

Chapter 17

Soil Mapping Based on Landscape Classification in the Semiarid Chaco, Argentina

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Abstract The semiarid Chaco is an ecosystem shared by Argentina, Paraguay, Bolivia, and Brazil where land use changes from forest to commercial agriculture and social conflicts have been intensive during the last decade. These changes and the lack of reliable soil information at suitable scales are threatening the sustainable development of the region. In Santiago del Estero province, Argentina, a soil survey was carried out with the objective of reducing the knowledge gap. Due to the large area, geomorphology diversity, limited funding, and high demand of information, a geopedologic survey using remote sensing and GIS was considered an appropriate approach. Map units were determined based on the integration of geoforms and soils, knowledge of landscape and soil forming factors, field observations, and laboratory determinations. Three main landscape units were recognized: (1) a fluvio-eolian Chaco plain including a megafan with Haplustolls and Torripsamments,

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(2) the Río Dulce valley with Torripsamments, and (3) the alluvial migratory plain of Río Salado with Torripsamments, Ustifluvents, and Natraqualfs. The used approach helped speed up the soil information collection at appropriate scale for land use planning.

Keywords Geopedology • Soil mapping • Remote sensing • GIS • Landscape classification

17.1 Introduction

The semiarid Chaco ecosystem (Cabrera 1976; Vargas Gil 1988; Sebastián et al. 2006) is a flat mixed woodland-grassland landscape shared by Argentina, Paraguay, Bolivia, and Brazil. Temperature rises from south to north and rainfall from west to east. Using unrestricted forest clearing and fire, traditional land use has changed to commercial agriculture in the last decade (Morello et al. 2006). This process, together with the lack of adequate soil information for land use planning, is threatening the sustainable development of the region.

Mitigation of the impacts caused by agricultural expansion on fragile natural resources and land use sustainability require balanced environmental performance, better understanding of the physical and anthropogenic factors affecting land use, and systematic organization of regional data and information (Angueira 1994).

The knowledge of soils and their geographic distribution is basic information for (a) agricultural research and modelling (Jhorar et al. 2003; Walter et al. 2007), (b) land capability assessment (Bouma and Bregt 1989; Angueira and Zamora 2003); (c) sustainable land use planning at regional, local, and farm scale (McRae and Burnham 1981; Rossiter and van Wambeke 1991), and (d) integration of relevant information in geographic information systems (Zinck 1994; Burrough and McDonnell 1998; Angueira et al. 2007).

Earlier traditional soil inventory methods were expensive and time consuming due to the high cost of remote sensing documents, difficulties to plan fieldwork properly, and limited application of integrated soil-landscape survey. Nowadays, these restrictions have been overcome by the development of tools, methods, and systems in remote sensing, geostatistics, GIS, and data processing (McBratney et al. 2003), provided by progress in computer technology and informatics.

The geomorphic approach helps understand the spatial distribution of soils on the landscape, and geomorphic processes influence soil formation and features (Bockheim et al. 2005). The synergism between pedology and geomorphology is important for predicting areal distribution of soils on the landscape, and it is the basis of geopedology, a transdisciplinary soil survey approach (Zinck 1994, 2012, 2013).

Satellite images offer the possibility of segmenting the landscape into units whose soil composition can be determined by conventional or advanced methods,

and their use supports extending soil survey to inaccessible areas by reducing time and fieldwork (Mulder et al. 2011). Landsat satellite data have been used for physiographic soil mapping (Sayago 1982), geological mapping (Moore et al. 2007), and surface features mapping (Metternicht and Zinck 2003). Moreover, the combination of multi-source geographic datasets (Krol et al. 2007), digital elevation model (DEM), and spectral satellite data may improve landform classification in complex landscapes (Dobos et al. 2000).

In Argentina, a national soil map at scales of 1:500,000 and 1:1,000,000 shows cartographic units labeled on the basis of soil-landscape relationships (INTA 1990). A soil survey of the Pampa region carried out at scale 1:50,000 provides map units in terms of soil associations and complexes (Echevehere 1976). The semiarid Chaco is covered by detailed soil surveys only for small parts (Peña and Salazar 1978; Angueira and Vargas Gil 1993; Angueira and Zamora 2003).

This chapter presents the geopedologic survey of an area covering the south-western semiarid Chaco region at 1:500,000 scale. The combination of geopedology and modern geomatic techniques was considered appropriate for soil inventory in the semiarid Chaco because of the lack of soil studies at suitable scales, large area extent, diversity of geomorphology, soil types and land uses, high demand of information, and limited funding and trained staff.

17.2 Materials and Methods

17.2.1 Study Area

The semiarid Chaco ecosystem is a sedimentary plain fractured and dislocated in depth. A depression with subsequent accumulation of sediments formed during the Tertiary, followed by an uplift accompanied by strong parallel and transverse folds and faults (Abitbol 1997; Martin 1999; Peri and Rosello 2010).

The present landscape, the fluvial network, and the Mar Chiquita depression were formed in the late Pleistocene and covered by aeolian sediments (Sayago 1995; Carignano et al. 2014). These physiographic processes determined changes in the Salado and Dulce river systems. The Rio Dulce formed complex alluvial fans (Martin 1994; Barbeito and Ambrosino 2007) and its main channel is assumed to have shifted southward to the Salinas Ambargasta Sumampa or together with Rio Salado to Mar Chiquita, until the current position (Martin 1999).

The study area of 8,800 km² is located in the south-west of the semiarid Chaco region (Vargas Gil 1988), in Santiago del Estero province, between 27°30'–28°35'S and 63°45'–64°35'W (Fig. 17.1). The climate according to the Thornthwaite classification is DB'4da' semiarid, without or with little excess of water, mesothermal, with rainfall concentrated during the summer months.

The landscape is gently sloping from the west to north-east, east and south-east, and shows a set of landforms resulting from exogenous and endogenous processes.

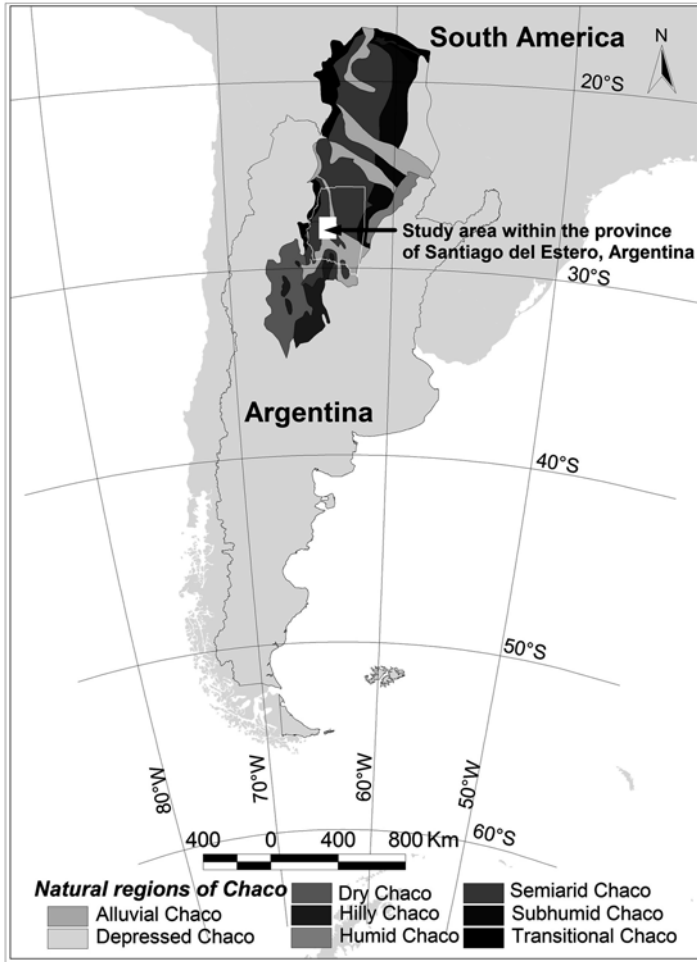


Fig. 17.1 Location of the study area in the semi-arid Chaco, province of Santiago del Estero, Argentina (Vargas Gil 1988)

It comprises part of a fluvio-eolian plain and the alluvial plains of Rio Dulce and Rio Salado (Angueira et al. 2007) with their ancient and present meanders characteristic of rivers in areas with low slope or energy.

17.2.2 Materials

Data were obtained from maps and reports, remote sensing documents, field observations, and laboratory determinations of soil properties. The material used included the geomorphology map of Santiago del Estero (Angueira et al. 2007), the soil maps

of Santiago del Estero (INTA 1990; Angueira et al. 2007) and the right bank of Rio Dulce (Angueira and Zamora 2003), and topographic data derived from a DEM 90-m (CGIAR-CSI 2004) with altitude values with 3 arc sec interval.

Landsat satellite images (NASA-USGS 1972) were selected on the basis of adequate spatial resolution for the scale of work and availability of long term records, even from the decade of the 1970s with unchanged native vegetation. Selected scenes included MSS 246-79 (02/75); TM 230-079 and 229-079 in dry and wet seasons from 1984 to 2011; and 8 OLI (05/14). Complementary data were obtained from CBERS (INPE 2008) and SAC-C (CONAE 2000) images.

ArcGis 9.3 (ESRI), Imagine 9.3.1 (Leica), and SAGA (Böhner et al. 2006) software were used for mapping, digital processing of satellite images, calculating derivative morphographic and morphometric attributes, and displaying the results.

17.2.3 Methods

17.2.3.1 General Methodology for the Geopedologic Survey

The work started with a review of available information and an overview of the area to identify major geomorphic features, while maps were displayed in a GIS environment for easy and efficient handling.

Using an iterative and exhaustive visual interpretation of topographic data and satellite imagery, preliminary map units were delineated, a draft hierarchic geomorph legend as cartographic frame was established to define soil-landscape relationships, and sites for describing soils and checking boundaries in the preliminary physiographic units were identified. Physical and chemical soil properties were determined, and soils were classified according to Soil Survey Staff (2010). The interpretative map was converted into geopedologic map after confirming boundaries, legend, characterization of soils and their spatial distribution patterns.

17.2.3.2 Geospatial and Soil Analysis Tools and Methods

Morphographic and morphometric attribute maps were established from DEM 90-m to describe, identify, and classify by visual interpretation the geomorphs at different levels of the taxonomic system (Zinck 2013). The following attributes were calculated with the ArcGis software: slope, hillshade, profile curvature, viewshed, wetness index, flow direction, flow accumulation, flow length, stream link, stream network, stream order, drainage network, watershed basin, aspect, cross-sectional curvature, longitudinal curvature, convergence index, and closed depressions. To improve visualization of the drainage network, the ratio of surface area drained by each outlet more appropriate to the scale of work was selected.

For automated classification of geomorphs, the attributes of analytical hillshading, slope, aspect, cross-sectional curvature, longitudinal curvature, convergence index,

and closed depressions were combined using the isodata cluster analysis by SAGA software for an isoform map.

Systematic visual interpretation of Landsat, SAC, and CBERS satellite images was carried out after preprocessing, radiometric correction, and georeferencing on the Gauss-Krüger projection IGN (2000). Criteria and procedures of visual interpretation, analysis of elements, landscape patterns, and physiographic methods (Goosen 1967) were applied. Tone, texture, color, pattern, shape, size, height, elevation, location, and their association with other objects, were all elements considered to characterize the physiographic system that has controlled the formation of the area.

DEM-derived maps were combined with Landsat images to improve visual interpretability and understanding of the relationships between the landscape elements (Shepande 2010). Images from dry and wet seasons were analyzed with different band composition to identify water bodies, sediments in water, drainage networks, vegetation types, texture, soil moisture, terrain features, and soil conditions.

The SAC-C scene was used to identify patterns of waterlogging following the extremely heavy rainfall of 30.03.2006. CBERS high-resolution (CCD) scenes were used to improve the delineation of fluvial landforms, meanders, and spill areas with accumulation of material.

A set of 176 georeferenced soil profiles and observations, approximately 1/50 km², was described according to the guidelines of Echevehere (1976). Laboratory determinations on dried soil samples included soil texture by Bouyoucos, pH in soil paste, EC in saturated soil paste extract, organic carbon by Walkley-Black, CEC by ammonium acetate 1N pH 7, and percentage of CaCO₃ by the Scheibler method.

17.3 Results

17.3.1 Geospatial Analysis

Visual interpretation of a DEM 90-m contour map with 1 m vertical intervals (Fig. 17.2) allowed distinguishing relief characteristics such as faults (1) and slope changes, while a 5 m interval map was useful to identify runoff ways and separate high- and low-lying areas.

The drainage network map shows a watershed flowing to the north and east of the Rio Salado, an alluvial fan to the south-east, and a main course to the south of Río Dulce. From the isoform map (Fig. 17.3) were recognized the following features: a fan with its apex in the west and a divergent gently sloping area to north-east and south-east (1), a main and a secondary fault (2), north-south parallel valleys at the foot of the main fault (3), and a shallow sag pond (4) at the foot of the secondary fault.

Water bodies, main rivers, streams, meanders, soil wetness, vegetation type changes were identified by distinguishing color patterns, tones, and texture, analyzed

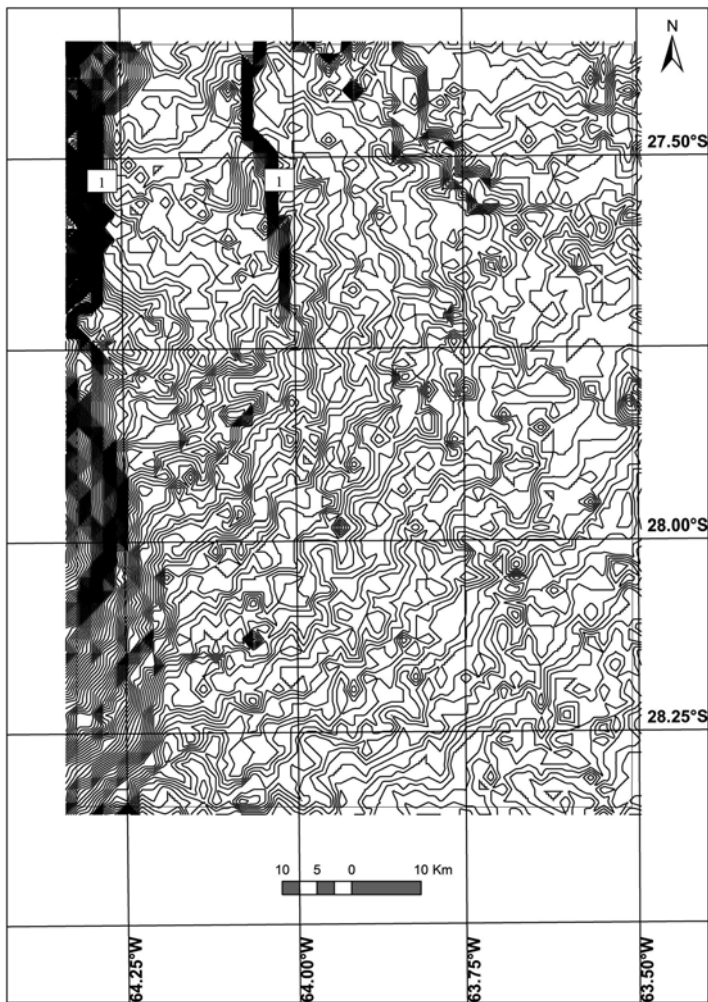


Fig. 17.2 Contour map with 1 m vertical intervals, (1) main fault in the west and secondary in the east

in sequences of different band composition of satellite images. Visual analysis revealed that bands (2,3,4), (3,4,5), (3,5,7), and in gray colors, provided optimal contrast.

17.3.2 Soil-Landscape Relationships

Iterative analysis of the soil-landscape relationships, fieldwork, and laboratory data allowed classifying the soil subgroups recognized in each landform. Mean values of selected soil properties are shown in Table 17.1.

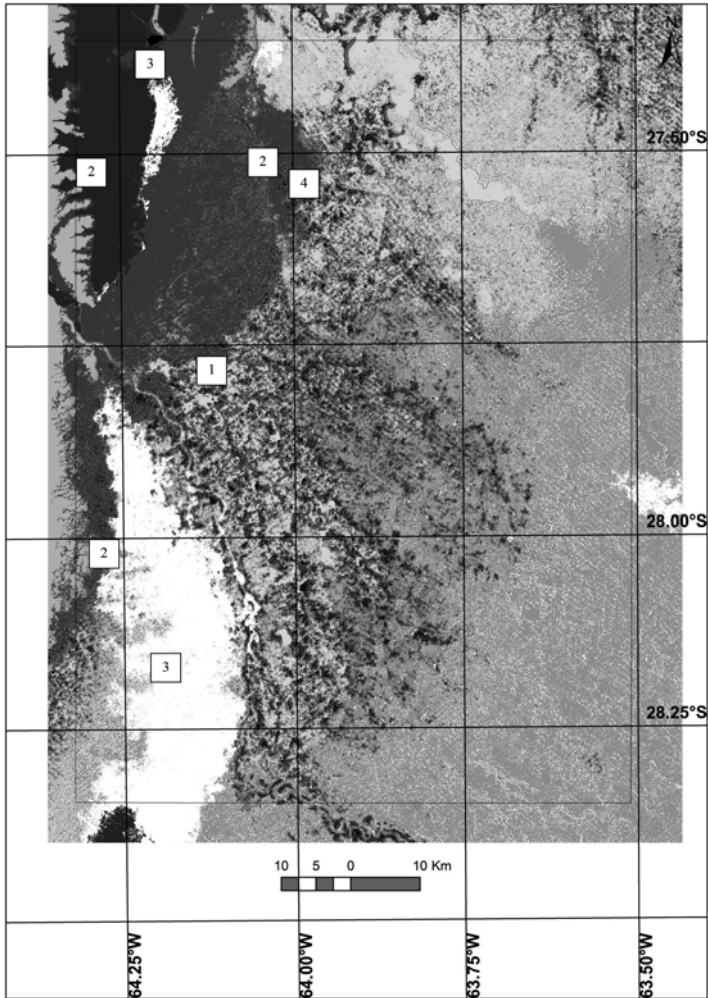


Fig. 17.3 Isoform map showing 1 fan, 2 secondary fault, 3 valleys, 4 shallow sag pond at the foot of the secondary fault

Geoforms and soils influence each other, being one of them the dominant factor according to circumstances, natural conditions, and landscape types. The main characteristic in the study area is that the sedimentary processes control soil distribution and properties, the type of pedogenesis, and the degree of soil development in all landscapes.

In the loess-covered proximal megafan dominate Torriorthentic Haplustolls without cambic horizon, together with Aquic Haplustolls in blowout depressions that have excess water and aquic conditions in some periods of most years.

In the distal megafan, characterized by a radial drainage network and interfluvial plains, Torriorthentic Haplustolls associated with Aridic Haplustolls are the main

Table 17.1 Mean values of relevant soil properties per landscape unit and subgroup

Hor	Taxon	Text	Clay %	Silt %	Sand %	OM %	CO ₃ %	pH	EC dS/m	CEC cmol kg ⁻¹	ESP %
Fluvio-eolian Chaco plain – proximal megafan (Río Sali-Dulce) – 1 loess cover – 1P											
A	Torriortentic Haplustoll		11	60	29	2.1	0.0	0.0	0.3	15.7	0.0
AC			8	60	32	0.9	0.0	7.2	0.2	13.1	4.2
Ck			6	58	36	0.4	1.5	7.7	1.0	11.6	18.7
Fluvio-eolian Chaco plain – proximal megafan (Río Sali-Dulce) – 2 blowout depression – 2P											
A	Aquic Haplustoll	L	10	60	29	1.6	0.0	5.7	0.2	2.0	2.3
AC		L	8	64	28	1.0	0.0	7.2	0.3	15.3	2.8
C		L	8	65	27	0.7	0.0	7.7	0.3	14.9	3.2
Fluvio-eolian Chaco plain – distal megafan (Río Sali-Dulce) – 3 interfluvial plain – 3P											
A	Aridic Haplustoll		20	54.9	25.3	2.2	0.9	7.5	2.2	18.0	10.7
Bw			19	53.5	27.5	0.8	1.4	7.8	3.1	16.1	19.1
Ck			20	52.6	27.7	0.6	2.2	7.8	3.8	16.2	19.9
A	Torriortentic Haplustoll		14	53	34	2.0	0.3	6.8	3.5	14.4	6.3
AC			13	54	33	0.8	0.7	7.3	2.7	12.6	6.7
Ck			12	52	36	0.4	2.6	7.6	4.1	10.7	17.3
A	Aridic Argiustoll		21	51	28	2.8	1.5	7.2	1.0	19.7	4.0
Bt		CL	28	46	27	1.3	0.0	7.6	0.6	17.7	8.0
BC		SIL	20	51	22	0.7	1.4	7.5	0.9	17.2	25.0
Ck		L	23	44	33	0.2	1.5	7.6	1.0	16.1	22.5
Fluvio-eolian Chaco plain – distal megafan (Río Sali-Dulce) – 4 infilled channel – 4P											
A	Ustic Torripsamment		3	30	67	0.8	0.0	6.9	13.5	7.4	19.0
C		LSa	1	20	79	0.3	2.1	7.4	17.3	7.0	21.0
A	Ustic Torriorthent		10	38	52	1.5	0.0	8.1	1.0	10.2	2.5
AC		SIL	8	43	49	0.6	0.0	7.9	0.5	9.8	2.1
CI		SIL	7	45	48	0.3	3.0	8.1	0.6	9.4	5.8

(continued)

Table 17.1 (continued)

Hor	Taxon	Text	Clay %	Silt %	Sand %	OM %	CO ₃ %	pH	EC dS/m	CEC cmol kg ⁻¹	ESP %
Fluvio-eolian Chaco plain – old alluvial overland flow (Río Sali-Dulce) – 5 overflowed depression – 5P											
A	Aridic Haplustalf	L	24	48	28	1.6	0.0	6.9	5.8	21.0	3.0
Bt		CL	37	43	20	1.7	0.0	6.4	17.0	20.1	3.0
BC		L	26	43	31	1.0	1.7	6.6	37.5	15.8	22.0
Fluvio-eolian Chaco plain – old alluvial overland flow (Río Sali-Dulce) – 6 alluvial overflow levee – 6P											
A	Ustic Torriorthent	L	13	43	44	2.0	0.9	7.3	18.7	14.7	21.0
AC		L	15	48	37	0.7	1.4	7.6	53.0	13.6	31.0
C		L	13	47	40	0.4	6.1	7.6	66.5	12.8	33.0
A	Ustic Torrifluvent	SiL	8	70	22	2.0	1.3	6.8	2.5	13.6	6.0
AC		SiL	6	70	24	0.4	1.2	7.0	12.4	10.0	15.0
II		SiC	40	44	16	1.0	0.0	6.8	17.5	18.8	15.0
Valley (Río Dulce) – middle terrace – 7 Levee and overflows (mt) – 7D											
A	Aridic Haplustoll	SiL	19	63	18	4.3	0.0	6.1	0.0	15.4	16.0
Bw		SiL	16	68	16	1.2	0.0	6.4	0.0	13.8	18.0
Ck		SiL	19	61	20	1.4	1.9	6.7	0.0	11.0	23.0
Valley (Río Dulce) – low terrace – 8 levee and overflow (lt) – 8D											
A	Typic Haplustoll	SaL	6	44	50	3.5	1.1	6.8	6.1	13.1	6.0
C		SaL	3	36	61	0.1	3.0	8.2	1.3	7.8	27.0
Valley (Río Dulce) – active floodplain – 9 river – 9D											
A	Ustic Torripsamment	Sa	1	3	96	0.2	0.0	7.3	0.1	3.2	0.2
C		Sa	1	5	94	0.6	0.0	6.3	0.2	2.9	6.9
Alluvial migratory plain (Río Salado) – active fluvial valley- alluvial overflow plain 10S											
A	Typic Natraqualf	L	18	40	42	3.1	0.0	6.3	0.9	15.8	5.0
Bn		L	35	43	22	0.6	0.0	6.1	10.6	13.8	15.0
BC		L	26	48	26	0.3	0.0	6.3	36.0	12.6	20.0
Ck		L	22	46	32	0.1	3.0	7.4	16.3	11.6	16.0

Alluvial migratory plain (Río Salado) – active fluvial valley – levee 11S											
A	Ustic Torripsamment	SiL	14	52	34	1.4	1.0	7.7	1.8	12.4	13.0
AC		L	10	50	40	0.4	2.2	7.4	49.0	10.6	36.0
Csa		L	14	44	42	0.1	2.7	7.5	65.0	11.0	36.0
Alluvial migratory plain (Río Salado) – active floodplain – 12 alluvial overflow swamp – 12S											
I	Ustic Torrifluvent	SiL	11	63	26	3.5	3.0	7.9	1.9	21.2	11.7
II		SiL	9	65	26	0.6	2.5	8.2	4.3	12.2	42.0
III		SiL	9	35	56	0.4	0.9	7.9	12.0	9.1	28.0
Alluvial migratory plain (Río Salado) – Fluvio-eolian terrace remnant – 13 alluvial flat – 13S											
A	Aridic Haplustoll	L	16	48	36	2.2	0.0	7.2	4.0	14.8	5.0
Bw		L	15	47	38	1.2	0.0	7.2	10.8	12.7	16.0
BC		L	16	48	36	0.6	0.0	7.4	18.5	12.6	22.0
Ck		L	14	50	36	0.4	2.0	7.7	19.4	12.5	24.0
Alluvial migratory plain (Río Salado) – Fluvio-eolian terrace remnant – 14 alluvial channel – 14S											
A	Ustic Torripsamment	SaL	9	34	57	2.4	0.0	6.4	0.7	9.0	6.0
AC		SaL	7	34	59	0.8	0.0	6.8	12.9	9.0	22.0
C		SaL	4	32	64	0.5	0.0	7.6	17.7	7.8	36.0

soils, while Aridic Argiustolls occur in micro-depressions. Ustic Torriorthents are common on sandy alluvial overflow levees and Aridic Haplustalfs in overflowed depressions.

In the Río Dulce valley, soils of different levels of development and contrasting textures occur, with poorly developed Entisols on modern floodplain deposits and more developed Aridic and Typic Haplustolls on terrace levels. In the alluvial migratory plain of Río Salado, Typic Natraqualfs developed on the overflow plain with high water table, and Ustic Torripsamments on the sandy levees.

In the active floodplain of the streams draining the Huyamampa depression occur Ustic Torrifluents together with alluvial saline-sodic soils. On the fluvio-eolian terrace remnant, Aridic Haplustolls are the dominant soils, with Ustic Torripsamments in elongated and irregular depressions.

17.3.3 Geopedologic Map and Legend

The hierarchic classification of the geopedologic map units in landscapes, moldings, and landforms together with their soil components at various scales was established from the integrated analysis of the relationships and interactions between geoforms and soils. The spatial distribution of soils is related to landforms at all scales. The map units are soil associations and complexes, consisting of two or more soil taxa geographically associated in a landform.

The study area comprises 3 landscape types, 9 molding types, and 14 landform types. They are described including name, symbol, and soil composition, and shown in the geopedologic map (Fig. 17.4) and legend (Fig. 17.5).

17.3.3.1 Fluvio-eolian Chaco Plain

The fluvio-eolian Chaco plain in the west and center of the study area, a slightly convex landscape with 0.5–1 % slope, presents three moldings belonging to the Río Sali-Dulce system and including a proximal megafan, a distal megafan, and an old alluvial overland flow area, with their corresponding landform units and soil components.

- (a) The *proximal megafan* is a gently sloping terrain covered by a loess mantle including at the level of landform: a *loess cover unit* (1P), a gently sloping surface with Torriorthentic Haplustolls, dissected by *blowout depressions* (2P), which are wide and elongated shallow areas occasionally acting as runoff paths with Aquic Haplustolls.
- (b) The *distal megafan* is a cone-shaped deposit of sand and finer materials formed in the area where the river slows down and spreads into a flatter plain at the exit of the Huyamampa N-S fault. It is composed of two landforms: an *interfluvial plain* (3P), flat or gently sloping areas, with dominant Aridic Haplustolls and Torriorthentic Haplustolls, and subordinate Aridic Argiustolls, and an *infilled*

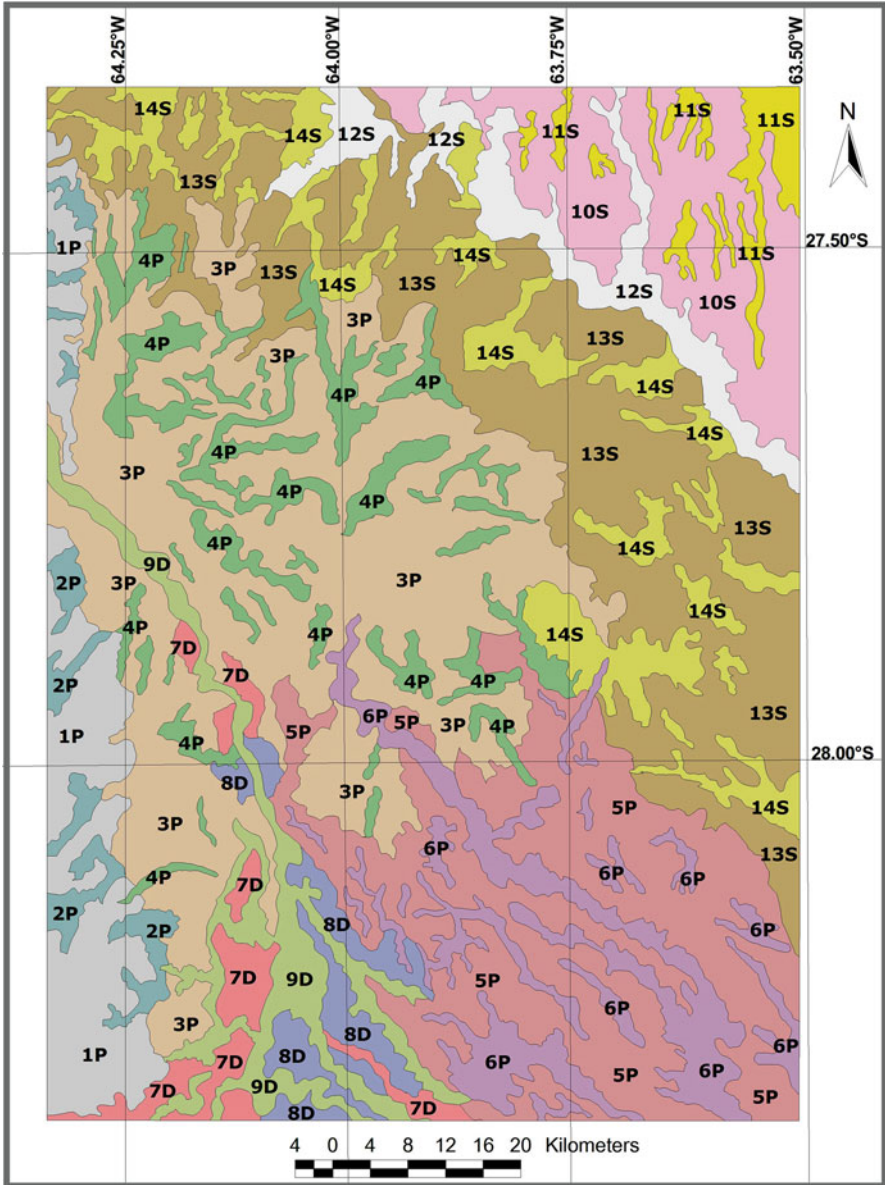


Fig. 17.4 Geopedologic map of the study area (See legend in Fig. 17.5)

channel (4P), flat irregular, elongated or curvilinear shallow depressions, back-filled with sediments, located within the interfluvial plain, with Ustic Torripsamments as dominant and Ustic Torriorthents as subordinate soils.

- (c) *The old alluvial overland flow area with an overflowed depression (5P), a relatively flat, nearly closed fan-shaped accumulation of sand and finer sediments*

LANDSCAPE	MOLDING	FACIES	LANDFORM	CODE	SOILS
Fluvio-eolian Chaco plain (Rio Sali-Dulce)	Proximal megafan	Eolian	1 Loess cover	1P	Torriorthentic Haplustolls
			2 Blowout depression	2P	Aquic Haplustolls
	Distal megafan	Alluvial	3 Interfluvial plain	3P	Aridic Haplustolls Torriorthentic Haplustolls Aridic Argiustolls
			4 Infilled channel	4P	Ustic Torripsamments Ustic Torriorthents
	Old alluvial overland flow	Alluvial	5 Overflowed depression	5P	Aridic Haplustalfs
			6 Alluvial overflow levee	6P	Ustic Torriorthents Ustic Torrifluvents
Valley (Rio Dulce)	Middle terrace	Alluvial	7 Levee and overflows (mt)	7D	Aridic Haplustolls
	Low terrace		8 Levee and overflows (lt)	8D	Typic Haplustolls
	Active floodplain		9 River	9D	UsticTorripsamments
Alluvial migratory plain (Rio Salado)	Active fluvial valley	Alluvial	10 Alluvial overflow plain	10S	Typic Natraqualfs
			11 Levee	11S	Ustic Torripsamments
	Active floodplain	Alluvial	12 Alluvial overflow swamp	12S	UsticTorrifluvents
	Fluvio-eolian terrace remnant	Eolian over alluvial	13 Alluvial flat	13S	Aridic Haplustolls
14 Alluvial channel			14S	Ustic Torripsamments	

Fig. 17.5 Legend of the geopedologic map of the study area (See map in Fig. 17.4)

that formed where the currents slow down and dissipate, with Aridic Haplustalfs as dominant soils. It is crossed by many channels and levees, elongated parallel areas oriented NW-SE crossing the slightly lower floodplain, named *alluvial overflow levees (6P)*, with Ustic Thorriorthents as dominant and Ustic Torrifluvents as subordinate soils.

17.3.3.2 Rio Dulce Valley

The Rio Dulce Valley is characterized by watercourses and three molding types, i.e. a middle terrace, a low terrace, and an active floodplain.

- (a) The *middle terrace* is the higher terrain area formed by the river on its right side with levee and former watercourse included in the landform labelled as *levee and overflows (mt) (7D)*, with Aridic Haplustolls as dominant soils.
- (b) The *low terrace* was identified at the left side of the river. The main landform labelled as *levee and overflows (lt) (8D)* comprises flat surfaces above the floodplain that are formed by the deposition of alluvium adjacent to the river exposed to periodic overflows, with Typic Haplustolls as dominant soils.
- (c) The *active floodplain* includes the landform named *river (9D)*, formed by the main course of the Rio Dulce and lower order courses generally dry, with floodwaters spilling out of the riverbed. Ustic Torripsamments are the dominant soils with subordinate Ustic Torrifluvents.

17.3.3.3 Alluvial Migratory Plain of Rio Salado

The alluvial migratory plain of Rio Salado is an area with 0.5–1 % slope to the south-east, composed by three moldings including an active fluvial valley, an active floodplain, and a fluvio-eolian terrace remnant.

- (a) The *active fluvial valley* comprises two landforms: an *alluvial overflow plain* (10S), an extensive, depressed area between natural levees and terraces with Typic Natraqualfs as dominant and Ustic Torrifluvents as subordinate soils, and *levees* (11S), elongated high areas, almost parallel in north-south direction, distributed throughout the alluvial overflow plain, with dominant Ustic Torripsammets and subordinate Aridic Natrustalfs.
- (b) The *active floodplain* consists of an *alluvial overflow swamp* (12S), streams and a low-lying saturated ground, intermittently covered with water and vegetated by shrubs and trees, with Ustic Torrifluvents as dominant soils.
- (c) The *fluvio-eolian terrace remnant* is formed by two landforms: an *alluvial flat* (13S), a large gently sloping area, nearly level, erosional remnant of an alluvial plain without drainage network, with dominant Aridic Haplustolls and subordinate Ustic Torriorthents, and an *alluvial channel* (14S), a concave shallow microrelief through which runoff is drained in periods of high water, with Ustic Torripsammets as dominant soils.

17.4 Discussion

The geopedologic survey provided information highlighting the complex and intricate soil-geoform patterns of a representative semiarid Chaco area. The integration between geomorphology and pedology along the survey process is reflected in the legend structure, the geomorphic units providing the cartographic frames for the soil types.

Because soils have formed from loess in the west and from alluvial material in the center and north-east, the textures in the C horizons vary: they are mainly silty loam in the megafan landforms (1P and 2P); in alluvial landscapes the sand content increases and is variable according to the position on the relief with sandy loam in levees (9D, 12S and 14S), loam (3P, 4P, 5P, 8D, 10S) and silty loam (6P, 7D, 11S, 13S) in wide flat positions, and variable in slightly concave low positions (Fig. 17.6).

The versatility of multi-spectral satellite images was demonstrated to study soil-landscape features in different seasons and scales. During the dry season (June–September), characterized by the scarcity of vegetation, the visibility of the terrain surface was better, consistent with observations by Shepande (2010).

Visual image interpretation, despite being time consuming and subjective, allows the surveyor to use his/her own knowledge and experience to improve the delineation of map units, as stated by Sarapaka and Netopi (2010) and Trotter (1991) quoted by Shepande (2010). Maps generated through visual interpretation have the advantage of being relatively simple and inexpensive (Manchanda et al. 2002).

The use of DEM and Landsat imagery in a GIS framework proved to be an improved method for mapping soil patterns in the Chaco flat study area, as well as in hilly terrain (Aksoy et al. 2009). DEM was important to derive morphographic and morphometric attributes that are used in soil-landscape characterization at regional scale (Dobos et al. 2000) and to reduce the disadvantage caused by the absence of stereovision in visual interpretation of images.

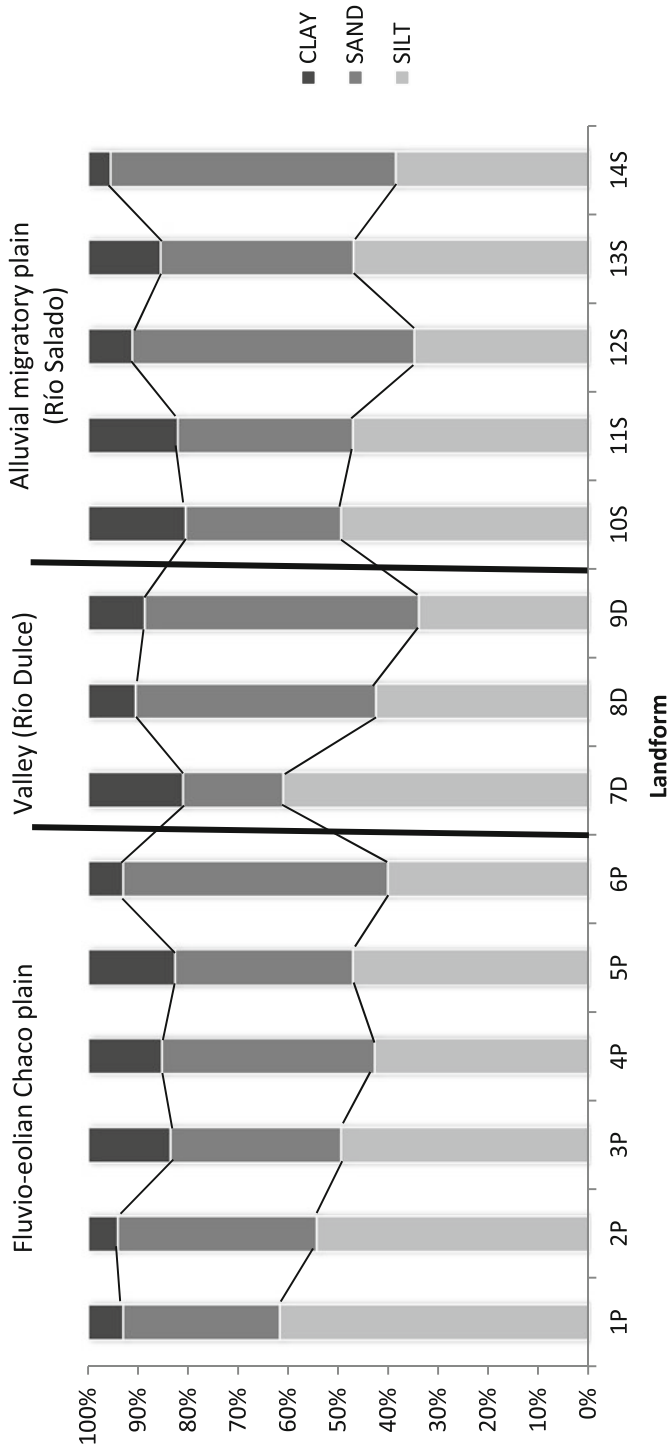


Fig. 17.6 Clay, silt, and sand contents of the C horizons in landscape and landform map units. (1P loess cover, 2P blowout depression, 3P interfluvial plain, 4P infilled channel, 5P overflowed depression, 6Pc alluvial overflow levee, 7D levee and overflows (mt), 8D levee and overflows (lt), 9D river, 10S alluvial overflow plain, 11S levee, 12S alluvial overflow swamp, 13S alluvial flat, 14S alluvial channel)

Geopedology improves the perspective of soil studies at regional scale, together with digital soil mapping to improve and complete the spatial and thematic coverage of regional soil-landscape relationships.

17.5 Conclusions

The geopedologic survey proved to be useful for mapping large and complex geomorphic areas, with a variety of landscapes, very sparsely populated, and lacking sufficient all-weather roads and basic infrastructure.

The use of DEM map derivatives, multiple spectral, temporal and spatial resolution satellite images, and visual interpretation techniques were useful to enhance the ability to identify and classify landscapes and soils.

The application of the geopedologic approach based on remote sensing data, use of modern survey techniques, knowledge of landscape and soil forming factors, and fieldwork contributed to soil mapping at appropriate scales in areas of agricultural expansion for land evaluation and planning.

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References

- Abitbol AE (1997) Programa de desarrollo de pequeñas comunidades. Informe Técnico Santiago del Estero. CFI, Buenos Aires
- Aksoy E, Ozsoy G, Sabri Dirim M (2009) Soil mapping approach in GIS using Landsat satellite imagery and DEM data. *Afr J Agric Res* 4(11):1295–1302
- Angueira C (1994) Evaluación de tierra, esquema FAO: Lavalle-Tapso-Frias. INTA, Santiago del Estero
- Angueira C, Vargas Gil JR (1993) Carta de suelos de Lavalle-Tapso-Frias. INTA, Santiago del Estero
- Angueira C, Zamora E (2003) Oeste del área de riego del Río Dulce, Santiago del Estero, Argentina. Carta de Suelos. INTA, Santiago del Estero
- Angueira C, Prieto D, López J, Barraza G (2007) Sistema de información geográfica de Santiago del Estero, 2.0. CD ROM and <http://sigse.inta.gov.ar>. INTA, Santiago del Estero
- Barbeito O, Ambrosino S (2007) Estudio de áreas de inundación extraordinaria del curso inferior del Río Dulce; análisis geomorfológico. Hidroeléctrica Río Hondo SA
- Bockheim JG, Gennadiyev AN, Hammer RD, Tandarich JP (2005) Historical development of key concepts in pedology. *Geoderma* 124:23–36
- Böhner J, McCloy KR, Strobl J (2006) SAGA: analysis and modeling applications, vol 115, Göttingen Geographische Abhandlungen. Verlag Erich Goltze GmbH, Göttingen
- Bouma J, Bregt AK (1989) Land qualities in space and time. In: Proceedings of a symposium organized by ISSS. Pudoc, Wageningen, The Netherlands

- Burrough PA, McDonnell RA (1998) Principles of geographical information systems. Oxford University Press, Oxford
- Cabrera AL (1976) Regiones fitogeográficas argentinas. Enciclopedia Argentina de Agricultura y Jardinería. Tomo II Fs 1 Acme, Buenos Aires, pp 1–85
- Carignano C, Kröhlhng D, Degiovanni S, Cioccale M (2014) Geomorfología. Relatorio XIX Congreso Geológico Argentino, Córdoba
- CGIAR-CSI (2004) The CGIAR Consortium Spatial Information. <http://srtm.csi.cgiar.org>
- CONAE (2000) Mission SAC-C. <http://www.conae.gov.ar/satelites/sac-c.html>
- Dobos E, Michelli E, Baumgardner MF, Biehl L, Helt T (2000) Use of combined digital elevation model and satellite radiometric data for regional soil mapping. *Geoderma* 97:376–391
- Echevehere PH (1976) Normas de reconocimiento de suelos. INTA-CIRN, Pub 152 2da edn, Buenos Aires
- Goosen D (1967) Aerial photo interpretation in soil survey, *Soils Bull* 6. FAO, Rome
- IGN (2000) <http://www.ign.gov.ar/NuestrasActividades/ProduccionCartografica>
- INPE-CBERS (2008) <http://www.cbers.inpe.br>
- INTA (1990) Atlas de suelos de la República Argentina. Tomo II. Proyecto SAG-INTA PNUD Argentina 85/010
- Jhorar RK, Rossiter W, Siderius W, Feddes RH (2003) Calibration of effective soil hydraulic parameters of heterogeneous soil profiles. *J Hydrol* 28:233–247
- Krol B, Rossiter DG, Siderius W (2007) Ontology-based multi-source data integration for digital soil mapping. In: Lagacherie P, McBratney AB, Voltz M (eds) Digital soil mapping. An introductory perspective, vol 31, Developments in soil science. Elsevier, Amsterdam, pp 119–133
- Manchanda MI, Kudrat M, Tiwari AK (2002) Soil survey and mapping using remote sensing. *Trop Ecol* 43(1):61–74
- Martín AP (1994) Hidrogeología del abanico aluvial del Río Dulce en las ciudades de Santiago del Estero y La Banda XXIV Congreso Iberoamericano de Ingeniería Sanitaria. AIDIS. Tomo II Diagua 44:22. Buenos Aires, Argentina
- Martín AP (1999) Hidrogeología de la Provincia de Santiago del Estero. Edición del Rectorado de la Universidad Nacional de Tucumán, Tucumán, Argentina
- McBratney AB, Mendonça Santos ML, Minasny B (2003) On digital soil mapping. *Geoderma* 117:3–52
- McRae CP, Burnham SG (1981) Land evaluation. Clarendon, Oxford
- Metternicht GI, Zinck JA (2003) Remote sensing of soil salinity: potentials and constraints. *Remote Sens Environ* 85:1–20
- Moore CA, Hoffmann GA, Glenn NF (2007) Quantifying basalt rock outcrops in NRCS soil map units using Landsat-5 data. *SSSA Madison Soil Surv Horiz* 48:59–62
- Morello J, Pengue W, Rodríguez A (2006) Etapas de uso de los recursos naturales y desmantelamiento de la biota del Chaco. In: Brown A, Martínez Ortiz U, Acerbi M, Corcuera J (eds) La situación ambiental argentina 2005. Fundación Vida Silvestre Argentina, Buenos Aires, pp 83–90
- Mulder VL, de Bruin S, Schaepman ME, Mayr TR (2011) The use of remote sensing in soil and terrain mapping. *Geoderma* 162(1–2):1–19
- NASA-USGS (1972) Landsat mission. <http://landsat.usgs.gov>
- Peña Zubieta C, Salazar Lea Plaza J (1978) Carta de suelos de los Departamentos Belgrano y Gral. Taboada. INTA, Buenos Aires
- Peri VG, Rosello EA (2010) Anomalías morfoestructurales del drenaje del Río Salado sobre las Lomadas de Otumpa (Santiago del Estero y Chaco) detectadas por procesamiento digital. *Rev Asoc Geol Argent* 66(4):634–645
- Rossiter DG, van Wambeke AR (1991) Automated land evaluation system (ALES). Cornell University, Ithaca
- Sarapaka B, Netopi P (2010) Erosion processes on intensively farmed land in the Czech Republic: comparison of alternative research methods. 19th World Congress of Soil Science, Soil Solutions for a Changing World, Brisbane

- Sayago JM (1982) Interpretability of Landsat images for physiography and soil mapping in the sub-humid region of the Northeast of Argentina. In: Proceedings of the international symposium on remote sensing of environment, Buenos Aires, pp 977–987
- Sayago JM (1995) The Argentine neotropical loess: an overview. *Q Sci Rev* 14:755–766
- Sebastián A, Torrella SA, Adámoli J (2006) Situación ambiental de la ecorregión del Chaco Seco. In: Brown A, Martínez Ortiz U, Acerbi M, Corcuera J (eds) *La situación ambiental argentina*. Fundación Vida Silvestre Argentina, Buenos Aires, pp 75–82
- Shepande C (2010) Development of geospatial analysis tools for inventory and mapping of soils of the Chongwe Region of Zambia. PhD dissertation, Minnesota University USA
- Soil Survey Staff (2010) Keys to soil taxonomy, 11th edn. USDA-NRCS, Washington, DC
- Trotter G (1991) Remotely-sensed data as an information source for geographical information systems in natural resource management: a review. *Int J Geogr Inform Syst* 5(2):225–239
- Vargas Gil JR (1988) Chaco Sudamericano. Regiones Naturales en X Reunión Grupo Técnico Regional en Forrajeras. FAO, Córdoba
- Walter C, Lagacherie P, Follain S (2007) Integrating pedological knowledge into digital soil mapping. In: Lagacherie P, McBratney AB, Voltz M (eds) *Digital soil mapping. An introductory perspective*, vol 31, *Developments in soil science*. Elsevier, Amsterdam, pp 281–300
- Zinck JA (1994) Soil survey: perspectives and strategies for the 21st century. ITC publication 21. Enschede
- Zinck JA (2012) Geopedología. Elementos de geomorfología para estudios de suelos y de riesgos naturales, ITC special lecture notes series. ITC, Enschede
- Zinck JA (2013) Geopedology. Elements of geomorphology for soil and geohazard studies, ITC special lectures notes series. ITC, Enschede