Chapter 27
Geopedology and Land Degradation in North-West Argentina

J.M. Sayago and M.M. Collantes

Abstract The subtropical region of north-western Argentina shows marked land degradation resulting from unrestricted use of ecosystems during the last centuries. From a geopedologic perspective, the land historical occupation and the distinctive features of the relief-soil relationship in a representative area, the province of Tucumán, are described in this work. For assessing the intensity and distribution of soil erosion in the region, soil potential loss is mapped at small scale, based on geomorphic sectorization and criteria of Universal Soil Loss Equation. Models of land erosivity are developed in two scenarios of future climate change from extreme rainfall values recorded over the last century. The assessment of erosion hazard at small scale using USLE, teledetection and geographic information system, helps develop programs oriented to the recovery of extensive degraded and desertified regions, through management systems adapted to current and future environmental conditions.

Keywords Relief-soil • Soil erosion • Erosion hazard • Climate change • Soil loss scenarios

27.1 Introduction

In a world exposed to socio-economic and environmental crisis and climate change, it seems appropriate to address the issue of land degradation in one of the least developed regions of a developing country. Paradoxically, the Argentine north-western region was the first territory colonized by the Spanish Crown, with flourishing economy during the first centuries of the Conquest.

The main ecosystems of the region, including the Yungas cloudy forest, the Chaco forest, the region of "El Monte" and the alto Andean steppe (Cabrera 1976),

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are highly fragile as a consequence of a climate with strong seasonal variations, loess-developed soils, and an irregular relief with elevations higher than 5000 m.a.s.l. to the west and a flat plain to the east. Unrestricted and uncontrolled current land management is causing accelerated deterioration. This is in contrast with the careful management applied to natural ecosystems by native cultures that occupied the territory before the arrival of the Europeans (Caria et al. 2001). From a paleoclimatic perspective, the dry-wet subtropical landscape started developing in the early last millennium, contemporaneously with the extreme aridity of the Warm Medieval Period (Garralla 1999; Caria and Garralla 2003).

Since the arrival of the Spanish conqueror Francisco de Almagro in 1536, at the beginning of the colonial period (sixteenth to eighteenth centuries), the region was the annual wintering place of thousands of mules and horses (Niz 2003) used in mining activities in Chile, Bolivia (especially Potosí) and Perú. This was the beginning of intensive landscape degradation, first through deforestation, followed by the progressive disappearance of natural pastures (replaced by xerophytic species) in response to overgrazing. During the following centuries, deforestation expanded with the construction of a railway to the Andean mining area, particularly during World Wars I and II as the coal supply from Europe had to be replaced by the wood of carob trees (*Prosopis sp*.) and quebracho forests as fuel for steam locomotives (Sayago 1969). Native forests in the north-western region continued disappearing without interruption during the second half of the twentieth century because of rainfall increase that turned a large part of the region suitable for cereal cropping (Busnelli et al. 2009). Accelerated clearing of the western Chaco forest (about 2 million ha) for soybean and corn cultivation metamorphosed the primitive landscape.

Despite that in the late twentieth century three laws were enacted to protect natural forests, deforestation continued more intensively due to high international prices for soybean and corn. More than two million ha of native forest have been cleared in the last 10 years with variable impact (Secretaría de Medio Ambiente 2012). Assessment of environmental degradation is consequently imperative for the implementation of land conservation programs that will contribute to mitigate or neutralize such a situation.

This background accounts partly for the aim of this work, which is the application of geopedology to the inventory and assessment of land degradation in an extensive territory of the Argentine north-western region. The formation and evolution of landforms are described in their relationship with the soil cover in the Province of Tucumán. The erosion hazard under the current climate is evaluated and the impact of future climate changes on the surface geodynamics and land degradation is assessed through two scenarios based on extreme values of regional rainfall variability.

27.2 Materials and Methods

Geomorphology constitutes the structuring factor of the pedological landscape (Zinck 2012). In this sense, geomorphology covers a large part of the physical framework of soil formation through relief, morphodynamics, morphoclimatic context, non-consolidated or altered materials that serve as parental material to soils, and the time factor. Likewise, Jungerius (1985) states that the preparation of geomorphic and soil erosion maps substantially benefits from pedology contribution.

Zonneveld (1983) analyzes in depth the problem of the interaction of landscape elements and highlights the importance of applying geoecology concepts. He establishes a hierarchy of environmental factors based on the higher or lower capacity of some of them to influence unilaterally the others without being affected reciprocally by them. Although relief and climate have an independent position in the geoecological dynamics, the intensity and character of such an influence depend on the scale or level of perception at which it is considered. Climate is dominant at continental level (atmospheric circulation), but its influence is modified by the distribution of seas and mountain masses. At regional scale, although relief conditions climate (exposure, rainfall shadow, etc.), the latter influences directly or indirectly (arid, periglacial, subtropical morphogenesis, etc.). At local level, the influence of climate and relief depends on the landscape endogenous interrelationships. Thus, relief and climate show an ambivalent relationship with the remaining landscape elements and the prevalence of one or the other depends on the scale taken into consideration (Tricart 1982; Zonneveld 1983).

This work contributes methodologically to the inventory of water erosion processes, considering that mapping at a small scale of the relief-soil relationship constitutes the foundation for future actions. The inclusion of geomorphology as a conceptual and cartographic basis in erosion mapping involves the recognition of the essentially morphodynamic character of every degradation process. The relief classification applied in this work (Fig. 27.1, Tables 27.1 and 27.2) to obtain a partitioning of the Tucumán Province into geomorphic units, as a basis for the assessment of relief-soil relationships and potential erosion, is tentative, coinciding in its philosophy with Sayago (1982) and Zinck (2012).

The classification categories are as follows:

(a) Geomorphic province: it coincides with the generalized concept of geological province (Rolleri 1975), that is, an area characterized by a determined stratigraphic succession, a structural character of its own, and peculiar geomorphic features, the expression of a determined geological history (Puna, Cordillera Oriental, etc.) as a whole.
(b) Geomorphic region: territory characterized by a distinctive morphostructural style, defined by the recurrence of lithologic and morphogenic features developed during the Quaternary (Ancasti Range, Aconquija Range).
(c) Geomorphic association: defined as a part of a region, determined by the recurrence of typical morphogenic units conditioned by climate, which can be identified and mapped on aerial photographs and/or satellite images (Aconquija wet subtropical piedmont plain, constituted by fluvial valleys, erosion glacis, and alluvial paleo-fans).
(d) Geomorphic complex: it exhibits the same structure as the geomorphic association, but cannot be easily mapped due to the presence of dense vegetation cover or complex and spatially variable fluvial network (oriental slope of Calchaquí summits covered with vegetation, constituted by fluvial valleys, covered glacis, and covered slopes).

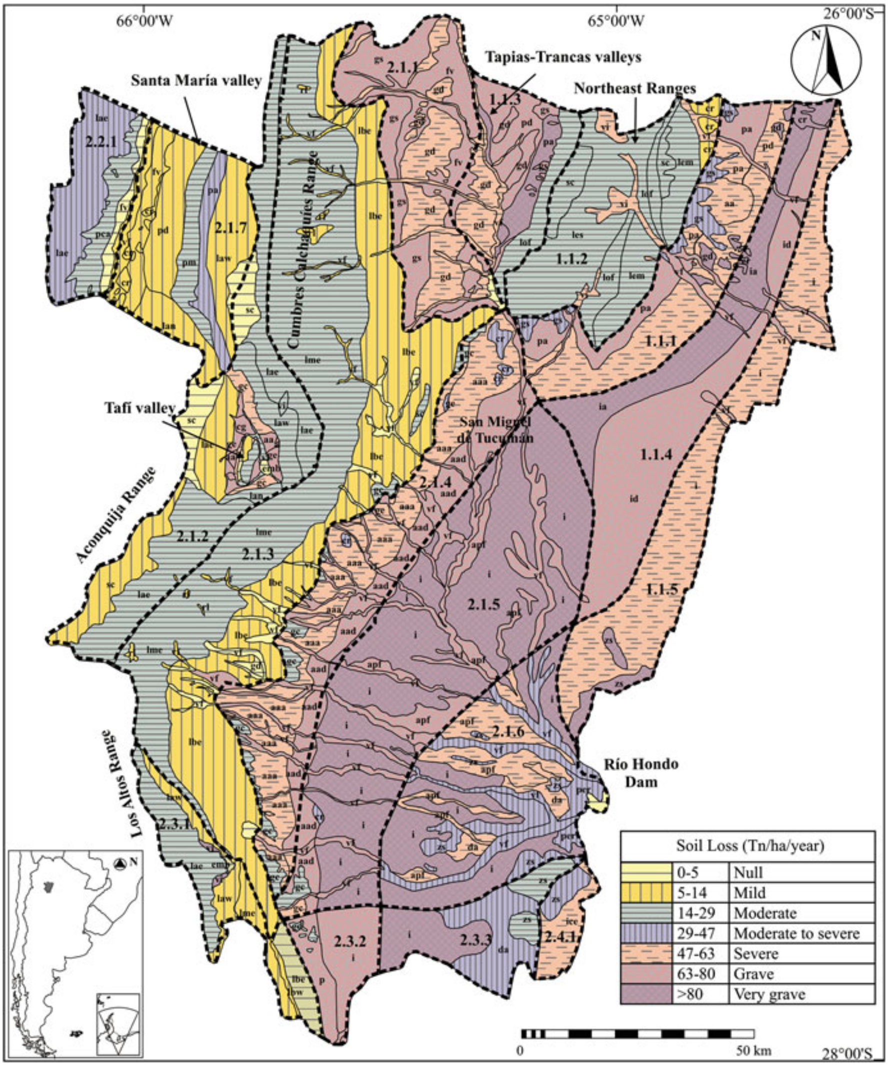

Fig. 27.1 Current soil erosion map (tn/ha/year), Tucumán province, Argentina (After Busnelli et al. 2009) Numbers (e.g. *1.1.1*) refer to the geomorphic map units as shown in Table 27.1

(e) Geomorphic unit: characteristic relief shapes, defined by a particular morphogenesis (alluvial fan, fluvial terrace, landslide, etc.) and mappable only at large scales (1:50,000 or more).

Erosion hazard was surveyed using GIS up to the level of geomorphic unit and delimited in every relief association. When considering the nature and causes of land degradation, different approaches influence the methodology used to represent what could be considered a complex environmental problem, although according to

Table 27.1 Geomorphic provinces, regions, and associations (legend of Fig. 27.1)

1. Geomorphic province subandean ranges
1.1. Geomorphic region northeast sierras (Medina, del Campo, and La Ramada)
1.1.1. Association humid subtropical eastern hillslope
1.1.2. Association humid subtropical mountainous sector
1.1.3. Association semiarid western hillslope
1.1.4. Association dry/wet subtropical floodplain
1.1.5. Association subtropical dry floodplain
2. Geomorphic province pampean ranges
2.1. Geomorphic region Calchaquíes and Aconquija ranges
2.1.1. Association subhumid to semiarid eastern hillslope of Calchaquíes range
2.1.2. Association dry-cold eastern hillslope of Aconquija and Calchaquíes ranges
2.1.3. Association humid subtropical eastern hillslope of Aconquija and Calchaquíes summits
2.1.4. Association humid subtropical piedmont plain of Aconquija range
2.1.5. Association subtropical dry-wet alluvial plain
2.1.6. Association subtropical dry alluvial overflow plain
2.1.7. Association western arid hillslope of Aconquija and Calchaquíes ranges
2.2. Geomorphic region Quilmes
2.2.1. Association arid eastern hillslope
2.3. Geomorphic region Ancasti/Los Altos range
2.3.1. Association cold subhumid summit
2.3.2. Association subtropical dry-wet subtropical hillslope
2.3.3. Association northern subtropical dry alluvial plain
2.4. Geomorphic region Guasayán range
2.4.1. Association western subtropical dry hillslope

Imeson (2012) what is more important are "people's actions, what they do and the relationships between them".

The use of quantitative criteria such as those of USLE (Universal Soil Loss Equation), developed by Wischmeir and Smith (1978) to assess erosion intensity at land parcel level, was updated by Sayago (1985) for the inventory of erosion hazard at small scale in the subtropics of Argentina, coinciding with Wischmeier (1984) in that USLE can be applied at small scale on the basis of proper geomorphic sectorization and the intensive use of visual and digital teledetection.

Quantification of soil erodibility by the potential loss in tn/ha/year is reflected in the behavior of all the USLE factors: rain erosivity, soil erodibility, slope length and gradient, vegetation cover, and conservation management (Wischmeier and Smith 1978; Renard et al. 1991). Rain erodibility is a key factor in the determination of soil loss by erosion because it relates to storm energy in a determined time span rather than to the total volume of rainfall. The difficulty to estimate the E130 index of the formula developed by Wischmeier and Smith (1978) in large areas, due to the lack of rainfall data, can be replaced by the index obtained by Arnoldus (1978) based on early work by Fournier (1960). This index has the advantage to use simple meteorological data (rainfall) and a good correlation with the measured values of

Table 27.2 Geomorphic units (legend of Fig. 27.1)

Fluvial valley	vf
Fluvial terrace	tf
Valley bottom	fv
Interfluve area	i
Apical interfluve	ia
Distal interfluve	id
Interfluve with structural control	ice
Saline area	ed
Flooded depression	da
Perilake	per
Older floodplain	apf
Erosion glacis	ge
Covered glacis	gc
Upper	gs
Lower	gi
Dissected	gd
Glacis cone	cg
Undifferentiated piedmont	p
Apical	pa
Middle	pm
Distal	pd
Piedmont dominated by alluvial fans	pca
Alluvial fan	aa
Apical	aaa
Distal	aad
Residual hill	cr
Intermountain valley	vi
Stepped hillslope	rl
Summit surface	sc
Denudational hillslope	ld
Slopes: strong	lf
Moderate	lm
Gentle	ls
High sector	la
Middle sector	lm
Low sector	lb
North orientation	ln
South orientation	ls
West orientation	lo
East orientation	le
Dam	emb

the E130 index of USLE. Arnoldus (1978) established the general correlation equation $R = a \times \text{FAO index} + b$, where R is the USLE rain erosivity factor and “a” and “b” are constants based on regional climatic conditions. This equation was tested in different parts of the world, showing high correlation with the USLE rain erosivity index in the USA, whose climatic characteristics range from arid/semiarid to humid subtropical.

Soil erodibility was assessed using the Wischmeier and Smith (1978) nomogram with soil data from laboratory and field to estimate the percentage of very fine sand and silt, organic matter content, permeability, and structure, the K factor values being obtained in every geomorphic unit. The LS factor, a combination of slope gradient and length, was estimated from a DEM (digital elevation model).

According to Imeson (2012), the vegetation cover (C) in the USLE equation is by far the most significant and critical quantitative term, but quite easy to estimate. The estimation of this factor was based on the separation of cultivated areas and natural vegetation. The cover in cultivated areas was measured in three stages, including plowing, emergence, and pre-harvest; the natural cover (mulch) of the wet and dry seasons was averaged.

The USLE management factor has major importance in the preservation and recovery of eroded areas, especially in regions of intensive agriculture in developed as well as in developing countries. The assessment of climate changes was carried out from extreme rainfall values recorded in the region (Torres Bruchmann 1977; Bianchi and Yañes 1992; Minetti 1999; Bianchi and Cravero 2010). Two scenarios were established: a wet scenario with rainfall 30 % higher than the average, and an arid scenario with 30 % less rainfall than average.

27.3 Results

27.3.1 Soil-Landscape Relationships

It has been said “every soil is a landscape” as an expression of the close relationship existing between relief and soil in their genesis and evolution (Birkeland 1999). Every geomorphic unit, delimited based on coherent taxonomic criteria, shows a spatial homogeneity given by the recurrence of shapes and endogenous processes, thus constituting itself a basic unit of soil/landscape (Sayago 1982).

In the undulating plain to the east of Tucumán province, Mollisols and Entisols predominate, whose moderate development on the loessic or detritic substratum responds to rainfall scarcity in winter, reflected in the Chaco forest vegetation, partly replaced by annual crops. To the southeast, in the depressed plain, the presence of Entisols on fluvial deposits and Mollisols with aquic and sodic characteristics reflects the persistence of past and current fluvial actions. Precipitation increase to the west due to a “rain shadow” process coincides with the appearance of more developed Mollisols, promoting significant agricultural activity in the alluvial plain without water deficit, in the Aconquija Range piedmont, and in the southern Sub-Andean Sierras. The wet subtropical climate of the eastern slope and part of the summit areas of the mountain ranges contributes to the development of Inceptisols under the Yungas perennial cloud forest. In the summit areas and western slopes of the Aconquija and Calchaquí ranges, cold climate and precipitation decrease intensify cryoclastism and mass movement, which accounts for the presence of Regosols and Entisols.

In the western piedmont of the mountain ranges, rainfall scarcity causes the presence of shrub communities with giant cacti, Regosols and Aridisols, and intense alluvial/torrential dynamics. At the bottom of the Santa María Valley, dryness accounts for the development of sodic and natric Aridisols, Entisols and Alfisols of fluvial origin, while on the eastern slope of the Quilmes Range, Entisols of lithic and detritic origin predominate. At last, in the Tapia-Trancas basin, the semiarid climate together with the subtropical lower mountain forest and the Chaco forest contributes to weakly developed Entisols and Mollisols that cover piedmont glacis and lower valleys. Similar soils occur also in the south-eastern tip of the province on the north-western piedmont of the Guasayán Range.

Modifications produced by deforestation during the last century have created a soil-landscape metamorphosis in the areas incorporated to intensive agriculture. In brief, it is a priority to assess land use and land occupation for determining the types of management best suited to the current and future environmental and socio-economic conditions.

27.3.2 Erosion Hazard Assessment

The meaning of the term "soil erodibility" differs from "soil erosion". The volume of soil loss through erosion may be controlled more by slope, cover or management than by the intrinsic soil properties. However, some soils erode more than others, even though all the other factors are similar (Bergsma 1986).

In the east of the Tucuman territory, rainfall erosivity is relatively low, but increases gradually towards west together with the "rainfall shadow" effect in the pre-Andean ranges. In the uplands, the adiabatic influence causes rainfall to progressively decrease together with higher elevation to the west. Orographic rain has as a consequence rainfall reduction and aridity in the western valleys. In the oriental plains, sheet erosion predominates due to unrestricted cultivation or overgrazing in relatively poor soils, previously covered by the Chaco forest (Fig. 27.1).

In areas with irregular relief, gully erosion predominates and soil loss is mostly related to concentrated overland flow and sediment transportation to riverbeds, canals or dams. Extensive low-gradient slopes account for sheet erosion caused by hortonian overland flow or top saturation overland flow (Bergsma 1986). Both surface erosion processes are closely related to soil characteristics. In the east of the Tucuman plain, soils show uniform permeability: the longer the slope, the higher the overland flow and, consequently, the higher the erosion. More developed soils have usually dense subsurface horizons (Bt, claypan, etc.) that influence the overland flow/infiltration relationship and the surface horizon saturation time, causing stronger erosion hazard (Bergsma 1986).

The influence of the vegetation (C factor), either natural vegetation or crops, is directly correlated with soil use and cover values. The eastern side of the mountain region with subtropical cloud forest has dense cover, thus low C values (<0.1). In contrast, the intermountain valleys have relatively high values (0.21–0.25), reflecting intense and long-standing agricultural activity. To the west, deciduous forests on relief summits have slightly higher C values (0.11–0.15) than those of the Yungas cloud forest (0.01–0.05). To the east, in the undulating alluvial plain where the Chaco forest has not been totally cleared, C values are moderate (0.16–0.20). The simplicity and effectiveness of the vegetation cover measurement according USLE make it a useful tool to evaluate the "tipping point" process (Scheffer 2010) or ecosystem landscape collapse due to extreme soil degradation. In the Santa María valley, located in the west of the study area, erosion hazard was determined using USLE in every relief unit. Vegetation in some relief units did not show changes of mulch cover between winter and summer due to heavy soil deterioration that prevented ecosystem recovery and resilience (Sayago et al. 2012).

North-western Argentina is an important agricultural region, without systematic and generalized use of soil conservation practices. The criteria used to assess the M factor (management) in dry areas may help evaluate the proximity to the landscape collapse point or "tipping point" or to test the effectiveness of changes in management systems to attenuate desertification. The erosion hazard values of the Argentine subtropical region are similar to the erosion classes established by El Swaify (1977) for Hawaii, where the erosion hazard values are higher than those normally measured in non-tropical regions.

27.3.3 Soil Loss Prediction Under Future Climate Changes

Climate changes resulting from "greenhouse effect" constitute one of the most distressing events in the history of humankind. The increase in greenhouse gases (carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons, among others), as a consequence of industrial activity, deforestation, forest fires, etc., is responsible for global warming that might reach 1.5–6 °C in the next decades, with doubling of the CO_2 content in the atmosphere (Allen and Ingram 2002; IGPCC 2007).

Research programs dealing with the causes of climate change and mitigation and adaptation actions do not refer concretely to their influence on surface geodynamics (droughts, floods, erosion, sea level rise, etc.). The morphogenic and morphodynamic processes that model the earth surface result from the interaction between the geologic substratum and the morphoclimatic systems that influence soil development, surface and underground water distribution and, especially, the genesis and evolution of the main biomes and types of land occupation (Sayago and Collantes

2009). Future climate changes will influence the type, intensity, rhythm and duration of the processes that integrate surface geodynamics, whose effects on the landscape and living beings could only be mitigated from a thorough understanding of geomorphodynamics.

The severity of the erosion hazard in the subtropical region of north-western Argentina was assessed against two climate change scenarios determined on the basis of extreme values of rainfall variability during the last century. Erosion hazard was estimated for every map unit from the values of soil loss in the current conditions, obtained using the USLE criteria as defined in this work (Fig. 27.1, Tables 27.1 and 27.2). The relative difference in percent of soil loss between dry scenario (Fig. 27.2) and wet scenario (Fig. 27.3) was established, and both scenarios were compared with the current soil erosion loss (Fig. 27.1). The erosion values obtained for both scenarios are limited by the uncertainty of the future greenhouse effect on climate dynamics (rainfall intensity, extreme droughts, etc.). However, the strength of the USLE information (i.e. rainfall erosivity, soil erodibility, topography, vegetation cover, and management (Sayago 1985) allows an adaptation of the dominant conditions at least in the short term.

In the analysis, a modification of the K factor (soil erodibility) was taken into account in response to the two scenarios. Under wet conditions, higher organic matter content in the surface horizon can decrease the K factor, whereas the reverse would occur in arid conditions. Considering the relative stability of the relief as compared to climate variability, the LS factor (slope length and gradient) is assumed to vary little in both climate change settings. Variation rates of the K factor (soil erodibility) and C factor (cover) were estimated using the Langbein and Schumm (1958) curve for the both scenarios. In the wet setting, the C factor decreases in response to vegetation cover increase in cultivated areas and the Yungas forest. By contrast, in the western arid region, water erosion would increase despite cover increase because of larger bare soil areas susceptible to erode due to increasing R factor (rainfall erosivity).

Considering 30 % rainfall increase, the erosion hazard is assumed to increase in an equivalent percentage, although soil erodibility would decrease according to Langbein and Schumm (1958) because cover and organic matter content would also increase. Severely eroded units in dry environment would not experience any cover change, even with seasonal rainfall increase, because they have exceeded the threshold of the landscape resilience or "tipping point" (Sayago et al. 2012; Collantes and González 2012).

Summarizing, the maps of Figs. 27.2 and 27.3 show that, in both climate change scenarios, erosion would increase. Heavy rainfalls of the wet period would be reflected in the erosion intensity in the piedmont and eastern plains. In the desertified western regions, erosion increase would reflect intense landscape degradation, in many cases close to the ecosystem collapse point. During arid interruptions, the long slopes in the piedmont and eastern plain would be exposed to high erosion increase. In contrast, rainfall decrease in the arid western areas would account for the lowest erosion in the pre-Andean valleys and ranges.

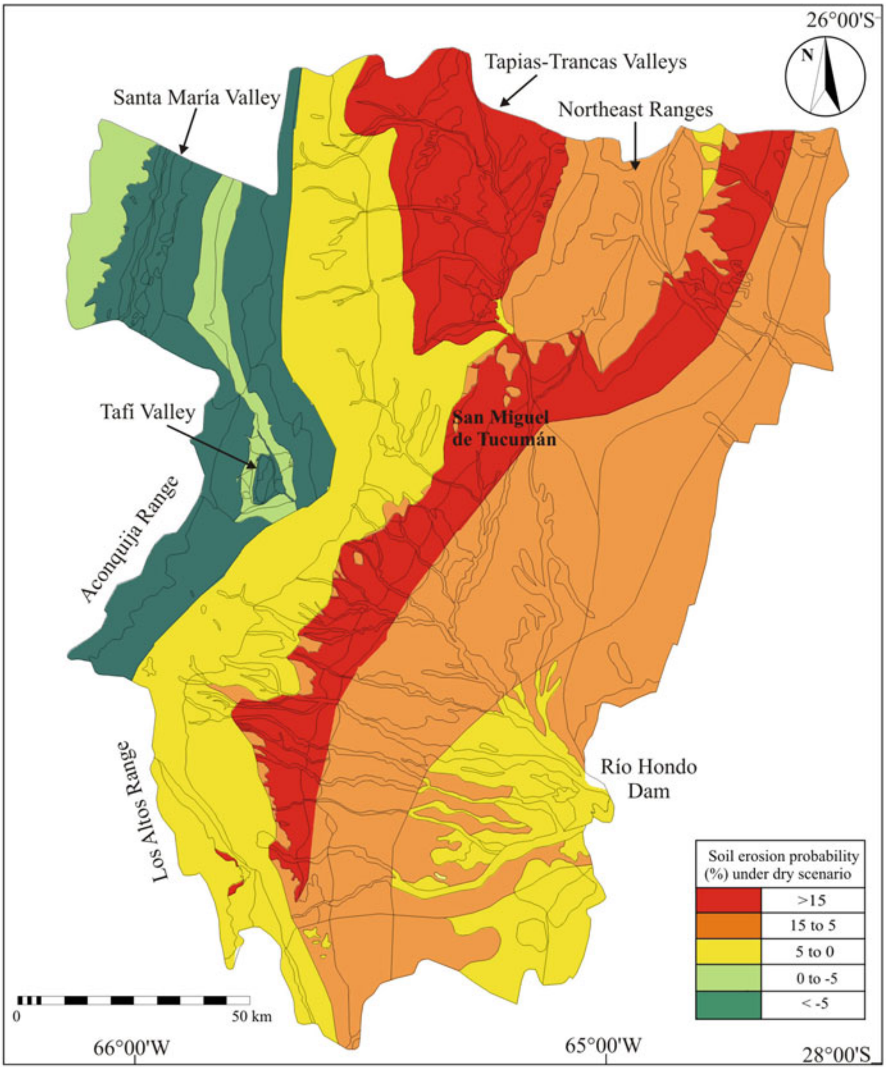

Fig. 27.2 Percentual differences in soil loss between the dry scenario and current soil erosion, Tucumán province, Argentina (Modified from Busnelli et al. 2009)

27.4 Discussion and Conclusions

The region shows, in general, high erosion hazard due to increasing anthropic pressure affecting especially areas still covered with natural vegetation. The maximal erosion hazard occurs in cultivated mountain areas where conservation practices are needed. On the contrary, mountain areas covered by cloud forest show low erosion hazard; potential deforestation would affect the soil integrity and the regional hydrologic balance.

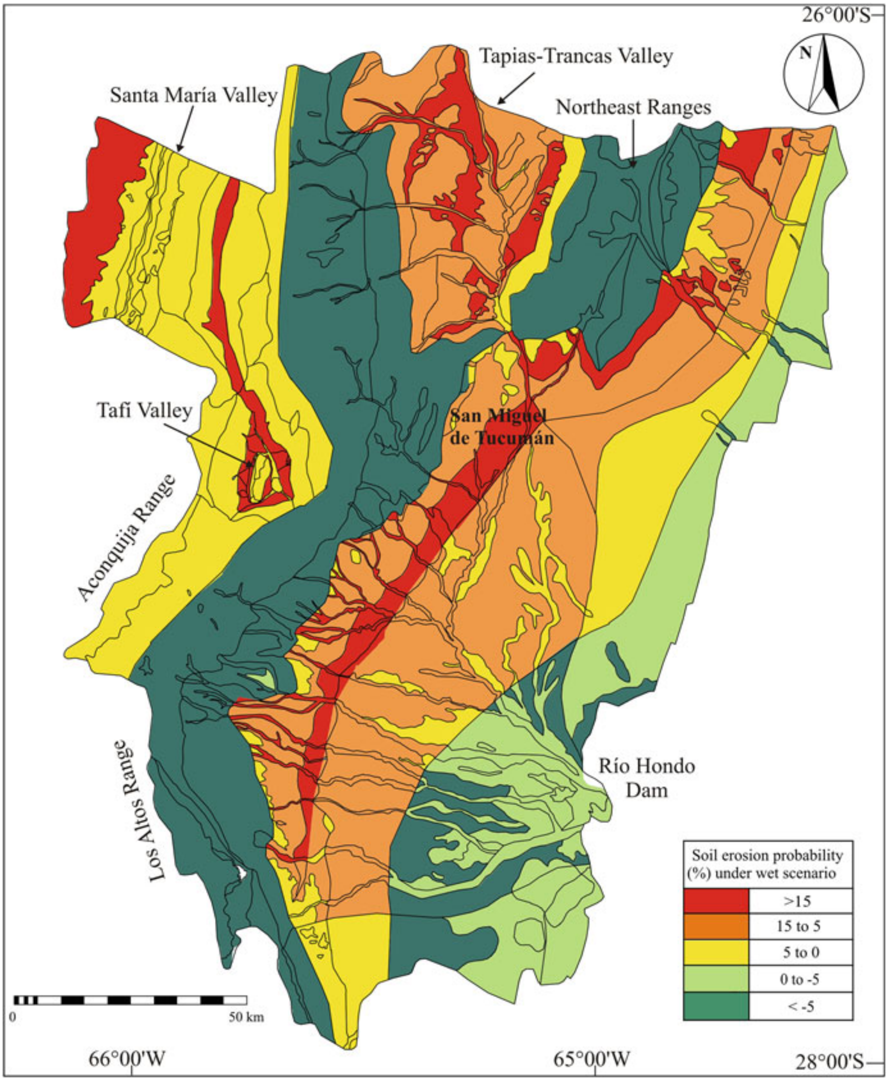

Fig. 27.3 Percentual differences in soil loss between the wet scenario and current soil erosion, Tucumán province, Argentina (Modified from Busnelli et al. 2009)

In plain areas, erosion hazard values are moderately high because of soil erodibility and rainfall aggressiveness. Soils derived from loess are naturally vulnerable to the impact of farming due to their unbalanced particle size distribution, with high silt and low clay contents causing weak structural stability, making loess soils prone to wind and water erosion and susceptible to sealing and crusting (Zinck 2006). The absence of conservation practices, despite the generalized use of “direct sowing” to neutralize soil erosion, the risk of soil compaction by heavy machinery, the nutrient loss due to soybean monoculture, and the drop of international corn prices create a worrying perspective for farmers. It would be advisable to reduce the intensive use of agrochemicals, not only due to their negative effect on health, but also because the return to simple conservation management (plowing, minimal tillage, rotations) would contribute to develop agro-forestry and secure pasture sustainability, with higher demand of local labor.

In the western arid regions, the risk of desertification is high. It is therefore relevant to assess in every landscape environment the proximity to the collapse point or "tipping point" to adapt the agricultural systems to land suitability and restrictions.

Due to their relative simplicity, the USLE methodological criteria (Wischmeier and Smith 1978), together with the use of teledetection and geographic information systems, are useful for erosion evaluation at small scale, on the condition of field validation of the evaluation results.

A map showing geomorphic regions or associations, with evaluation of erosion hazard values, can contribute to regional planning and development such as in the Argentine north-western region. Within this perspective, predictive models of erosion hazard, based on the historical periodicity of rainfall in a region, may guide the adaptation to the possible consequences of future climate changes.

Finally, although not less important, successful development of a land conservation program, especially in a region as fragile as the Argentine subtropics, demands the collaboration of producers, extensionists, and scientists as a necessary condition to achieve consistent progress.

Acknowledgements This chapter is dedicated to the memory of Dr. José Busnelli.

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