described for the northern pampa are "*Stipa, Oryzopsis, Aristida, Andropogon, Chloris, Poa, Bromus, Setaria, Paspalum*, etc., interspersed with Compositae, Leguminoseae, Oxalidaceae, Solanaceae, etc." (23).

The forest is composed of trees that belong to the genera: *Prosopis, Acaccia, Geofroea, Iodina, Aspidosperma, Condalia, Moya, Cassia, Parkinsonia*, etc.

The natural vegetation has been almost entirely altered by grass fires and different crop systems in the last century. All the trees in the zonal soils are introduced.

Materials and Methods

The three soil series studied are tentatively named Rafaela, Castellanos and Lehmann. Pedons for study were selected on the Rafaela Experiment Station, then described and sampled by horizons from pits. Five loess samples, between 3 and 9 m depths beneath the Castellanos series were also collected with an auger. Detailed descriptions of these profiles are included in Appendix A and their landscape relationships are shown schematically later in Figure 4.

All the series are well drained and were developed over the same parent material, loess pampeano.

The pipette method was used for particle size analysis (65). Organic carbon was determined by the Jackson method (4). Organic matter contents were estimated by multiplying the organic carbon contents by 1.724.

Soil pH was measured with a Beckman zeromatic glass electrode pH meter on 1:1, by weight, soil-water mixtures.

Exchangeable bases were extracted with neutral 1 N NH_4OAc. Exchangeable calcium and magnesium were determined with the Perkin-Elmer 303 Atomic absorption unit. Exchangeable sodium and potassium were determined with a flame photometer. Base saturation values were estimated by the ratio of exchangeable Ca, Mg, K and Na to C.E.C. values. C.E.C. was determined by the distillation of absorbed ammonia method of Peech *et al.* (65).

Calcium carbonate was measured with the Bundy and Bremner (7) method. Bulk density was determined using saran-coated clod samples (65). Total nitrogen was determined by Kjeldahl procedure as described by Jackson (4).

Electrical conductivity of the soil extract was determined with a conductance bridge and cell, on extracts collected from samples placed on Buchner funnels where vacuum was applied.

The Pollack *et al.* (48) method was used to study quartz distribution in the soil profile to determine relative changes during soil formation. Quartz was determined with the X-ray diffraction spectrometer using CaF_2 as an internal standard.

Carbon isotope analyses were performed on $CaCO_3$ concentrations, separated from loess samples, by Krueger Enterprises, Geochron Laboratories, Cambridge, Massachusetts.

The depth of the water table was measured weekly in the Meteorological Observatory of Rafaela Experiment Station.

Results and Discussion

The Mollisols of the northern pampa, of Argentina, have developed in loess pampeano under the influence of tall grasses, a temperate climate, and nearly level topography with well drained conditions. As Miaczynski and Tschapek (33) stated, there is no agreement about the parent material age in the pampa. Scoppa (53) studied Mollisols in the "Ondulating pampa", south of the area sampled for the study presented here. He, citing different authors, concluded

> The parent material age corresponds to the Pleistocene and has received new volcanic contributions during the Holocene. The age of the soils can consequently vary from several hundred thousand years for the oldest to a few thousands for the most recent. It is assumed, however, that the age of the selected profiles is the same, this formation time would not go beyond the Holocene.

Teruggi (61) concluded that none of the important minerals composing the Argentine loess deposits are of local origin. He also stated "The Argentine loessoid sediments are mainly formed by minerals of volcanic origin." The loess source area is assumed to be in the west and southwest of the pampa, in Patagonia and in the Andes. Since $CaCO_3$ concretions were present in some C horizons sampled for this study, they were used to analyze carbon isotopes for age determination. Table 1 shows the results. From the two

Table 1. Age determination in $CaCO_3$ concretions from loess samples

Horizon	Depth	Age	δC^{13}
	m	C-14 years BP	$^0/_{00}$
C - profile 4	1.3	1,155 ± 145	-0.6
C4 - profile 3	6.0	25,145 ± 795	-7.0
C6 - profile 3	9.0	28,835 ± 1,350	-7.0

deeper samples it can be concluded that loess deposition at these levels and above (considering leaching processes) occurred during the equivalent stage of Wisconsinan glaciation, Farmdalian Substage in North America (24).

The two older and deeper samples give δC^{13} values that are similar to those found in caliche or concretion deposits. That means these carbonates or carbons were deposited from CO_2 bearing waters in equilibrium with the atmosphere and probably was not altered by ground waters (49). The concretions at shallow depth, C horizon at 1.3 m, by its δC^{13} of -0.6 $^0/00$ suggests a marine or saline origin. The marine origin is discarded due to area characteristics, but a saline origin will be discussed later. These shallow $CaCO_3$ concretions were separated from the C horizon of Castellanos series, profile 4. This horizon has the highest electrical conductivity of all samples used here; it is not classified as saline, but 2.0 mmhos/cm at 25° C was obtained in the extract from a saturated paste, Appendix, Table B4.

The age determination obtained from the shallower sample is noticeably young considering its position below a well developed soil profile. Organic carbon contamination was excluded by the chemical treatment applied to remove it, to allow study of $CaCO_3$ only. More data are needed for this area, but the following possibility must be considered: these young concretions started earlier but present or recent growth was produced by new carbonaceous dust and loess transported to the area, with leaching processes that let the carbonates pass through the acid and neutral solum and reach the alkaline C horizon, enlarging the concretions already there.

Exchangeable Ca and Mg are the major cations present in these soils. Both, expressed as m.e./100 g, reach maximum values in B2t horizons. Exchangeable Ca calculated in m.e./100 g and expressed as % of C.E.C. has minimum values in Ap and nearly constant values from A12 to the C horizon in each profile but with higher % in Rafaela series, lower for Castellanos and intermediate values for Lehmann. Exchangeable Mg calculated in m.e./100 g and expressed as % of C.E.C. present the same tendency in the three series, with nearly 15% in A1 horizons and between 21 and 23% in B and C horizons. Tables in Appendix B show the data for all soils.

Exchangeable K, expressed in m.e./100 g, has higher values in deep B and C horizons, but K calculated as % of C.E.C. has larger values in Ap and C horizons for all series, with nearly 15% in Rafaela series. The high values in the A1 horizon, with more K in Ap, must be due to plant transfer and residue accumulation. In support of this statement are the values of K in topsoil of profile 4, under Agriculture Rotation (40) where crop residue incorporation is larger than profile 3, and commonly deep plowing also incorporates residues into the A12 horizon.

Extractable Na increases with depth in all profiles, and Castellanos series has the higher values (Figure 3), with 15% of C.E.C. saturated with this cation in the C horizon, which is closer to the surface than in the other series.

The Castellanos series is sometimes identified as a Solonetzic profile. This term is used here because the Castellanos series has some morphological features like Solonetz profiles. The chemical composition does not agree with this term, nor with the Solodized

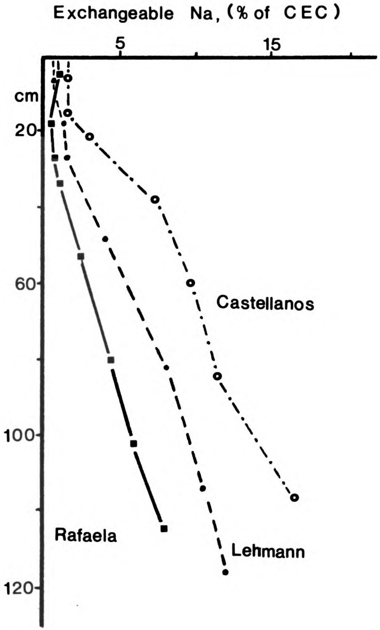

Figure 3. Exchangeable Na, expressed as % of C.E.C., versus depth in the three soil series.

Solonetz. The morphological characteristics of this series, a Typic Argialboll, that has some similarities with Solonetzic profiles, are: a) presence of an A2 horizon, b) an abrupt boundary between the A2 and B2t horizon, c) an abrupt textural change, and d) a strong Bt horizon with different degrees of development of columnar structure.

The absence of argillans and the presence of skeletans on ped surfaces in the B&A, and the A2 horizons of Lehmann and Castellanos series, respectively, is an evidence of degradation at this level. Micromorphological studies of these horizons (39) show clay skins inside some voids of B&A and A2 horizon peds. This means that the A2 horizon is growing at the expense of the top of the B2.

Castellanos series has pH values of 7.0 or higher from the B21t down. The C horizon in profile 4 (Cca with 15% Na) has pH 8.5. Deep loess samples, profile 3, contain the same amount of K, except the C6 at 9 m depth, if they are compared with C1 horizon above them. In these deep loess samples, exchangeable Na is lower at 3 m and 4.5 m, compared with the C1 above, then increases twofold at 6 and 7.5 m and shows another increase at 9 m.

It is known that 70-80 years ago the water table was at 5-7 m; now it fluctuates between 8 and 12 m. These situations can be the cause of Na increases with depth. $CaCO_3$ concretions at 6 m had irregular, nearly black mottles attributed to Mn.

Exchangeable Na content in the Castellanos series (profile 3) reaches a high value in C1 horizon, decreases with depth, and finally increases again, as was mentioned before and attributed to H_2O table fluctuation. The high value of exchangeable Na in C1 horizon must be explained as a result of a combination of runoff, leaching and evapotranspiration actions. These working alternatively permit an increase of this cation in concave areas with the induction of solonetzic morphological characteristics in the profile.

C horizons in the profiles studied here were considered parent materials and sampled, based on their morphological characteristics, i.e., lack of structure and clay skins, but not based on carbonate presence. Similar loess material but unleached is present at greater depth, and loess samples at 3 and 4.5 m are representative samples of parent material for the Mollisols presented here.

Unleached loess has nearly 3.0 m.e./100 g of exchangeable Na, at levels not influenced by the water table. Electrical conductivity is close to 1 mmhos/cm at 25° C, so the upper two loess samples are not saline nor alkaline materials. In C1 horizons of Castellanos series, and also in B3 horizon of profile 4, Na content expressed as % of C.E.C. is nearly 15% or higher. In the upper B and A horizons, Na content is lower and there are no alkalinity problems.

Differences in loess composition in the three series are minimal due to a) short distances between them, b) similar particle size distribution, and c) similar clay mineral compositions.

Wilding *et al.* (73) mention:

> In an attempt to develop a theory for the genesis of solonetzic soils occurring on nearly level, loess-mantled uplands of south-central and western Illinois, it seems appropriate to abandon the traditional Solonetz cycle. Solonetzic soils of Illinois have developed from non-saline parent material and presumably never occurred in this landscape as Solonchaks.

Miaczynski and Tchapek (33) discussed soil characteristics in the pampa with characteristics close to Solod profiles, but they do not believe these soils went through halomorphic steps. The data presented here for the three series agree with both ideas applied in soils developed on nonsaline silty loess.

Buylov (9) concluded that high exchangeable Mg is the reason of solonetz morphology in some Russian soils. Cerana (11), in a review of Mg influence on solonetzic properties, indicates that some Argentina soils with solonetzic morphology are relatively low in exchangeable Na. He, citing other authors, agrees that Mg, and in some cases K, or both, with Na contribute to soil genesis with solonetzic morphology.

Kelly (31) stated that exchangeable Mg "effects" appear to be quite variable, depending on the nature of the cation exchange material of the soil. In some soils, Mg has an effect similar to Ca and in some others it acts like Na. Cerana (11) discussed this point and agrees that Mg has a divalent-monovalent complex behavior that is pH dependent. At low pH, Mg^{++} ions have similar action to Ca^{++}, but as pH increases the Mg complex ($MgOH^{+}$) increases and its effect is similar to Na. As exchangeable Na increases, a rise in pH is obtained and consequently an increase in formation of a monovalent Mg complex could be produced. The evolution of solonetzic morphology could thus be a result of Mg and Na action in an alkaline medium.

Stock and Davies (58) studied the second dissociation constant of $Mg(OH)_2$. They found that $MgOH^{+}$ begins to form at pH higher than 7.9, increases in concentration until pH 9.5, at which time precipitation of $Mg(OH)_2$ is produced.

Magnesian Solonetz soils (33) have a compact illuvial horizon but there is no difference in colloid contents between eluvial and illuvial horizons. This is not the situation of Mollisols studied here that have well developed texture profiles with Mg expressed as % of C.E.C. not higher than 25%.

The solonetzic structure developed in the Castellanos series could be a combination of effects (3). To increase exchangeable Na effects in the series, the Mg effect could be present particularly in concave areas where Na gives alkaline reaction. In another paper (40) a Mg depletion in A horizon is discussed, due to soil management. The Mg decrease in these horizons can be as high as 45%.

The series studied here belong to an area with soils, named by Miaczynski and Tchapek (33) as Chernozoids with strong textural B horizon. They give some values as C.E.C. up to 40 m.e./100 g, exchangeable Ca as 50% of C.E.C. and increasing with depth; Ca/Mg ratio between 3 and 4 and exchangeable Na values between 2 and 5 m.e./100 g without a tendency to increase with depth. From the values obtained with the series studied here the exchangeable Na fails to increase with depth only in Virgin soil profile 5 (Appendix Table B5), but in that profile the exchangeable Na is below the amounts cited. In the other four profiles, exchangeable Na increases with depth.

Profile 4, Castellanos series, has more evidences of what is called here solonetzic structure with more abrupt change in clay content at the A2-B2 boundary.

The Ca/Mg ratio decreases with depth to the B2; from there down the ratio is nearly constant. In B2 and B3 horizons, Castellanos series, a Typic Argialboll, has a ratio of 2.0-2.2, Rafaela series, a Typic Argiudoll, has the highest values with 2.3-2.4.

Cerana (11) discussed Mg and K influence on soil properties and concluded that more attention must be given to exchangeable potassium and its influence on soil structure. As it was reported above, exchangeable K is nearly 15% of C.E.C. in some profiles and there is a tendency to increase with different managements when compared with a Virgin profile (40). The % of C.E.C. saturated with K is lower in Castellanos than in Rafaela series, but the opposite is true for Na; from these values it can be concluded that the solonetzic morphology is from the Na effect and not from K. Potassium increase in the A horizon, due to management, could enhance deterioration of physical properties as was found in two Mollisols from the pampa (19,71).

More attention must be given to exchangeable cations, microclimate and microrelief in relation with profile morphology and soil development in the northern pampa (Figure 4). With these mentioned features, a discussion is presented here as a possible trend in Mollisol genesis. Here the degree of profile maturity is: Rafaela< Lehmann<Castellanos, in which the boundary between A and B horizon decreases in thickness and increases in abruptness to the right. It must be assumed that loess was deposited uniformly, with the same properties, but with a microrelief produced by an internal or external action. This microrelief that is not generally observed (42) is indirectly indicated by water standing over concave places for only a few hours after heavy rains, as commonly occur during the summer (37). This situation is important because runoff is produced from convex to concave areas, with an uneven water distribution on the soil surface.

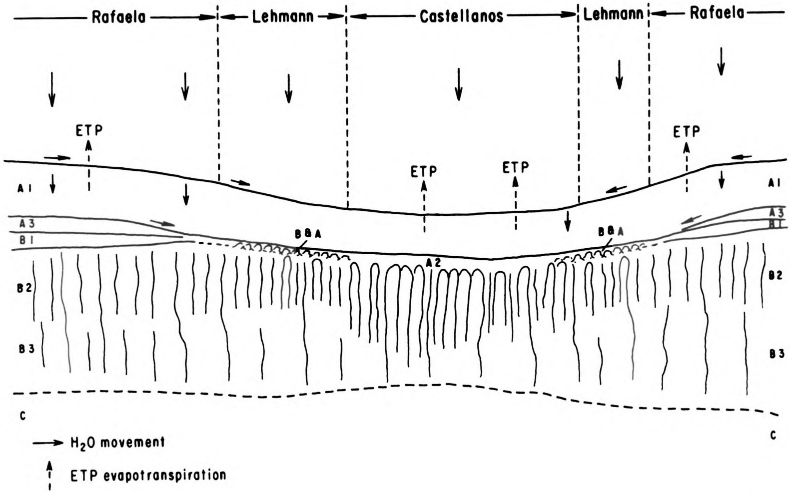

Figure 4. Schematic representation of series distribution in relation with microrelief in the northern pampa.

Rafaela's climate, in annual average, presents two periods in which the soils have water accumulation or recharge and another two periods of water deficits that alternate with the surpluses. During the spring through fall period, heavy rains are common and potential evapotranspiration is high enough to produce water deficits; as a consequence soil profiles can pass through wet-dry cycles easily in short periods of time.

With this kind of climate and water distribution, some salts could be carried in solution on top of the soil and, after the B horizon developed, the solution could move on top of it from the higher to the lower areas. As larger water amounts were available in some concave areas, and more pronounced wet-dry cycles are produced, a difference in degree of weathering must not be discarded.

As denoted by electrical conductivity in the three series, they are not saline, but profiles 3 and 4 of Castellanos series have the highest values in C1 horizons with 1.8 and 2.0 mmhos/cm, respectively. These series were developed over non-saline loess with electrical conductivity 0.8-1.1 mmhos/cm. Profile position in the microrelief permits a slight salt content increase that, concurrently with other actions, results in a Castellanos series. The leaching process lets this small increase in salt content appear in the C1 horizons. As a parallel effect with salt movement, exchangeable Na must be considered in the sequence of profiles from concave to convex positions. The Castellanos series has more than 15% of exchangeable Na expressed as C.E.C. saturation in the B3 and C horizons of profile 4 and principally this cation must be considered related to the solonetzic morphology in this series.

Profile 4 is the one with shallowest unleached C horizon. This is believed due to the solonetzic morphology development that produced a heavier B2 and thinner A horizon with abrupt textural change. These properties reduced leaching processes effectively and enhanced evapotranspiration due to a perched water table on top of B21 and near the surface.

Some of these effects were discussed in a Planosol's genesis by Pineiro and Panigatti (45) in the same macrorelief that influences the production of inundation for periods as long as three months.

Another evidence that supports the microrelief influence in profile development is the δC13 values in $CaCO_3$ concentrations (Table 1). The -0.6 $^{0}/00$ value suggests a saline environment. These concretions were formed and grown at recent age, at levels with no ground water influence, but in a level with electrical conductivity higher than any other horizon considering a three dimensional space.

The higher amount of clay in B21t of Castellanos series, profiles 3 and 4, compared with Rafaela, profile 1, Appendix B, presents evidence of either more clay formation or more clay movement into the B horizon, or both processes. Either of these situations must be because a more humid microclimate results from the microrelief position of the Castellanos soils.

From Tables B1, B2 and B3, clay ratios were calculated between some subhorizons and also with average values using the formula:

$$\frac{\Sigma\ (\%\ \text{clay} \times \text{subhorizon depth})}{\text{total horizon depth}}$$

for the whole horizons. Table 2 shows that clay ratio values are larger in B21t/Ap and B/A than B21t/C and B/C. We can consider the B/C ratio as more directly related to weathering and illuviation processes while the B/A ratio reflects eluviation and illuviation processes. All the values increase to the right, in relation to soil profile maturity in these three series, with Castellanos showing more weathering and leaching than Rafaela, leaving Lehmann series in an intermediate position. These ratios are other evidence of

Table 2. Clay % and ratios in horizons of Mollisols of the northern pampa

Horizon	Soil Series		
	Rafaela	Lehmann	Castellanos
Ap	28.0	28.3	26.3
A	29.4	28.3	26.3
B21t	47.8	52.9	51.4
B	45.0	47.8	49.9
C	38.3	41.4	40.3
B21t/C	1.25	1.28	1.28
B/C	1.17	1.16	1.24
B21t/Ap	1.70	1.87	1.95
B/A	1.53	1.69	1.90

processes in relation to microrelief positions in which Rafaela is in the upper part, Castellanos in concavities, and Lehmann occupying intermediate positions (Figure 4). The maturity differences cannot be attributed to age of parent materials but, as mentioned before, are associated with differences in microrelief.

With the objective to distinguish between clay movement and clay formation in these three series, the clay gain or loss for each horizon was calculated, and also in the solums compared with parent material. It was assumed that erosion was not present, the clay content in the parent material was uniform with depth and it preserved its original properties. Clay gains and losses were obtained on volume percent basis by subtracting % of clay in C from % of clay in each horizon and then multiplying this value by bulk density and thickness of each horizon (25). Table 3 shows that Rafaela and Lehmann series, both Typic Argiudoll, have similar amounts of clay gains in the solums, but they present a difference in loss and gain per horizon. Lehmann has more loss in A horizon and also more gains in B horizon, from which it can be concluded that differences are due to clay movement but not to authigenic formation.

Rafaela and Castellanos series present different values not only among horizons but also in the solum. In Castellanos, nearly 30% more clay than in Rafaela was formed in place from the loess parent material. The clay loss in A horizon and clay gain in B are greater in Castellanos. From these results it can be concluded that microrelief resulted in more clay formation due to weathering processes and more clay movement in the lower concave areas, where Castellanos series is present.

Simonson (54) stated "individual bodies of soils are seldom set apart from their neighbors by sharp boundaries. Adjacent bodies

Table 3. Depth, clay content, bulk density and clay gain or loss for horizons and series

Horizon	Depth	Clay	Bulk density	Clay gain or loss/ 100 cm^2/horizon	Clay gain or loss/ 100 cm^2/cm
	cm	%	g/cm^3	g	
	Rafaela				
Ap	0-12	28.0	1.36	-168.10	-14.0
A12	12-23	29.6	1.30	-124.41	-11.3
A3	23-29	31.5	1.33	-54.26	-9.0
B1	29-36	37.0	1.31	-11.92	-1.7
B21t	36-68	47.8	1.59	483.36	15.1
B22t	68-90	49.3	1.58	382.36	17.4
B3	90-115	39.9	1.36	54.40	2.2
C	115-132↓	38.3			
Solum				561.43	
	Lehmann				
Ap	0-14	28.3	1.39	-254.93	-18.2
A12	14-23	28.4	1.44	-168.48	-18.7
B&A	23-30	29.2	1.34	-114.44	-16.3
B21t	30-65	52.9	1.51	607.78	17.37
B22t	65-99	49.5	1.38	380.05	11.18
B3	99-128	44.3	1.33	111.85	3.9
C	128-143↓	44.4			
Solum				561.83	

Table 3 (continued)

Horizon	Depth	Clay	Bulk density	Clay gain or loss/ 100 cm^2/horizon	Clay gain or loss/ 100 cm^2/cm
	cm	%	g/cm^3	g	
	Castellanos				
Ap	0-12	26.3	1.50	-252.00	-21.0
A12	12-18	26.3	1.50	-126.00	-21.0
A2	18-22	26.2	1.34	-75.58	-18.9
B21t	22-53	51.4	1.65	567.77	18.3
B22t	53-66	52.8	1.51	245.38	18.9
B3	66-102	47.6	1.39	365.29	10.1
C	102-132+	40.3			
Solum				724.86	

commonly grade into one another." This is true for Castellanos-Rafaela series that have Lehmann as a transition. Until now it has not been possible to associate the Lehmann soils with some landscape feature. The first two series are correlated with concave and convex microrelief, respectively, but generally the intermediate situation cannot be mapped with distinct geomorphic criteria. Other problems presented by these tentatively named series is that they were separated on the basis of transitional horizons between A1 and B2t. These horizons are thin as A2 or not easily identified when they are moist (A2 and B&A). Natural vegetation or crops do not give evidences of microrelief on productivity during rainy seasons, but some differences in dry season pasture composition and crop production were found to be related to microrelief (42). It seems practical to emphasize the survey of these three series in associations or complexes by determining their relative proportions in the landscapes without an exhausting amount of hole boring.

From the productivity point of view, Lehmann series has an intermediate position but leans toward Rafaela's productivity. Another thing that complicates this series' separation is the present microrelief produced by man and animal influences.

In Rafaela Experiment Station, during 1972, nearly 480 soil observations were performed in pits approximately 60 cm in diameter, dug into the center part of the B21t. These pits were dug and left for 2-5 days until they were dry to facilitate the observations and improve the transitional horizon identifications. Five observations per hectare were completed and the results are shown in Table 4.

Table 4. Identification of soil series in Rafaela Experiment Station

Series	Observations	%
Rafaela	129	28.3
Lehmann	142	31.1
Prismatic B2	137	30.0
Columnar B2	5 (3.5%)	1.1
Castellanos	147	32.3
Prismatic B2	65	14.3
Columnar B2	82 (56%)	18.0
Others	38	8.3
Total	456	100.0

Twenty-five observations, about 5%, were discarded due to profile disturbances.

These observations cover 100 ha in three areas separated by less than 1,000 m. The Castellanos series has nearly 56% of its observed profiles with columnar structure in B2 while only 3.5% of Lehmann has this morphology. Rafaela does not have columnar structure and the transitional horizon is B1. When the thickness and morphology permit, an A3 horizon can be identified and sampled independently as in profile 1.

The three series studied and the five profiles sampled have mollic epipedons with all the properties in agreement. Profile 4 of Castellanos series has a higher color value in Ap and must be attributed to a soil management effect (40). Organic matter content is higher than in other Ap horizons, so the color difference must be due to quality and state of organic matter decomposition. The structure in the virgin epipedon is moderate medium subangular blocky and also granular. This favorable structure is already modified by management with different results; an extreme structureless condition in some A horizons was produced. The Rafaela series has moderate blocky structure in the B1 transitional horizon, a strong prismatic B2 and, as all other profiles, a structureless C horizon. The Lehmann series presents a transitional B&A horizon with a moderate coarse subangular blocky structure. Below it is a prismatic B with a few incipient columns. The Castellanos has a thin, weak, subangular blocky or structureless A2 horizon over a columnar or prismatic B2. This series can present interfingering of A2 into the top of the B21t, particularly when a columnar structure is present.

The profile textures are characterized by low % of sand, high silt content (particularly fine silt) and a maximum clay content in B2 that reaches values higher than 50%. The epipedons are near the boundary of silt loam and silty clay loam, with the lower clay values in Castellanos series and the higher in the virgin profile. In Rafaela series, clay content increases gradually in transitional horizons, A3 and B1. In the other series the increase is abrupt. Profile 4 of Castellanos shows more than double the amount of clay in B2 compared with A2.

Castellanos, among the three series studied here, is the most mature profile; it was used to study total weight changes (34) as well as clay and non-clay changes (8). Pollack *et al.*'s (48) method was used to measure quartz distribution in the soil profile. Table 5 shows that A horizons lost more than 1/3 of their weight. These changes are nearly compensated with the gains in the B horizons, giving a net 5% loss in parent material in the solum. Net clay translocations, calculated according to Buol *et al.*'s (6) method, are in agreement with total parent material changes (columns 6 and 9, Table 5).

Ignoring the possibility that some quartz may have moved differently in the profile as fine silt or clay, these changes are principally due to changes in the non-clay fraction. It can be theorized that part of the non-clay fraction was weathered and also that some fine silt could move from A to B horizon. The decrease of the non-clay fraction in the solum is responsible for total parent material change for this soil. It is not possible to evaluate the

Table 5. Weight, clay and non-clay changes in Castellanos series

Horizon	Depth	Quartz	Weight: organic matter	Weight: solubles (incl. O.M.)	Weight: total P.M. change	Change in non-clay (8)	Change in clay (8)	Net clay trans-location (8)
	cm	%						
Ap	12	27.0	2.65	4.89	-34.45	-25.39	-9.03	-34.42
A12	6	27.4	2.88	4.80	-35.39	-26.06	-9.33	-35.39
A2	4	28.0	1.65	3.86	-36.79	-27.12	-9.55	-36.67
B21t	31	16.5	1.04	3.90	7.28	3.55	3.75	7.30
B22t	13	16.2	0.63	3.93	9.24	4.40	4.90	9.30
B3	36	16.2	0.36	3.90	9.26	4.87	4.41	9.28
Solum	102		1.07	4.07	-5.05	-5.02	0.06	-4.96
C		17.7	0.18	3.66				

influence of fine quartz movement in this profile with the data at hand.

With the age and depth loess value (Table 1) assuming a similar rate of leaching and $CaCO_3$ formation for the 6.0 and 9.0 m samples, it can be theorized that between them the rate of loess deposition was at 1 cm for each 12.3 years or 0.8 mm/year.

Accepting these assumptions and values suggests that nearly 18,000 years BP, loess deposition had to be stopped to reach the level the soil has at present time. It is already known that climate changed during the Pleistocene. The influence on material transportation must be quite different between moist or wet vs. dry climatic conditions. The rate of loess deposition must have changed after the loess was deposited at 6.0 m and an evidence of it is the age of younger concretions.

Using the 6.0 and 1.3 m samples, with the same assumptions as before, the average rate of loess deposition of this more recent material means that 51 years are necessary to deposit 1 cm of loess, or nearly 0.2 mm/year.

The rate of loess deposition calculated between the two shallower $CaCO_3$ samples, 0.2 mm/year, must be lower because the starting point used was an age that was still during a glaciation stage. The wind transported material, loess pampeano, has a finer tendency along a SW-NE direction (53). Teruggi (61), who made studies of loess composition, concluded: the loess origin must be in the W and SW of the pampa, in the Patagonia and the Andes. Tricart, cited by Scoppa (53) concluded that the pampa had alternating cycles of dry and humid climate during the glacial and interglacial stages, respectively.

With loess age, obtained in $CaCO_3$ concretions at greater depth, it can be concluded that its deposition was during the Farmdalian stage of Wisconsin glaciation (24) in the United States. The dry cycle during this glaciation period with the SW and W wind action could be more effective in loess deposition in the pampa. The present time is an interglacial stage, with more humid climate; thus the effectiveness in loess deposition must now be considerably reduced.

PART II

MOLLISOLS OF THE NORTHERN "PAMPA", ARGENTINA:

2. CLASSIFICATION, MINERALOGY AND MICROMORPHOLOGY

Introduction

Morphology and genesis of three series of the northern pampa in Argentina are presented and discussed in Part I. The profiles have mollic epipedons and argillic horizons, with a thin albic horizon in one series. All are well drained soils, developed in loess with limited weathering and high natural fertility.

Since there is no detailed soil survey in the area, these soils were not mapped and the series names are given tentatively. The three series presented here are classified according to the U.S.A. 1938, Soil Taxonomy and Australian classification systems.

The micropedology for one series and some horizons of the others are also discussed in relation to the natural and culturally induced properties.

The purpose of this study was to examine the quality of the clay fraction, discuss the micromorphology and classify the three soil series of the northern pampa under different soil classification systems.

Materials and Methods

For clay identification, X-ray diffraction was used. The samples were treated with N NaOAc buffered to pH 5 with HOAc, H_2O_2 and $Na_2S_2O_4$-Na citrate-$NaHCO_3$, to remove carbonates, organic matter and free iron oxides, respectively. The less than 2 μ fraction was separated by sedimentation. Clay suspensions were oriented on porous ceramic plates using a vacuum. The samples were saturated with a 0.1 N $MgCl_2$ solution, which was 10% glycerol by volume, to solvate them. The plates were dried over $CaCl_2$ and then X-rayed using Cu K_α radiation and sca

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and scanned between 2 and 31° 2 Θ. Then the clays were saturated with N KCl, air dried and heated at 300° and 550° C. They were scanned again over the same angular range after each drying and heating.

Vermiculite was determined on the basis of K fixation on oven drying (1). Allophane was studied according to Jackson's method (4), and also identified qualitatively by the Fieldes and Perrot (22) quick method. In addition, C.E.C. was measured at three different pHs.

Thin sections were prepared from natural peds of each horizon of the Castellanos series, profile 3, and also transitional horizons, A3 and B1, and B&A in Rafaela and Lehmann series, profiles 1 and 2, respectively. Thin sections of Ap, A11 and A12 horizons of profiles 4 and 5 were also prepared. The method used for sample impregnation and thin section preparation is described in Part III. Micromorphological features were described with the aid of a petrographic microscope.

Data presented in the Appendices were used to classify the soil profiles into different categories with three soil classification systems (36,57,64).

Results and Discussion

Soil Classification. Under the soil classification presented in 1938 (64) the three series studied here are in the Zonal soils Order; Dark-colored soil of the semiarid, subhumid, and humid grassland Suborder; and in the Prairie soil Great Soil Group. Rafaela and Lehmann series are more in agreement with this classification than

Castellanos. The morphology, natural drainage, soil development processes and productivity of Castellanos let us classify it with other Great Group than Prairie. Thus the two series mentioned first fit into the classification without problem, but Castellanos reaches the same great group by elimination of others.

Applying the Australian, Northcote, soil classification (36) to the three series studied here, from the higher category (Division) through the lower category or Principal Profile Form (PPF), provided the following notations: Rafaela silt loam, Gn 3.22; Lehmann silt loam, Dy 4.12; and Castellanos silt loam, Dy 4.22.

Rafaela series is separated from the others at the Division Level, because it has a gradational (G) textural change in the solum; it is not calcareous (Gn), has a smooth-ped fabric (Gn 3), without A2 horizon (Gn 3.2) and is neutral in reaction (Gn 3.22).

The Lehmann and Castellanos series are in the Duplex Division (D) due to texture contrast in A-B boundary; they are in a Dy Subdivision due to color of top B. Both series are in Dy 4 Section because the A's do not set hard and B's have not mottles. Lehmann has no A2 (Dy 4.1) but Castellanos has an A2 (Dy 4.2); both series present neutral soil reaction trend (Dy 4.12 or Dy 4.22).

According to Soil Taxonomy, since all the profiles have mollic epipedons and argillic horizons, they are Mollisols (57). The Rafaela and Lehmann series are of the Arguidoll, Great Group. Due to the albic horizon in Castellanos there is a distinction between it and the other series. It is an Argialboll that has an udic soil moisture regime. The three series represent the central concepts of their great groups; Rafaela and Lehmann are in the Typic Arguidolls subgroup while Castellanos is in a Typic Argialboll subgroup. They have a fine family texture class, mixed mineralogy and thermic temperature class. Thus the three series are each in fine, mixed, thermic families of their subgroups. All are called silt loam types of their respective series in their subgroups, but only the Castellanos has a silt loam instead of a silty clay loam surface (Tables in Appendix B).

Clay Mineralogy. The X-ray diffraction patterns of the clay fraction are similar for the three series studied. Figure 1 presents the X-ray patterns for the Mg saturated, glycerol solvated clays of profile 3, Castellanos silt loam, and loess samples. In all the samples a peak at 10.1 Å indicates illite is present. These peaks remain when the clays were saturated with K and air dried or heated at 300° or at 550° C. Illite has a tendency to give a better defined peak toward the soil surface. This can be an indication of better crystallinity or a larger percentage of illite.

The assymetric illite peak gives evidence of interstratifications of illite-vermiculite. This feature is similar in all horizons.

The low and not well defined peaks at 7.15 Å indicates a low amount of kaolinite, which is confirmed by their disappearance with K saturation and 550° C heat treatment. Quartz is present in the clay fraction of all samples as is evidenced by the 4.26 and 3.34 Å peaks. The 3.18-3.24 Å peaks reveal the presence of feldspars in all horizons.

Vermiculite does not give its characteristic peaks with the X-ray diffractograms, but its presence was measured by chemical

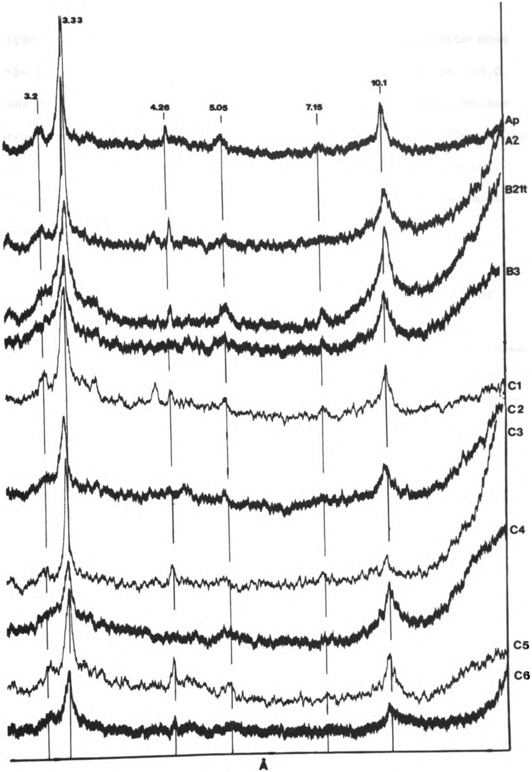

Figure 1. X-ray diffraction pattern of profile 3, Castellanos and loess samples. All samples are Mg-saturated, glycerol-solvated and air dried.

analyses, as shown in Table 1. The low amount of vermiculite must be the reason of the lack of a peak at 14 Å. Comparing the C.E.C. values in B22t horizons, or at greater depth, where organic matter content is only 0.6% or lower, and clay content is nearly 50%, it is found to be between 28 and 31 m.e./100 g. These characteristics cannot be explained with illite properties nor with the low amount of vermiculite present in these soils.

Table 1. Allophane and vermiculite contents in clay fraction of Castellanos series, profile 3

Horizon	Allophane	Vermiculite
	%	
Ap	10.2	3.7
A12	7.0	
A2	8.8	8.0
B21t	23.2	13.1
B22t	22.7	
B3	18.3	
C1	16.2	13.7
C2	19.3	10.9
C3	16.1	
C4	16.3	13.0
C5	24.2	
C6	20.1	12.7

Due to the diffractograms' flatness, the volcanic and dust origin of loess material and the relation of C.E.C. and % of clay, the presence of allophane was suspected. Jackson's (4) method to measure Δ C.E.C. was used to quantify the allophane in the Castellanos series and loess samples (Table 1).

The qualitative NaF quick test method for allophane (22) was used in all horizons of the five profiles. After the treatment the reaction was nearly colorless in A horizons, pink in B1 and B&A, and red in all others. The lack of color in A horizons is attributed to adsorption produced by organic matter. The other colors confirm the allophane presence in all profiles.

As another way to detect allophane presence in these soils, C.E.C. was measured at three pH's with the results shown in Figure 2. The C.E.C. increase with pH is in agreement with the results of other methods mentioned before and with research dealing with allophane (29,68,69).

The mineralogical results in these soils indicate that parent material has more influence on clay mineralogy than weathering processes during pedogenesis; at least this statement is true from the clay quality point of view.

Micromorphology. The following description and fabric analyses (6) are based on the examination of thin sections of oriented samples from undisturbed or natural structure examined under the petrographic microscope, using magnifications from 20 x to 880 x. One limitation this material presents is the dense nature of the soil and the low amount of sand. Four samples of each horizon were

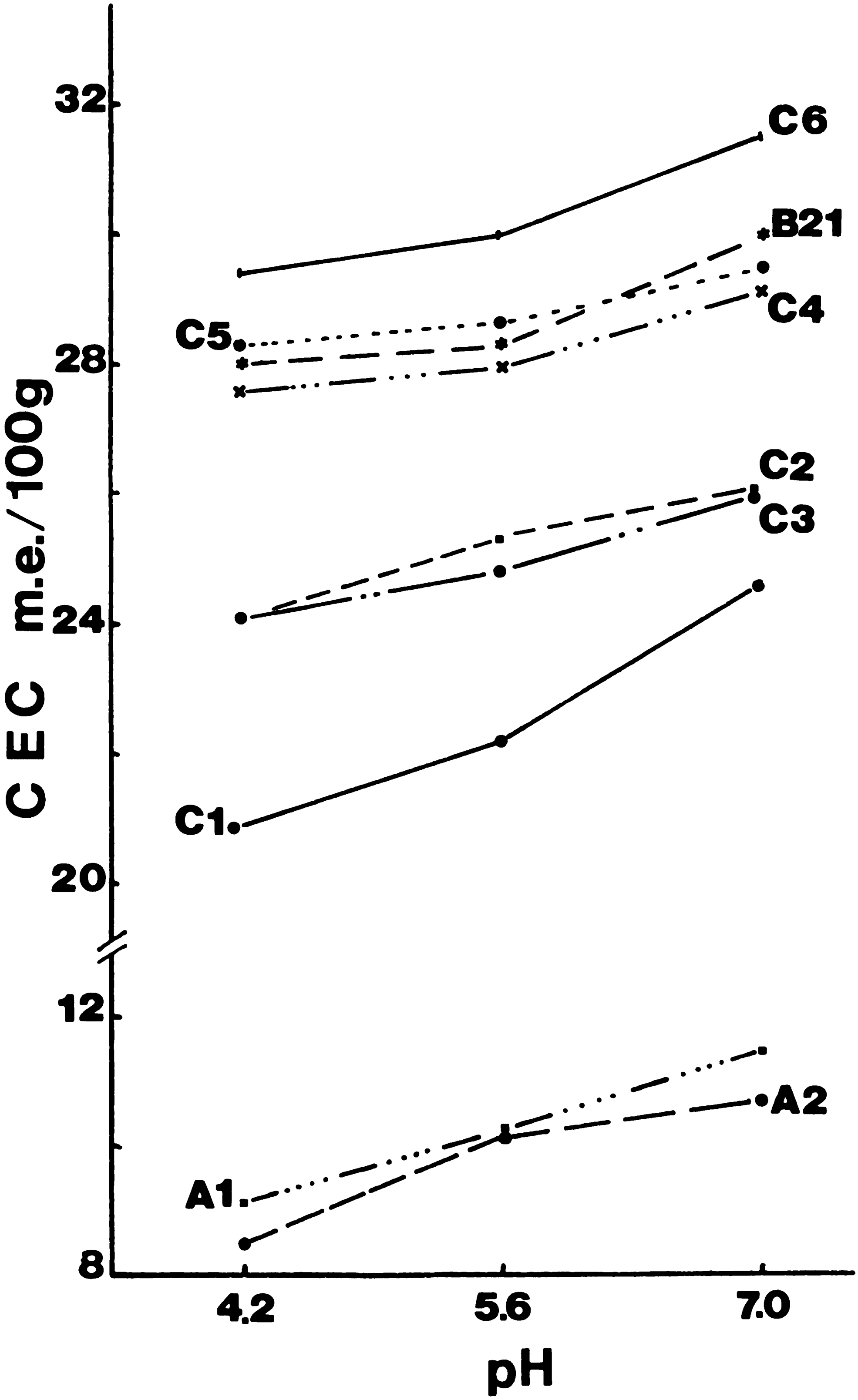

Figure 2. C.E.C. vs. pH in horizons of Castellanos series, profile 3.

studied, two vertical and two horizontal sections. All horizons of the Castellanos series were sampled. Their descriptions are the following:

Ap - The microstructure is of low porosity and compact. There is no evidence of segregation of components in some kind of structure. Porosity is nearly uniform and, like sand grains, the voids have a random distribution pattern. This horizon is characterized not only by a lack of structure but is siltier than B's and C. The organic matter is well decomposed and thoroughly mixed with the mineral material.

Like the whole profile, the Ap has a porphyroskelic related distribution pattern. The basic orientation pattern for the features described for this horizon are unoriented at 100 x magnification. Neither the pores nor the grains have coatings of oriented clays; this is also true for the A12. Due to lack of orientation and association with organic matter, the clay cannot be distinguished.

Some areas present an orientation pattern that contrasts with the domain in the horizon. There the orientation is in the form of parallel bands, generally with smooth curved shape, attributed to external forces as shear due to machines or animal trampling. Other features produced by soil fauna are present as pedotubules with circular boundaires produced by earthworms.

Due to plow influence and crop residue additions, there are parallel curved accommodated grains and plasma that, by contraction and organic matter decomposition, produce joint planes.

Plant and insect residues are present with evidences of partial decomposition leaving more resistant black and brown residues.

Most of the pedological features have rather diffuse or rather sharp boundaries, and it seems that these are due to presence of organic matter, fine silt and clay in them.

The size and percentage of voids are reported in another paper (40), but definitely the small voids predominate. Due to lack of peds or the predominance of massive structure, the voids must be considered intrapedal. There are a few irregular smoothed metavughs, single channels and meta-skew planes.

The plasmic fabric is silasepic for the A horizons. Pedality is not described since samples for thin section studies were received already impregnated and the bulk samples for other analyses were disturbed. In another paper (38) there are complete profile descriptions from the field (Appendix A).

The sand fraction (<2%), most of it very fine sand, is principally volcanic glass, quartz and feldspars, impregnated in a matrix dominated by silty material mixed with colloids. The grains have sharp broken edges and acute angles, typical of wind blow material with weak evidence of weathering.

A12 - This horizon has the same fabric, S-matrix and pedological features as the Ap. At this level of A1 there are more evidences of biological activity, maybe due to lack of mixture produced by implements as normal practices in Ap.

As in all the horizons, Mn and Fe nodules with some quartz grains included are present. Vughs have wider range than in the Ap, principally irregular orthovughs. The presence of vesicles was noted.

In one thin section there are areas with small peds and more porous material, contrasting with other more compacted areas. Dendroid channels are only present in parts of samples. Also there are patterns of accommodated grains and "peds" that form parallel features. They look like a complex area that was pressured by a strong external force over a wet soil producing deformation of structure and reaccommodation of matrix. The difference in the ones observed here and those described for Ap is that the A12 features have no organic matter forming bands or alternating with soil material, so there are no joint planes. The described features must be produced by pressures without intervention of plant residues.

A2 - The dominant related distribution is porphyroskelic but some small areas are agglomeratic. The lack of uniformity is evidenced also by areas with no segregation of components into any structure and with random distribution, while small areas present evidences of laminar structure with ortho-joint planes. A third structure pattern is represented by high porosity in which there are predominant irregular ortho-intrapedal macrovoids.

Since the purpose of this description is not a quantification of each feature, they are mentioned and described, sometimes only as an approximation.

There are abundant, not uniformly distributed, round, black or opaque nodules of Mn-Fe oxides.

The organic matter not thoroughly decomposed is greatly reduced compared with the A1 horizons; the color is light brown, and few remains of roots are present.

The clay fraction is not uniformly distributed and three patterns could be identified: a) as in Ap and A12, clay is randomly distributed with non-cutanic or unrelated referred distribution, associated with organic matter to form soil plasma; b) as illuviation cutans forming relict argillans in voids and peds; and c) some isolated areas of oriented clay with no pedal relation, but irregular and diffuse boundaries that must be a former part of a B horizon, now partially degraded or leached.

To the void argillans mentioned, it must be added the presence of a loose part of argillans occluding channels. They must be relicts of channel argillans that became loose and moved through the channel until they were trapped in a neck. These argillans are illuviated organo-argillans.

A wide variety of voids are present in the A2; there are irregular orthovughs and interconnected irregular smoothed metavughs; compound packing voids are common and the presence of equant vesicles was noted.

Three kinds of channels can be distinguished: a) single short channels that interconnect metavughs and chambers, b) dendroid channels, and c) single channels, with parallel distribution among them and also with relations to ped surface. Plasmic structure of S-matrix is silasepic.

B21t - The orientation pattern in some areas can be described as "strongly oriented" because more than 60% of the individuals are oriented as can be observed with 100 x magnification.

Organic matter is still important at this level of the profile. It gives a brown color contrasting with the reddish of argillans. All the interpedal voids have cutans, they are continuous but with irregular thicknesses, while the intrapedal voids have thinner cutans or lack them. Only a few grain argillans could be observed. The degree of separation for cutans is classified as strongly separated, and the process of formation is illuviation; there are no evidences of other processes.

The presence of intrapedal packing voids is not identified under any magnification due to the high plasma concentration. But the irregular smoothed metavughs, single and anastomosed channels, and craze planes have strong parallel oriented organo-argillans that can be as thick as 400 μ.

Spherical nodules of sesquioxides are present. Cutanic channeled vosepic fabric is the elementary fabric of this horizon.

B22t - The general characteristics of this horizon are similar to B21t, but the amount of organic matter is reduced leaving a lighter color, from brown to yellowish brown. Clay particles are more evenly distributed, with less and thinner void cutans compared with B21t. Chips of clay with well defined extinctions under polarized light are forming a plasma. Plasmic fabric is vosepic. For most pedological features this horizon presents intermediate characteristics between B21t and B3.

B3 - The fabric is porphyroskelic; some areas are intertextic with porosity not uniform in size and distribution as A1 and B2 horizons. Reddish, parallel, well oriented clay skins are present on void surfaces. There is a general tendency of greater thickness of cutans in the larger voids; in some of the smaller pores there are no identified cutans with 100 x magnifications. As in B21t, this horizon contains some clay chips that have no relation with voids. Clay films are present on sand grains.

The organic matter content is too low to darken the soil matrix, so without considering cutans the aggregates are yellowish brown.

Oriented clays form bands with no orientation with respect to pedological features; they are embedded within the plasma. A wide variety in size and shape of voids is present, most of them smoothed by cutans. Compound packing voids, irregular metavughs, single channels and chambers are common.

As in all other horizons sesquioxidic and Mn nodules are present. An elliptical isotubule was observed.

The plasmic fabric is predominantly vosepic with areas vomasepic. The elementary fabric is cutanic as both B2 horizons.

C - The basic distribution is random while referred distribution is unrelated. The fabric is mainly intertextic with small porphyroskelic areas.

The clay fraction is predominantly unoriented and is not evenly distributed. The plasma aggregates have flecked orientation. Only one small channel clayskin was observed, but some grain cutans are present, although not as well developed as in B3.

There is a wide variety in void size and shape; some areas have predominantly compound packing voids due to microaggregates; they correspond with intertextic fabric. Irregular orthovughs with compound packing voids are the most common, with interconnected metavughs in lower amount. Only a few single and dendroid channels were observed.

The nearly uniform yellowish color contrasts with the opaque and black Mn and sesquioxides nodules. Organic matter content has no influence on color or features of this horizon.

Plasmic fabric is silasepic and it has darker areas of low porosity with well defined boundaries that can be attributed to soil fauna influences or pedotubules.

Following are the descriptions of transitional horizons of the Rafaela series:

A3 - It has a random basic distribution pattern with unrelated referred distribution and intertextic related distribution in its fabric. A large variety in shape, size and amount of voids characterize this horizon. Compound packing voids and irregular smoothed metavughs predominate. Single and dendroid channels are unevenly distributed.

The presence of thin illuvial argillans was found in a few normal voids and channels. The cutans are thicker in occluded areas or protected tortuous channel segments. Good evidences of organism activities are present; unfortunately the macromorphology was not described in enough detail to positively identify what are suspected to be cross sections of aggrotubules.

The plasmic fabric is silasepic. The well decomposed organic matter content is thoroughly mixed and gives a dark brown color as in the A1.

B1 - The same features described in A3 fit here, with some differences that include the following: it has less organic matter, that results in a light brown color, and pedoturbation as a result of fauna activity is comparatively less than in A3. Void shapes are more widely variable but void sizes are smaller if compared with A3 horizon. Illuvial argillans are in almost all voids but not in larger metavughs and on ped faces. The smaller the void the thicker are the cutans but, when compared with argillans in the B2 of the Castellanos series, the latter are many times thicker, as evidence of greater illuviation in B2t horizons.

The plasmic fabric is vo-insepic. As in all the samples observed in these profiles, sesquioxides and Mn nodules are widespread. These nodules are smaller than 200 μ and cannot be seen during the soil profile observation and description in the field.

In the Lehmann series, the B&A horizon was sampled and prepared for micropedology description.

B&A - The fabric has a random basic distribution pattern and flecked unrelated orientation. As in A3 and B1 horizons, there is a wide variety in void shapes and sizes. Almost all the voids have smoothed walls and must be classified as metavoids. In only a few small pores and irregular channels protected from leaching can relicts of thin argillans be observed. The samples present some areas with differences in bleaching that must be attributed to an excess of water that remains on top of the B2 horizon of this profile for a few hours after heavy summer rains (42).

As a transitional horizon it has features of both. Like A it has high organic matter content, biological activity and organic residues. It has reddish brown colored argillans like B horizons. S-matrix has a silasepic plasmic fabric.

From the micropedological study it can be concluded that clay accumulation is a maximum in the B21t horizon and decreases in both directions, up and down, in the soil profile. These observations agree with laboratory analysis, calculations and field observations which concluded that clay accumulation is a maximum in the B2 of

Castellanos series due to its position in the microrelief with a more humid microclimate.

The A2 and B&A horizons, in Castellanos and Lehmann series respectively, are leached with more intensity on the ped surfaces. They have argillans in the ped interiors as evidences of their participation in former B horizons. The A2 horizon is growing at the expense of the top of the B2.

PART III

MOLLISOLS OF THE NORTHERN "PAMPA", ARGENTINA:

3. SOIL CHANGES WITH DIFFERENT MANAGEMENT SYSTEMS

Introduction

Since the beginning of agriculture, the influence of crops, animals and man on soil properties has been observed and reported. The changes in soil properties and productivity are not always positive. In the last two decades, more emphasis has been given to quantifying the soil property changes and their influence on crop development.

Some studies used to measure soil evolution under different managements compared them with soils treated with fertilizers. In some cases a soil without chemical additions was used for comparison purposes; in others the virgin soil was incorporated for the same purpose (16,27,28,59,66). There is a lack of information on soil composition and its evolution under management, with or without fertilization, and in comparison with the same soil under virgin conditions.

The natural fertility of the Argentine pampas has been known for over two centuries as evidenced by luxuriant vegetation that strikes foreigners' attention (15).

The northern pampa's characteristics and the principal soil problems were studied with more intensity in the last ten years. From the problems studied, one is very important for its frequency and intensity. It is the drought effect that can destroy either winter or summer crops (41,42,44).

The study of some chemical properties, particularly assimilable nutrients, and physical properties in virgin soil and under different rotations would contribute to better soil characterization and its evolution under different managements. The objective of this study is to compare some properties of A1 horizons in a soil series from the northern pampa, under different management treatments.

Materials and Methods

Three soil profiles were used in this study. Two of them belong to the tentative series named Castellanos, a Typic Argialboll in the fine, mixed, thermic family. The virgin profile was sampled in the only small undisturbed area close to the sampling site of other profiles. A representative soil profile of Castellanos series could not be found there. Instead was sampled a virgin profile that is an intergrade close to Lehmann series, a Typic Argiudoll of the same family. They developed over loess pampeano under tall grasses on dominant slopes of about 0.5%. Profile descriptions and analyses are given and discussed in two other papers by the author (38,39). Here, some of those results are presented for discussion and conclusions.

The soil profiles were sampled in the Experimental Station of Rafaela, Santa Fe, Argentina. The Castellanos series is the most important and extensive soil in the area that has Rafaela city as a center and within a radius of 60 km.

Organic carbon was determined by the Jackson method (4), organic matter contents were estimated by multiplying organic C values by 1.724. Exchangeable bases were extracted with neutral 1 N NH_4OAc and exchangeable Ca and Mg were determined with the Perkin-Elmer 303 atomic absorption unit. Exchangeable Na and K were determined by flame photometer. Total N was measured by the Kjeldahl procedure as described by Jackson (4). C.E.C. was determined by the distillation of absorbed ammonia method (65). Soil pH was measured with a Beckman zeromatic glass electrode pH meter on a 1:1, by weight, soil-water mixture. The pipette method was used for particle size analyses (65).

Soil samples for thin section studies were impregnated with Crystic N° 195 resin, diluted with Monomero C from Ubyco S.A.I.C. of Buenos Aires. Air day samples were impregnated under vacuum and dried for 30 days under 100 W lamps. The thin sections were prepared by Gary Section Service, Tulsa, Oklahoma.

The following analyses were completed in Michigan State University Soil Testing Laboratory: assimilable P by the Bray N° 1 method; Ca, Mg and K were extracted with 1 N NH_4OAc; for Mn and Zn a 0.1 N HCl extractant was used; and for Cu, 1.0 N HCl was used as extractant. All these elements were analyzed with the Perkin-Elmer 290 atomic absorption unit. B and S were analyzed in the University of Wisconsin Soil Analysis Laboratory. B was extracted with nearly boiling water and measured with photocolorimeter, Coleman Model 8. Sulfur was extracted with Ca $(H_2PO_4)_2$ in HOAc (500 ppm of P in 2 N HOAc) and measured with a nephelometer Coleman Model 9 (51).

For soil pore measurement, a slide projector was used, projecting the thin sections on millimeter (cross section) paper, over which the pore diameters were measured on 25 point samples, distributed at random. Four thin section samples were used for each horizon and two diameters at right angles were measured in each pore. The soil channels were evaluated in the same samples. The projector position was maintained horizontally to avoid image distortion. The sample boundaries and all the channels were drawn on the paper. Each sample area was obtained by cutting and weighting the paper. The real area of all samples was calculated with the weight and area relation of the paper and considering the magnification produced by the projector. The channels were measured with a map measurer, Keuffel & Esser N° 620300. Atterberg limits were determined by the method described by Sowers (4).

The three different managements selected for this study have been in practice for the last 50 years and are: *Soil under Grazing Rotation*: cropped predominantly to alfalfa, grain and forage sorghum and winter grasses (rye and barley). These species were produced for forage, with 70 to 80% harvested by grazing. *Soil under Agriculture Rotation*: in this management, different summer and winter annual crops (corn, sorghum, rye, barley, wheat, etc.) are grown and the soil is prepared with a large number of tillage operations every year. *Virgin Soil*: soil sampled under natural grasses, without animal influence, because it is in a park.

Results and Discussion

The Mollisol order is known for its fertility (17). Since in the north of the pampa there is no study reported on fertility levels, and there is a predominance of Mollisols, it is of interest to repeat Daus' (15) statements about the pampa:

> The extraordinary prowess of its meteoric progress, which in 25 years - between 1880 and 1905 - advanced leaving other argentine regions far behind. This would not be possible if the economic conquest of the pampean soils had presented problems to the techniques applied in agricultural production.

Simonson (17) stated that "many people do not yet realize that many soils of the world had low levels of plant nutrient elements before they were cultivated the first time." As an example of this situation it might be pointed out that some soil series from Michigan responded to N fertilizers in virgin conditions (16).

Chemical analyses for the Mollisols with different managements are presented in Table 1. From C.E.C. values, a 25% reduction was found in the soil under both rotations. This effect must be attributed to a reduction in clay and organic matter content (Table 5). Microstructure studies (39) have shown colloid migration in the soil profile and clay skin formation in the B horizon. The lower clay content in the A1 horizons under both rotations and the higher values in the B21 when compared with the virgin soil area could be a result of enhanced migration as a result of soil management that produced a decrease in aggregate stability (32,52,67). There is a possibility that part of these differences is due to natural properties of these profiles.

Ca and Mg, both analyzed independently by the author (Table 1) and by the Michigan State University Soil Testing Laboratory (Table 2) represent a depletion in surface soils (Ap or A1) under rotation. In the A12 of the Agriculture Rotation this reduction is greatest, reaching 45% or more. As a consequence of Ca and Mg diminution, there is an acidification of A horizons, which is evident in a decreased pH and increased exchangeable H (Table 1). These results agree with other studies (14,52, 72). One of them (52), working with the same soils but at different times, obtained pH 4.9 in Ap horizon of Agriculture Rotation treatment. Organic matter, Ca and colloid reduction contribute to a greater aggregate instability mentioned before.

Table 1. Chemical data obtained by the author on Mollisols under different managements

	Treatment					
	Virgin		Grazing Rotation		Agriculture Rotation	
	A11	A12	Ap	A12	Ap	A12
Ca m.e./100 g	11.0	11.5	7.0	7.9	7.0	6.4
Mg "	3.2	2.9	1.9	2.4	1.9	1.7
K "	2.3	2.0	2.1	1.5	2.2	2.2
Na "	0.1	0.1	0.1	0.2	0.1	0.1
H "	4.0	3.8	4.2	3.4	4.5	4.5
C.E.C. "	20.6	20.3	15.3	15.4	15.7	14.9
Saturation (%)	80.6	81.3	72.5	77.9	71.3	69.8
pH	6.7	6.7	5.8	5.9	5.6	5.5
% Ca	53.4	56.7	45.8	51.3	44.6	43.0
% Mg	15.5	14.3	12.4	15.6	12.1	11.4
% K	11.2	9.9	13.7	9.7	14.0	14.8
% C	2.28	1.84	1.60	1.54	1.83	1.66
% N	0.171	0.139	0.157	0.140	0.148	0.154
C/N	13.3	13.2	10.2	11.0	12.4	10.8

Table 2. Chemical data obtained by M.S.U. Soil Fertility Laboratory on Mollisols under different managements

Horizon	Treatment: Virgin	Treatment: Grazing Rotation	Treatment: Agriculture Rotation	Desirable Level (1)
		P kg/ha		
Ap or A11	142	142	131	
A12	111	103	137	>35-55
B21t	86	39	27	
		K kg/ha		
Ap or A11	1986	1793	1865	
A12	1671	1154	1961	>266
B21t	1914	2208	2461	
		Ca kg/ha		
Ap or A11	4700	2977	2821	
A12	5172	3448	2664	
B21t	7679	6581	7365	
		Mg kg/ha		
Ap or A11	786	480	493	
A12	733	613	400	
B21t	1279	1717	1717	

(1) Values adopted in several states in the corn belt.

Exchangeable Na and K do not show evidences of absolute value changes, but there is an increment in K calculated as percentage of saturation in the Agriculture Rotation. These values are naturally high as in most soils of the northern pampa.

Mg levels in all treatments, expressed as m.e./100 g or % of C.E.C. (Table 1) or as kg/ha (Table 2), do not present any problem in relation to deficiency levels (70). Soil management produced a decrease in Mg levels under both rotations, and an increase in % of exchangeable K, as mentioned before. The K/Mg ratio is important to express Mg status in soils. This ratio, it is reported by Doll and Lucas (70), should be less than 5 for field crops, less than 3 for vegetables, and below 2 for fruit crops. Table 3 shows the K/Mg ratio in mg/100 g calculated from Table 1 values. An increase of the ratio values due to management is present in the Agriculture Rotation. This treatment is similar to an accelerated exhausting system, where nutrient cycling, removal or leaching is at a maximum due to a sequence of annual crops, very often two crops per year. The higher values in both subhorizons in Agriculture Rotation must be the consequence of crop residues incorporation at different levels in A1, as is practiced in this treatment. Grazing Rotation treatment has a minimum residue incorporation and always at the same level, 12-14 cm.

Erosion and drainage are not believed to be important in the principal soil nutrient losses from Castellanos series. This view is supported by the profile morphology and texture, but also as a consequence of the climate and nearly level topography (44). The

Table 3. K/Mg ratio in A1 horizons of Mollisols under different managements, expressed in mg/100 g

	Treatment		
	Virgin	Grazing Rotation	Agriculture Rotation
Ap or A11	2.31	3.56	3.73
A12	2.22	2.01	4.17

changes in exchangeable cations must be attributed to nutrient movement in the soil profile and their extraction by crops.

Several researchers (16,18,27,30) concluded that N and organic matter losses are produced by cropping. Generally these losses increase with an increase in the amount of tillage. These losses are greatest at the beginning of virgin soil tillage but decrease with time until a new equilibrium is reached. N content in the Castellanos Ap horizon decreased with tillage, but this was not true for the A12 and B21t horizons of both rotations compared with the virgin soil. Percent N in Virgin soil B21t is 0.065, while in the Grazing and Agriculture Rotation it is 0.081. Higher N content in A12 of the Agriculture Rotation can be a result of sweet clover incorporation with plowing in the season before sampling. Hobbs and Brown (30) found that N losses from the topsoil can be accompanied by an increase of N in the lower horizons. In B21t there is an increase in organic matter content on both rotations (Table 5). It was reported (46) that N additions with rain is 7 kg/ha/year in the area where these soils were sampled.

The C/N ratio is narrowed by tillage practices, and this effect is larger in the Grazing Rotation where incorporation of crop residues is minimal due to grazing practices. This observed trend in C/N ratio evolution coincides with the conclusions of Gosdin *et al.* (27).

Allaway (2) discussed how management practices can change soil trace nutrient availability for crops. The micronutrients and S data (Table 4) do not consistently show lower values due to different management, except for B in the A12. Since there are no studies in the pampa dealing with minimum or desirable levels for available micronutrients, the levels in Table 4 are given for Wisconsin and Michigan (13,51), the states where such analyses have been performed. The available micronutrient levels are over these minimum desirable levels (except for S) and in some cases, as for Mn in Agriculture Rotation, there is an increment that can be attributed to soil acidification (70).

The statements for micronutrients are also true for P and K data (Table 2). The values, except for P in B21t of Agriculture Rotation, are so high above the minimum desirable levels that the soil management influence is commonly disdained. However, the depletion trend in the rotations is clearly evident. The high K levels, as mentioned before, are common for the northern pampa. To Simonson's statments about low fertility of some virgin soils it can be added here that maybe many people do not yet realize that some soils, as the Castellanos series, and the Mollisols of the northern pampa, have high fertility levels independent of the soil management given in more than 50 years and without fertilizer additions.

Table 4. S and micronutrient contents of Mollisols under different managements

Horizon	Treatment: Virgin	Treatment: Grazing Rotation	Treatment: Agriculture Rotation	Desirable Level
	S (SO_4) kg/ha (1)			
Ap or A11	13.2	16.7	14.9	>16.5 (3)
A12	13.2	13.8	13.8	
	B kg/ha (1)			
Ap or A11	2.5	3.0	3.0	>2.8 (3)
A12	3.5	2.3	2.4	
	Cu ppm (2)			
Ap or A11	9.6	11.2	8.0	
A12	8.0	9.6	8.0	>0.5 (4)
B21t	8.0	9.6	9.6	
	Zn ppm (2)			
Ap or A11	8.3	10.2	8.4	
A12	7.7	7.7	8.6	≥3 (4)
B21t	4.5	3.8	5.1	
	Mn ppm (2)			
Ap or A11	681.6	672.0	748.8	
A12	547.2	538.0	691.2	>10 (4)
B21t	107.2	120.0	120.0	

(1) Analyzed in: University of Wisconsin

(2) Analyzed in: Michigan State University

(3) Used in the State of Wisconsin

(4) Used in the State of Michigan

Soil tillage and its efficiency is controlled by soil water content, particularly in the horizons where the implements work. Atterberg limits are useful to define some soil characteristics and optimum soil water content for tillage. Tillage of soil at water content of friable consistency obtains simultaneously a better soil rupture and granulation, with a minimum structure destruction (35,55). From the Atterberg constants, the most interesting one for use in agriculture of the pampas is the lower plastic limit (LPL). In addition to the puddling hazard when the soil is tilled at moisture contents over the LPL, Terzaghi (62) stated that compression increases rapidly at water contents above this constant.

Table 5 shows the lower values of LPL in A horizons under rotations, with the lowest value in Ap of Grazing Rotation, due to the lower colloidal and organic matter content. This is due to soil management and as a consequence it probably increases the puddling hazard, because after each soaking rain or soil saturation, a greater desiccation is necessary to avoid soil puddling by tilling the soil above the LPL.

Due to common soil physical properties, climate and early soil plowing it is easy to find fields with undesirable effects of tillage. In another of the senior author's papers (39) some micromorphology study results and the effect of pressure on wet soils are given. The harmful tillage effect due to excess of water content is not so important in North America and Europe due to the desirable effect produced by freezing and thawing on soil structure. Unfortunately this is not true in the northern pampa of Argentina. The puddling

Table 5. Atterberg limits, organic matter and clay contents of Mollisols under different managements

Treatment	Horizon	UPL	LPL	PI	Organic Matter	Clay
					%	%
	A11	37.0	28.9	8.1	3.93	31.34
Virgin	A12	36.7	27.3	9.4	3.17	30.87
	B21t	41.0	21.7	19.3	0.59	50.03
	Ap	30.5	24.9	5.6	2.65	26.33
Grazing Rotation	A12	31.3	25.3	6.0	2.88	26.29
	B21t	44.5	24.6	19.9	1.04	51.35
	Ap	32.0	27.2	4.8	3.14	27.46
Agriculture Rotation	A12	31.5	25.9	5.6	2.85	27.36
	B21t	42.5	24.6	17.9	1.15	53.82

UPL - Upper plastic Limit

LPL - Lower plastic limit

PI - Plasticity index

is also produced by animal trampling, that can reach even to the A12 horizon.

Since soil porosity is directly related to structure, and the mollic epipedons in the northern pampa have commonly lost their natural granular structure, there is a need to study porosity and its evolution. In other papers (41,52), total porosity and stability of aggregates were studied and both were found to be reduced due to soil managements such as reported here. Figure 1 shows the results obtained from porosity measurements in thin sections of A1 horizons. For the size of pores measured, Virgin soil has wider pore size distribution, while Grazing Rotation soil shows a reduction in larger pores with a consequent increase in small pore percentage. Agriculture Rotation shows an intermediate situation but with a large increment in finer pores. These observations are similar to the results reported by Swanson and Peterson (59), who used another measuring technique on a Marshall silt loam in Iowa.

The method used to measure porosity in Castellanos silt loam is simple, quick and inexpensive, but it can only be recommended in special studies like the present. Since a slide projector does not have polarized light, there is a limitation to distinguish pores from some sand grains. It is however considered useful for Castellanos series and Mollisols of the northern pampa, because: a) the sand fraction is less than 2%, with a predominance of fine and very fine sand; b) A horizons are impregnated with organic matter and contrast with voids; and c) the method was used for comparison purposes, with the A1 horizon of a defined series with management variations.

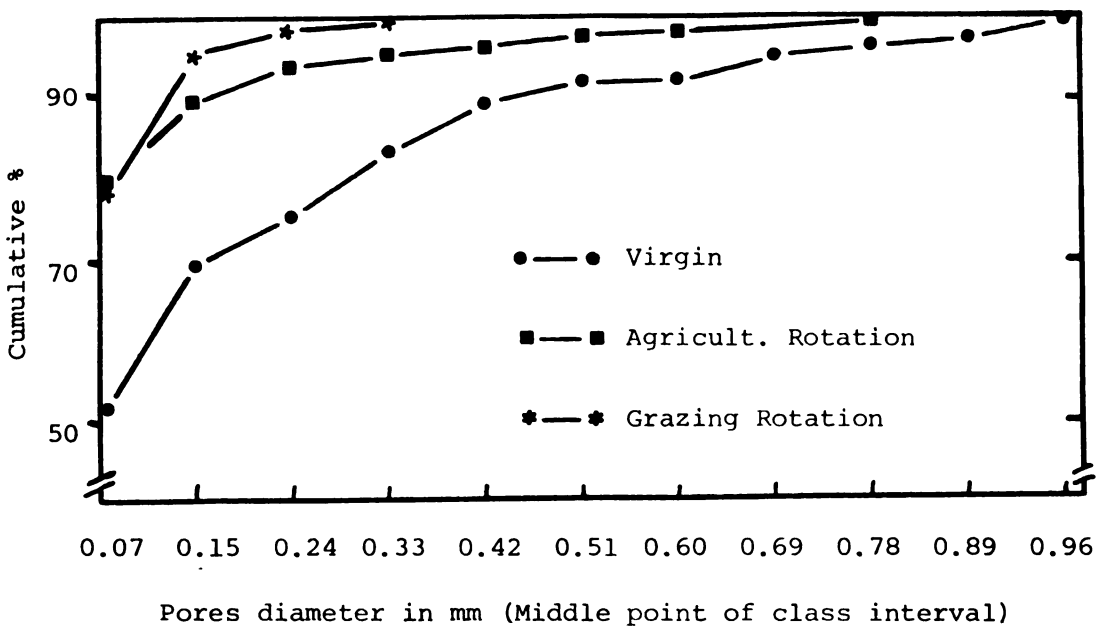

Figure 1. Effect of management on soil porosity in Al horizons.

Due to the importance of soil channels in water and gases movements (12,50), the channels were evaluated independently of other soil pores. Table 6 presents the channel length values observed in the thin sections of A1 horizons. From the average channel length values for A1 (Ap+A12) horizon (8 samples per treatment), there is a reduction to less than half the channel length, in both rotations, compared to the Virgin soil. The values in subhorizons show a minimum in the Ap of Agriculture Rotation which can be attributed to a high number of tillage operations and low aggregate stability (52,60). The lower value for A12 in Grazing Rotation can be a result of animal trampling in wet soil conditions, an effect that is not reduced by plow action because tillage is not present at this level.

Table 6. Channel lengths expressed in mm of channels/cm^2 of thin section in epipedons of Mollisols under different managements

	Treatment		
	Virgin	Grazing Rotation	Agriculture Rotation
Ap	32.04	17.27	6.51
A12	26.01	8.15	17.39
A1(Ap+A12)	29.02	12.71	11.95

CONCLUSIONS

The Mollisols of the northern pampa studied here are Typic Argiudolls and Typic Argialbolls in the fine, mixed, thermic family. They developed on deep loess pampeano, a fine, calcareous material of volcanic and dust origin. The age of parent material deposition at 6 to 9 m was found to be nearly 27,000 years BP. The process of deposition continued until recent time and possibly to the present.

Microclimate, produced as a result of microrelief, influences soil profiles development as different degrees of maturity. In the convex area are Typic Argiudolls with vertical gradational texture change, while in concave areas the results are Typic Argialbolls with abrupt textural change, plus more clay formation and more clay movement in the soil profile. Also associated with the lower landscape position, Na content is higher than in other positions, a cation that contributes to a solonetzic morphology.

In the more mature profiles, Argialbolls, only 5% of the parent material weight was lost during their evolution. From these results, micromorphological studies and clay gain and loss calculations, it can be concluded that clay movement is more important than clay formation due to weathering in their development.

The actual clay mineral composition, that is similar in all profiles, is: illite with a tendency to increase in amount, crystallinity or both toward the soil surface; allophane and vermiculite, which increase with depth; and a low amount of kaolinite throughout the soil profile and parent materials. This is a result of soil forming factors and soil development processes, such as the volcanic origin of some minerals in parent materials, plus weathering and clay movement.

The high natural fertility of these soils is due to moderate leaching, nutrient recycling by grass vegetation and high contents of clay, fine silt and organic matter. It remains high in spite of agriculture or grazing rotation managements practiced in the area in the last 50 years. These soil managements have produced a reduction in pH, organic matter, exchangeable Ca and Mg, C/N ratio and C.E.C. in Al horizons.

Macro and micromorphological studies complement former field studies and laboratory analyses. They point out that natural soil physical properties reflect marked deterioration due to soil management.

APPENDICES

APPENDIX A

APPENDIX A

Soil Profiles Descriptions

Profile 1. Rafaela silt loam

Location: Rafaela Experimental Station, Rafaela, Santa Fe, Section 2, Plot 2, 250 m W and 130 m N of SE corner.

Soil Classification: Typic Argiudoll, fine, mixed, thermic.

Vegetation: Alfalfa, rye-grass, bromus sp, stipa sp.

Drainage: Well drained.

Slope: 0.5%, ENE.

Elevation: 95 m.

Horizon	Depth (cm)	Description
Ap	0-12	Very dark grayish brown (10YR 3/2) moist; grayish brown (10YR 5/2) dry; silt loam; moderate, fine granular structure; friable; medium acid; abrupt smooth boundary.
A12	12-23	Very dark grayish brown (10YR 3/2) moist; grayish brown (10YR 5/2) dry; silt loam; moderate, fine, granular structure; friable; slightly acid; clear smooth boundary.
A3	23-29	Dark brown (10YR 3/3) moist; brown (10YR 5/3) dry; silty clay loam; moderate, medium subangular

		blocky structure; friable; slightly acid; clear smooth boundary.
B1	29-36	Brown-dark brown (10YR 4/3) moist; brown (10YR 5/3) dry; silty clay loam; moderate medium angular blocky structure; friable; slightly acid; abrupt wavy boundary.
B21t	36-68	Brown-dark brown (7.5YR 4/2) moist; brown (7.5YR 5/4) dry; silty clay; strong, medium prismatic structure; firm; neutral; gradual smooth boundary.
B22t	68-90	Brown-dark brown (7.5YR 4/4) moist; brown (7.5YR 5/4) dry; silty clay; strong, medium, prismatic structure; very firm; mildly alkaline; gradual smooth boundary.
B3	90-115	Brown-dark brown (7.5YR 4/4) moist; light brown (7.5YR 6/4) dry; silty clay loam; moderate, medium, subangular blocky structure; firm; mildly alkaline; diffuse smooth boundary.
C1	115-132+	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay loam; structureless; friable; mildly alkaline.

Profile 2. Lehmann silt loam

Location: Rafaela Experimental Station, Rafaela, Santa Fe, Section 2, Plot 2, 32 m NE of profile 1.

Soil Classification: Typic Argiudoll, fine, mixed, thermic.

Vegetation: Alfalfa, rye-grass, bromus sp, stipa sp.

Drainage: Well drained.

Slope: 0.5% ENE.

Elevation: 95 m.

Horizon	Depth (cm)	Description
Ap	0-14	Dark grayish brown (10YR 3.5/2) moist; grayish brown (10YR 5/2) dry; silt loam; weak, medium granular structure; friable; medium acid; abrupt smooth boundary.
A12	14-23	Very dark grayish brown (10YR 3/2) moist; grayish brown (10YR 5/2) dry; silt loam; moderate, medium subangular blocky structure; friable; medium acid; clear smooth boundary.
B+A	23-30	Dark grayish brown (10YR 4/2) moist; grayish brown-brown (10YR 5/2.5) dry; silty clay loam; moderate, coarse, subangular blocky structure; firm; slightly acid; abrupt, wavy boundary.
B21t	30-65	Brown-dark brown (7.5YR 4/2) moist; brown (7.5YR 5/4) dry; silty clay; strong, medium, prismatic and columnar structure; firm; neutral; gradual, smooth boundary.
B22t	65-99	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay; strong, medium, prismatic structure; very firm; mildly alkaline; gradual, smooth boundary.
B3	99-128	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay; moderate, medium, subangular blocky structure; firm, mildly alkaline; diffuse, smooth boundary.

C1	128-143+	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay; structureless; friable; mildly alkaline.

Profile 3. Castellanos silt loam under Grazing Rotation

Location: Rafaela Experimental Station, Rafaela, Santa Fe, Section 2, Plot 2, 50 m E of profile 1.

Soil Classification: Typic Argialboll, fine, mixed, thermic.

Vegetation: Alfalfa, rye-grass, bromus sp, stipa sp.

Drainage: Well drained.

Slope: 0.5% ENE.

Elevation: 95 m.

Horizon	Depth (cm)	Description
Ap	0-12	Very dark grayish brown (10YR 3/2) moist; grayish brown (10YR 5/2) dry; silt loam; weak, medium, granular structure; friable; medium acid; abrupt, smooth boundary.
A12	12-18	Very dark grayish brown (10YR 3/2) moist; grayish brown (10YR 5/2) dry; silt loam; moderate, medium, subangular blocky structure; friable; medium acid; clear, smooth boundary.
A2	18-22	Dark grayish brown (10YR 4/2) moist; light brownish gray (10YR 6.5/2) dry; silt loam; weak, fine, subangular blocky structure (also structureless in parts); very friable; slightly acid; abrupt, wavy boundary.

B21t	22-53	Brown-dark brown (7.5YR 4/2) moist; light brown-brown (7.5YR 5.5/4) dry; silty clay; strong, medium, columnar structure; firm; neutral; gradual, smooth boundary.
B22t	53-66	Brown-dark brown (7.5YR 4/4) moist; light brown (7.5YR 6/4) dry; silty clay; strong, medium, prismatic structure; very firm; mildly alkaline; gradual, smooth boundary.
B3	66-102	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay; moderate, medium, subangular blocky structure; firm; mildly alkaline; diffuse, smooth boundary.
C1	102-132↓	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay loam; structureless; friable; mildly alkaline.

Profile 4. Castellanos silt loam under Agriculture Rotation.

Location: Rafaela Experimental Station, Rafaela, Santa Fe, Section 3, Experimental plots, 150 m W of meteorological observatory.

Soil Classification: Typic Argialboll, fine, mixed, thermic.

Vegetation: bare, plowed.

Drainage: Well drained.

Slope: 0.5% E.

Elevation: 94 m.

Horizon	Depth (cm)	Description
Ap	0-11	Dark grayish brown (10YR 4/2) moist; light brownish gray (10YR 6/2) dry; silt loam; structureless; very

		friable; medium acid; abrupt, smooth boundary.
A12	11-21	Very dark grayish brown (10YR 3/2) moist; grayish brown-light grayish brown (10YR 5.5/2) dry; silt loam; weak, medium, subangular blocky structure; friable; strongly acid; clear, smooth boundary.
A2	21-26	Dark grayish brown (10YR 4/2) moist; gray-light brownish gray (10YR 6/1.5) dry; silt loam; weak, fine, subangular blocky structure (also structureless in parts); very friable; slightly acid; abrupt, wavy boundary.
B21t	26-63	Brown-dark brown (7.5YR 4/2) moist; brown (7.5YR 5/4) dry; silty clay; strong, coarse columnar structure; very firm; neutral; gradual, smooth boundary.
B22t	63-93	Brown-dark brown (7.5YR 4/4) moist; light brown (7.5YR 6/4) dry; silty clay; strong coarse, prismatic structure; very firm; mildly alkaline; gradual, smooth boundary.
B3	93-109	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay; moderate, medium, subangular blocky structure; firm; mildly alkaline; gradual, smooth boundary.
Cca	109-141↓	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay loam; structureless; friable; strongly alkaline.

Profile 5. Virgin soil

Location: Rafaela Experimental Station, Rafaela, Santa Fe, Section 3, park, 230 m S of main building.

Soil Classification: Typic Argiudoll, fine, mixed, thermic.

Vegetation: Cynnodon sp, bromus sp, papalum dilatatum, stipa spp, introduced trees.

Drainage: Well drained.

Slope: 0.5% E.

Elevation: 94 m.

Horizon	Depth (cm)	Description
A11	0-15	Very dark grayish brown (10YR 3/2) moist; grayish brown (10YR 5/2) dry; silty clay loam; moderate, fine-medium, subangular blocky structure; friable; neutral; clear, wavy boundary.
A12	15-25	Very dark grayish brown (10YR 3/2) moist; grayish brown (10YR 5/2) dry; silty clay loam; moderate, medium, subangular blocky structure; friable; neutral; clear wavy boundary.
B+A	25-31	Dark grayish brown (10YR 4/2) moist; light brownish gray (10YR 6/2) dry; silty clay loam; weak, fine, subangular blocky structure (also some parts are structureless); friable; slightly acid; clear, wavy boundary.
B1	31-41	Brown-dark brown (10YR 4/3) moist; brown (10YR 5/3) dry; silty clay loam; moderate medium, subangular blocky structure; firm; slightly acid; abrupt, wavy boundary.

B21t	44-72	Dark grayish brown (10YR 4/2) moist; brown (7.5YR 5/4) dry; silty clay; strong, medium, prismatic (also some columns) structure; firm; neutral; clear, wavy boundary.
B22t	72-110	Dark yellowish brown (10YR 4/4) moist; light brown (7.5YR 6/4) dry; silty clay; strong, medium, prismatic structure; very firm; neutral; gradual, smooth boundary.
B3	110-140	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay; moderate, medium, subangular blocky structure; firm; neutral; gradual, smooth boundary.
C1	140-159↓	Brown (7.5YR 5/4) moist; light brown (7.5YR 6/4) dry; silty clay loam; structureless; friable; neutral.

APPENDIX B

APPENDIX B

Physical and chemical data for soil profiles

Table B1. Physical and chemical data for profile 1, Rafaela series.

Property	Horizon and depth in cm							
	Ap, 0–14	A12, 10–23	A3, 23–29	B1, 29–36	B21t, 36–68	B22t, 68–90	B3, 90–115	C, 115–132+
Particle size dist. (%)								
Very coarse sand, 2–1 mm	0	0	0	0	0	0	0	0
Coarse sand, 1–0.5	00	0	0	0	0	0	0	0
Medium sand, 0.5–0.25	0.02	0.02	0.01	0.01	0	0.01	0.02	0.03
Fine sand, 0.25–0.1	0.23	0.23	0.19	0.22	0.15	0.32	0.69	0.85
Very fine sand, 0.1–0.05	1.61	1.43	1.50	1.48	1.08	1.41	2.32	2.41
Coarse silt, 0.05–0.02	28.11	27.53	27.63	25.47	21.30	19.77	21.66	23.01
Fine silt, 0.02–0.002	42.05	41.24	39.16	35.85	29.68	29.23	35.19	35.41
Clay, < 0.002	27.98	29.55	31.51	36.98	47.79	49.26	39.90	38.28
Bulk density, (g/cm^3)	1.36	1.30	1.33	1.31	1.59	1.58	1.36	
Organic matter (%)	2.70	2.44	1.45	0.91	0.73	0.30	0.15	0.08
Carbon (%)	1.57	1.42	0.84	0.53	0.42	0.17	0.09	0.05
Total nitrogen (% N)	0.161	0.140	0.087	0.070	0.077	0.054	0.035	0.026
C/N	9.8	10.2	9.7	7.6	5.5	3.2	2.6	1.9
$CaCO_3$ equivalent (%)	0	0	0	0	0	0	0	0
Exchangeable cations								
Calcium (m.e./100 g)	7.98	8.74	8.38	9.52	13.40	14.84	13.68	12.54
Magnesium "	2.15	2.52	2.66	3.59	5.49	6.46	5.76	5.57
Sodium "	0.07	0.07	0.10	0.22	0.59	1.27	1.45	1.94
Potassium "	2.52	1.94	1.70	1.90	1.63	3.58	3.79	3.80
C.E.C. "	16.00	16.22	15.18	17.96	24.74	27.99	27.78	23.79
Saturation (%)	79.5	81.8	84.6	84.8	85.7	93.5	88.8	100
pH (1:1)	6.0	6.1	6.2	6.3	6.8	7.4	7.4	7.7
Electrical cond. (mmhos/cm)	0.7	0.8						0.4

Table B2. Physical and chemical data for profile 2, Lehmann series.

Property	Horizon and depth in cm						
	Ap, 0–14	A12, 14–23	B&A, 23–30	B21t, 30–65	B22t, 65–99	B3, 99–128	C, 128–143+
Particle size dist. (%)							
Very coarse sand, 2–1 mm	0	0	0	0	0	0	0
Coarse sand, 1–0.5	0	0	0	0	0	0	0.01
Midium sand, 0.5–0.25	0.02	0.02	0.01	0	0.01	0.02	0.02
Fine sand, 0.25–0.1	0.22	0.19	0.17	0.08	0.30	0.50	0.59
Very fine sand, 0.1–0.05	1.36	1.30	1.24	0.63	1.36	1.86	2.09
Coarse silt, 0.05–0.02	26.62	28.49	26.85	17.42	19.65	22.29	22.61
Fine silt, 0.02–0.002	43.45	41.65	42.52	28.94	29.19	31.01	33.27
Clay , <0.002	28.33	28.36	29.32	52.91	49.49	44.32	41.41
Bulk density (g/cm^3)	1.39	1.44	1.34	1.51	1.38	1.33	
Organic matter (%)	2.91	2.61	1.62	1.10	0.36	0.18	0.22
Carbon (%)	1.69	1.52	0.94	0.64	0.21	0.10	0.13
Total nitrogen (% N)	0.162	0.145	0.086	0.080	0.054	0.045	0.048
C/N	10.4	10.5	10.9	8.0	3.9	2.2	2.7
$CaCO_3$ equivalent (%)	0	0	0	0	0	0	0
Exchangeable cations							
Calcium (m.e./100 g)	8.24	8.30	7.66	14.48	14.58	13.03	12.18
Magnesium "	2.29	2.51	2.53	6.22	6.45	5.65	5.25
Sodium "	0.09	0.17	0.23	1.13	2.40	2.66	3.05
Potassium "	2.42	1.74	1.58	2.93	3.40	3.42	3.21
C.E.C. "	16.24	15.75	14.84	27.17	28.74	25.45	24.80
Saturation (%)	80.3	80.8	80.9	91.1	93.4	97.3	95.5
pH (1:1)	6.0	6.0	6.1	6.7	7.6	7.6	7.6
Electrical cond. (mmhos/cm)	0.8	0.8				0.8	0.7

Table B3. Physical and chemical data for profile 3, Castellanos series and loess samples.

Property	Horizon and depth in cm											
	Ap, 0-12	A12, 12-18	A2, 18-22	B21t, 22-53	B22t, 53-66	B3, 66-102	C1, 102-132	C2, 300	C3, 450	C4, 600	C5, 750	C6, 900
Particle size dist. (%)												
Very coarse sand, 2-1 mm	0	0	0	0	0	0	0	0	0	0	0	0
Coarse sand, 1-0.5	0	0	0	0	0	0	0	0	0	0	0	0
Medium sand, 0.5-0.25	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.09	0.03	0.03	0.16
Fine sand, 0.25-0.1	0.22	0.22	0.23	0.13	0.20	0.39	0.70	0.39	0.60	0.36	0.31	1.00
V. fine sand, 0.1-0.05	1.61	1.47	1.58	0.94	1.08	1.53	2.02	1.09	1.62	1.04	0.94	2.05
Coarse silt, 0.05-0.02	29.45	29.63	29.20	18.23	17.67	19.47	20.95	22.43	24.13	19.71	19.30	21.12
Fine silt, 0.02-0.002	42.38	42.38	42.78	29.33	28.70	30.97	36.02	33.13	31.38	29.98	28.51	40.98
Clay, < 0.002	26.33	26.29	26.19	51.35	52.84	47.62	40.30	42.91	42.18	48.88	50.91	34.69
Bulk density (g/cm^3)	1.50	1.50	1.34	1.65	1.51	1.39						
Organic matter (%)	2.65	2.88	1.65	1.04	0.63	0.36	0.18	0.24	0.16	0.09	0.08	0
Carbon (%)	1.54	1.67	0.96	0.60	0.37	0.21	0.10	0.14	0.09	0.05	0.05	0
Total nitrogen (% N)	0.148	0.136	0.073	0.085	0.063	0.048	0.041					
C/N	10.4	12.3	13.2	7.2	5.9	4.3	2.4					
$CaCO_3$ equivalent (%)	0	0	0	0	0	0	0	1.66	1.69	1.37	2.17	1.10
Exchangeable cations												
Calcium (m.e./100 g)	7.04	7.94	7.07	14.68	14.42	13.54	11.02					
Magnesium "	1.93	2.39	2.50	6.83	7.06	6.20	5.37					
Sodium "	0.14	0.19	0.44	2.18	2.88	3.31	4.12	2.89	3.10	6.02	6.21	7.90
Potassium "	2.06	1.49	1.12	3.04	3.65	3.78	3.47	3.50	3.39	3.40	3.42	4.50
C.E.C. "	15.30	15.37	13.76	29.97	30.66	28.07	24.61	25.79	26.00	29.09	29.51	31.50
Saturation (%)	73.0	77.6	80.9	89.2	91.4	95.6	97.4	100	100	100	100	100
pH (1:1)	5.8	5.9	6.2	7.0	7.4	7.7	7.4	8.7	8.9	8.7	8.7	8.8
Electrical cond. (mmhos/cm)	0.7	0.8	0.5	0.6	0.8	1.2	1.8	1.0	0.9	0.8	1.0	1.1

Table B4. Physical and chemical data for profile 4, Castellanos series under Agriculture Rotation.

Property	Horizon and depth in cm						
	Ap, 0-10	A12, 10-21	A2, 21-26	B21t, 26-63	B22t, 63-93	B3, 93-109	C, 109-141 +
Particle size dist. (%)							
Sand, 2-0.05 mm	1.71	1.72	1.82	1.14	2.04	2.52	4.22
Coarse silt, 0.05-0.02	27.89	28.62	28.86	17.99	19.31	21.32	25.13
Fine silt, 0.02-0.002	42.94	42.30	44.35	27.05	31.43	32.68	34.66
Clay, <0.002	27.46	27.36	24.97	53.82	47.21	43.48	35.98
Bulk density (g/cm^3)	1.40	1.38	1.35	1.62	1.57	1.46	
Organic matter (%)	3.14	2.85	1.41	1.15	0.36	0.24	0.23
Carbon (%)	1.83	1.66	0.82	0.67	0.21	0.14	0.13
Total nitrogen (% N)	0.148	0.154	0.074	0.081	0.062	0.047	0.041
C/N	12.4	10.8	11.1	8.3	3.4	3.0	3.2
$CaCO_3$ equivalent (%)	0	0	0	0	0	0	1.27
Exchangeable cations							
Calcium (m.e./100 g)	7.00	6.38	6.87	15.16	15.12	12.45	
Magnesium "	1.90	1.69	1.99	6.88	6.61	6.07	
Sodium "	0.07	0.08	0.31	1.76	3.03	3.68	4.06
Potasium "	2.24	2.24	1.14	3.28	3.77	3.90	3.82
C.E.C. "	15.70	14.91	12.46	30.00	30.14	24.33	23.06
Saturation (%)	71.4	69.6	82.7	90.3	94.7	100	100
pH (1:1)	5.6	5.5	6.2	7.2	7.7	7.6	8.5
Electrical cond. (mmhos/cm)	0.9	0.8	0.5	0.7	1.1	1.4	2.0

Table B4. Physical and chemical data for profile 4, Castellanos series under Agriculture Rotation.

Property	Horizon and depth in cm						
	Ap, 0-10	A12, 10-21	A2, 21-26	B21t, 26-63	B22t, 63-93	B3, 93-109	C, 109-141 +
Particle size dist. (%)							
Sand, 2-0.05 mm	1.71	1.72	1.82	1.14	2.04	2.52	4.22
Coarse silt, 0.05-0.02	27.89	28.62	28.86	17.99	19.31	21.32	25.13
Fine silt, 0.02-0.002	42.94	42.30	44.35	27.05	31.43	32.68	34.66
Clay, < 0.002	27.46	27.36	24.97	53.82	47.21	43.48	35.98
Bulk density (g/cm^3)	1.40	1.38	1.35	1.62	1.57	1.46	
Organic matter (%)	3.14	2.85	1.41	1.15	0.36	0.24	0.23
Carbon (%)	1.83	1.66	0.82	0.67	0.21	0.14	0.13
Total nitrogen (% N)	0.148	0.154	0.074	0.081	0.062	0.047	0.041
C/N	12.4	10.8	11.1	8.3	3.4	3.0	3.2
$CaCO_3$ equivalent (%)	0	0	0	0	0	0	1.27
Exchangeable cations							
Calcium (m.e./100 g)	7.00	6.38	6.87	15.16	15.12	12.45	
Magnesium "	1.90	1.69	1.99	6.88	6.61	6.07	
Sodium "	0.07	0.08	0.31	1.76	3.03	3.68	4.06
Potasium "	2.24	2.24	1.14	3.28	3.77	3.90	3.82
C.E.C. "	15.70	14.91	12.46	30.00	30.14	24.33	23.06
Saturation (%)	71.4	69.6	82.7	90.3	94.7	100	100
pH (1:1)	5.6	5.5	6.2	7.2	7.7	7.6	8.5
Electrical cond. (mmhos/cm)	0.9	0.8	0.5	0.7	1.1	1.4	2.0

Table B5. Physical and chemical data for profile 5, Virgin soil.

Property	Horizon and depth in cm							
	A11, 0-15	A12, 15-25	B&A, 25-31	B1, 31-44	B21t, 44-72	B22t, 72-110	B3, 110-140	C, 140-159 +
Particle size dist. (%)								
Sand, 2-0.05 mm	1.79	1.53	1.55	1.45	1.31	1.57	2.53	5.28
Coarse silt, 0.05-0.02	23.60	25.00	22.82	22.84	18.70	18.36	20.72	26.15
Fine silt, 0.02-0.002	43.27	42.61	41.26	37.14	29.96	27.97	30.60	34.65
Clay, < 0.002	31.34	30.87	34.36	38.57	50.03	52.10	46.16	33.92
Bulk density (g/cm^3)	1.30	1.35	1.20	1.39	1.46	1.52	1.35	
Organic matter (%)	3.93	3.17	2.19	1.65	0.59	0.47	0.28	0.10
Carbom (%)	2.28	1.84	1.27	0.96	0.34	0.27	0.16	0.06
Total nitrogen (% N)	0.171	0.139	0.097	0.083	0.065	0.057	0.046	0.039
C/N	13.3	13.2	13.1	11.6	5.2	4.7	3.5	1.5
$CaCO_3$ equivalent (%)	0	0	0	0	0	0	0	0
Exchangeable cations								
Calcium (m.e./100 g)	11.93	11.45	10.96	11.26	15.80	16.01	14.35	13.02
Magnesium "	3.23	2.88	3.04	3.62	5.54	5.52	4.80	4.05
Sodium "	0.06	0.07	0.08	0.07	0.10	0.17	0.11	0.17
Potassium "	2.33	1.97	1.69	1.98	2.48	2.59	2.74	2.68
C.E.C. "	20.63	20.26	20.03	21.26	28.50	28.36	20.37	22.80
Saturation (%)	80.7	80.8	78.7	79.6	83.9	85.6	83.4	87.4
pH (1:1)	6.7	6.7	6.4	6.5	6.6	6.6	6.6	6.7
Electrical cond. (mmhos/cm)	0.7	0.7					0.5	0.4

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