Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina

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Abstract

Temperature and precipitation have strong effects on soil processes. The Pampa and the Chaco are vast plains with soils mainly derived from loess. Our objective was to study the effects of temperature and precipitation of both regions on selected soil properties. Using data from soil surveys for ca. 65 Mha, we defined 40 geographic units of ca. 1.6 Mha each. Organic carbon content (g cm⁻³), solum thickness and clay content were averaged for each unit. Temperature, precipitation and potential evapotranspiration were obtained from climatic records. Carbon inputs to the different soil layers were estimated by calculating net primary productivity of ecosystems and partitioning coefficients of above and belowground biomass. Inputs were affected by a retention factor taking into account temperature effects on organic matter decomposition. Soil organic carbon increases with higher precipitation and decreases with higher temperature. Consequently, the organic carbon content in the top 0–50 cm soil layer is positively correlated with the precipitation/temperature ratio (potential model \( r^2 = 0.693, \ P < 0.001 \)). Carbon inputs to the soil explained 72% of organic carbon variations. Mean turnover time of soil carbon was estimated to be 14 yr. Solum thickness and clay amount (g cm⁻³) are not associated with temperature but the ratio precipitation/potential evapotranspiration explained 85% (\( P < 0.001 \)) of the variation in the former and 79% (\( P < 0.001 \)) in the later. Soils are deeper and with higher clay contents where this ratio increases, a consequence of available water for pedogenic processes. Climate is a main soil forming factor in the Pampa and Chaco regions. Clay neoformation and possible future trends of organic carbon under different climatic global change scenarios were estimated. © 1998 Elsevier Science B.V.

Keywords: organic carbon; clay; climate; soil development; climatic change

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1. Introduction

After the works of Dokuchaev and Hilgard, performed last century, it is known that climate has strong effects on several soil properties (Brady, 1990). Quantitative relationships between temperature and moisture on soil organic matter and clay (particles < 2 µm) contents were established several decades ago (Jenny, 1941). It has been established that the interaction between temperature and precipitation regulates the soil organic carbon content in natural ecosystems, by determining the type of biome and soil (Post et al., 1982). This regulation occurs through the influence on litter production and soil organic matter mineralization. Geographical distribution of soil organic carbon follows precipitation trends. This is due to the fact that plant debris inputs are regulated by net primary production, a function of water availability (Webb et al., 1978). With higher temperatures, carbon content in the soil decreases because of more intense organic matter mineralization (Cole et al., 1993; Kirschbaum, 1995). On the other hand, when other factors are constant, soil clay content increases with precipitation and temperature rises, a consequence of rock weathering and clay neoformation (Jenny, 1941).

The soils of the Pampa and Chaco Plains developed mainly from loessic material and to a lesser degree from fluvial sediments (Teruggi, 1957; Iriondo, 1993). The soils mineralogy varies over the region, but usually illite is the dominant clay mineral (Lavado and Camilion, 1984). Soil temperature regimes in the area range from thermic to hyperthermic and soil moisture regimes from udic to ustic, bordered in the west by an aridic moisture regime with areas having aquic moisture regime widespread (Van Wambeke and Scoppa, 1976).

Due to climatic differences and similar parent materials the Pampa and Chaco plains are adequate to quantify and forecast the effects of climate on soil properties. The objectives of this study were (1) to determine the importance of the climatic factor in the genesis of local soils and (2) to estimate clay neoformation and possible future changes of the soil organic carbon level under climatic change scenarios.

2. Materials and methods

2.1. Description of the study area

The Argentinean Pampa covers the vast plains of the Provinces of Buenos Aires, La Pampa, Cordoba, Santa Fe, San Luis and the east of Entre Rios. This area runs from 28 to 40°S and its natural vegetation consist of grasslands in which graminaceous species are dominant. The region is flat or slightly rolling and is formed mainly of a deep mantle of loessic sediments (Soriano et al., 1991). The Argentinean part of the Chaco Plain comprises the Provinces of
Table 1
Range of some characteristics of the main soil orders found in the Pampa and Chaco

<table>
<thead>
<tr>
<th>Soil order</th>
<th>Depth 0–50 cm</th>
<th>Solum depth (cm)</th>
<th>clay (g kg⁻¹)</th>
<th>organic carbon (g kg⁻¹)</th>
<th>clay (g kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aridisols</td>
<td>2–8</td>
<td>50–260</td>
<td>5–70</td>
<td>50–260</td>
<td></td>
</tr>
<tr>
<td>Entisols</td>
<td>1–17</td>
<td>30–560</td>
<td>10–75</td>
<td>30–530</td>
<td></td>
</tr>
<tr>
<td>Mollisols</td>
<td>5–26</td>
<td>100–440</td>
<td>25–200</td>
<td>120–540</td>
<td></td>
</tr>
<tr>
<td>Alfisols</td>
<td>3–11</td>
<td>150–610</td>
<td>42–150</td>
<td>90–620</td>
<td></td>
</tr>
</tbody>
</table>

Chaco, Formosa and the east of Salta. It runs from 24 to 28°S and is characterized by subtropical deciduous forest, savannas and swamps. Loess mantles and fluvial sediments are the main parent soil materials (Iriondo, 1993). The main Soil Taxonomy (Soil Survey Staff, 1994) orders found are Mollisols in the Pampa, Alfisols in the Chaco, Entisols and Aridisols in the west of both regions. Their general characteristic are shown in Table 1. In the wet borders of the Pampa, there are areas of Vertisols, not significant in the whole region.

The annual average air temperature ranges from 14°C in the south to 23°C in the north and precipitation ranges from 200 mm in the west to 1200 in the east (Fig. 1). About one third of the area is at present used for agriculture or intensive livestock production using seeded pastures (INDEC, 1994). The area constitutes one of the main croplands of the Southern Hemisphere.

2.2. Procedure to handle soil data

The data used were taken from soil surveys of the Provinces of La Pampa (INTA et al., 1980), Buenos Aires (INTA, 1989), Santa Fe (INTA and MAG-PSF, 1981, 1983), Chaco (OEA and INCYTH, 1975) and Formosa (SRNE-Prov. Formosa, 1980). The area is ca. 1700 km long from north to south and ca. 1000 km from east to west (Fig. 1). These five Argentinean provinces which occupy ca. 65 Mha, were divided into 40 geographic units of ca. 1.6 Mha. Each unit was uniform in annual average precipitation and temperature but independent of geomorphology, vegetation or soil taxonomy considerations. On the basis of the soil profiles characteristics described in soil surveys and their corresponding area, the weighed average value of organic carbon (Walkley–Black method, Allison, 1965) and clay for the 40 geographic units were calculated. Each value obtained was the mean carbon or clay content of the geographic unit, and includes the mean of all the soils within the unit weighed by the area that occupied. The method allowed an estimate to be made of the total carbon pool of the region. The organic carbon and clay contents were integrated for 0–20, 20–50 and 0–50 cm depth layers. Due to the lack of complete bulk density data of different soil layers, they were estimated from texture and organic carbon contents (Rawls, 1983). The method used was highly correlated to the limited
local data for bulk density. The clay amount for the entire solum was calculated by the same procedure, taken into account clay content and bulk density at different depths. When B horizons were absent, the solum depth was fixed as the bottom of the AC horizon. Soil profiles where lithologic discontinuities were identified or where the C horizons were not described, were not taken into account. As a consequence, the clay amount could be calculated for the entire solum only for 28 geographic units. The weighed average data of those units corresponded to areas of ca. 1 ± 0.2 Mha. Clay neoformation in the soil was estimated as the difference in clay content of the solum and the C horizon (Academia Sinica, 1990).

2.3. Procedure to handle climate data and estimation of carbon inputs

Climatic data were obtained from published records. The average annual precipitation in each unit was calculated for the period 1901–1950 (SMN, 1954) plus the period 1951–1990 (Sierra et al., 1994). The average annual air temperature was calculated for the period 1901–1950 (SMN, 1954), the only available averaged record. The potential evapotranspiration was estimated from
maps using the Penman and Papadakis methods (Damario and Catán, 1982).
Both methods were highly correlated ($r^2 = 0.843$, $P < 0.001$) although, the
former gave higher estimations. In order to avoid methodological deviations,
both potential evapotranspiration estimations were averaged in each unit.

For estimation of net primary production the Chikugo and the Efimova
models (Uchijima and Seino, 1987) were used. Both methods showed remark-
able similarities ($r^2 = 0.944$, $P < 0.001$). However, in areas with less than 500
mm precipitation, the Efimova model gave higher values (50–100%) than the
Chicugo model. In the same way as it was done with the evapotranspiration,
results from both models were averaged. Net primary production was partitioned
in above and belowground biomass production using for the steppes in the arid
environments a ratio above ground/below ground biomass of 0.20 (Liang et al.,
1989), for grassland of semiarid to humid environments a ratio of 1.5 and for
forest areas a ratio of 4 (Mueller and Kramer, 1994). Distribution of root
biomass in depth was partitioned considering that under steppe conditions 45%
was located in the 0–20 cm layer and 35% in the 20–50 cm layer (Jackson et
al., 1996). For grasslands it was estimated that 70% of roots biomass was
allocated in the 0–20 cm layer and 25% in the 20–50 cm layer and for forest, 50
and 30%, respectively (Jackson et al., 1996). Plant debris carbon was assumed
to be 45%. Carbon inputs to the 0–20 cm layer were considered as the sum of
aboveground net primary production and roots grown in that layer. Carbon
inputs to the 20–50 cm layer were only roots.

2.4. Statistical methods

Relations between soil characteristics and climate were analyzed by regres-
sion methods. Several functions were tested; the potential model ($PM_{\text{y}} = ax^b$)
proved to be the best to adjust using the least squares criteria. Unless otherwise
stated, the later was used in all the regressions. The significance was checked by
the $F$ test.

3. Results and discussion

3.1. Climate and organic carbon relationship

While soil organic carbon level showed no significant relationship with
temperature, it showed correlation with precipitation ($PM \ r^2 = 0.550$, $P <$
0.001). Considering only the units with precipitation between 800 and 1000 mm,
it was found that at higher temperatures, there were lower concentrations of
organic carbon (Fig. 2A). Likewise, for units with temperature between 14 and
16°C, organic carbon was positively associated with precipitation (Fig. 2B). An
index that combine the effects of precipitation and temperature on the content of
Fig. 2. Relationships between organic carbon in the 0–50 cm soil layer and mean annual temperature (A) and precipitation (B). Equations adjust to dots which correspond to geographic units with precipitation ranging from 800 to 1000 mm (A) and with temperatures from 14 to 16°C (B). Circles correspond to geographic units with other precipitation and temperature than the ranges mentioned.

carbon is the precipitation/temperature ratio. This ratio was highly correlated with organic carbon, considering all the 40 geographic units (Fig. 3). This precipitation/temperature ratio was able to explain 69% of carbon content.

Fig. 3. Correlation between organic carbon content of soils of the Pampa and Chaco regions in the 0–50 cm depth and the precipitation/temperature ratio.
variations in the Pampa and Chaco soils. In other parts of the world also, a close association between the precipitation/temperature ratio and the level of soil organic matter was also observed (Theng et al., 1989; Tate, 1992).

Carbon content usually decreases exponentially with depth (Oades, 1995) as a consequence of higher carbon inputs in topsoil. The upper soil layer receives organic matter from the aboveground net primary production and a greater portion of the root production. The carbon level in soil is a direct consequence of plant debris inputs (Cole et al., 1993). In our study, this effect was found when the estimated carbon inputs to different soil layers were affected by a retention factor, that accounted for the effect of temperature on organic matter decomposition. A close association was found between carbon inputs and soil carbon content (Fig. 4). The retention factor was calculated using the equation in Fig. 2A and giving a value of 1 to a mean annual temperature of 14°C. As temperature raises, the organic carbon content of the soils in relation to the carbon level of soils at 14°C was the retention factor. Similar results were obtained using the decomposition factor (% decrease in soil carbon °C⁻¹) calculated by Kirschbaum (1995). This method for correction of litter inputs takes into account that under the same net primary production different organic

![Fig. 4. Carbon retention factor and relation between carbon inputs affected by the retention factor and soil organic carbon.](image)
carbon contents in the soil may be found if the temperature of the regions are different, because of different decomposition rates.

The particle size distribution can regulate the level of organic carbon, irrespective of climate. Within an area climatically homogeneous, an increase in clay content means an increase in soil carbon concentration because of the protecting effect of clays on organic compounds (Burke et al., 1989; Buschiazzo et al., 1991). In some locations a strong correlation between clay and organic carbon concentration has been reported; this being higher than between precipitation and organic carbon (Nichols, 1984). In other locations, precipitation (Sims and Nielsen, 1986) or temperature (Arrouays et al., 1995) were more closely associated with soil carbon than soil texture.

A high correlation between the content of carbon and clay in the 0–50 cm layers was found in the present study (PM $r^2 = 0.671$, $P < 0.001$). However,
the analysis of carbon and clay distribution in depth indicates that in soils belonging to the udic moisture regime, clay tends to accumulate at depth, while organic carbon accumulates in the topsoil. Under ustic moisture conditions, where the distribution of clay was uniform in the 0–50 cm layer, organic carbon was less stratified. As the ecosystem tends to be more humid clay and organic carbon follow opposite trends in their location in the profile (Fig. 5). Conse-

Fig. 6. Turnover time of organic carbon in the Pampas and Chaco soils for the 0–50 cm layer in relation to a precipitation x temperature index.

Fig. 7. Relationships between solum thickness (A) and clay content in the solum (B) with precipitation.
sequently, no significant correlation was found between both elements, considering 80 points (40 geographic units × 2 depths). The turnover time of soil carbon, calculated as the ratio organic soil carbon/annual carbon input, decrease as temperature or precipitation increase. In consequence, a negative relationship was found between the turnover time and the precipitation × temperature index (Fig. 6). Mean turnover time is 14 yr for the region in the 0–50 cm layer. It decreases with depth from 10 yr in the 0–20 cm layer to 50 yr in the 20–50 cm layer. From data of Mueller and Kramer (1994) and Smith and Paul (1990) a 25–35 yr turnover time may be calculated for carbon in grassland soils and 20–25 yr for temperate forest. Our data are lower than these estimations and are a result of the high mean temperatures and precipitations of the region. All data indicate that climate is the main factor in the regulation of the carbon content of these soils because of its influence on plant productivity and carbon mineralization.

3.2. Climate, solum depth and clay content relationships

There were no significant correlations between temperature and solum depth or clay content, either in the solum or in the C horizon. Precipitation was correlated with solum depth and its clay content (Fig. 7), but not with clay content in the C horizon. When the precipitation/potential evapotranspiration ratio was regressed against solum depth and clay content, it explained 85% of variability in the former and 62% of variability in the later (Fig. 8). A significant but weak relation (PM $r^2 = 0.406$, $P < 0.05$) was found between the precipitation/potential evapotranspiration ratio and the clay content in the C horizon. The total quantity of clay in the solum was highly correlated with the precipita-

![Fig. 8. Correlation between solum depth (A) and clay content (B) of the soils of the Pampa and Chaco regions with the precipitation/potential evapotranspiration ratio.](image)
Fig. 9. Association between total clay content of the soils in the solum (A) and clay content corrected for clay in the C horizon (B) of the soils of the Pampa and Chaco regions with the precipitation/potential evapotranspiration ratio.

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produced in soils in a few decades. It has been estimated that if the actual CO₂ concentration in the atmosphere doubled, possibly around 2040, the mean annual temperature of the study area would increase 2.5–5°C (IPCC, 1990; Burgos et al., 1991). Precipitation changes are not well defined for the area since expected variations run from decreases of 5% to increases of 30% (Paruelo and Sala, 1993; Baethgen and Magrin, 1995).

Making use of the equation in Fig. 3 it was possible to estimate changes of the soil organic carbon level under different scenarios, assuming that the present conditions represent a near-equilibrium state or that a new equilibrium has been reached (Fig. 10). If mean annual temperature increases with no variation in precipitation, soil organic carbon will fall. Depending upon the magnitude of a rise in temperature, an increase of precipitation may rise carbon content of the soils. The decreases of soil carbon due to global warming would be greater (ca. 40%) in the Pampa than in the Chaco. This is because mean annual temperature is lower in the former and, consequently, under a similar level of temperature increase a deeper change would occur in the Pampean ecosystem.

The total carbon content of the surveyed area is at present ca. 4.7 x 10¹⁵ g, which represents 0.30% of the carbon stored in the soils of the world (Eswaran et al., 1993). A decrease of the carbon concentration of these regions of 33%, an extreme situation of loss of carbon under a 5°C warmer scenario, will produce an emission of 1.6 x 10¹⁵ g C as CO₂ to the atmosphere. This represents 0.45% of the world emission of CO₂ from fossil fuel combustion and land cultivation to

![Fig. 10. Organic carbon change in soils of the Pampa and Chaco under different scenarios of climatic global change. Estimations were performed using equation in Fig. 3 assuming that a steady state has been reached.](image-url)
the atmosphere if present-day fluxes are extrapolated for the next 50 yr (Schlesinger, 1993). In other parts of the world losses of carbon from soils due to global warming have been estimated, using methods of estimation based on data from soil survey or climosequences (Buol et al., 1990; Tate, 1992). These estimations, however, are oversimplifications because the CO₂ fertilization effect on the vegetation is not considered. This effect will compensate partially the losses of carbon from the soil as it determines a higher plant debris inputs by an increase in net primary productivity (Melillo et al., 1993).

By modelling possible future changes of the Pampa soil organic matter level using the CENTURY model, losses from ca. 14% of the soil carbon content in the west of the region to 2% in the east were estimated (Parton et al., 1995). This model includes the CO₂ fertilization effect on net primary production, and these estimations have been performed under the scenarios predicted by the GFHI general circulation model. The different carbon losses from west to east were attributed to different patterns of alteration in precipitation and to the CO₂ effect. The latter apparently will counteract half of the carbon losses, due to climate change in wet parts of the Pampa. The equation in Fig. 3 gave similar results to the CENTURY model in arid to semiarid Pampa but gave higher losses of carbon in the east (20% decrease in carbon concentration) under GFHI scenarios. The time needed for soil organic carbon to reach near-equilibrium level is also difficult to ascertain, but from the CENTURY model, it has been calculated in ca. 100–150 yr after CO₂ doubled in the atmosphere and climate change. Whether any of these foreseen changes are realistic or not is still difficult to evaluate. The CENTURY is a sophisticated model which analyze all the main components of the ecosystems, but is not validated against local data. Conversely, our equations are based on extended local data but are a very simple approach. This quantitative information may be used by simulation models to obtain higher accuracy in predicting climate influences on soil organic carbon.

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References


