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Distribution, Properties, Land Use and Management of Mollisols in South America

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Abstract: Mollisols are common in South America. They cover about 8.87 $\times 10^7$ ha, 1.3 $\times 10^7$ ha and 4.3 $\times 10^6$ ha in Argentina, Uruguay and Southern Brazil respectively, which is 11.5% of the world total. Most of South American Mollisols were developed on Pleistocene and Holocene sediments and lie within the limits of the temperate zone, though the extreme north is bordering subtropical and the extreme south is within a cold-temperate zone. All suborders of Mollisols occur in Argentina, the most extensive being Udolls followed by Ustolls, whereas only Udolls, Aquolls and Albolls occur in Uruguay. Vertisols in Uruguay have many properties similar to Mollisols, and the occurrence of Vertisols is strongly associated with Mollisols. The Pampean Mollisols are a significant component of the global breadbasket of modern times. The main Argentine crops are wheat, corn, sorghum, barley, soybeans and sunflower, while Mollisols in Uruguay remain mostly dedicated to cattle and sheep grazing though crop production has been increasing very rapidly in the last decade. Throughout South America, research has shown that Mollisols are experiencing losses of soil organic matter and nutrients, and degradation of physical properties after long cropping periods, resulting in soil scientists calling for increased conservation practices to reduce future losses and a deterioration of soil quality, and thus a more sustainable agriculture in the region.

Keywords: Mollisols; classification; sustainability; soil fertility; no tillage; South America

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1 Introduction

Most soils that formed under prairie are classified as Mollisols when using Soil Taxonomy. Mollisols are identified by a thick or relatively thick (> 18–25 cm in most profiles), dark-colored (moist value and chroma ≤ 3), humus and base-rich surface horizon (mollic epipedon) with a high base saturation (≥ 50% by ammonium acetate) to 1.8 m depth (Soil Survey Staff, 2010). Yet the minimum thickness may be only 10 cm if hard rock is directly underlying. Most Mollisols have a moderate or strong structure in the epipedon, with an organic carbon content ≥ 0.6%. They generally have a high cation exchange capacity (CEC) throughout their sola with calcium as main exchangeable cation throughout the profile. The CEC of the upper profile is derived from humus with pH-dependent charge and clay-sized phyllosilicates with permanent charge whereas in their lower part the CEC is nearly exclusively from clay-sized phyllosilicates such as smectite, vermiculite, or illite. Calcium is generally the main exchangeable cation throughout the profile. Mollisols have a significant con-

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tent of weatherable minerals in their silt and sand fractions (Soil Survey Staff, 2010) which supply basic cations in preventing acidification and desaturation of the exchange complex through leaching.

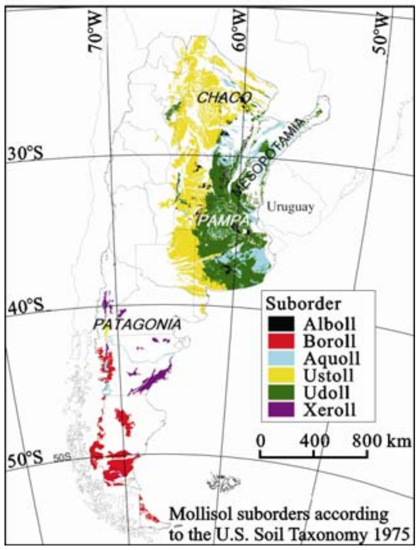
Mollisols are known in other soil classification systems as Chernozems (Russia, Canada, FAO), Kastanozems and Phaeozems (FAO) and Isohumosols or Black soils (China). Soil Taxonomy is officially used in Argentina where the Spanish name of the soil order is Molisoles. In the National Soil Classification System of Uruguay, they are included in the Great Groups of Brunosols and Argisols (Durán and García Préchac, 2007). The natural areas of occurrence of these soils are the prairies and steppes of the temperate earth. More specifically, Mollisols are most extensive in mid-latitude regions, but they are also recognized in some colder and drier climates.

There are even minor areas of Mollisols in the tropics and subtropics. On a world-wide basis, soil scientists generally speak of four major regions of Mollisols. One is located in central North America radiating across the central plains of the United States and southern Canada. The next two appear as a discontinuous belt which extends across southeastern Europe and central Asia. The western belt begins in the sub-humid steppes of south-central Europe and extends across Russia and into the eastern belt, which is best represented in Northeast China. The fourth major region corresponds to the Pampas of South America, covering most of northeastern Argentina and almost all of Uruguay. Thus, most of the world′s Mollisols (9.16×10^8 ha) occur in three regions of the northern hemisphere and one region south of the equator, the Parana-La Plata basin of South America (Durán, 2010; Liu *et al*., 2011). The understanding of the distribution as well as the formation, uses and risks of these soils, is crucial given that these four Mollisols regions collectively form the world′s natural granary (Liu *et al*., 2011).

This paper presents recent information on the distribution and land use of Mollisols in Argentina and Uruguay with an aim to provide regional experience that could contribute to the proper management and sustainable use of these soils in similar regions.

2 Distribution of Mollisols in South America

Most of the South American Mollisols lie within the limits of the temperate zone, roughly between the latitudes 30°S and 40°S, including Uruguay and the Pampa region of Argentina. Mollisols are also widely distributed in association with several other dominant soil Orders in the Chaco and Mesopotamia subtropical regions on the one hand, as well as in Patagonia, in the extreme south of Argentina, on the other hand (Fig. 1). Thus, Mollisols are extended over 8.87×10^7 ha in Argentina (31.8% of the territory) (Fig. 1) and 1.30×10^7 ha in Uruguay (75% of total land) (Fig. 3). Minor areas of occurrence are also found in southern Brazil (4.26×10^6 ha, about 0.5% of the country) (Palmieri *et al*., 2002) and in isolated locations in other countries.



Soils were classified according to the 1975 edition of the U.S. Soil Taxonomy; map and quantification of total area occupied by Mollisols by Cruzate G, from SAGyP-INTA, 1990

Fig. 1 Geographical distribution of Mollisols suborders in Argentina

2.1 Climate, vegetation and geology of Mollisols in Argentina

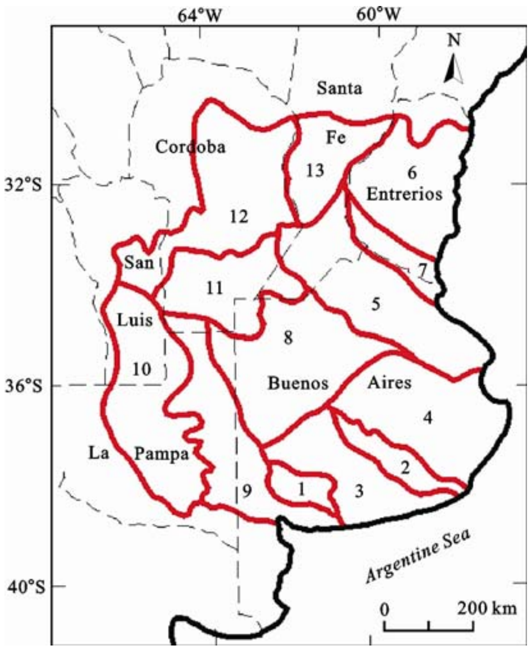
In the Pampean region, mean annual temperature ranges from 14℃ in its southern limit to 19℃ in the northern border, without large daily or annual amplitude due to the moderate influence of the Atlantic Ocean in most of the area. The increasing continental conditions in the westernmost part of this region results in larger thermic amplitudes there, while winter is mild everywhere without snowfall except very infrequent extreme events. Frosts, although not very severe, can be expected in the Pampean region over a period ranging from 125 days in the west to only 20 days in the east (Burgos, 1963).

Mean annual rainfall ranges from 500 mm in the southwest to 1100 mm in the northeastern part of the Pampa. Thus the western border of the Pampa has a semiarid climate that changes gradually to a moist climate in the east. But even there the relatively high temperature of the hottest months (December, January, and February) gives rise to moderate soil water deficiency in normal years because of the high evapotranspiration. Water deficiency becomes severe in years with a summer rainfall below the average and is more remarkable if soil water recharge in winter is incomplete because of insufficient rainfall. Thus the water balance is positive in the east of Argentina with an excess of about 100 mm, while marked deficits appear in the west. It is worth mentioning that frequent periods of water excess as well as periods of water deficit characterise the climate in the Argentinean Pampas. As a consequence extensive floodings mainly affecting the arid areas of the central Pampa alternate periodically with severe droughts that may affect at different extent across the region (Moncaut, 2003).

At the time of the European colonization, extensive steppes and grasslands characterized by medium-height, both perennial and annual grasses (*Stipa*, *Aristida*, *Poa*, *Bromus*, *Panicum*, *Paspalum*, *etc*.) covered the Pampa region. Grasslands were interrupted only by gallery or riparian forests along the margins of the Parana and La Plata rivers and some of their tributaries, and along the Atlantic littoral (Ragonese, 1967). A broad arc of xerophytic forests known as Espinal (Cabrera, 1976) and dominated by *Prosopis* sp., surrounded these steppes and grasslands.

According to Soil Taxonomy, all the Pampean Mollisols have a thermic temperature regime or mesic bordering thermic, whereas the moisture regimes are udic, the most extensive, and ustic in the dryer sector. Flat and low terrains are usually poorly drained and have an aquic moisture regime. Aquic Mollisols are widespread along the country and are particularly extensive in the Flooding Pampa and in the southern Chaco lowlands in Argentina (Fig. 1 and Fig. 2).

The Pampa region is a vast and continuous plain, rising very slightly and gradually to the north and to the west where total flat areas alternate with slightly undulating plains and rolling landscapes. Rocky hills occur only in minor areas in the south of Buenos Aires Province: hills of the Tandilia System (maximum altitude of 500 m) and hills of the Ventania System (maximum altitude of 1200 m). Although often considered as an extensive and uniform terrain, several units can be recognized in the Pampa on the basis of lithology, geomorphology, vegetation and soils. The subregions here considered synthesized the geomorphologic differentiation of Cappannini and Dominguez (1961), the subdivisions considered by Moscatelli (1991) and the more recent ecoregions map by Pereyra (2001) (Fig. 2).



1. Hill range and piedmont of Ventania; 2. Hill range and piedmont of Tandilia; 3. Interrange Pampa; 4. Depressed or flooding Pampa; 5. Rolling Pampa; 6. Mesopotamian Pampa; 7. Delta of the Parana River; 8. Sandy Pampa; 9. Polygenetic Pampean plains; 10. Western or dry Pampa; 11. Endorreic Pampa; 12. Piedmont Pampa (piedmont of the Cordoba and San Luis hill ranges); 13. Flat Pampa of Santa Fe

Fig. 2 Subregions of Argentinean Pampa

From a geological point of view, the Pampa region is an extensive and deep sedimentary basin where the crystalline Precambrian basement, partially covered by a mantle of Cretaceous basaltic flows, is covered by hundreds to thousands meters of sediments of Tertiary and Quaternary age of continental and marine origin. The most recent Quaternary deposits lying on the surface and therefore the parent material of Pampean Mollisols are loess and loessoid sediments to the east and aeolian sands to the west of the region. This loessic plain, the largest one in the southern Hemisphere, is made of superposed mantles of varying thickness (reaching in whole 40 m depth in the eastern part) where the superficial sediments of middle to upper Pleistocene age are known as Upper Pampean and the Holocene sediments as Post Pampean. Several levels of paleosols are found in these sediments, mainly characterized by clayey Bt horizons, thus reflecting periods of humid paleoclimatic conditions similar to those prevailing at present (Imbellone and Giménez, 1998; Nabel *et al.*, 1999; Zárate *et al.*, 2002; Imbellone and Cumba, 2003). A petrocalcic layer, considered Plio-Pleistocene in age and covered by a thin mantle (less than 1.5 m thick) of mostly Holocene loess, is widespread in the southern part of the Pampa region and in several places of northern and western Pampa. In the northern Pampa the calcrete, usually discontinuous, occurs at higher depth and is covered by a thicker mantle of Pleistocene and Holocene loess.

These superficial sediments were modeled during the arid periods in the recent Quaternary and a desert landscape with several types of dunes and erosional geoforms are found in most of the Pampean region with the exception of the eastern areas covered by the finer loess (Tricart, 1973; Malagnino, 1988; Iriondo and Kröhling, 1996; Zárate, 2005).

The bulk of loess and sand deposits in the Chaco-Pampean plains came from andesitic and basaltic rocks located in the northern Patagonia and in the Andes piedmont of Mendoza Province (Teruggi, 1957), though several other sources have also been identified. As a consequence of aeolian transport by winds from southwest particularly in the Pampa, a granulometric sorting of sediments occurred, resulting in a trend of decreasing grain size from the southwest to the northeast, which determined three successive belts consisting of sandy loess, typical loess and clayey loess, the latter being close to the Parana-Rio de la Plata axis (Morrás and Cruzate, 2000).

As a difference with the typical loess in the northern Hemisphere where quartz ranges between 50%–70% (Pye, 1987), the light mineral suite in the Pampean loess is dominated in general by the abundance of volcanic glass, with pyroxenes and amphiboles usually abundant in the heavy fraction (Teruggi, 1957; Zárate and Blasi, 1991). Thus, the mineralogy of the sand fraction reveals a dominance of volcanoclastic components of Andean origin in sediments all across the Pampean region. Nevertheless, an evident contribution of sediments from the Parana River Basin is observed in the northeastern Pampa and Chaco region, while in northwestern Pampa clear contributions from the Pampean hill range of Cordoba has been identified (Bertoldi de Pomar, 1969; Morrás and Delaune, 1985; Etchichury *et al.*, 1988; Morrás, 2003; Etchichury and Tófalo, 2004). Some sedimentary inputs from the hilly areas of Ventania and Tandilia systems were also identified in superficial sediments in the southern Pampa region (Fidalgo *et al.*, 1991; Blanco and Sánchez, 1994; Morrás, 1996; Pereyra and Ferrer, 1997).

With regard to the clay fraction composition, it has been accepted since long ago that the Pampean sediments are mineralogically homogeneous. González Bonorino (1965; 1966), Scoppa (1976) and Camilión (1993) reported that illite is the dominant, and in many instances practically the only clay mineral in the superficial sediments and in the soils of the Pampa. Nevertheless, several mineralogical studies carried on loess, loessoid sediments and soils of the Chaco and Pampa regions indicate a clear dominance of illite in the west and an increase of smectite and interstratified illite-smectite to the east, close to the Parana River (Iñiguez and Scoppa, 1970; Stephan *et al.*, 1977; Morrás *et al.*, 1982; Nabel *et al.*, 1999; Castiglioni *et al.*, 2005).

These sedimentological and mineralogical variations of soil parent materials explain some of the main differences observed on chemical composition and fertility of soils among different areas of the Pampa and Chaco plains. Thus low contents of total and soluble phosphorus and potassium in the Mesopotamian area are related to sedimentary materials from the Parana and Uruguay basins. Conversely, Mollisols in the north western Pampa (western Santa Fe and Cordoba Provinces) are rich in total and available phosphorus and potassium due to mineral contributions from Pampean Hills of Cordoba. In turn, in the southern Pampa, extended along most of Buenos Aires and La Pampa Provinces with sediments mainly originated in the Andean ranges, the total and soluble phosphorus and potassium have intermediate values (Morrás, 1999; Morrás and Cruzate, 2001).

The geology of the Chaco is equivalent to the one described for the Pampa, though the surface sediments differs somewhat in their composition, origin and distribution. Generally speaking, late Pleistocene loessoid sediments cover large areas in the central and western Chaco while Holocene fluvial silty and clayey sediments are widespread in the eastern alluvial floodplains. Mineral contributions from the northern Andean ranges and the Altiplano are also present in the loessoid sediments in the Chaco region and could have arrived to this area by a combination of fluvial and eolian transport, with some intervention of westerly tropospheric winds and northerly winds (Morrás and Delaune, 1985; Bloom, 1990; Iriondo, 1997; Zárate, 2003). In the subtropical plains of Chaco region (Fig. 1), rainfall also increases from the subhumid western area to about 1200 mm/yr in the humid eastern part. Mean annual temperature increases from 19℃ in the limit with the Pampean region to 24℃ in the northern border of Argentina. In contrast to the Pampean grasslands, the vegetation in the Chaco is mainly characterized by forests and savannas, though herbaceous communities are typical in the extended alluvial plains and wetlands in the eastern Chaco. Alfisols, Mollisols and Entisols are the main soils in this region.

In the central part of the Mesopotamia region, in the province of Corrientes, the landscape is flat to gently undulated. The Iberá wetlands, the second largest in the world, occupy the center and center-north of the province. Its surface is covered by different types of sediments, from sandy to clayey texture, mostly of Pleistocene age and fluvial origin. Jurassic-Cretacic basalts and sandstones outcrop to a limited extent in the southern part of Corrientes. Savannas and parklands characterize most part of the area. Vertisols and different types of Mollisols with udic and aquic regimes are developed on sedimentary materials, mostly in its southern part.

In the extreme north of the Mesopotamia region, the province of Misiones is characterized by the outcropping of basalt rocks in a hilly landscape, a subtropical forest and the development of Ultisol soils. Mean annual precipitation ranges between 1500 mm and 2000 mm and the mean annual temperature is about 20℃. Mollisols are restricted to stony scarped areas, mainly on the central plateau, and to the lower parts of the landscape with herbaceous vegetation, at foot of slopes and in alluvial plains.

The patagonian environments differ diametrically from those found in the northern part of the country. To the west, the narrow strips of the southern Andes mountain ranges are characterized by glacio-fluvial valleys, extended and deep lakes, a great variety of hard and sedimentary rocks at the surface and forest vegetation. Apart from this north-south mountainous narrow strip, central and eastern Patagonia appears as a temperate-cold desert. The main geoforms in this area are tablelands and structural and erosional terraces due to fluvial erosion. The lithology at the surface varies with rocks of different origin and age. Concerning the climate, the Andean and sub Andean ranges have a strong west to east precipitation gradient (more than 3000 mm to 300 mm), which decreases in the extra-Andean region to only 150 mm in the Atlantic coast. The mean annual temperature oscillates between 2℃ and 6℃ in the Patagonian ranges while in the extra-Andean region mean annual temperature decreases from about 14℃ in the north to 6–8℃ in the extreme south of Tierra del Fuego plains. Snowfalls are frequent during winter in the west and in the south of the region. Andisols and Inceptisols are the dominant soils in the Andean ranges while Aridisols and Entisols characterize most part of Patagonia. In the Andean ranges Mollisols appear in valleys and flat areas with hebaceous vegetation between the subantartic *Nothofagus* forests while in the extra-andean Patagonia, Mollisols are found in the xerophytic herbaceous and shrubby steppes. According to Soil Taxonomy, the soil temperature regime of Mollisols in Patagonia is cryic, frigid, mesic or thermic, and the soil moisture regime is aquic, udic, ustic or xeric. The total area occupied by this order in Patagonia is about 13% (del Valle, 1998).

2.2 Climate, vegetation and geology of Mollisols in Uruguay

Uruguay has a temperate climate though bordering to subtropical in the north. Mean annual temperature varies from 16℃ in the south to 19℃ in the north with an average of 17.5℃. Winter is mild, without snow fall and a mean temperature in the range from 11℃ (south) to 14.1℃ (north). The frost free period is shortest in the central region (250 days) and increases to 340 days in the north (latitude effect) and to 320 days in the south (oceanic influence). According to Soil Survey Staff (1999), the soil temperature regime is thermic in the whole territory though in the extreme north it borders the hyperthermic regime.

Mean annual rainfall ranges from 1100 mm in the south-southeast to 1500 mm in the north-northeast, with a national average of 1300 mm. Rainfall is fairly well distributed all year round though there is a slight trend of summer concentration in the western zone or to winter concentration in the east and southeast, and in general terms there is not a well defined dry season. The water balance is positive everywhere though following the trend in Argentina. The annual water excess increases from 150–200 mm in the west to 300–350 mm in the east and northeast. On very shallow soils the water excess is even higher (400 mm). Yet an annual water deficit of 50 mm exists in the summer because of high evapotranspiration, and deficit increases to 100 mm on shallow soils. Interannual variation of rainfall is rather high and consequently drought and above average rainy periods alternate every few years. The soil moisture regime is udic in most uplands and aquic in the eastern flat lands and in alluvial plains all over the country.

Grasslands are virtually the only natural vegetation cover of the Uruguayan territory and natural forests are limited to riparian areas along rivers and rivulets or in narrow sloping valleys in rolling terrains on igneous and metamorphic rocks. The dominant grasses are *Paspalum*, *Stipa*, *Eragrostis*, *Sporobolus*, *Axonopus*, *Piptochaetium* and many others. In wetlands some characteristic species occur: *Zizaniopsis*, *Leersia*, *Eryngium*, *Typha*, *Scirpus*, *etc*. Yet some differences in the Mollisol area in Argentina are noteworthy: species diversity is higher than in the Pampa and several authors (Durán and García, 2007) claim that until the introduction of cattle in 1616 certain areas had a forest vegetation of medium density, mainly in the west and southwest, the crystalline hills and the eastern palm tree region. Present woody areas would be thus relicts of a more extensive forest canopy and most of the authors cited by Durán and García (2007) concluded that the Uruguayan vegetation is transitional between the dry and colder steppes of southern Buenos Aires Province in Argentina and the warmer and more humid forests of southern Brazil.

Mollisols of Uruguay and Brazil are found on the southern border of the Brazilian shields of Precambrian age outcropping on the eastern side of the continent. Shield rocks are mainly metamorphic and widely variable in composition and degree of metamorphism but are covered in large areas by sediments of various ages, from Devonian to Cenozoic, and also by basaltic outflows of Cretaceous age. All these rocks are parent materials of the present soils although in extensive areas have been exposed to different weathering and erosion cycles under which at least two erosion surfaces of Mid and Upper Tertiary age were developed (Antón, 1975a; 1975b). Under the humid climate of the Lower Quaternary the old erosion surfaces were dissected and the rock substratum was significantly weathered and the weathering products, mixed with aeolian silt-sized particles, were later reworked and moved downslope as a mud flow under a dryer climate as reported by different authors (Bossi, 1966; Elizalde and Eugüi, 1973; Anton, 1974; Antón and Prost, 1975; Bossi and Ferrando, 2001). The resulting sediment, highly important as parent material of Mollisols, is a brown-colored, soft mudstone of silty clay or silty clay loam texture and variable carbonate content either in nodules or as soft powdery lime. This sediment is known as Libertad Formation. The geomorphic processes involved in the mudstone accumulation resulted in a subdued landscape of gently or very gently undulating relief (pseudo ′peneplanization′) in many areas of Uruguay. The accumulation of the Libertad Formation took place during the Low-mid to Low-central Pleistocene, i.e., 780–450 thousand years BP. Geomorphic processes have not been particularly active since then, except for either aggradation or down-cutting of alluvial plains by streams following minor climatic changes. Therefore, the landscape has been stable, mostly in the uplands, for a long time and pedogenesis resulted in very well developed soils, often showing a strong horizonation. Thus, it is noteworthy the generalized occurrence of a distinct argillic horizon of fine texture in almost all non-shallow soils, indicative of soil formation during a long time since clay translocation is a very slow process (Soil Survey Staff, 1999). Yet the long period of time elapsed since the beginning of deposition is marked by some cyclic alternation of erosion and soil formation as indicated by the presence of a well developed paleosol at the base of the Libertad Formation (Tofalo *et al.*, 2009). The paleosol is an Argiudoll as the present soil on top, suggesting the existence of similar conditions for soil formation during the development of ancient and modern soils.

Regarding mineralogy, the clay fraction of Uruguayan Mollisols is currently dominated by an association of illite and smectite with only minor amounts of kaolinite. Vertic Mollisols very frequent in Uruguay have a larger amount of smectite, while other Subgroups are higher in illite. Most Mollisols developed on metamorphic rocks have illite and kaolinite in similar amounts but smectite is always lacking. These Mollisols are usually intergrades to Alfisols since base saturation is usually very close to the lower limit of 50% either in surface or in subsurface horizons, and they also are free of carbonates, often present in other Mollisols. The coarse fractions of Mollisols are quartz, K-feldspars or plagioclases, and some amphiboles and other weatherable minerals but volcanic glass is extremely infrequent. The lack of volcanic materials and the significant content of quartz make a difference with the Pampean Mollisols and is an indication of differences in the origin of their parent materials.

3 Distribution of Mollisols in Argentina and Uruguay

3.1 Argentina

Soil resource inventories compiled at a small scale in the Soil Atlas of Argentina (SAGyP-INTA, 1990) show that all Suborders of Mollisols are found in the country (Fig. 1). According to the more recent version of the Soil Taxonomy (Soil Survey Staff, 2010) they are the following:

Aquolls, the Mollisols affected by wetness and reflecting local topography occur mainly in the eastern part of the country, from 65°W to 55°W. They are well represented in the subsident large areas of the Flooding Pampa and the Subsouthern Lowlands (Bajos Submeridionales) in the southern Chaco, where Natraquolls occupy extensive areas and have drainage and management limitations. These areas are devoted to extensive livestock raising on natural grasslands. The Aquolls are also present in the Delta and islands of the Parana River. These soils have also some representation in the humid pre-Andean northwestern Patagonia.

Albolls, with a lower representation than the Aquolls, occur in flatlands and concave areas with a seasonal water excess enhanced by argillic or natric horizons, particularly in the northern Pampa and southern Chaco, and in the Mesopotamian Corrientes Province. They also appear in minor proportion in western provinces.

Udolls: these are the main soils in the grasslands of the humid Pampa, particularly in the Buenos Aires and Santa Fe Provinces; they also appear in lower proportion in the Chaco and Mesopotamia regions and in humid areas of northwestern Argentina; these soils usually also display an argillic or a cambic horizon. The Argiudolls developed on loessic sediments and under a tall-grass prairie are the typical and more productive soils in the eastern Pampa region. These soils also appear in some areas in the Mesopotamia region and in patches in the northwestern Tucumán and Santiago del Estero Provinces. The Hapludolls are represented to a lesser extent in the humid Pampa; they usually have a cambic horizon and some free calcium carbonate, and they are very suitable for different crop productions. The Paleudolls are localized in some areas of Buenos Aires and Corrientes provinces.

Ustolls: these Mollisols extend along a subhumid-semiarid belt in the center of the country, more or less coincident with the meridian 55°W, from the temperate southern part of the Pampa to the warm northern Chaco, up to the border with Paraguay and Bolivia. A patch of Ustolls also occurs in the pre-Andean area in the Rio Negro Province and they occupy a considerable area in the Santa Cruz and Tierra del Fuego Patagonian provinces. These Mollisols have a diversity of subsurface horizons as cambic, argillic, natric and albic. Haplustolls are well represented along the subhumid Pampean region, where they are used for livestock and agricultural production. They are also extended in the northwestern part of the country, and localized in several other regions. In Patagonia they account for 5% of the total area. Calciustolls also appear in the western Pampa while Argiustolls are more extended in northwestern Argentina. Natrustolls occupy limited areas in the Pampa and Chaco regions. Paleustolls appear in limited extent in ancient and stable surfaces in northwestern provinces (Catamarca, Salta, Jujuy, and Tucuman) and Durustolls are scarcely represented in the Chaco region.

Xerolls: these soils occur in limited extent in several areas in Patagonia. They usually have a thin mollic epipedon followed by an argillic or cambic horizon: dry for long periods during the summer and humid during the winter.

Rendolls: these soils are restricted to fossil shell banks deposited during recent Quaternary marine ingressions in the north-east of the Buenos Aires Province, and characterized by their xerophytic forest.

Cryolls: these are soils of cold regions, developed in some areas in the Andean ranges of western humid Patagonia down to Tierra del Fuego. Mollisols with a cryic soil temperature regime were included within the Borolls suborder in the 1975 edition of the U.S. Soil Taxonomy (Fig. 1).

Gellols: some pedons that can be classified in this new suborder of the Soil Taxonomy have been described in the Antarctic area claimed by Argentina (Godagnone, 2001; Godagnone and de la Fuente, 2010).

Mollisols are the most representative soils in the Pampa grasslands and steppes (Fig. 2). At a suborder level and according to the climatic criteria of the Soil Taxonomy, the most extensive are Udolls followed by Ustolls. The Great Group of Argiudolls is undoubtedly the most characteristic of the Argentinean Pampa as well as the most productive and where agricultural activity is more intense.

In the southern Pampa, three geomorphologic areas can be distinguished. In the hill range and piedmont of Ventania (Austral Hills of Buenos Aires Province) (1- Fig. 2), with an ustic moisture regime and a thin sedimentary veneer overlying hard rocks, dominant soils are Petrocalcic Paleustolls and Haplustolls, with some Calciustolls. In the area of the hill range of Tandilia (Northern Hills of Buenos Aires Province) (2-Fig. 2), with an udic moisture regime and a thicker sedimentary cover, the main soils are Argiudolls or Petrocalcic Paleudolls, with some Hapludolls. In the Interrange Pampa (3-Fig. 2) the loess is thicker than in both previously mentioned southern areas (about 150 cm) and dominant soils are Petrocalcic Paleudolls, with lower proportions of Argiudolls on thicker loess. In the Ventania subregion soils are used for cattle raising and crops, while in the other two subregions agriculture is more intense because of the better quality of soils and a more humid climate.

On the east, a very flat plain known as Depressed or Flooding Pampa is found (4-Fig. 2), and morphogenesis is of very low intensity. The main geoforms are alluvial plains, fluvial terraces and numerous small depressions and very shallow lakes. Despite the udic regime, soils with an excess of exchangeable sodium are typical in this region. In the western portion of this region dominant soils are Petrocalcic Paleudolls, Natraquolls and Natrudolls, with Natraquolls and Natraqualfs in the central part and a few Argiudolls in the micro-meso elevations. The easternmost part of this region, known as Littoral Pampean Plains (Pereyra, 2001), is covered by clays deposited by marine ingressions of recent Quaternary age. The soils are Hapluderts with some sodic Mollisols. On shellbanks of limited extent close to the coast the soils are Haprendolls. Due to soil limitations by the excess of wetness and sodicity, most of this region is used for extensive cattle raising.

Northeastern Pampa is the one with the higher agricultural activity in the country. In the Rolling Pampa (5-Fig. 2) the drainage network is well defined and the relief is gently undulating (slopes of about 2% and up to 5%). Typic Argiudolls are the most extensive and the best suited soils for crops. The mollic epipedon has at present about 3% of organic matter, the argillic horizon is deep with a clay content that ranges between 30% to the west and 50% to the east, and the solum easily reaches 120 cm depth. Some calcium carbonate nodules frequently occur in the BC and C horizons. Also Vertic Argiudolls are common in the margins of the Parana-de la Plata axis, due to the higher content of expanding clay minerals in the soil parent material. The southern part of the Rolling Pampa, transitional to the Depressed Pampa, is known as the Low Rolling Pampa, with flat upper slopes and sediments high in smectitic minerals. Vertic Argiudolls are very extensive and Hapluderts are frequent. Aquic Argiudolls and Argialbolls occur in concave micro depressions. In the Mesopotamian Pampa of southern Entre Rios Province (6-Fig. 2) there is a well developed drainage system, with a mantle of loess and a rolling landscape in the western sector. Typic Argiudolls are present close to the Parana River and Vertic Argiudolls appear towards the center of the Province, while Aquic Argiudolls occur in the lower topographic positions. The eastern part of this subregion is gently undulating and covered by Early Quaternary lacustrine sediments high in smectites; typical soils here are dark and deep Vertisols.

Thus, in the Rolling and in the Mesopotamian Pampas, Mollisols and Vertisols, together with intergrade soil types as Vertic Argiudolls, are associated in the landscape. This fact is in connection with two distinct parent materials in this area. Mollisols were developed on loessial sediments from western sources while Vertisols were developed on clayey sediments mainly derived from the weathering of Cretaceous basalts outcropping in northern Argentina and Uruguay and southern Brazil. Intergrade soil types are usually developed on parent materials with a mixture of both main types of sediments. Consequently, northeastern Pampa and particularly the Mesopotamian area, represent a transition to the environment and soils found in western Uruguay.

Between the Mesopotamian Pampa and the Rolling Pampa flows the Parana River where alluvial plains and the extended Delta are continuously built by fluvial sedimentation (7-Fig. 2). Most of the soils are Entisols (e.g., Typic Haplacuents), but some Mollisols on the higher topographic positions and some Histosols in some wet depressions are also found.

The Sandy Pampa (8-Fig. 2) in the center Pampean region has an endorreic and poorly developed drainage system. The coarse parent material and a rainfall lower than in eastern Pampa have limited the development of a clayey horizon. This subregion has a paleorelief of dunes reflecting a desertic paleoenvironment. The most extensive soils are Hapludolls, mainly of Typic and Entic Subgroups. Hydromorphic and Na-rich soils as Natraquolls, Natralbolls, Natraqualfs and Aquic Hapludolls occur in concave positions between the dunes. Typic or Abruptic Argiudolls of polygenetic nature, which also occur in the Depressed Pampa and were formerly locally classified as Thapto-Argic or Thapto-Natric Hapludolls, are very characteristic soils in this area. They consist of a recent superficial loamy sedimentary layer of about 30–50 cm depth where an A-C or A-AC sequence overlies the buried argillic horizon of a paleosol developed in a relatively finer (silty loam) sediment (Imbellone and Giménez, 1998).

In the Polygenetic Pampean plains (9-Fig. 2), along the ustic belt in the western part of the region, Entisols are considerably extensive whereas the associated Mollisols are Typic and Entic Haplustolls with A-Bw-C, A-AC-C or A-C sequences. A petrocalcic layer underlies some of these soils which then are classified as Petrocalcic Paleustolls. All these soils are coarse textured and have a low content of organic matter. In the transitional zone known as Western or Dry Pampa (10-Fig. 2), with a mean annual rainfall of about 400 mm yr^{-1}, the dominant soils are Entisols in the west and Aridisols in the south. Calciustolls and Haplustolls are restricted to the eastern part of this zone.

In northern Pampa, three subregions can be distinguished from the west to the east. The Endorreic Pampa (11-Fig. 2) lies in the south of the Cordoba Province and some portions of the neighboring Provinces. Here, the surface sediments are coarse, from silty to sandy textures and some rivers and streams flowing from the Pampean hill range infiltrate in many depressions and expand in large permanent swamps. The transition between the udic and ustic regimes is found in this unit and thus the characteristic Mollisols are Hapludolls as well as Haplustolls. In the Piedmont Pampa (12-Fig. 2), in eastern Cordoba Province, the moisture regime is mostly ustic and becomes udic in the easternmost portion. The parent materials are fluviatile sands and silts as well as loess. Mollisols are clearly predominant, being mainly Haplustolls of Typic, Entic or Udic subgroups. Argiustolls and Argiudolls also occur in some extent and Aquic subgroups are recognized in some low-lying areas (Pereyra, 2001). The Flat Pampa of Santa Fe (13-Fig. 2) appears to the northeast, north of the Rolling Pampa, in the center of Santa Fe Province. This area is flat to gently undulating, with long slopes of less than 1%. The representative soils here are Typic Argiudolls, with a deep and highly clayey Bt horizon. In frequent circular flat-concave depressions sparse in this subregion, the soils are Aquic Argiudolls and Typic Argialbolls, often alkaline and sometimes saline in their lower horizons (Moscatelli, 1991).

3.2 Uruguay

Uruguay developed a National Classification System greatly influenced by the FAO nomenclature for the soil map of the world with adaptations to fit the local needs but it proved to be inadequate for international scientific communication. Efforts have been made in the last decade to classify Uruguayan soils in a well known system of vast acceptation almost everywhere as the U.S.A. Soil Taxonomy (Durán *et al*., 2002; Durán *et al*., 2005a; 2005b). As a result, a soil map of Uruguay is available for soil scientists, students, consultants and all possible users in the web site of the Faculty of Agronomy (http://www.fagro.edu.uy/~edafologia) where the soil mapping units are classified according to Soil Taxonomy. Although being a small country, seven of the ten Orders in Soil Taxonomy have been identified in Uruguay: Alfisols, Entisols, Inceptisols, Mollisols, Ultisols, Vertisols and Histosols (Fig. 3). Yet only the udic Subgroups of most Orders occur in the country plus the aquic Subgroups in some of them. Moreover, Entisols, Inceptisols and Histosols are found in limited areas and thus only four Orders are of significance in Uruguay.

Mollisols are the most extensive soils of Uruguay. As shown in the sketch soils map (Fig. 3) pure Mollisols occur in extensive areas whereas they are associated to other taxa in a number of associations. Vertisols in Uruguay have many properties similar to Mollisols, such as high organic matter content, and thus the occurrence of Vertisols is strongly associated to Mollisols. Highly productive ′black soils′, mainly Mollisols but including Vertisols as well, are distributed all over Uruguay especially in the western half of the territory. Moreover, black soils in this region are, in average, more fertile, higher in organic matter, more resistant to water erosion and occurring in a smoother relief than those in the eastern half of the country, where extensive hilly and rocky landscape impose severe restrictions for crops and at least partially for cattle grazing too.

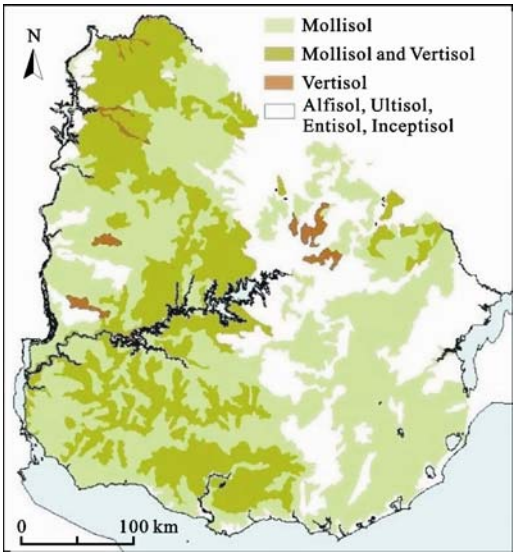


Fig. 3 Geographical distribution and relative importance of Mollisols and Vertisols in Uruguay

Soil organic carbon (SOC) is high in most Mollisols even in subsurface horizons and the analytical data base shows a mean of 2.7% SOC in the topsoil and 1.1% in the B horizon. The deep incorporation of organic remnants, the high organic matter content and the high base saturation throughout the soil result in a thick epipedon. From a total of 250 mollic epipedons investigated, 60% are thicker than 50 cm and 75% are 30–80 cm thick. Thus the Pachic Subgroup is the most frequent in deep or moderately deep Mollisols regardless the Suborder they belong to. The mean SOC content of the epipedon is 12.3 kg/m^2 though the range is wide and this is related to the variation in thickness rather than to the carbon content. Mollic epipedons less than 20 cm thick are few and always occur in shallow pedons belonging to lithic subgroups. Vertisols have properties very similar to Mollisols since they always have a mollic epipedon but in addition they have in average a finer texture in the topsoil (43% clay) and a higher organic carbon content: 3.9% in the A horizon (19.7 kg/m^2). Smectite is clearly dominant in the clay fraction.

Mollisols as described above are developed from a large variety of sediments, mostly of fine or medium texture, but also from basalt. On the acid crystalline rocks of the Precambrian shield, Mollisols have usually a reddish brown or red argillic horizon, a sandy loam A horizon overlying a clay loam or clay B horizon and often showing a stone line between both major horizons. They have neither swelling clays nor free carbonates and are more acid in depth. Base saturation does not increase significantly in the lower horizons (B and C) as in other Mollisols. Three Suborders of Mollisols occur in Uruguay (Durán *et al.*, 2005a): Albolls, Aquolls and Udolls.

Albolls: they are rather extensive in the southern sector of the Eastern Flatlands and also occur in minor concave areas where runoff concentrates creating a hydric excess enhanced by the presence of strongly developed argillic horizon of very low permeability. As a whole they are much less extensive than other Mollisols. All Albolls identified in Uruguay are Argialbolls classified either in Typic or Argiaquic Subgroups.

Aquolls: these are the Mollisols with an aquic moisture regime occurring in the extensive wetlands of the Eastern Plains and in most of the lowlands in alluvial plains along streams. The most extended Aquolls are perhaps Argiaquolls, with an argillic horizon but they have not been studied in detail. Endoaquolls, with a cambic horizon or with no B horizon are the current Aquolls of the Eastern Flatlands, while Natraquolls occur usually in small spots associated to Argiaquolls in flat lands.

Udolls: they are by far the most extensive Mollisols since they include all the freely drained soils of the Order of Uruguay. The vastly dominant Udolls are the Argiudolls, with a moderately thick argillic horizon of medium or fine texture. The most common Subgroups are the Pachic, Vertic and Pachic Vertic. Typic Argiudolls are also frequent and the Abruptic occur in minor areas although a number of Pachic and Vertic Argiudolls also meet the requirements of the Abruptic but because of the rigid principles of Soil Taxonomy are keyed out as belonging to either one or the other Subgroups. Hapludolls are less extensive than Argiudolls and are mostly developed on hard igneous or metamorphic rocks (granites, gneisses, basalt) or on lime-cemented sediments. Because of the physical resistance to weathering of the parent material, Hapludolls are usually shallow or only moderately deep. The natural fertility varies in relation to the nature of the parent rock being high on calcareous silty sediments or basalt but medium or somewhat low on acid igneous rocks. The limited thickness of the soil profile results in a medium to low water holding capacity. Natrudolls occur in a few patchy spots in western Uruguay, associated Hapludolls and Argiudolls.

Mollisols occur in most of the physiographic regions of Uruguay (Fig. 4) so only few areas have dominance of other soil orders. Moreover, Mollisols are minor associates in some regions where the main soils belong to other Orders, often rather similar in most of the chemical, mineralogical or physical properties of relevance when assessing soil suitability for different alternatives of land use or soil management practices. Soils distribution by physiographic regions is as follows.

The Crystalline Highlands is an extensive arch-shaped region of rolling hills and valleys, up to 400 m high, underlain by metamorphic rocks of the Precambrian shield. Argiudolls and Hapludolls occur in this region, particularly in the southern part, whereas Alfisols and Dystrudepts become extensive associated soils in the northern sector. The Mollisols of this region are somewhat acid, of medium base saturation and are free of carbonates in all horizons; rock outcrops are locally frequent.

The Basaltic Cuesta is an extensive region in northern Uruguay with a *cuesta* structure, gently dipping towards Uruguay River in the west, and a steeply sloping east-facing abrupt escarpment. Shallow Mollisols (Lithic Hapludolls) are dominant in the upper eastern cuesta while deeper Vertic Argiudolls and Vertisols are extensive in the western region. Vertisols are particularly dominant in the valleys. Rock outcrops are about 2%–10%. Extensive cattle (and sheep) raising is the main land use because of the limited water retention capacity of shallow Mollisols, but as a whole most soils are of high fertility. Dystrudepts, Udorthents, Alfisols and Ultisols occur in a complex soil pattern in the steep slopes of the east-facing escarpment.

Eastwards of the Crystalline Highlands a narrow area of gently undulating to somewhat rolling relief is known as the Eastern Uplands and Low Uplands, where Argiudolls are very dominant in the south while Hapludalfs become important to the north. Many Argiudolls belong to the Typic and Pachic or Vertic Subgroups, but some of them, especially to the north, qualify as Abruptic; all Mollisols have a strongly developed argillic horizon with very slow saturated hydraulic conductivity. Cattle raising is dominant but summer crops (mainly soybean) became important in recent years.

The Central-South Crystalline Region extends over a considerable area in the center of Uruguay, south of the Black River (Rio Negro). The rock substratum does not differ significantly from the subsoil of the Crystalline Highlands but the altitude is much lower and the relief is considerable smoother and consists of undulating to rolling low hills and uplands; in many hilltops or interfluves the metamorphic rocks are covered by a thin veneer of Quaternary mudstones. The soils are moderately deep to deep Argiudolls and shallow Hapludolls, somewhat gravelly, directly overlying the shield rocks, but

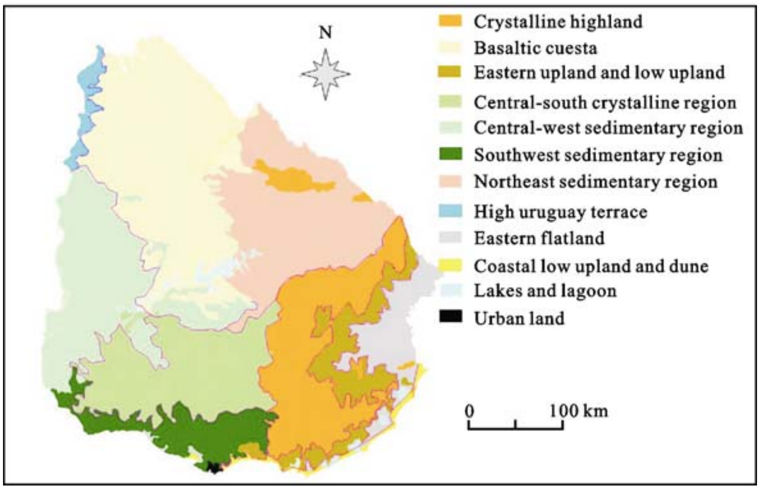


Fig. 4 Physiographic regions of Uruguay (Durán *et al*., 2005a)

Hapluderts also occur (very locally) on fine sedimentary parent material. Cattle raising and dairy farming are important in this region and grain crops have extended in recent years.

The Central-West Sedimentary Region is an area of low altitude and gently undulating to somewhat rolling relief. Its origin dates from the Cretaceous when tectonic subsidence resulted in a basin where aeolian and fluviatile sandstones of the same age were deposited and later covered by calcareous loess and very fine sandstones of Oligocene age and locally by Pliocene fluviatile sandstones. Sandy loam Hapludalfs and Argiudolls of medium or low fertility overlie the sandstones but Argiudolls and Hapludolls on the Cenozoic loess are the most fertile and productive soils of Uruguay. Most of the area is under intensive land use: annual crops (cereals and oilseeds, mainly soybean) and pastures for cattle raising and dairy farming. Traditionally crops and pastures were associated in rotations but the most recent trend is towards continuous cropping; this system is often criticized because its sustainability is questionable. Hapludalfs and Argiudolls on sandstones are under eucalyptus forests in extensive areas.

Along the central and west coast of the River Plate the Southwest Sedimentary Region occupies a tectonic basin of cretaceous age where a very thick succession of sediments was deposited until Cenozoic times. The upper layers are the mudstones of the Libertad fm. where dark, deep and very fertile Argiudolls (Pachic and Vertic) and Hapluderts have been cropped since long ago. Pastures for dairy farming are widespread and vegetables and fruits are cultivated close to Montevideo. Because of the long agricultural use many soils, especially north and east from that city are severely or moderately eroded.

The Northeast Sedimentary Region is an extensive area, between the Basaltic Cuesta and the northern section of the Crystalline Highlands, which is in fact a sedimentary basin of gondwanic origin where a great diversity of sediments was deposited from the Devonian to the Jurassic (sandstone, glacial till, siltstone, shales and limestone). The relief varies from undulating to rolling and the soils are Argiudolls (Typic, Pachic and Vertic) and some Hapludolls and Hapluderts on medium and fine textured sediments whereas Hapludults and Hapludalfs are dominant on sandstones. Land use has been traditionally cattle farming with some crops on the most fertile soils; afforestation with eucalyptus and pines has been important on Ultisols and Alfisols sine the 1990s.

The High Uruguay Terraces make up a narrow band of dissected sloping old terraces of the Uruguay River and low uplands and *glacis* of very gentle slope. Argiudolls of medium or low fertility, often gravelly and stony, occur in the old terraces and Pachic and Typic fertile Argiudolls in the *glacis* but most of the latter are under water after the filling of the Salto hydroelectric dam reservoir in the 1980s.

The plains and wetlands of southeast and east Uruguay known as Eastern Flatlands border the Merim Lagoon on the frontier with Brazil and have a completely flat relief with an altitude of 25 m or less underlain by variable sediments but mostly clayey of alluvial origin. The soils have an aquic regime and are Argiaquolls and Endoaquolls with some Natraquolls, Natraqualfs and Albolls and a small area of Histosols. Soils are used for paddy rice and cattle raising in the non floodable plains. In the wetlands only extensive cattle grazing was feasible because of the permanent or winter flooding but most or the area was drained in the 1980s and paddy rice became also important.

The Coastal Low Uplands and Dunes is a narrow band along the River Plate (east from Montevideo) and the Atlantic Ocean which includes recent sand dunes or aeolian origin and gently undulating uplands 20–30 m a. s. l. Mollisols do no occur in this physiographic unit; soils are Hapludalfs in the uplands and Quartzipsamments and sand in the dunes.

4 Land Use in Argentina and Uruguay

Mollisols of Argentina are among the most fertile and productive soils of the world and especially the Pampean Mollisols have been considered a significant component of the breadbasket of modern times. Consequently these Mollisols have been cropped since the final decade of the last century. The main crops are wheat, corn, sorghum, barley, soybeans and sunflower (Fig. 5). The area of soybeans has increased steadily in recent years in Uruguay.

Sound information about the cropping and economic history of the Pampa region up to the end of 1980′s is found in the paper by Hall *et al.* (1991). Figure 5 is the evolution of cropping area in the Pampa region in Argentina which shows the notorious changes in cropping system. Soybean is the only crop that has increased its acreage in the last years, while the area under the other crops remained relatively stable or slightly decreased (e.g., sunflower). Yields of crops in the Pampean region have been traditionally higher than on the Uruguayan Mollisols because of a higher natural fertility and the higher technological level of the cropping systems (Fig. 6). The latter can be explained by the 'cropping' tradition of the Pampa contrasting to the 'livestock farming' tradition of Uruguay, though in recent years this model has been changing towards a more extended use for cropping.

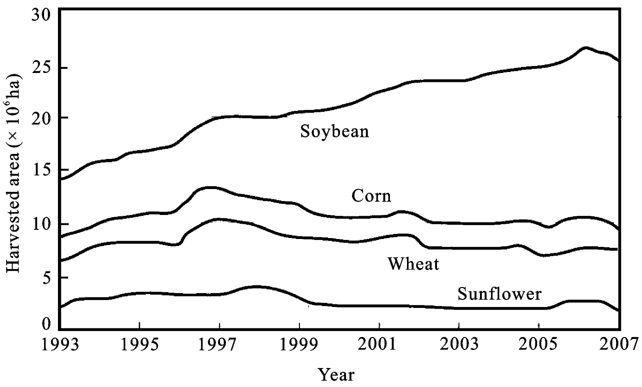


Fig. 5 Harvested area of main crops in Pampean region, Argentina (MAGyP, 2010)

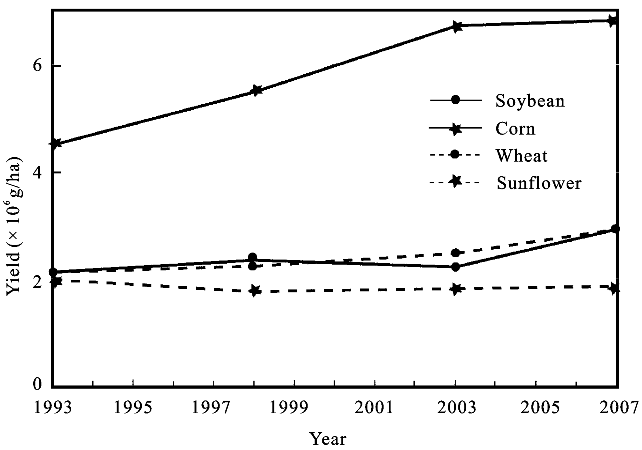


Fig. 6 Crop yields in Pampean region, Argentina (MAGyP, 2010)

Livestock raising, though very important, is not as extentive in the Pampean region of Argentina as in Uruguay (Table 1). Considering the areas of the Pampa (630 000 km^2) and Uruguay (130 000 km^2), the number of heads of beef cattle is comparatively high in the latter.

Table 1 Beef cattle and sheep stock in Pampean region and in Uruguay ($\times 10^6$ heads)

Animal	Argentina (Pampean region)	Uruguay
Beef cattle	37.7	11.6
Sheep	2.2	10.3

Sources: INDEC, National Agricultural Census 2002 (Argentina); MGAP, General Agricultural Census 2000 (Uruguay)

Sheep raising is important in Uruguay but not so much in the Pampean region because Argentinean sheep are raised mostly in the arid Patagonia.

Mollisols in Uruguay have been used mostly for cattle and sheep grazing due to the higher productivity of natural grasslands that can be grazed all year round under a humid and temperate climate with neither snowfall nor dry season. Cropping was historically limited to the more fertile soils of the south, southwest and western regions which is the area of occurrence of the most productive Mollisols. Out of a total area of 1.65×10^7 ha, about 85% was grazing land including 80% of natural grassland. This situation prevailed during the second half of the 20th century and the beginning of the 21st. Cropping land (grains, oil seeds and permanent crops) never exceeded 1.3×10^6 ha and after 1960 the total area under crops decreased to 8.2×10^5 ha.

Yet in the present century and particularly after 2005 crop land has increased rapidly, soybeans and also wheat are responsible for the major expansion as seen in Fig. 7.

As it can be seen in Fig. 7, the area of most crops increased in the present decade with the exception of rice and barley that remained stable. The latter is regulated by the seed processing plants by cropping contracts with farmers whereas rice stabilization may be due to full use of available irrigation sources that limits further expansion of the crop without additional investments to increase water supply.

No significant increases in crop yields occurred in summer crops, except rice which shows some increase though starting from a high productivity. Winter crops behaved in an opposite way since both wheat and barley yields steadily increased in the decade at similar rate. Both trends are shown in Fig. 8. Beef cattle and sheep raising has ever been the main sector in the country and even now, after the great increase or the area under crops, the total cultivated area reached 1.50×10^6 ha out of 1.65×10^7 ha total land area. If the area under eucalyptus and pines, which also increased significantly

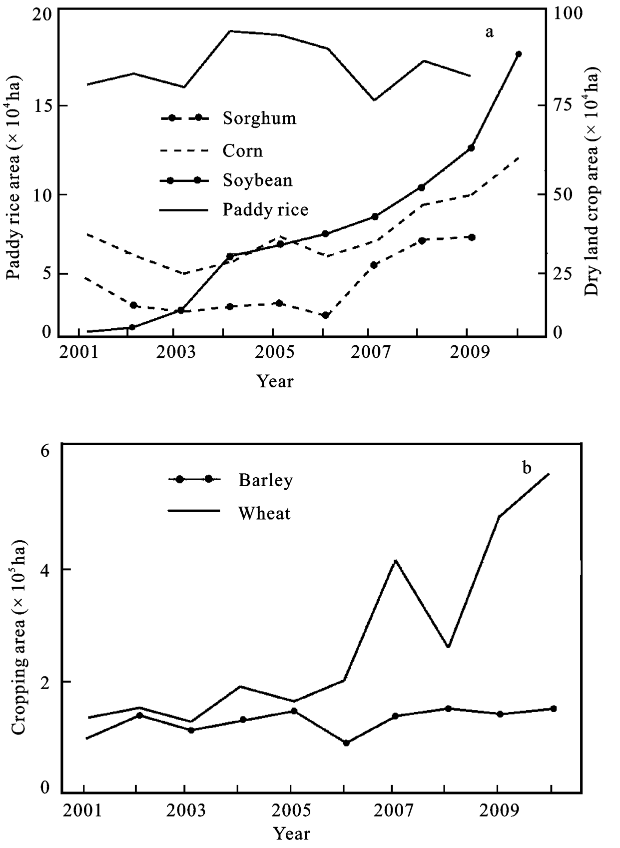


Fig. 7 Cropping area of summer crops (a) and winter crops (b) in Uruguay (MGAP, 2000)

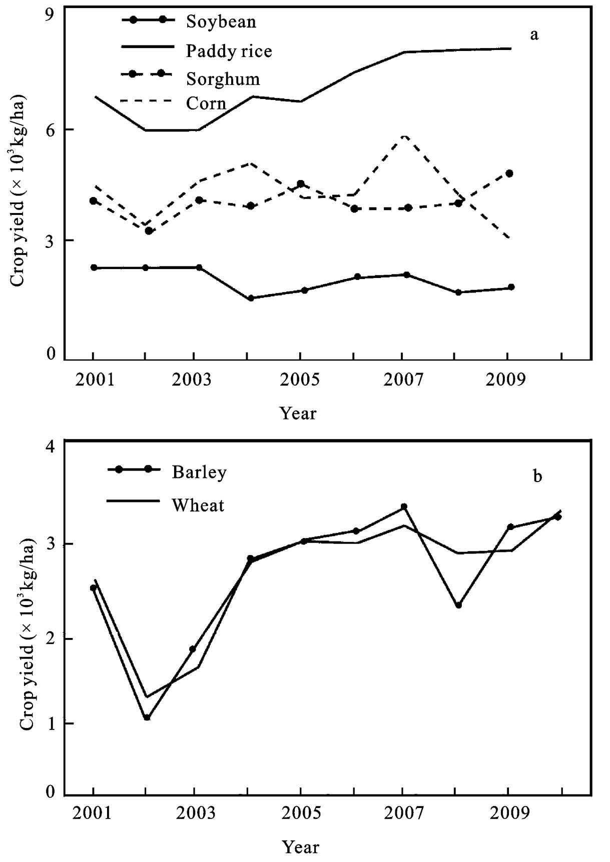


Fig. 8 Crop yields of summer crops (a) and winter crops (b) in Uruguay (MGAP, 2000)

in the last 15 years reaching about 8.00×10^5 ha, is taken into account, the land used for grazing (beef cattle, sheep and dairy farming) is still by far the most extended. Although traditional grazing took place on natural grasslands, since the 1960s the improvement of forage production by sod seeding and seeding of pastures and forage crops became progressively more and more important either in beef cattle farms and dairy farms. As a result improved pastures, including forage annual crops, increased 75% between 1990 and 2000. Yet improved pastures are mostly concentrated in the south and southwest of the country which is also the region with the highest proportion of annual crops and so the area under the highest land use intensity. Pastures in the southwest and west regions became progressively associated to crops in rotation since many farmers in Uruguay combined agriculture with beef cattle raising. This system was highly beneficial for both crops and forage production from the point of view of soil organic matter conservation which usually decreases during the cropping cycle (under traditional tillage) and increases during the pasture cycle.

5 Management of Mollisols in Argentina and Uruguay

5.1 Argentina

Pampean Mollisols were originally soils high in organic matter and of very high natural fertility but because of the long cropping history they have undergone losses in both properties. Loss of organic matter under conventional tillage is shown in Table 2. Yet soil organic matter content is still high as a result of the original level in virgin soils and even in the western semiarid Pampa it meets the minimum requirement (1%) of the mollic epipedon. The data in Table 2 provide evidence of the decrease of soil organic matter after a long cropping period that demands for conservation practices to reduce future losses and a deterioration of soil quality.

It has been demonstrated that careful use of tillage systems, crop rotations and other management practices (i.e., fertilization and cover crops) could be effectively used to manage and recover soil organic matter contents (Studdert *et al.*, 1997; Studdert and Echeverría, 2000;

Table 2 Change in soil organic matter content from virgin to cropped soils in different subregions of Argentinean Pampa

Province	Zone	Soil organic matter content (g/kg)		Variation (%)
		Virgin (S.E.)	Actual (S.E.)	
Buenos Aires	Southwest	85.9 (18.5) (n = 21)	55.3 (9.0) (n = 1036)	–35.6
	North	50.5 (10.3) (n = 41)	29.0 (12.1) (n = 2081)	–42.5
Santa Fe	South	42.6 (11.2) (n = 6)	26.2 (5.1) (n = 2853)	–38.4
Cordoba	Southeast	33.5 (8.4) (n = 7)	20.2 (5.7) (n = 1903)	–39.6
La Pampa	East	34.5 (6.8) (n = 7)	16.4 (6.1) (n = 527)	–52.5

Source: Sainz-Rozas *et al.*, 2011

Díaz-Zorita *et al.*, 2002; Steinbach and Álvarez, 2006; Domínguez *et al.*, 2009; Studdert *et al.*, 2010). The alternation of short pasture periods with cropping periods allows recovering organic matter stock lost along cropping periods either under conventional tillage or no tillage (Studdert *et al.*, 1997; Studdert *et al.*, 2010). Likewise, crop rotations including high residue producing crops (e.g., corn, wheat) or increasing crop yields (Studdert and Echeverría, 2000; Steinbach and Álvarez, 2006; Domínguez *et al.*, 2009) tended to reduce soil organic matter loss rates. The reduction of tillage intensity has also been proposed as an effective approach in contribution to reduce soil organic matter (Díaz-Zorita *et al.*, 2002; Steinbach and Álvarez, 2006; Domínguez *et al.*, 2009).

Regarding soil fertility, the high nutrient content of Pampean Mollisols allowed a long cropping period with low fertilization to replace extraction by crops. More recently, application of fertilizers has increased which resulted in the reversion of the steady losses of nutrients. Nevertheless, even though effective reposition of nutrients is increasing, the ratio application/extraction is still below 1 (Fig. 9). The high fertility of Pampean soils explains the late beginning of systematic fertilization in Argentina.

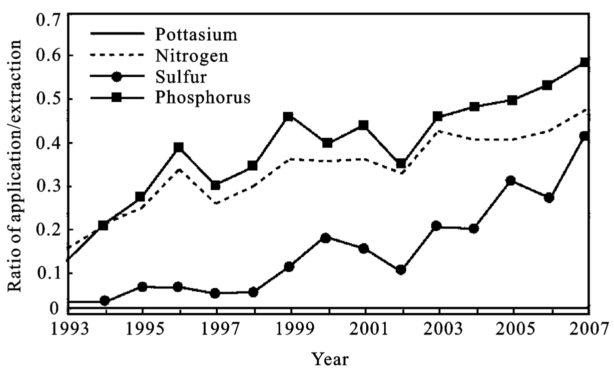


Fig. 9 Soil nutrients relationship in Pampean Mollisols

Besides the negative nutrient balance and biological degradation (Table 2), long lasting cropping history and present cropping intensification and expansion has led to increased soil degradation processes (Manuel-Navarrete *et al.*, 2005). Soil erosion is the most serious and less taken into account degradation process in Argentina, especially in the area occupied by Mollisols in the central- northeastern part of the country (Fig. 1) (FAO, 1993). The western part of the Pampean region is mostly affected by wind erosion (FAO, 1993; Buschiazzo *et al.*, 1999; Díaz-Zorita *et al.*, 2002) whereas the eastern part is affected by water erosion (FAO, 1993; Orúe *et al.*, 2007). Around 30%–40% of the surface of the Pampean region is at present affected by some degree of erosion, and this proportion is greater where cropping history has been longer lasting (northeastern Buenos Aires province, southern-central Santa Fe province, southwestern Entre Ríos province) (FAO, 1993). However, the risk of water erosion is highest in areas where cropping has expanded and intensified recently (northwestern part of the Mollisol region of Argentina (Fig. 1)) (Orúe *et al.*, 2007). Despite conservation techniques are available to control both wind and water erosion, the level of adoption by producers is low (FAO, 1993).

No tillage cropping is rapidly increasing in Argentinean Mollisols which results in reduction of organic matter losses and a more sustainable agriculture as illustrated in Fig. 10. Despite cropping intensification, the generalized use of no tillage is contributing to mitigation of soil degradation rates (Manuel-Navarrete *et al.*, 2005). The incorporation of no tillage systems is actually practiced in Uruguay and other South American countries.

5.2 Uruguay

Durán and García Préchac (2007) recognize four periods defined by the dominant cropping technology and its impacts on soil conservation. (1) 1950–1965: promotion

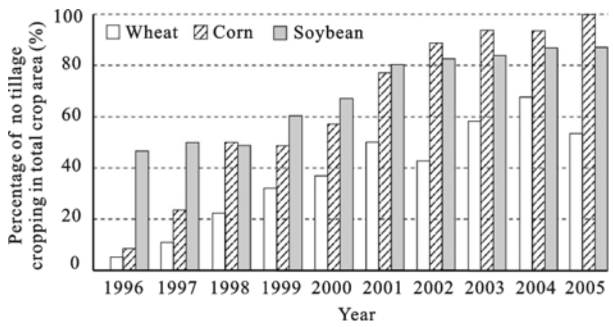


Fig. 10 Area percentage of no tillage cropping in Mollisols of Argentina (AAPRESID, 2010)

of mechanical practices (terraces) in rented state-owned farms under very intensive land use. Poor performance and lack of proper management of terraces resulted in abandoning the system. (2) 1965 to present: introduction and expansion (until the present decade) of rotations of crops and pastures. (3) 1975–1990: inclusion of contour cropping in the crops phase of the rotations. (4) 1990 to present: Introduction of no tillage systems both in rotations and in continuous cropping systems that is increasing rapidly in the last years.

Long-term tillage of arable crops in the older farming areas (southern region) resulted in severe sheet and gully erosion affecting mostly small holdings with originally fertile and productive Mollisols and Vertisols. These soils are used mainly for orchards, vineyards of dairy farming.

Water erosion is yet the main environmental problem regarding soil management and conservation in Uruguay and different investigations conclude that erosion is always related to arable cropping. No clear evidence of influence of overgrazing on soil losses has been identified. Since most of the territory has remained under natural grassland until a few years ago (and extensive areas of rangeland still exist) it is not surprising that most of the territory (70%) is not affected by erosion or is only slightly (18%) or moderately eroded (10%). The severely eroded area comprises only 2% of the country.

The large increase of the cropping area that took place in the last years is a challenge for sustainable land use because of the unquestionable relationship between crop production and erosion already mentioned. Yet there are available approches and technologies to prevent soil losses under cropping systems of increasing intensity rapidly expanding in Uruguay. Some of these approaches are summarized below:

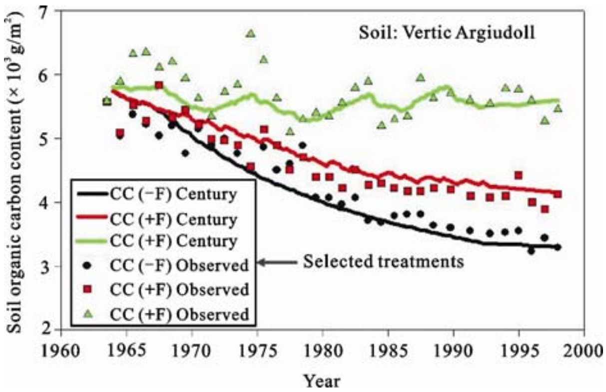
(1) The well known model (universal soil loss equation (USLE), revised universal soil loss equaion (RUSLE)) can be used to anticipate the expected soil losses under a variety of the common cropping systems including both continuous cropping and rotation. The model has been validated for the conditions of soils and rainfall characteristics prevailing in Uruguay by the thorough research conducted by Garcia Préchac of which a complete description is available in Garcia Préchac (1992) and Garcia Préchac *et al.* (2005). More recently Durán and Garcia Préchac (2007) compiled a complete literature on this issue. The USLE/RUSLE model is freely available for farmers, extensionists and professional consultants either in CD format or it can be downloaded from the website http://www.fagro.edu.uy (Garcia Préchac *et al.*, 2005).

(2) Widespread incorporation of no tillage systems which has been proved to be the most effective tool in soil conservation. An additional advantage is that elimination of tillage allowed sustainable agriculture in soils previously considered as non arable because of steep slope or limited depth.

(3) Combination of no tillage with crop-pasture rotations is recommended to take advantage of the reduction of soil losses under conventional tillage and the prevention of herbicide-resistant weeds as a result of the alternation of grain crops and pastures. No tillage also reduces soil organic matter losses and CO_2 emissions resulting of organic matter oxidation under long-term tillage (Fig. 11). Additional advantages of no tillage systems are: improvement of soil macrofauna biodiversity, increase in soil water content, higher soil bearing capacity which allows for timeliness of seeding, harvest and grazing, possibility of cropping on non arable soils and lower costs of crop production (Durán and Garcia Préchac, 2007). The modern crop systems should promote high productivity levels without the negative effects of land use intensification or at least reducing such effects to tolerable levels.

Figure 11 shows that continuous cropping under conventional tillage resulted in a steady loss of soil organic carbon; fertilization decreased but did not prevent losses. On the other hand, a crop-pasture rotation successfully kept the initial organic carbon content since losses during the cropping cycle were reversed in the pasture cycle.

At the beginning of the 1990s, the government promoted the forestation through a specific national program which resulted in a substantial increase of forested



Organic carbon prediction according to the Century model; CC (-F): conventional continuous cropping, not fertilized; CC (+F): conventional continuous cropping, fertilized; CP (+F): crop-pasture rotation, fertilized; experiment started in 1963

Fig. 11 Observed and predicted soil organic carbon content in a long term rotations experiment (Baethgen and Morón, 1994)

areas: 180 000 ha at the beginning of the period, 650 000 ha in 2000 and more than 800 000 ha at present. The plan supported technically and financially plantations of eucalyptus and pines on soils of good forest suitability but of relatively low productivity for grains and pasture with the purpose of developing forestation but not at the expense of affecting the best cropping and grazing areas. Therefore most forests planted in the frame of the plan are on soils other than Mollisols or Vertisols. These forested lands significantly contribute to a positive balance of the CO_2 cycle since its sequestration or fixation is now higher under forests than emissions, and contributes together with modern technology in cropping systems to a more sustainable primary production.

6 Conclusions

World Mollisols extend over 9.16×10^8 ha (6.9% of land mass) of which 1.06×10^8 ha (11.5 %) occur in South America, almost exclusively in Argentina and Uruguay. In these countries, Mollisols were developed mostly on Pleistocene and Holocene sediments of loessial type, and also on other aeolian and fluviatile sediments. South American Mollisols were developed in temperate to cool, moist to semiarid climates under natural grass vegetation, with or without scattered trees, but a few were formed under forest. They are dark colored, organic matter rich soils of high base status, free of Al toxicity and therefore very fertile. A clay fraction dominated by illitic and smectitic minerals and, over extended areas, an important proportion of volcanoclastic minerals in the coarse fraction, are also contributing to the high fertility of these soils. Thus, though limited in area, Mollisols are extremely important because of its high natural productivity which makes them very suitable for food production. Most of South American Mollisols are used for cropping to grain, oilseed, orchard, forage, and fiber crop production. They are also used for cattle raising and dairy farming feeding the cattle with grains, forage crops or natural pastures.

Erosion and degradation are extremely severe in South American Mollisols although they have been cropped for not more than 120 years. However, the increasing demand for food is leading to an intensification of agriculture on Mollisols of Argentina and Uruguay in order to satisfy that demand. The acreage under crops, improved pastures or forage crops has been increasing as well as the use of technological inputs (fertilizers, chemicals, improved seeds and varieties) resulting in higher yields and total grain, beef and milk production. Land use intensification imposes higher pressure on the soil resource and makes production sustainability highly dependent on the proper use of conservation practices (reduced or no tillage cropping, crop-pasture rotations). Wise use of chemicals for the prevention of pollution of drinking or irrigation water and adaptation to climate change, a major challenge for agriculture, are also required for a sustained use of Mollisols′ high productivity without negative environmental consequences.

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