4 Human-Induced Soil Degradation in Chile

Land degradation is an old and serious problem for many communities throughout Chile, with adverse impacts on agricultural productivity, food security and rural livelihoods. Numerous connections to other environmental problems such climate change, biodiversity losses, droughts, etc., have been observed, which calls for action-orientated science. It is not the intention of this chapter to review the contested field of definitions of land degradation. Instead, we apply the following wide description of the process: *Land degradation is a long-term loss of ecosystem function and service, caused by disturbances from which the system cannot recover unaided* (UNEP 2007).

Regardless of any ultimate definition, the problem is exacerbated by humans and soil degradation manifests itself in at least two very serious environmental expressions, a quantitative and qualitative reduction in soil quality (Table 4.1).

Only considering the Metropolitan Region, around 14,000 ha of arable soils (Land Capability Classes I–IV) located in the floodplains of Santiago's rivers were lost between 1989 and 2003. In addition, another 5,500 ha of non-arable soils (Land Capability Classes V–VIII) from the Andean piedmont have disappeared as the result of urban land use (Romero and Órdenes 2004). This urban sprawl is illustrated in Fig. 4.1.

As regards land lost to mining, there are 746 abandoned mining dams in Chile which store around 749 million m^3 of tailings and cover an approximate area of 192,107 ha (Ginocchio 2011). Figure 4.2 shows two examples of these dams in extreme zones of Chile, which are normally exposed to seepage, dust, long-term erosion, bio-intrusion etc. Regarding landfills, another important anthropogenic invasion of soil in Chile, at least 300 sites within its territory have been authorised or earmarked for disposal of wastes of different origins (household, industry and construction).

It is also necessary in this context to take account of a major hydroelectric project involving dams in Chilean Patagonia, which will obviously result in quantitative losses of edaphic national patrimony due to flooding of wide trough valleys in a pristine landscape of 5,900 ha in area (artificial lakes on the Baker and Pascua rivers). This project has the potential to satisfy Chile's growing energy needs, but it is imperative try to explore every alternative in order to prevent any long-term damage to zonal natural resources. Pfeiffer et al. (2010) describe Histosols, Entisols and Inceptisols in the zone, but additional area and other important soil orders will be affected along nearly 2,400 km of energy transmission lines (pylon alignment) to northern Chile.

From a general point of view, the mining sector in the centre and north, growing pressure of agriculture in the centre and south, and deforestation in the south of Chile are the main causes of soil degradation caused by man. It is important to note that growth and over-concentration of population and industrial activity around the principal cities are also increasing concerns related to soil degradation processes. Moreover, the scenario becomes more complex and worrying when intense desertification processes are included.

Although generalised, two maps presented by FAO (scale 1:10,000,000) for Chile give a general spatial idea of soil constraints and human-induced soil degradation in the country (Fig. 4.3).

Therefore, it is within this context that the present chapter aims to describe the relevant human induced processes in Chile, considering the Barrow (1991) concept of erosive and non-erosive (physical, chemical and organic) soil degradation processes.

4.1 Erosive Soil Degradation

Soil degradation by accelerated erosion is a serious concern, especially in developing countries of the tropics and subtropics. In Latin America and the Caribbean in particular, the extent, severity and economic and environmental impacts of soil degradation are the subject of continuous debate, with uncertain magnitude for the twenty-first century. Moreover, estimates of the regional land area affected

M. Casanova et al., *The Soils of Chile*, World Soils Book Series, DOI: 10.1007/978-94-007-5949-7_4,
© Springer Science+Business Media Dordrecht 2013

Table 4.1 Main human-induced soil degradation problems observed in Chile

Quantity reduction		
	Uncontrolled urbanisation	
	Mining wastes deposits and landfills	
	Losses by accelerated erosion	
Quality reduction		
	Physical quality changes	Compaction and crusting
		Subsidence
		Waterlogging
	Chemical quality changes	Excess and depletion of nutrients
		Acidification/ alkalinisation
		Salinisation
		Pollution (heavy metals, pesticides, industrial wastes)
	Biological quality changes	Organic matter changes
		Biodiversity changes

are tentative and subjective, with field measurements often technique dependent (Casanova et al. 2010a). Although natural erosion occurs on most landforms in Chile, as soon as land is newly put into production the process increases, triggering accelerated degradation that represents the main focus for most control initiatives.

An abundance of valuable research has been developed in Chile to create initial awareness among land users about the seriousness of the erosion problem in their operations (Rodríguez and Suárez 1946; Elizalde 1970; Peralta 1976; Contreras 1986; Vargas et al. 1998; Gayoso and Alarcon 1999; Lagos 2005; Ruiz 2005). In parallel to proposing soil conservation practices, some engineering solutions are being specified for soil erosion within an environmentally acceptable level of reliability (Pizarro et al. 2009; Lemus and Navarro 2003).

With the conviction that human-induced soil erosion is only the symptom of a deeper problem—incorrect land use and bad management—the main research emphasis has moved to better land management and to identifying how much and where soil is being lost in Chile.

Despite many parallel efforts in soil erosion research in Chile, few initiatives cover other important human-induced erosive processes such as streambank erosion, which is accelerated by deforestation (Fig. 4.4), tillage erosion and harvest erosion (Homer and Casanova 2011). Varnero et al. (2005) report that if grass cover (on soil) in the Metropolitan Region is not maintained, current extraction rates will not only cause a decline in the sustainability of this activity, but also the degradation of soils used for these purposes. According to Arroyo et al. (2005), peat per se comes under the Chilean Mining Code and, like any mineral, is considered to belong to the state, regardless of who the owner of the land may be. Peats are being exploited commercially by private companies (concessions granted) in the extreme south of Chile (Region XI and XII) and transported about 2,500 km to central Chile for use in the fruit, horticulture and mushroom industries.

Even though one could argue that the phenomena of landslides, collapses and so on are natural, it is equally true that human actions (mining, deforestation, fires, road networks, construction etc.) trigger these events to occur with greater severity (Espinosa et al. 1985). Indeed, a clear example is the change in productive land use in the Copiapó Valley from the mid 1970s, with an increase in the area planted with bush vines in the order of 236 % (Castro et al. 2009a, b). This has meant the introduction of significant morphological changes, exceeding in many places the morphodynamic thresholds, and generating impacts on the morphology dynamic. These impacts are significant in terms of increased vulnerability to mass removal occurring in episodes of heavy rains associated with the *El Niño* years, with hazard for the resident population and agricultural workers, and in generating significant loss of infrastructure.

4.1.1 Water Erosion

Conventional and nuclear methods, but also models and remote sensing, have been used in Chile to assess soil water erosion (Casanova et al. 2010b; Zapata et al. 2010).

Erosion pins have been recommended by Stocking and Murnaghan (2001) and used by many Chilean researchers from Coastal Range to Pre-Andean soils (Region VII) to assess sheet erosion and monitor gully head advance (Cuitiño 1999; Cartes et al. 2009). Likewise, Lagos (2006) and Cerda and Jimenez (2003) observed an elevated variability of soil erosion and sedimentation in Region IV and Region V, respectively. Youlton et al. (2010) reported that in Region V, soil erosion increases after building downward ridges (raised beds) along steep hillslopes, in particular during the first winter, but decreases when trees grow, while runoff increases. Thus, after 20 Mg ha^{-1} of soil erosion during the first year, erosion mitigation management (soil cover) reduced erosion by 90 %.

Despite methodological problems connected with measurement of soil erosion (Boix-Fayos et al. 2006, 2007), plots of diverse types and sizes have been utilised in Chile,

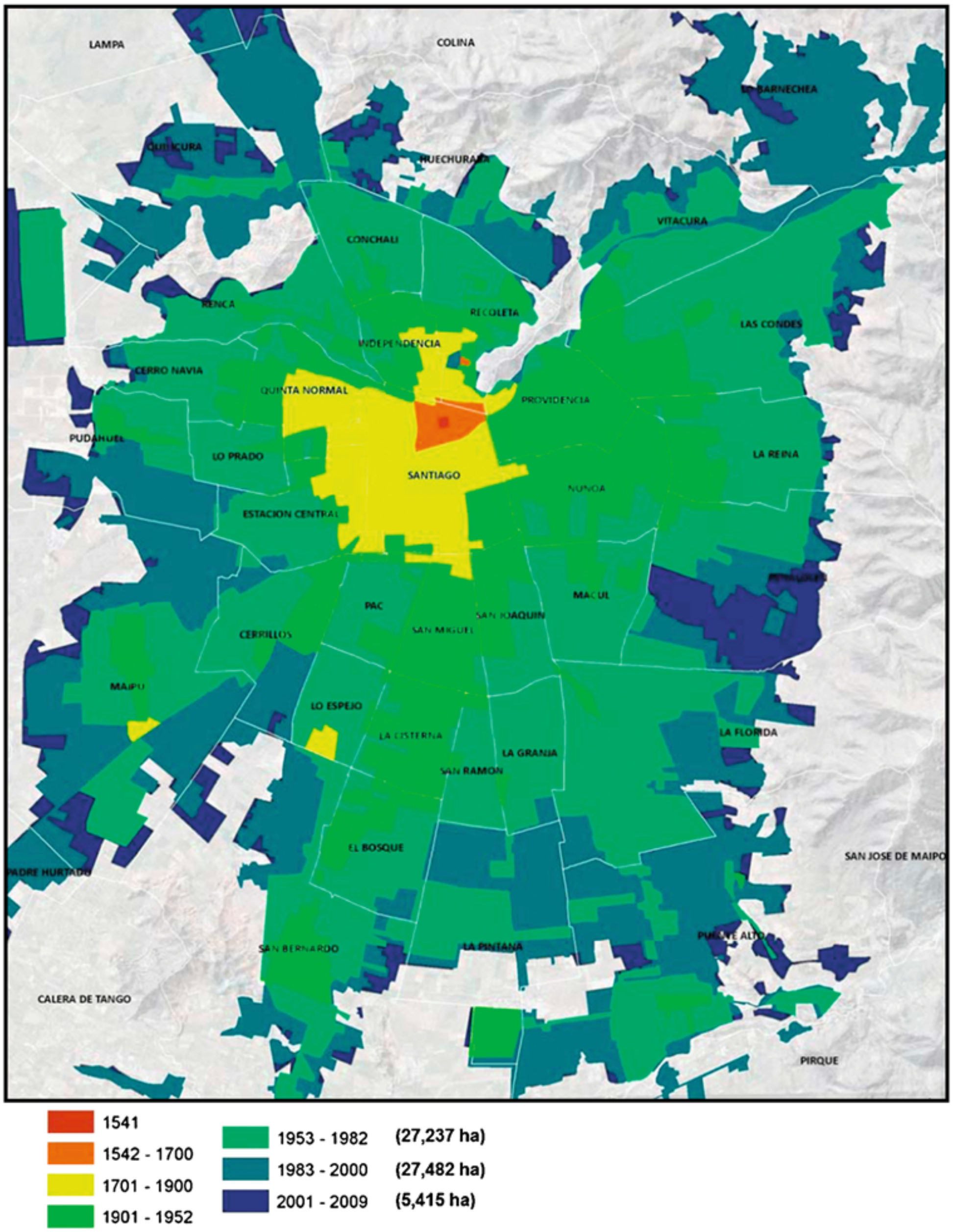


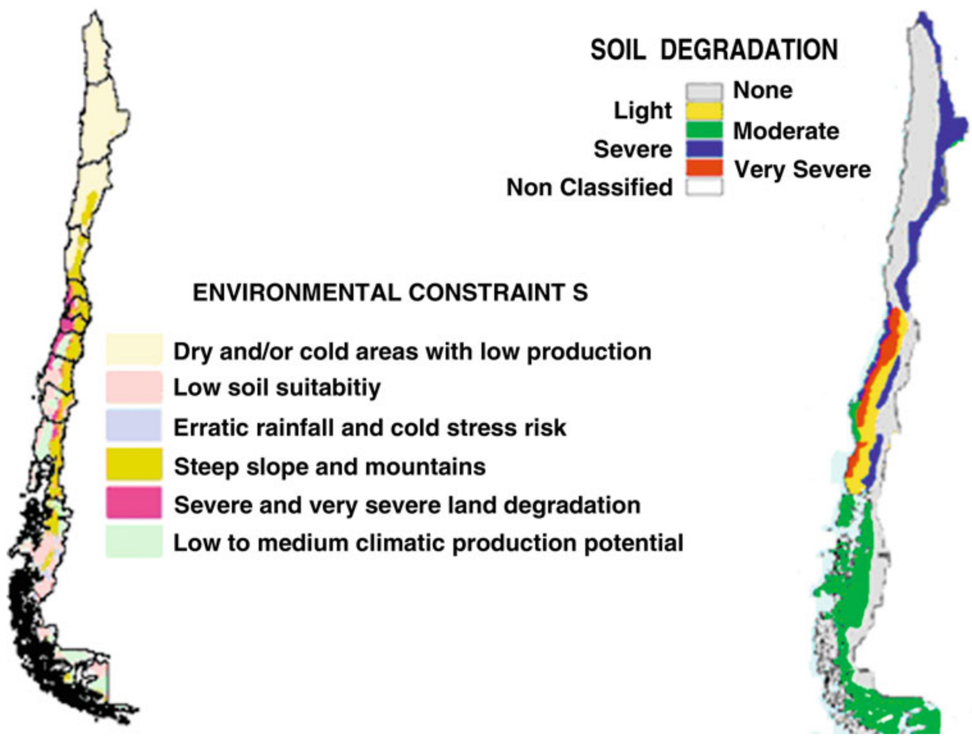
Fig. 4.1 Urban sprawl of Santiago city between 1541 and 2009 (MINVU 2010)

mainly with three objectives: (a) to characterise erosion processes in different zones; (b) to calibrate/verify models, both empirical and physical; and (c) to estimate soil erosion rate for assessing, developing and verifying control methods.

For example, for large and small plots, significant variations in runoff responses to rainfall rates were found by Joel et al. (2002) on hillsides of rainfed central Chile. They concluded that a characteristic minimum rainfall intensity (2 mm h^{-1}) for the site, irrespective of plot size, is required to generate runoff under continued rainfall conditions. This suggests that spatial and temporal variability of runoff generation across hillslides depends mainly upon the heterogeneity of soil hydraulic conductivity and rainfall characteristics. Casanova et al. (2007) studied 18 erosion plots (2 m × 1 m) at the same location (Fig. 4.5) and observed that spatial variability of erosion rate depends on the geomorphological components (slope aspect and gradient) and temporal variability depends on antecedent soil moisture conditions. However, they also confirmed a concept of 'critical slope gradient that represents a soil characteristic inclination threshold on sediment yield.

Fig. 4.2 Mining dams in Region IV (*left* Tambillo) and Region XI (*right* Laguna Verde) of Chile

Fig. 4.3 General environmental constraints (*left*) and human-induced soil degradation (*right*) in Chile (http://www.fao.org, Accessed 15 April 2011)



A study evaluating soil erosion as a result of tillage systems was carried out on Andisols (foothills of the Chilean Andes, Region VIII) by Rodríguez et al. (2000). For four soil treatments (conventional tillage, vertical ploughing, direct drilling and permanent pasture on 11 m × 3.6 m plots), annual erosion was found to be 19.3, 5.5, 3.0 and 0.64 Mg ha^{-1}, respectively.

The expansion in recent decades of fruit tree cultivation to steeper hillslopes, considered marginal land for agriculture in the past, is mainly comprised of production of table grapes, avocados and citrus on ridges in the Semi-arid zone of Chile (Fig. 4.6), while in the Mediterranean zone, vineyards for high quality wine production are occupying fragile sloping lands that were formerly protected by native forest.

In Region VI, where vineyards are normally aligned in the direction of the steepest slope (Fig. 4.7), a study is being carried out by University of Chile and the Chilean Commission of Nuclear Energy (Casanova et al. 2009) to assess water erosion control measurements. Mulch and/or organic emulsion were applied to soils (Ultic Haploxeralfs) in 12

Fig. 4.4 Streambank erosion at Region XI (*left* Chile Chico) and Region IX (*right* Laguna del Laja)

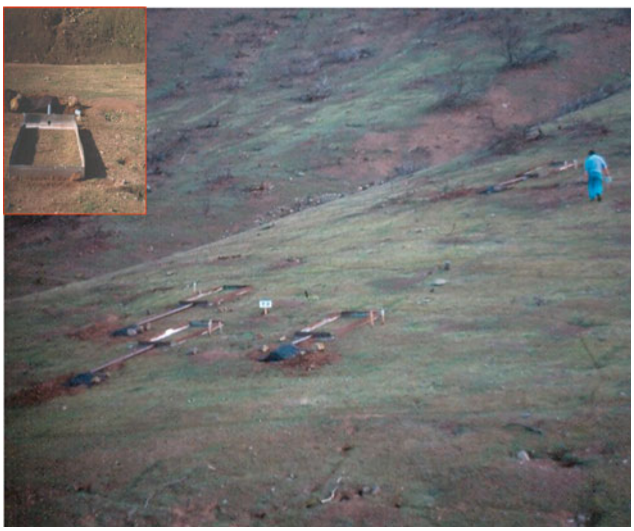


Fig. 4.5 Erosion plots at hillside of central Chile (Metropolitan Region)

plots (2 m × 10 m), with preliminary results as shown in Fig. 4.8.

A similar study (Casanova et al. 2011) is being conducted on abandoned and degraded hillsides of Region IV with 9 plots (3 m × 1 m) on the drainage tributary area above a gullied field. Here, emulsions are also being applied to improve soil infiltration rate and reduce runoff (Fig. 4.9).

The universal soil loss equation (USLE) model (Wischmeier and Smith 1978) and its revised version (RUSLE) have been widely used to predict soil erosion in Chile (Brito and Peña 1980; Peña 1983, 1985; Oyarzún 1993; Honorato et al. 2001), with an appropriate database modified to local conditions. Stolpe (2005) compared models (RUSLE-WEPP-EPIC) for Andisols and other models without plots (Honorato and Cruz 1999; Santibáñez et al. 2008; Bonilla et al. 2010) to verify soil losses, using the models to simulate different future scenarios. Figure 4.10 shows the close relationship between estimated and measured soil erosion rates in Regions IV, VI, VII, VIII and IX of Chile.

The quest for techniques as alternatives or complements to the existing methods has directed attention to the use of radionuclides (Zapata 2003). In southern Chile and Patagonia, a comprehensive study with ^{137}Cs and ^{7}Be has been conducted by researchers at Austral University of Chile (Schüller et al. 2000, 2003, 2004a, b, 2006; Sepúlveda et al. 2008), who report a clear advantage of radionuclides over erosion plots and erosion pins. An initial study provided information on selection of reference site and its spatial variability (Schüller et al. 1997), while recent work examined common soil forestry management practices, linear trash barriers (woody harvesting residues) along contour lines and the maintenance of riparian vegetation to act as a sediment filter (Schüller et al. 2010). In agronomic terms, 16 years after implementing zero tillage in southern Chile, there was a substantial reduction in soil erosion rates, as measured by ^{137}Cs, of about 87 % (from 1.1 to 1.4 Mg ha^{-1} yr^{-1}). However, such a beneficial effect may be readily lost if the mulch layer of old crop residues is removed or burned. Using ^{7}Be to measure a short-term erosion event occurring just after a dramatic burning event. Schüller et al. (2007) reported substantial soil losses of 12 Mg ha^{-1} over this 27d period of exceptionally wet (400 mm) weather.

On the other hand, a multi-scale approach has been implemented (Mathieu et al. 2007) to produce regional land degradation maps for the Coastal Range of central Chile, which is naturally sensitive to soil erosion, based on remote sensing technology. Radiometric indices were successfully applied to SPOT images to produce land degradation maps, but only broad classes of erosion status were discriminated and the detection of degradation processes was only possible when most of the fertile layer had already been removed.

Recently, the Natural Resources Information Centre (CIREN), a Chilean government-funded institution which

Fig. 4.6 Construction of soil ridges on hillsides with over 100 % slope gradient at Region IV of Chile

Fig. 4.7 Vineyards in sloping land and erosion at toeslope, Region VI of Chile

focuses on natural resources inventory and its corresponding cartography (GIS), released a study on current and potential soil erosion in Chile, which replaced a partial map published previously (IREN-CORFO 1979; Pérez and González 2001). This work, which used qualitative models, geomatic, remote sensing and SIG techniques (Flores et al. 2011), is published at 1:50,000 scale, except for extreme zones and the Andes mountains (1:250,000). A total area of 36.8 million ha (49.1 % of national territory) displays some level of erosion (Table 4.2), which increases from southern to northern Chile, with the north-central zone showing the highest eroded area (Region IV 84 %, Region V 57 % and Region VI 52 %). Human-induced soil erosion is concentrated principally from Region IV to X Region (Fig. 4.11).

4.1.2 Wind Erosion

A few studies on wind erosion in Chilean soils have been reported. The arid climate, flat geomorphology, strong south and south-westerly winds and the characteristics of the superficial sediments in the northern arid zone of Chile justify the study of wind erosion and transport processes in the coastal Atacama Desert (Flores-Aqueveque et al. 2009). Yardangs (wind-abraded ridges of cohesive material) are reported in these dry areas, where deflation is at a maximum, vegetation cover is minimal and sand abrasion is acting over the bare soil surface (Goudie 2008).

The Patagonian steppes occupy the southern tip of the continent from approximately 40 °S, are framed by the Andes to the west and the Atlantic coast to the east and south, and cover more than 800,000 km^2 of Chile and Argentina. Strong winds are a constraint to agricultural development in Patagonia and windbreaks are frequently planted to allow establishment of fruit trees, pasture and horticultural crops, and to protect agricultural crops, livestock and rural houses. Despite being mentioned as one of the main degradation processes in Southern Patagonia (Vött and Endlicher 2001), the conditions and rates of wind erosion in this region have not been studied extensively.

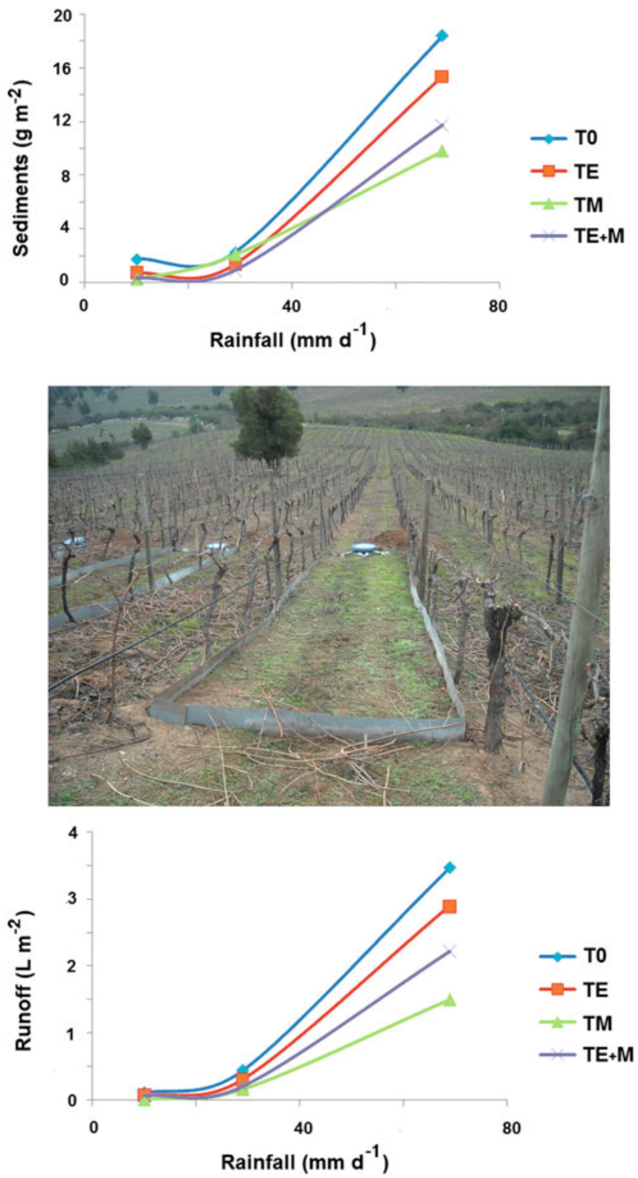


Fig. 4.8 Sediment yield and runoff generated by natural rainfall in plots according to treatments (*T0* control, *TE* emulsion, *TM* mulch, TE + M: emulsion plus mulch) at Region VI, Apalta Valley

Semi-arid steppes of this zone are prone to wind erosion, due to the soil remaining dry for periods during intense spring and summer winds (Gualterio 2006; Dube et al. 2011). Human mismanagement of soils has either initiated or accelerated this degradation process in vast areas of Eastern and Western Patagonia (Gut 2008). Rounded pebbles and gravels associated with glaciofluvial processes are characteristic of the Patagonian steppe soils and are responsible for the formation of extensive desert pavement, where wind erosion has been able to remove finer materials (Paruelo et al. 2007). Another indicator in this zone is related to volcanic activity. After eruption of the Hudson volcano in 1991, around 80,000 km^2 were covered by a layer of ash ranging in thickness from 10 cm to over 100 cm, but today most of this material has been removed from rough landscapes, principally by strong winds.

Most of the coastal dunes in Chile today are the result of soil erosion, with sediments from denuded soils being carried by the rivers to their mouths and then transported by prevailing winds north of the mouth. According to an old inventory by IREN (1966), 74,428 ha are occupied by dunes in Central Chile, between Regions IV and X. Most of the dunes present at that time were found in Region VIII, where they covered 30,709 ha, i.e. 41.3 % of total coastal dunes. An evaluation by Peña-Cortés et al. (2008) of the dynamics of dune systems of the coastal strip of Region IX between 1994 and 2004, defined eight fields of dunes with a total area of 4,597 ha, which represented an overall expansion of 314 ha in the period.

However, a general review of sites covered by dunes today shows that it is possible to observe their presence along all territory (Fig. 4.12). It is clear that this geomorphological feature is not always related to human-induced soil erosion, corresponding mainly to relict dunes, but is an indicator of wind erosivity.

4.2 Non Erosive Soil Degradation (Physical, Chemical and Biological)

The effect of soil formation factors is responsible for the evolution of soils, where the forces of these factors and soil formation processes are always operational in such a manner that under natural conditions a static equilibrium state is never attained. However, the tendencies in soil evolution at any given time are highly sensitive, particularly when there are man–made changes that may generate a new equilibrium towards soil chemical, physical and biological degradation processes. This section reviews the causes of the main soil chemical, physical and biological degradation processes in Chilean soils and some remediation measures are proposed and discussed.

4.2.1 Soil Physical Degradation

From a physical point of view, soil affects plant production through water, heat, air and mechanical conditions, all state variables of a dynamic nature, which affect the flows of matter and energy (Benavides 1992). Physical degradation generates concatenated effects on the soil, which ultimately depend on the soil water condition of the porous system and the stability of the unions between solid particles (Horn 2003).

Fig. 4.9 Erosion plots on hillside in Hyper-arid and Semi-arid zone of Chile (Region IV)

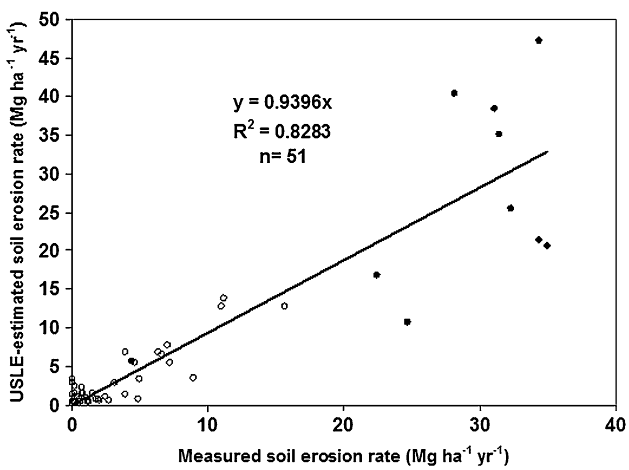


Fig. 4.10 Comparison of estimated and measured soil erosion rate (Stolpe 2005; Honorato et al. 2001). *Black circles* correspond to fallow conditions

Physical degradation may be related to a wide range of problems and processes, such as crusting, reduced permeability, compaction, poor aeration, destruction of the structure and subsidence (Table 4.1). Almost all of these are related to the reduction or alteration of soil porosity. Thus, soil physical degradation is related to direct or indirect human actions that may result in deterioration of properties such as bulk density, structure, aggregate stability, mechanical strength and porosity. All these actions impede the adequate development of roots in the soil, affecting the development of vegetation and rendering the soil more susceptible to degradation by erosion (Casanova et al. 2006).

In Chile, the Ministry of Agriculture, through a special programme for soil recovery (Incentive System for Agro-environmental Sustainability of Agricultural and Livestock Soils, ISRD-S) led by the Agriculture and Livestock Service (SAG), gives incentives and subsidies for the implementation of land reclamation works, including prairie sowing, organic amendment incorporation and implementation of conservation tillage systems (Ruiz 2011). The specific management practices are focused in special areas depending on specific needs, as well as the magnitude of the subsidies (50–90 % of the costs) depending on the kind of farm (size and economic resources).

Analysing the properties of the Chilean soils, it is possible to determine the strong influence of climate and parent material at the regional level in a north–south direction, and the effect of local relief in an east–west direction (Luzio et al. 2010). The climate-relief interaction affects the vegetation that grows on the surface of the land, being less important over time as a soil forming factor.

Thus, it is possible to identify three areas that present different problems related to soil physical degradation. The first includes the Hyper-arid to Semi-arid zone of the country (Sect. 2.2.1) with very low SOM content and a high risk of salinisation; a second zone developed under a Mediterranean climate (Sect. 2.2.2) with intense agricultural activity; and a third one including Rainy and Patagonian zone (Sect. 2.2.3), with soils that have volcanic influence, non-crystalline mineralogy and high levels of OM.

Bearing in mind that the problems are not exclusive to each area and can occur in any area, the limitations of soil physical properties derived from human-induced degradation by pressure on this scarce resource can be grouped into:

Table 4.2 Actual area of soil erosion (in 1,000 ha) in different regions of Chile (Flores et al. 2011)

Region	Non erosion	Light erosion	Moderate erosion	Severe erosion	Very severe erosion	Non apparent erosion	Other uses	Excluded areas	Eroded soil[a]	Studied area
XV	48.8	255.7	171.6	468.7	583.6	0	157.1	0	1,479.6	1,685.5
I	60.8	1.0466	6023	1.1532	838.4	0	524.4	0	3,640.4	4,225.6
II	138.1	1.341.4	3,271.3	3,592.8	2,021.4	0	2,237.3	0	10,226.9	12,602.4
III	178.5	825.2	536.6	2,029.9	629.1	0	3,330.4	36.8	4,020.9	7,566.5
IV	210.0	571.6	1,142.3	1,213.9	492.5	25.5	403.5	0	3,420.4	4,059.5
V	162.0	244.2	324.6	258.2	80.0	162.6	368.4	0	906.9	1,600.0
MR	354.5	93.4	189.5	213.5	186.8	68.0	435.0	0	683.2	1,540.6
VI	331.0	96.3	451.8	197.3	114.5	125.1	322.3	0	860.0	1,638.3
VII	655.9	349.0	416.1	377.8	335.8	453.3	446.2	0	1,478.7	3,034.0
VIII	840.1	393.4	429.1	211.6	148.6	1,443.8	245.4	0	1,182.7	3,712.0
IX	1,131.9	280.5	240.9	243.9	145.9	944.3	182.8	16.3	911.1	3,186.3
XIV	427.0	262.3	197.6	79.6	5.8	688.0	173.5	3.7	545.3	1,837.4
X	750.6	574.6	423.5	138.9	33.3	2,142.4	745.6	24.9	1,170.3	4,833.7
XI	234.7	894.7	743.5	383.1	583.4	4,550.6	3,361.1	0	2,604.6	10,751.0
XII	1,718.8	1,122.9	1,287.8	590.0	761.5	3,088.5	4,247.7	4.3	3,762.1	12,821.4
Total	7,242.6	8,351.9	10,428.3	11,152.4	6,960.4	13,692.1	17,180.7	86.0	36,893.0	75,094.4

[a] Eroded soil includes light, moderate, severe and very severe classes. Unregistered information by remote sensing in zones with vegetal cover >75 % (non apparent erosion)

a. Poor aeration caused by traffic or chemical dispersion by irrigation practices.
b. Compaction and high mechanical strength in medium to fine-textured soils.
c. Soil profile alterations in shallow or coarse-textured soils.
d. Problems associated with high organic matter content.

4.2.1.1 Poor Aeration by Restricted Horizons

Soils from the Hyper-arid to Semi-arid zone have lower average levels of OM (<4 %), making them susceptible to losing their structure owing to low stability. The problem increases when there is a high amount of sodium, which promotes the dispersion of soil. The sodium source may be natural, as is the case of marine terraces such as the Huentelauquén sector (Region IV), or induced by irrigation practices, and reflects the effect of soil stratification on the accumulation of salts (Fig. 4.13).

As a solution to the low OM contents, different organic amendments are used, especially manure and compost, being less used sources based on soluble humic substances. In recent years, cover crops have also been used to improve the soil physical properties in orchards (Baginsky et al. 2010; Cortés 2011). The advantage of adding OM is that it increases the stability of the structure, promotes a stable and functional porosity and allows air and water flow to the roots in an adequate amount and time. In coarse-textured soils OM also increases water retention, avoiding water stress (see Sect. 4.2.1.3).

As regards pore function, Fig. 4.14 shows the effect of two practices in an alluvial, deep, clay loam and stratified Typic Haplocambid (CIREN 2007) in Region III (Copiapó Valley). During 3 years, a manure application at doses of 40 Mg ha^{-1} and a crop rotation (maize/broad bean/barley) was implemented. The control was subjected to surface tillage with chisel plough, thus maintaining a high coarse porosity to 10 cm depth (Poblete 2011).

Even though the manure is applied on the surface, there is an effect on water dynamics in the soil profile in the form of higher infiltration rates (Fig. 4.14a). Nevertheless, this higher amount of water may result in a cooler soil, decreasing the rate of root development (Baginsky et al. 2010). In coarse-textured soils, growing crops (specifically grasses) can improve water infiltration (Seguel et al. 2011).

The high coarse porosity of the control as a result of tillage and the high porosity of the manure explain the high capacity for air flow observed at the surface (Fig. 4.14b). However, the flow decreases sharply at 20 cm depth because of a plough pan in the control and pore discontinuity in the manure treatment (Keller 2011). On the other hand, the crop rotation favours a continuous pore system at depth, maintaining the air flow capacity to renew oxygen to the roots. In fine-textured soils in particular, excessive traffic and poor irrigation practices affect the oxygen

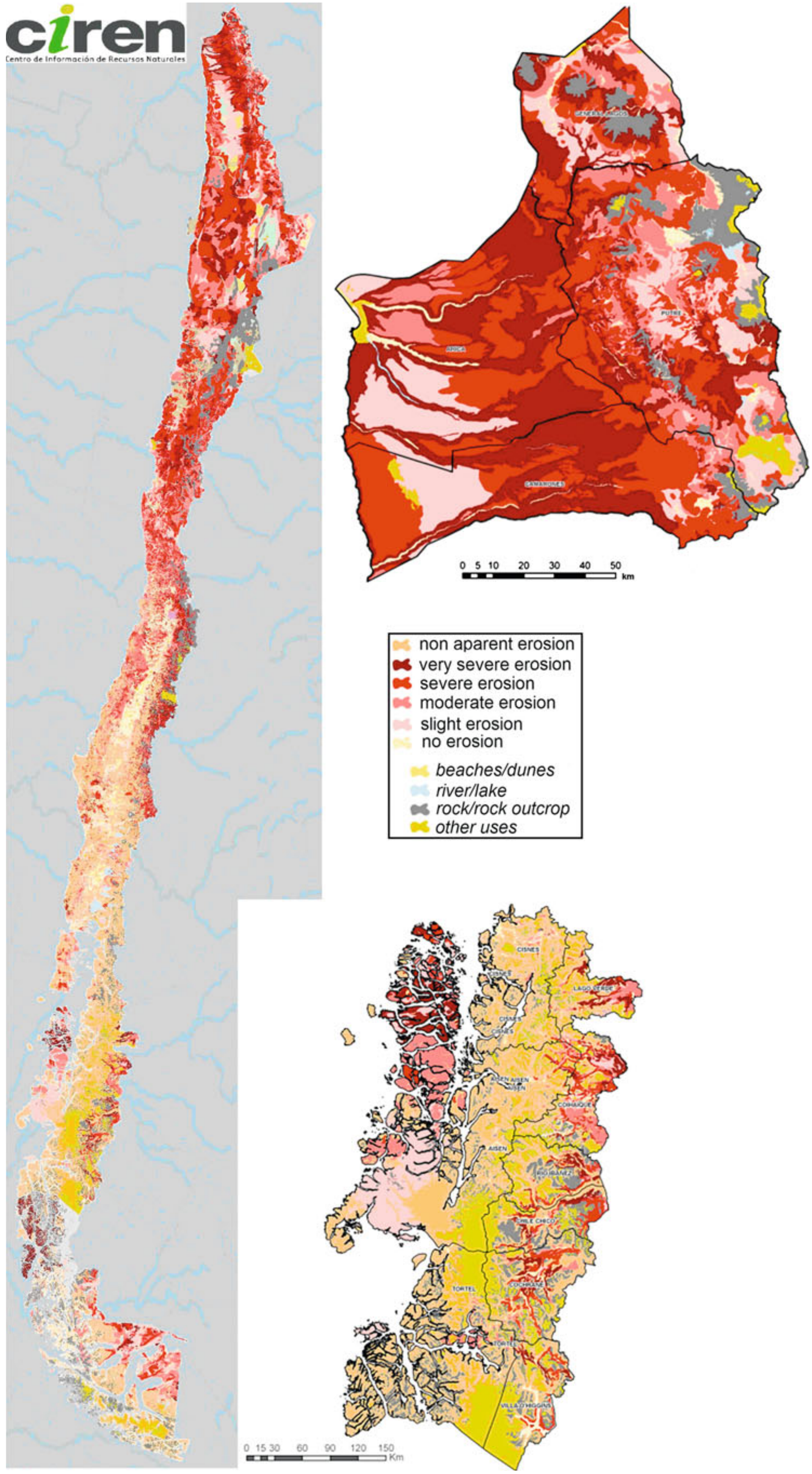


Fig. 4.11 Soil erosion map of Chile including a zoom of Region XV (*above*) and Region XI (*below*)

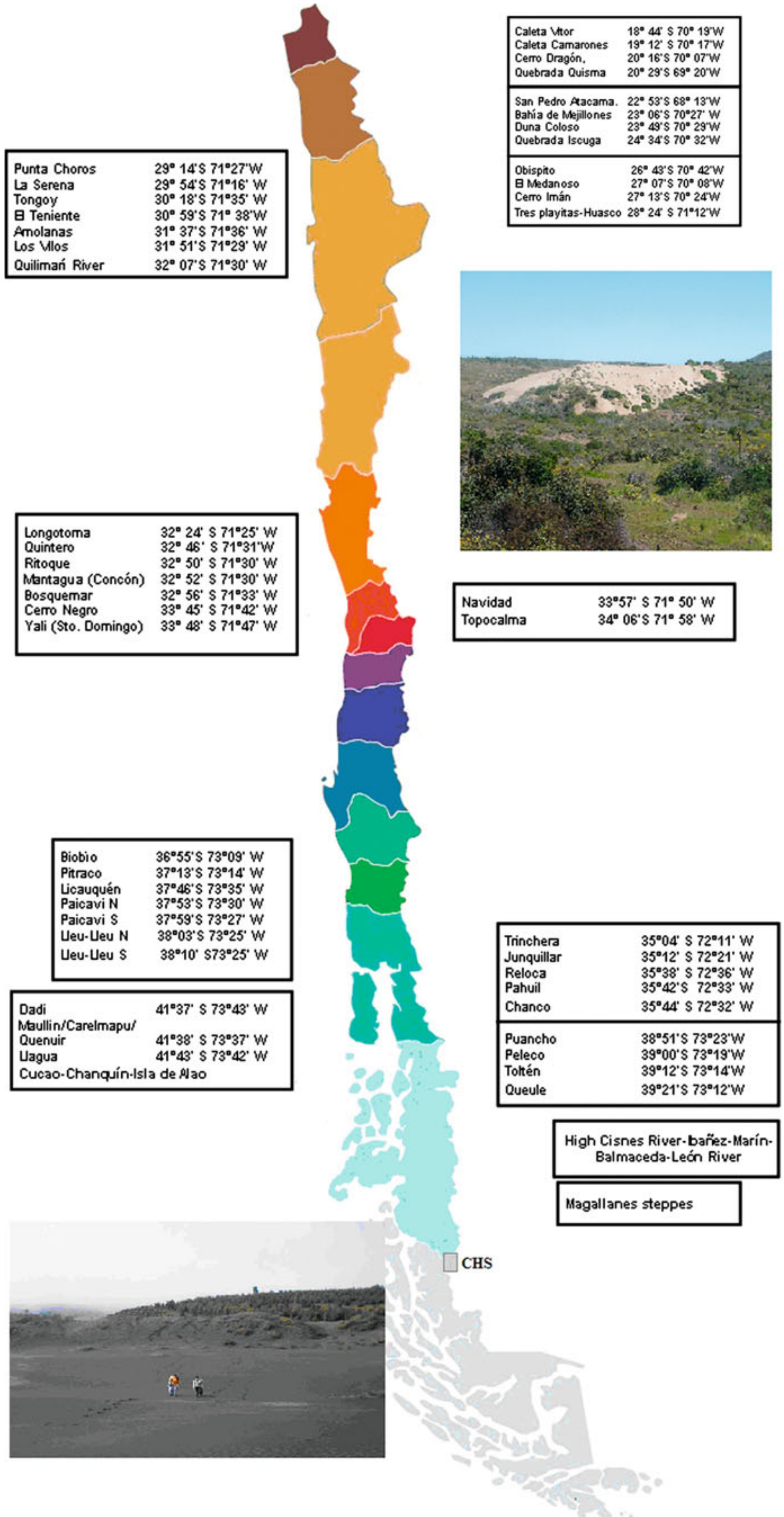


Fig. 4.12 Locations in Chile with dunes present. Examples: Region IV (*above*) and Region VII (*below*)

Fig. 4.13 Surface salt accumulation (*left*) caused by drip irrigation and soil stratification (*right*) increases the risk of salinisation

diffusion rate in the soil (waterlogging) resulting in low productivity (Ferreyra et al. 2011). The Chilean government and the private sector, coordinated by the National Commission for Irrigation (CNR), have made significant investment efforts for improving water management and irrigation infrastructure and resolve poor soil drainage. In fact, Law 18,450 (Development of Private Investment in Irrigation and Drainage Works) dating from 1985 not only allows an important irrigated area in Chile to be increased, but also improves water use efficiency, which is relatively low in the country. The programme is preferentially focused on regions where irrigation is most necessary for agriculture, with the public sector subsidising up to 75 % of the construction, refurbishment and equipment costs for minor irrigation or drainage works.

Both salinity and sodicity cause physical problems, decreasing the osmotic potential of water and dispersing the soil, respectively, affecting water uptake and the renewal of oxygen to the roots (Hillel 2004). For instance, a problem promoted by the use of manure is the salt intake, as shown in Fig. 4.14. At the end of the season, the manure treatment resulted in a surface EC of 6.6 dS m^{-1} and exchangeable Na value of 3.9 $cmol_c$ kg^{-1}, compared with 0.9 dS m^{-1} and 0.7 $cmol_c$ kg^{-1}, respectively, when a crop rotation was used. Meanwhile, the control without any management reached EC values of 11.5 dS m^{-1} as result of capillary rise, showing that soil physical properties may increase the effects of soil chemical degradation processes such as soil salinisation.

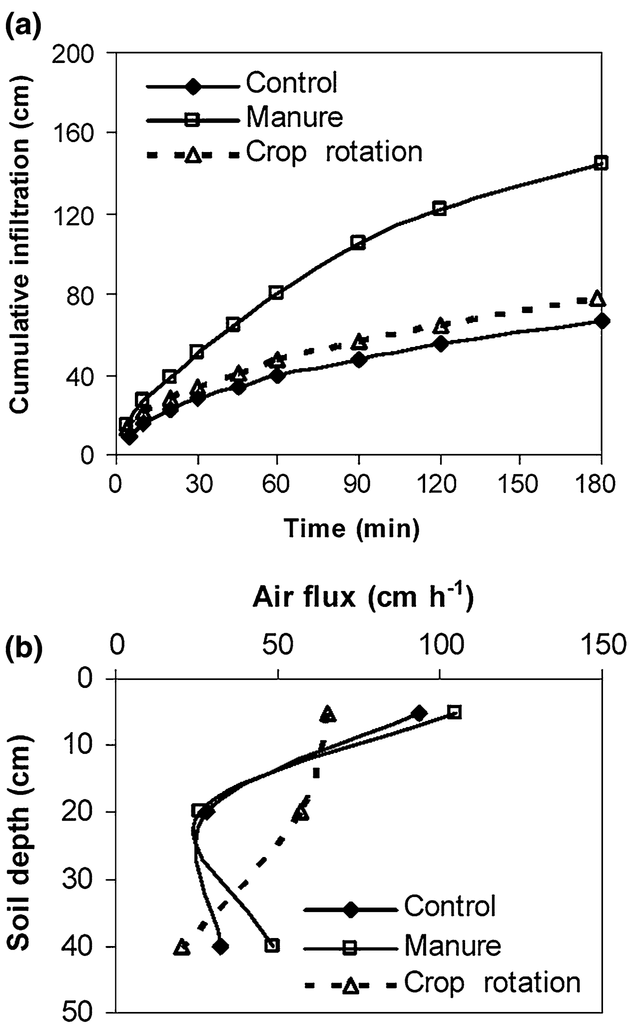


Fig. 4.14 Soil function as result of soil management. **a** Infiltration of water by a ring method test. **b** Air flux as a function of soil depth, performed by a laboratory test with samples equilibrated at −33 kPa

4.2.1.2 Compaction and High Mechanical Impedance

The first consequence of land use change from native vegetation to a mechanised productive use is a reduction in soil OM content. This decrease causes a loss of structural stability, resulting in compaction processes. In agricultural soils, the main factors responsible for compaction are excessive traffic, the use of farm equipment that exceeds the bearing capacity of soil and tillage at unsuitable soil water content (Ellies 1988; Cuevas and Ellies 2001). These result in a change in the proportion of pores with water and air (mainly loss of coarse pores) and an increase in mechanical resistance to root development (Ellies et al. 2000; Ellies 1999; Seguel et al. 2009). All the intense production areas in Chile are subject to this problem.

Early studies by Ellies (1986, 1988, 1999) evaluated changes in physical properties of Andisols and Ultisols (Rainy and Patagonian zone) with different use intensity. Later works (Farías 2009; Seguel et al. 2009; Fuentes 2010; Poblete 2011) included Alfisols, Mollisols and Aridisols. Table 4.3 presents some important results related to changes in soil physical properties as result of compaction.

The direct consequence of tillage is to incorporate the superficial organic mulch into the Ap horizon, making it more accessible to the action of soil microorganisms. As Table 4.3 shows, in general there is a reduction in OM as a consequence of soil use. This results in an increase in soil

Table 4.3 Soil physical properties as result of compaction processes by intense use

Pedon	Land use	Soil depth (cm)	Organic matter content (%)	Bulk density (Mg m^{-3})	Coarse pores (>10 μm) (%)	Mechanical stress (kPa)
Valdivia (Andisol)	Forest	0–20	19.3	nd	34.4	176[a]
	Grassland		17.1	0.68	26.6	215[a]
Cudico (Ultisol)	Forest		8.9	nd	30.4	125[a]
	Grassland		7.3	1.03	18.8	160[a]
La Lajuela (Alfisol)	Forest	0–10	10.5	1.13	23.0	115
		10–30	5.7	1.38	20.8	151
	Vineyard	0–10	4.8	1.53	23.5	349
		10–30	4.6	1.59	11.0	283
Santiago (Mollisol)	Grassland	0–10	3.6	1.29	17.4	114
	Rotation	0–10	3.7	1.53	16.0	197
La Capilla (Aridisol)	Grapes	0–10	2.8	1.46	19.2	nd
		10–30	nd	1.62	11.7	nd
	Grapes + OM	0–10	6.2	1.02	17.1	nd
		10–30	nd	1.47	14.9	nd

Valdivia and Cudico soils: Ellies (1986, 1988) and Ellies et al. (1995a), La Lajuela soil: Seguel et al. (2009), Santiago soil: Fuentes (2010), La Capilla soil: Poblete (2011) with organic management
nd non determined
[a] Bearing capacity in wet condition, the others are strength of air-dry aggregates

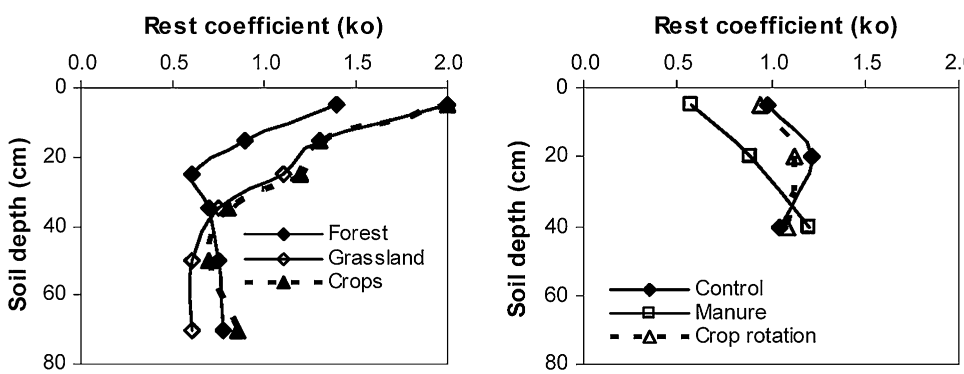


Fig. 4.15 Stress at rest coefficient (k_0) determined by penetrometer for an Andisol (*left* Contreras 2006) and an Aridisol (*right* Poblete 2011) with different management

bulk density (Db) values, with coarse porosity losses. According to Fuentes et al. (2011), it is possible to discriminate soils which by nature are more sensitive to others, i.e. soils with high clay content (Ultisols and Alfisols), which show great changes over time and space. In Andisols, the Db values are still lower than 0.9 Mg m^{-3}, even under conditions of high degradation (Ellies et al. 1996).

Under agricultural use without organic amendments, while the superficial tillage reduces soil densification, it is common to find a plough pan at 10–30 cm depth, as in the case of Alfisols and Aridisols, with low amounts of coarse pores. While a first effect of coarse porosity loss is reduced ability of soil to conduct air and water (Fig. 4.14), increased mechanical strength is also observed, hindering crop root growth (Table 4.3, Fig. 4.15).

Values of stress at rest coefficient (k_0 = horizontal tension/vertical tension) over 1.0 denote excessive mechanical strength (Bachmann et al. 2006), because of the rearrangement of soil particles or aggregates into a denser soil matrix. The surface of Andisols can be strengthened by critical stress levels, and with use there is a transmission of stress to depth, but the shape and the rigid nature of volcanic-derived minerals maintain high levels of coarse porosity (Table 4.3), enabling rooting (Ellies 1999; Ellies et al. 2000). The results for Aridisols in Fig. 4.15 (right) are from the same trial as Fig. 4.14, and only with high amounts of organic amendments does k_0 decrease below a critical level (<1). Considering the properties of Aridisols, with poor structure development and low OM content, natural sites (with native vegetation) probably develop high values of k_0.

Fig. 4.16 *Left* raised bed 1.2 m high built with San Julián soil (Typic Haplotorrert) and planted with 2-years-old mandarin trees; *right* Holocene sand dunes (Typic Usticpsamment) with pine forest

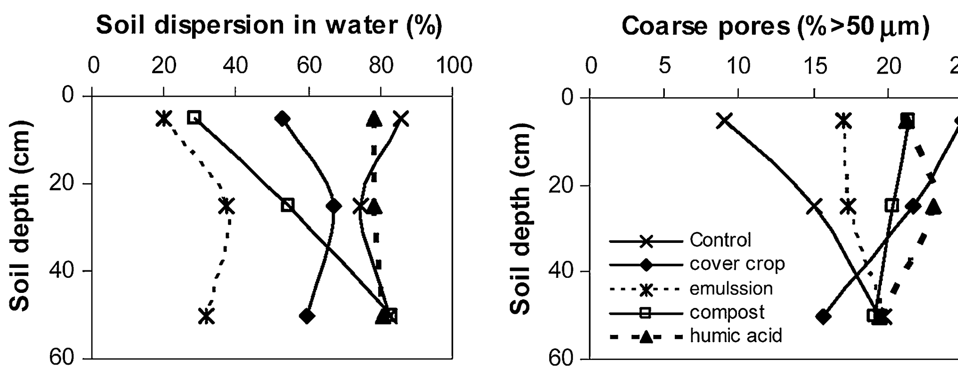


Fig. 4.17 Soil properties as a function of depth in a raised bed of San Julián soil series (Typic Haplotorrert). *Left*: macroaggregates dispersion in water (the lower value, the better stability); *right*: proportion of coarse pores. Adapted from Cortés (2011)

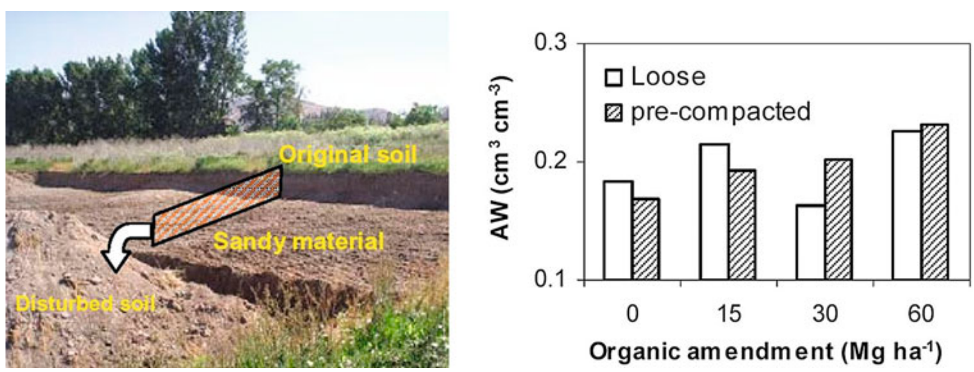


Fig. 4.18 Subsoil sand extraction from Rinconada Lo Vial soil series (Typic Xerochrept). *Left* disturbed/loosened soil deposited in the trench left by previous sand extraction; *right* available water (AW) as a function of organic amendment dose (OM). Adapted from Rodríguez (2011)

4.2.1.3 Soil Profile Modification

Many soils in Chile lack adequate depth due to poor structure or water retention due to coarse texture, both of which are influenced by continuous geological processes (volcanic eruptions, alluvial fans) alternating deposits or renewing the parent material. In the case of depth limitations, soils in the north of Chile (Hyper-arid to Semi-arid zone) restricted by cemented or massive horizons are common but the *ñadi,* an important soil type in the Rainy and Patagonian zone, is limited by a B_{hs} horizon at 50 cm depth on average. In shallow soils of the Hyper-arid to Semi-arid and Mediterranean zones, a raised bed 1.5 m high (locally called *camellón*) has been implemented during the past decade (Fig. 4.16) and causes mixing of the pedogenesis of the entire profile (Cortés 2011). On the other hand, artificial drainage of *ñadis* promotes settlement and a loss of soil function (Ellies 2001). Obviously, the rainy conditions provide greater potential in the latter case.

Coarse-textured soils are randomly distributed throughout the country, being associated with Holocene alluvial deposits, close to volcanoes and in dunes along the Coastal Range (Fig. 4.16, right). Typical coarse-textured soils derived from volcanic materials with alluvial transport are those grouped in the Arenales soil series from the Rainy and Patagonian zone (see Sect. 2.2.3), which are suitable for forest but have marginal agricultural use in flat areas. Even though these are naturally limited soils, in both cases (shallow and coarse-textured soils) they are being brought

Table 4.4 Soil properties (0–10 cm) related to water repellence in different Chilean soils

Soil	Land use (yr)	OM (%)	Wetting angle (°)	Water dispersion (%)
Valdivia (Andisol)	Forest (0)	24.3	105	2
	Grass (55)	16.0	79	4
	Crops (123)	11.7	70	7
Huiti (Andisol)	Forest (0)	33.8	118	nd
Cudico (Ultisol)	Forest (0)	12.6	83	3
	Crops (95)	6.4	48	75
La Lajuela (Alfisol)	Forest (0)	10.5	nd	3
	Vineyard (8)	4.8	nd	78

Adapted from Valdivia and Cudico soils: Ellies et al. (1995a, b), Huiti: Orellana (2010), La Lajuela soil: Seguel et al. (2009)
nd non determined

into agricultural use as a result of the need for new production area, and the impact on soil properties will affect the ecology of the area and promotes degradation unless correct management is implemented.

When a shallow soil is modified by building a raised bed, mixing of A_p and B horizons results in a loose material, which consolidates because of its low physical and mechanical stability, resulting in a reduction in coarse porosity. As shown in Fig. 4.17, it is necessary to use amendments to prevent excessive consolidation.

A soil disturbed by raised bed construction will have low physical and mechanical stability, losing coarse porosity and diminishing the capacity for air and water flux. The soil in Fig. 4.17 has clay content ranging between 44 and 52 %. Different soil amendments (commercial organic products such as humus and humic acids) improve the soil properties but to different extents depending on the property analysed, and some may need to be combined to restore degraded soil.

In the case of poorly drained soils, when an artificial drainage system is installed, natural soil settlement takes place, caused by OM and coarse porosity losses. In Frutillar soil series, a typical *ñadi* (Typic Placaquand) from the Rainy and Patagonian zone, 50 years of use after drainage caused soil settlement from 90 to 50 cm deep and loss of OM from 36 to 10 %, resulting in a decline in water availability from 400 to 120 mm (Ellies 2001).

When coarse-textured soils have no agricultural use, they generally serve a valuable ecological role. However, the limited agricultural area in Chile creates pressure on the soil resource, causing sectors that should not be in productive use, such as dunes, to be cultivated and affecting ecological niches. One example is the sand dunes near La Serena city (~30°S), which have been levelled, amended with organic materials and subjected to potato production with drip irrigation. While there is no risk of settlement in sandy materials, the excessive organic amendment could promote water repellence (Ellies 1978) and preferential flow, increasing the risk of pollution.

A special case is the extraction of sand from subsoil for construction purposes, which alters the superficial soil (Fig. 4.18). In this case, the soil is totally disturbed and deposited in a ditch beside the trench.

The soil from Fig. 4.18 was classified as II LCC, with slight restrictions by 80 cm soil depth. Subsoil sand extraction results in a totally loose material, without bearing capacity and with low fertility index, diluted along the profile. Restoration of soil physical properties requires organic amendment use, complemented with a pre-compaction work. Efforts have been made to restore these soils (Macaya and Gallardo 2007), but still there is a lack of effective legislation to protect the soil resource.

4.2.1.4 Organic Matter Content and Physical Soil Degradation

Soil OM ensures physical–mechanical stability and therefore the functionality of the pore system, but high amounts of OM could result in higher water repellence, creating a risk of erosion or generating preferential water flow into the

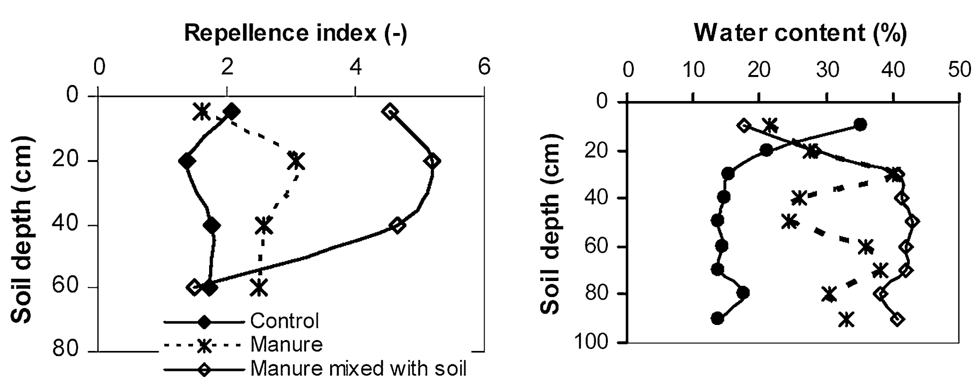


Fig. 4.19 Negative effect of high doses of organic amendment (3 years with 40 Mg ha^{-1}) in a Typic Haplocambid. *Left* soil repellence index (>4, excessive repellence). *Right* irregular available water (AW) distribution into the soil profile. Adapted from Keller (2011)

soil profile. Table 4.4 shows some soil properties related to hydrophobicity and aggregate stability in water.

The high OM in soils derived from volcanic ash ensures good aggregate water stability (low dispersion), even after 120 years of farming, and subsequent OM mineralisation. Nevertheless, there are potential problems with the hydrophobicity conferred by the OM (assessed as wetting angle) causing water repellence, depending on the type of OM and its interaction with mineral particles. This phenomenon is especially critical in Andisols from the Region VIII (Peña 1992), where dry summers promote the highest expression of water repellence (Orellana 2010) promoting runoff and erosion. Even in unsaturated conditions, the hydrophobicity may promote lower hydraulic conductivity at sites that naturally have higher OM contents (Nissen et al. 2006). However, with an adequate crop rotation a sufficient OM content can maintain hydraulic conductivity values that exceed rain intensity (Sandoval et al. 2007).

The difference between the Andisols shown in Table 4.4 is that Valdivia soil is a Hapludand (well-drained Andisol or *trumao*) and Huiti soil is a Duraquand (poorly drained Andisol or *ñadi*) (CIREN 2003). When these Duraquands are drained, their high shrinkage capacity and OM mineralisation cause irreversible contraction and settlement (Dörner et al. 2009), affecting pore functionality. In fact, an initial hydraulic conductivity close to 9 m d^{-1} has been measured in such soils, but after a second rotation of pine and 55 years of use it may decline to less than 4 m d^{-1} (Ellies et al. 1995b).

On the other hand non-volcanic soils (Table 4.4), with lower OM contents and lower water repellence risks than Andisols, show reduced aggregate stability under agricultural use, and under strong rain events are easily dispersed and sealed, favouring runoff processes. Ultisols and Alfisols, located in the Coastal Range, are particularly sensitive and erosion rates will depend on soil management, crop rotation and tillage system (Ellies 2000; Traub 2010). Finally, as shown in Fig. 4.19, it is also possible to generate problems with excessive applications of organic amendments or by particular situations of organic inputs (Sagardía et al. 2008). These problems are related to water flow continuity, water repellence and soil temperature (Keller 2011; Baginsky et al. 2010).

Table 4.5 Frequency of soils in the Mediterranean and Rainy and Patagonian zones with soil pH_{water} below 5.8 at 0–20 cm (Sadzawka 2006)

Region	Latitude	Soils with pH_{water} < 5.8 (%)
Metropolitan	(32–36°S)	1
V		14
VI		37
VII		35
VIII	(36–43°S)	37
IX		54
X		88

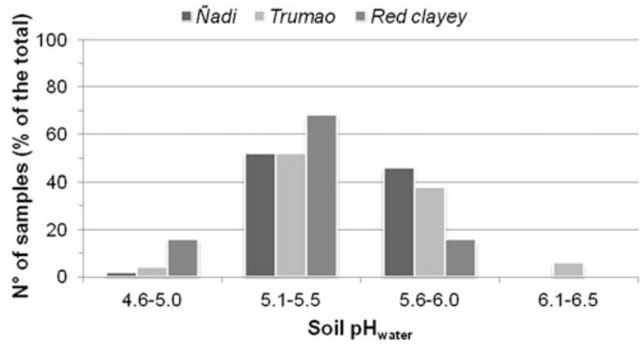


Fig. 4.20 Frequency of pH_{water} in soils at the Region X of Chile (Bernier and Alfaro 2006)

In NW Patagonia, Candan and Broquen (2009) reported highly water-stable aggregates under different types of vegetation (>80 % of >0.25 mm aggregates) in local Andisols (Udivitrands and Haplovitrand). Furthermore, the highest OM contents are found in the smallest-sized aggregates and there is a significant correlation between stable soil aggregate formation and OM, Al activity, base content and soil reaction, suggesting that these factors can potentially be used as edaphic indicators of aggregate stability in volcanic ash soils.

4.2.2 Soil Chemical Degradation

The main chemical soil degradation processes related to soils in Chile are:

a. Soil acidification.
b. Soil salinisation.
c. Soil contamination.

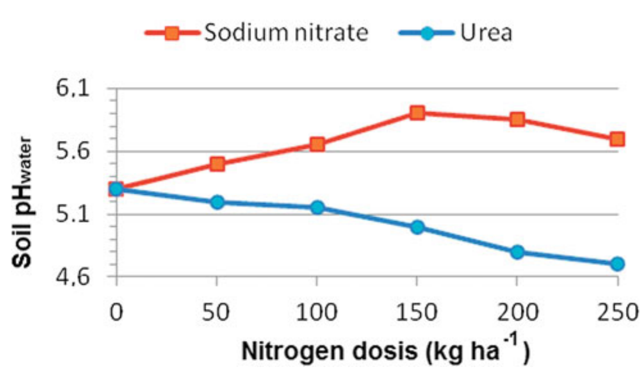


Fig. 4.21 Effect of nitrate sodium and urea in the soil pH in a strongly acid soil in the Rainy and Patagonian zone of Chile (Bernier and Alfaro 2006)

Fig. 4.22 Maize production in the Mediterranean zone with high NH_4^+-forming fertiliser application

It is important to note that the vulnerability of soils to these chemical degradation processes is mainly dependent on the initial state of the soil and its intrinsic soil properties, which are discussed in this section.

4.2.2.1 Soil Acidification

In Chile, accelerated soil acidification is tending to increase in some areas, and in the short term may cause a serious soil degradation problem, reducing agricultural production. As soil pH decreases, Al^{3+} saturation increases and plant growth and yield may be impaired, depending on their susceptibility to Al^{3+} toxicity.

Soil acidification is well-known as a natural process, but in many zones in Chile that contain a high proportion of soils with soil $pH_{water} < 5.8$ (Sadzawka 2006), which are considered moderately acid (see Table 4.5), agricultural practices and pollution from industrial, mining and other human activities may accelerate the acidification process. Soils in the Rainy and Patagonian zone are particularly susceptible, with 37–88 % of all soils having $pH_{water} < 5.8$ and with sufficient rainfall to leach out most of the base-forming cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), leaving the colloidal complex dominated by H^+ and Al^{3+}.

Areas with the highest percentage of acidic soils are located in Region X, dominated by Andisols and Ultisols (Fig. 4.20). These soils present a high risk of acidification and usually show a high Al saturation of the ECEC (effective cation exchange capacity) where ISRID (Incentives System to Recovery Degraded Soils) has subsidised farmers to apply lime. Several studies have confirmed that addition of lime to neutralise the acidity and reduce the toxic effect of Al^{3+} increases yield, forage quality, botanical composition and nitrogen symbiosis by legumes in pastures (Campillo et al. 2005; Bernier and Alfaro 2006). On the other hand, studies such as that by Inostroza-Blancheteau et al. (2008) suggest that liming is costly, laborious and not very effective and propose as an alternative a search for genetic variability in the genome of cropping grasses and/or their wild relatives to resist Al^{3+}.

One of the possible factors that may intensify soil acidification in the Rainy and Patagonian zone is continued application of NH_4^+-containing or NH_4^+-forming fertilisers that produce H^+ during nitrification (Bernier and Alfaro 2006; Campillo and Sadzawka 2006). In addition, following the application of NH_4^+, the adsorbed cations are subjected to replacement by NH_4^+ and can thus be potentially leached from soils (Sadzawka 2006). For example, a study by Bernier and Alfaro (2006) in a strongly acidic soil (pH 5.3) compared the effects of nitrate sodium and urea, where the maximum doses of N (250 kg ha^{-1}) as urea clearly generated a significant acidification effect on soil (Fig. 4.21). Similarly, Campillo and Rodríguez (1984) in a study in two Andisols found that application of urea may acidify the soil to levels where Al and Mn are toxic to crop development.

There is also a risk of soil acidification in the Mediterranean zone, in soils under maize production with high NH_4^+-forming fertiliser applications, mainly as urea, where in some cases N application can reach 500 kg N ha^{-1} (Fig. 4.22).

Other possible causes include continued application of organic wastes to soils, forming strong inorganic acids which lead to increased soil acidity. On the other hand, more local sources of soil acidification are acid deposition of sulphur dioxide (SO_2) and nitrogen oxides (NO_x) in areas close to copper smelters in the Mediterranean zone, where the impact on soil pH is more evident in the topsoil (Ginocchio et al. 2004; León and Carrasco 2011).

4.2.2.2 Soil Salinisation

In the Hyper-arid to Semi-arid zone, potential problems in irrigated soils have been identified due to high evaporation rates and low annual rainfall leaving accumulated salts in upper soil horizons. In this zone, the agricultural activities are mainly concentrated at the bottom of a number of valleys, where a river usually provides irrigation water throughout the growing season.

Table 4.6 Annual accumulation of salts at 0–50 cm by irrigation (8,000 m^3) in the Copiapó and Huasco valleys, Region III

Valley	Source irrigation	EC ($dS\ m^{-1}$)	Salt accumulation ($Mg\ ha^{-1}$)
		3.4	18
Copiapó	Tube well	2.2	11
	Ditch	5.8	30
Huasco	Ditch	4.3	22

Adapted from Benavides (2011)

In this zone two productivity areas can be identified: (i) valleys with intermittent rivers (the Lluta, Azapa and Loa valleys) with some horticultural crops, orchard fruits and lucerne production (ii) valleys with permanent watercourses (the Copiapó, Huasco, Elqui, Limarí and Choapa valleys) with some horticultural crops and intensive production of orchard fruits, such as avocado, citrus, table grapes and olives (see Chap. 2).

Torres and Acevedo (2008) reported that in the Lluta and Azapa valleys the salinity is increasing, causing a marked salt accumulation effect which is seriously affecting crop production in these areas. They noted that the electrical conductivity of the irrigation water (EC_{iw}) is high, with values of >2 and >1 $dS\ m^{-1}$ in the Lluta and Azapa valleys, respectively, which may contribute to the problem of salinity of these soils. In the Lluta Valley in particular, the salinity problems are more important in poorly drained soils located in lowlands, where EC_{iw} can reach values of 6 $dS\ m^{-1}$.

In the Lluta Valley, the concentration of boron (B) in irrigation waters ranges between 9 and 29 $mg\ L^{-1}$, which may cause toxicity in plants in irrigated soils.

Similarly, in the valleys with permanent watercourses (between 27 and 32°S), salt build-up may be caused by irrigation with poor quality water. For instance, Hugo (2008) noted that salinisation has been observed in many sectors of irrigated soils in these valleys. Since fruit-bearing species such as table grapes do not tolerate high concentrations of salt or sodium, this can delay the start of harvest and seed germination, decreasing the overall productivity.

In a study in the Copiapó Valley, Sierra et al. (2001) reported that the main rivers used for irrigation demonstrated a medium level of salinity (>0.76 $dS\ m^{-1}$), but in the valley 76 % of the soils showed EC > 4 $dS\ m^{-1}$ so the use of irrigation water poses a risk of soil salinisation. As an example, Table 4.6 shows salt build-up by irrigation with saline water in the Copiapó and Huasco Valleys calculated by Benavides (2011), where accumulation of soluble salts at 0–50 cm in the soil can reach 30 $Mg\ ha^{-1}\ yr^{-1}$.

In the Elqui Valley, where the main B input to the soil comes from irrigation water, table grapes have shown visual symptoms of B toxicity, which are correlated with high B contents in tissue analysis ranging between 135 and 376 ppm (Valenzuela and Narváez 1983). In addition, correction of soil B deficiency is complex due to the narrow range between sufficient and toxic levels, and there is a high risk of generating B toxicity in sensitive plants to excess B. For instance, Lavín (1988) in an experiment in the Mediterranean zone, evaluated the same B application by fertigation to 21 different fruit species, and found that fig, kaki, mulberry, pistachio raspberry and walnut showed some degree of B toxicity.

Another possible cause of soil salinisation in these valleys may be the use of fertilisers with a high saline index. Oyarzún et al. (2008) noted that with a larger contribution of fertilisers, the salinity will increase in the root area unless the irrigation is applied at washing rate to keep the original saline balance.

It is well-known that plants exhibit a wide range of tolerance to salinity and specific ions. One possible solution for these areas has been the use of salt-tolerant plant species or the selection of varieties more resistant to high salt levels in soil. Table 4.7 summarises some studies of salt-tolerant species carried out in the Hyper-arid to Semi-arid zone of Chile.

Native species such as quinoa (*Chenopodium quinoa*) have been cultivated for centuries in the Hyper-arid to Semi-arid zone in soils with high salinity, even with EC values close to 10 $dS\ m^{-1}$ (Delatorre et al. 1995). In addition, Delatorre and Pinto (2009) have taken advantage of quinoa by selecting plant material in the nursery according to relative salt tolerance, where they found that *Amarilla* selection was the most tolerant to salts.

In another study, Ferreyra et al. (1997) in a field experiment near Calama town (Region II) evaluated the effects of irrigation with saline water (EC_{iw} 8.2 $dS\ m^{-1}$ and B content of 17 $mg\ L^{-1}$) on the growth and yield of 42 crop species, including local varieties. They found that plant growth and yield were higher than expected from published information, which they attributed to the milder climate in Chile compared with that in Riverside-California, where much of the salt and B tolerance data have been obtained. They added that the productivity of the local variety of sweet corn (*Zea mays* L.) suggests that it is more salt-tolerant, which has arisen as a consequence of seed selection practised since the time irrigation began in the Region, which predates the sixteenth century. In the Lluta Valley too, a variety of sweetcorn (*Zea mays* L.*, amylacea*) have arisen as a consequence of seed selection, suggesting that it is extremely tolerant to salinity and high B levels (Bastías et al. 2004). Other species studied include jojoba (*Simmondsia chinensis*), some clones of which have been found to be particularly resistant to salinity (Botti et al. 1998a), which could be a profitable alternative for the Hyper-arid to Semi-arid zone. Botti et al. (1998b) found that the most salt-resistant clone

Table 4.7 Summary of some studies (Sotomayor et al. 1994; Benavides 2011; Botti et al. 1998a; Martínez et al. 2009) in salt-tolerant species carried out in the in Hyper-arid to Semi-arid and Mediterranean zones

Region or valley	Specie	Yield	Soil			Water		
			pH	EC (dS m^{-1})	B (mg kg^{-1})	pH	EC (dS m^{-1})	B (mg L^{-1})
Lluta Valley	Olive	36–73 (kg/tree)	7.3–7.7	2–13	31–55	7.7–8.4	2.2–3.4	8–23
CopiapóValley	Olive	12–37 (kg/tree)	7.7	5.2	4	–	3.4	–
Regions I and Region IV	Jojoba	81–1,131 (g seed/plant)	–	2–38	–	–	1–7	–
	Quinoa	1–7 (Mg ha^{-1})	7.5–8.1	1–4	–	–	–	–

had some differences in morphological and anatomical parameters compared with those grown under non-saline conditions, such as the lowest stomata and trichome density and the largest stomatal size.

Other studies (Ferreyra et al. 1997; Botti 2000; Silva et al. 2010) have focused on finding salt-tolerant fruit trees, bushes and CAM plants by evaluating new varieties or rootstocks in trees to be used in the Hyper-arid to Semi-arid zone of Chile. These species include olive (*Olea europaea* L.), pomegranate (*Punica granatum* L.), fig (*Ficus carica* L.), pistachio (*Pistacia vera* L.), caper bush (*Capparis spinosa* L.), aloe vera (*Aloe barbadensis* M.) and pickly pear (*Opuntia ficus-indica* L.). For example, Sotomayor et al. (1994) studied the natural adaptation of some olives in the Lluta Valley, where some trees can survive under extreme saline conditions. Other studies are looking at the introduction of more sensitive species to salinity. For instance, Castro et al. (2009a, b) evaluated the tolerance to saline irrigation waters for different rootstocks in avocado, because it is one of the most sensitive species to salinity (Fig. 4.23) and has been intensively planted in the Mediterranean zone of Chile. They found that the *Nabal* rootstock was the most tolerant to salts, by retaining the highest chloride concentration in the roots and greatly limiting the concentration found in the leaves.

On the other hand, more advanced irrigation techniques have been introduced in the Hyper-arid to Semi-arid zone (drip and sprinkler systems), which can control rhizosphere salinity by keeping soil water content high and free of salts near to the emitters, while the salts are accumulated in the boundary between the moist and dry zone. In the Copiapó Valley, Osorio and Césped (2000) found that in irrigated table grapes the soils showed EC > 5 dS m^{-1}, with the highest salinity values at the mid-point between two drip lines and in first 40 cm of the soil profile. The contents of Na, Cl and B were also high in relation to the tolerance range for table grapes. They tested several combinations of irrigation systems and found that single drip line and microjet sprinkler irrigation systems provided better control of the salinity in the root zone.

Fig. 4.23 Leaf symptoms of chloride excess in avocado in the Mediterranean zone of Chile

4.2.2.3 Soil Contamination

Although the principal criteria used to estimate trace element threats are bioaccumulation, toxicity and persistence (Kabata-Pendias 2011), trace elements such as cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), antimony (Sb) and zinc (Zn) can reach concentrations in soils that are toxic to plants and microorganisms (McBride 1994), but lead (Pb) and mercury (Hg) should be of concern as serious human health risks. In Chile, a number of studies have found that soil heavy metals pollution occurs mainly near Cu mines, Cu smelters and mine tailings, particularly in the Hyper-arid to Semi-arid and Mediterranean zones (González et al. 1984, 2008; González and Bergqvist 1986; González and Ite 1992; Ginocchio 2000; De Gregori et al. 2003; Ginocchio et al. 2004; Montenegro et al. 2009; Neaman et al. 2009). It is important to note that although the wastes from Cu mining activities in Chile can broadly vary in physico–chemical properties and total metal contents, they usually have high total Cu levels (Ginocchio 2011).

Even agricultural soils have been found to be polluted by heavy metals several kilometres from the source, where the

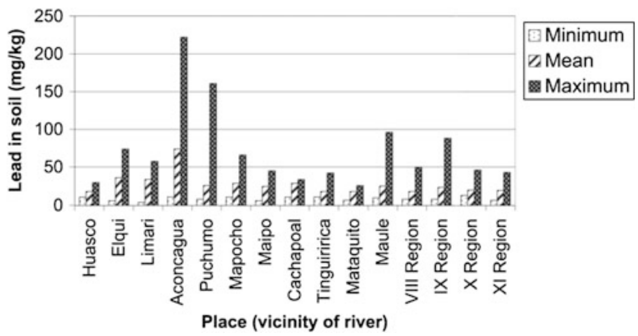


Fig. 4.24 Lead content in soils in the vicinity of various Chilean rivers (Tchernitchin et al. 2006)

magnitude of heavy metal pollution of the soils near these sources depends on the type of chemical element and the possibility of its dispersion by wind or irrigation water, affecting in this way extensive areas of agricultural soils (Romo-Kröger et al. 1994; González 2000; De Gregori et al. 2003). Pizarro et al. (2010) noted that rivers of central-northern Chile are exposed to heavy metal pollution from different sources, such as mining activities, natural orogeny processes, volcanic activity and geology. They suggested that mining pollution is the main process contributing to the increasing annual trend in As and Cu. Tchernitchin et al. (2006) evaluated the Pb content in soils in the vicinity of several Chilean rivers and suggested that in some cases the Pb originated from natural sources, while in others, it was anthropogenic and coincided with high Cu concentrations (Fig. 4.24). Similarly, González (2000) noted that in three valleys of the Mediterranean zone, high Cu concentrations in soils were associated with the soil concentrations of other metals such as Pb, As, Cd and Zn in the Puchuncaví (32°40′S) and Maipo (33°37′S) valleys, and with Pb, Cd and Zn in the Aconcagua (32°55′) Valley.

On the other hand, Biester et al. (2002) found an increase in Hg accumulation rates in moorlands in the Rainy and Patagonian zone within the past 100 years, and suggest that this is at least partly attributable to global dispersion of Hg derived from anthropogenic sources in the Northern Hemisphere.

Table 4.8 shows a list of studies examining heavy metal soil contamination, particularly by Cu, due to the great importance and impact of the copper mining activities carried out from the extreme north to the Mediterranean zone of Chile.

These studies clearly show that the total Cu in soils near copper mining activities centres far exceeds the normal range found in agricultural soils (McBride 1994; Kabata-Pendias 2011; Hooda 2010). These observed elevated values in soils are a consequence of Cu mining activities, and therefore pose a range of environmental and health risks. Copper is retained in soils essentially indefinite, because it is not degradable and consequently these Cu contaminated-soils pose a long-term risk of increased plant uptake and leaching, with potentially adverse implications for the wider environment, including human health. In some cases, the concentrations of other trace elements such as Zn, Pb, Cd, As, Sb and Hg were higher than the range of means for polluted soils worldwide, which also entails serious risks for human health (Higueras et al. 2004; Tchernitchin et al. 2006; Hugo 2008).

In addition, De Gregori et al. (2003) found a clear decrease in Cu, As and Sb concentrations in soils with increasing distance from a Cu smelter in Region V (Fig. 4.25). They highlighted the transport process downwind from the smelter or within the combined influence of the smelter and the tailings dams.

In a monitoring experiment in the same area, González and Ite (1992) found that in 9 years period the Cu content in some soils had increased by a factor of 6.5. Similarly, Hugo (2008) reported that at close proximity to Cu mining complexes, the Cu concentration in the soil exceeded the natural content 100 fold, easily surpassing the maximum tolerance limit for plants.

Kelm et al. (2009) added that once Cu is deposited in soils due to transport by wind, there is potential for acidity surges and Cu mobilisation in topsoils after rainfall. To avoid this transport, liming application may decrease Cu concentrations and Cu^{2+} activity in the soil solution (Muena et al. 2010). It is important to note that to predict the phytotoxicity and environmental risk of Cu the chemistry/mineralogy of mine materials, soil chemical conditions and plant physiological status should be also considered (Badilla-Ohlbaum et al. 2001; Ginocchio et al. 2002, 2009). These studies suggest that hot spots of heavy metal-contaminated soils are located around Cu mining activities, which are increasing in scale over time. Therefore, ameliorative measures should be carried out to stabilise the heavy metal in contaminated soils and to avoid its spread in the environment.

Another possible source of heavy metals to soils is fertiliser application. Molina et al. (2009) analysed the trace element composition of 22 fertilisers currently used in Chile and found that phosphorus (P) fertilisers had the highest trace element concentrations. They also noted that the long-term use of P fertilisers may increase the levels of As, Cd and other trace elements in agricultural soils.

On the other hand, few studies have been done in Chile to evaluate the impacts of persistent toxic chemicals in Mediterranean zone soils. Barra et al. (2005) evaluated the distribution of 15 polycyclic aromatic hydrocarbons

Table 4.8 Summary of some studies of soil contamination by total copper (Cu), zinc (Zn), chromium (Cr), lead (Pb), cadmium (Cd), arsenic (As) and antimony (Sb) in agricultural zones near copper mining areas in the Hyper-arid to Semi-arid and Mediterranean zones of Chile

Region	Cu	Zn	Cr	Pb (mg kg^{-1})	Cd	As	Sb	References
V	30–100[a]	10-200	–	56–225	1–5	–	–	González et al. (1984)
V	242–7,921	60–512	–	39–717	2–12	18–724	–	González and Ite (1992)
VI	162–751	138–153	–	47–50	0.2–0.4	–	–	Badilla-Ohlbaum et al. (2001)
I-II-V	11–530	–	–	–	–	3–202	0.4–11	De Gregori et al. (2003)
V	45–680	125–174	–	21–105	0–1	–	–	Ginocchio et al. (2004)
V	92–872	–	–	–	–	–	–	González et al. (2008)
V	310–640	–	–	–	–	–	–	Neaman et al. (2009)
IV	–	–	5–45	2–129	1–7	–	–	Montenegro et al. (2009)
V	60–800	85–220	–	29–103	–	–	–	Muena et al. (2010)

[a] Normal ranges of total heavy metal contents in agricultural soils [adapted from McBride (1994), Kabata-Pendias (2011) and Hooda (2010)]: As = 2.2–165 mg kg^{-1} ; Cu = 2–109 mg kg^{-1} ; Sb = 0.19–1.77 μg kg^{-1} ; Cd = 0.06–1.1 mg kg^{-1} ; Zn = 17–125 mg kg^{-1} ; Pb = 11–145 mg kg^{-1} ; Cr = 7–221 mg kg^{-1}

(PAHs), seven polychlorinated biphenyls (PCBs), and three organochlorine pesticides in topsoils in a watershed. They found that PCB levels in soil samples were very low and the level of chlorinated pesticides was generally low and reflected the historical use of pesticides. However, the PAH levels found were more related to local sources of contamination near the sampling areas, such as forest fires and the presence of boilers fed with wood residue pellets, where the reported data could be of some concern. In another study, Flores et al. (2009) studied simazine adsorption behaviour in two agricultural soils and suggested that it is mainly governed by simazine-organic matter interactions and simazine-clay interactions. In addition, Alister et al. (2005) reported that water quantity has a significant effect on the quantity of simazine moving downward through a soil in the Mediterranean zone. Nario et al. (2009), in a study on the risk of environmental contamination due to the application of pesticides in the same zone, highlighted that runoff is the main process for pesticide transport in the landscape.

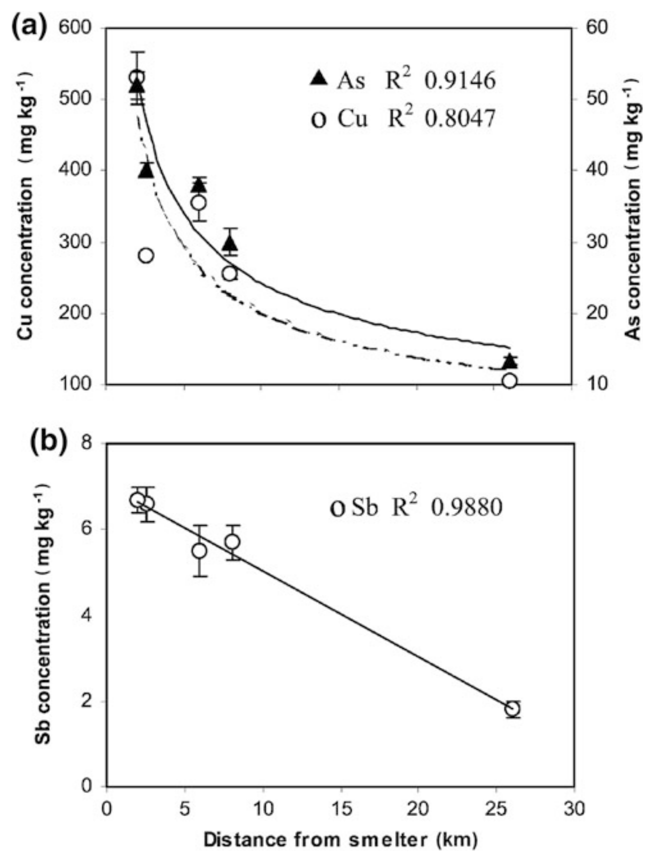


Fig. 4.25 Relationships between the element concentration in soil from Puchuncaví Valley, and the distance from Ventanas industrial complex, Region V of Chile; **a** copper (○) and arsenic (▲) and **b** antimony (○) (De Gregori et al. 2003)

4.2.3 Soil Biological Degradation

Soil organic matter (SOM) and biodiversity can decline due to biological soil degradation processes, leading to a reduction in soil functions such as decomposition and recycling of chemical and organic materials, as well as control of water and gas flows. This soil degradation problem is particularly important in Chile, for instance Ellies (2000) estimated that many soils have lost from 20 to 50 % of their SOM stocks in surface soil since cultivation began at the end of the nineteenth century.

In the Mediterranean zone, Ovalle et al. (1990) noted that possible causes of this continued decrease in soil organic carbon (SOC) stocks include inappropriate agricultural methods, excessive woodcutting and systematic overgrazing. This zone has a common natural agroecosystem, locally named e*spinal*, where the dominant vegetation is *Acacia caven* trees with a spring grass cover rich in

Fig. 4.26 Degraded *espinal* in the Mediterranean zone of Chile (Region V)

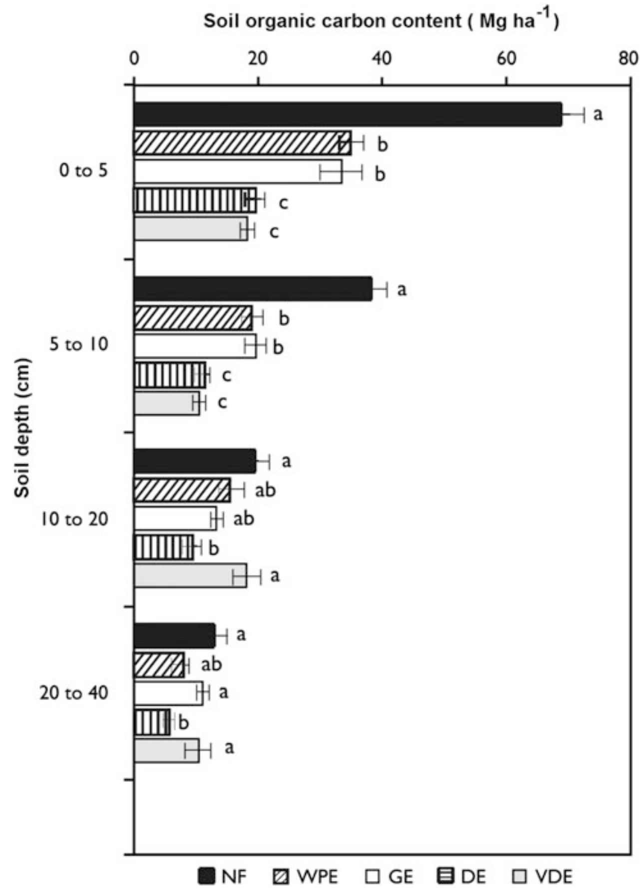


Fig. 4.27 Soil organic carbon stocks under canopy of *Acacia caven* in the *espinal* ecosystems in the Mediterranean zone soils. Ecosystem studied (n = 8): native forest is NF, well-preserved *espinal* is WPE, good *espinal* is GE, degraded *espinal* is DE and much degraded *espinal* is VDE. (Muñoz et al. 2007a)

annual plants (named *Mediterranean annual prairie*) (Silva and Lozano 1986; Ovalle and Squella 1988). In particular, unsustainable management of the vegetation in the *espinal* has progressively lowered the SOM content and soil fertility, as evidenced by decreasing forage production and lower coverage of trees (Stolpe et al. 2008), as shown in Fig. 4.26.

For instance, Muñoz et al. (2007a) found that at 0–40 cm depth in the soil the degree of coverage of *A. caven*, ranging from native forest to much degraded *espinal*, directly affected the C stocks, decreasing these when the tree coverage diminished and soil use intensity increased, as shown in Fig. 4.27.

In addition, Muñoz et al. (2008) in a study of the C distribution, structure and functional properties in different SOC fractions in *espinal* ecosystems with different land surface coverage, found that the aromaticity of SOC in the intermediate fraction was lower in well-preserved *espinal* (33 %) than in degraded *espinal* (50 %). They noted that these data reflect the effect of greater soil use intensity under degraded *espinal* due to the inverse relationship between *A. caven* land coverage and soil use intensity.

In the Rainy and Patagonian zone, there is also some evidence that organic matter (OM) in Chilean volcanic soils is being degraded after human intrusion. Heredia et al. (2007) found that soils under native forest showed higher OM level than agricultural soils. They found that in agricultural soils the soluble C or labile C is increased and contributes greatly to the solubilisation, mobility and availability of plant nutrients, but also enhances losses of organic C by lixiviation. Similarly, in this zone Ramírez et al. (2003) developed a study that compared the floristic composition and SOM content in native forest and anthropic prairie in an Andisol and an Ultisol. They found that compared with the forest, the OM at 0–20 cm in the prairie decreased from 15.5 to 13.6 % and from 11.5 to 5.1 % in the Andisol and Ultisol, respectively, with the floristic composition following the same tendency. In a study in Andisols in this zone, Undurraga et al. (2009) concluded that measurements of dissolved organic C (DOC) and N (DON) reflect non-intensive and intensive soil management and can be used as good biological indicators of changes in SOM, as more sensitive parameters than soil total C and N. In the same zone, Alvear et al. (2005) reported that tillage/residue management induced significant changes in soil biological activities, such as microbial biomass and soil enzyme activities. For instance, they found that no tillage increased C and N of microbial biomass in comparison with conventional tillage.

On the other hand, loss of biodiversity is also considered a soil biological degradation symptom, because soil organisms are a key components in a number of crucial processes, such as OM decomposition, nutrient cycling, nutrient retention, C sequestration, N fixation and pollutant

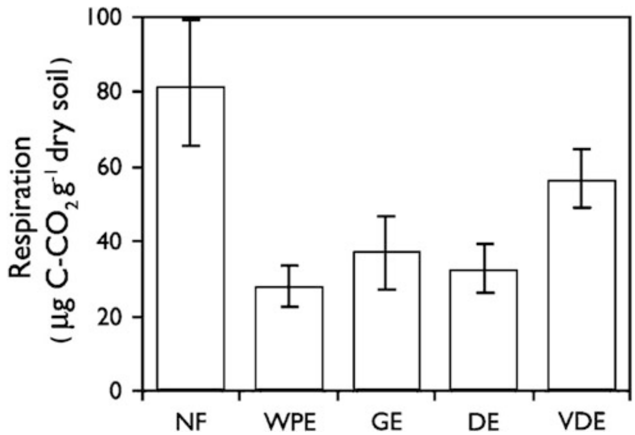


Fig. 4.28 Microbial respiration (μg C–CO_2 g^{-1} dry) in soil under canopy at 0−5 cm in ecosystems studied ($n = 8$): native forest is NF, well-preserved *espinal* is WPE, good *espinal* is GE, degraded *espinal* is DE and very degraded *espinal* is VDE (from Muñoz et al. 2007b)

degradation, among others. Fuentes and Varnero (2011) noted that in the Mediterranean zone the alteration of *espinal* ecosystems not only affects the C pools in the soils, but also the microbial communities and their enzymatic and biochemical activities. Therefore, they recommend that to evaluate the soil biological degradation the focus should not only be on quantification of the SOC stocks, but also on the role of microbial communities in the soils. On the other hand, microbial activity in soils has been related to soil respiration rate. For instance, Muñoz et al. (2007b) in the Mediterranean zone found that the respiration of microbial communities was affected by ecosystem degradation at 0–10 cm soil depth under the tree canopy, with soil respiration in native *espinal* ecosystems greater than in other degraded ecosystems (Fig. 4.28).

Therefore, ameliorative measures to recover OM and biodiversity are needed in soils affected by degradation processes. During recent decades, some efforts have been made by government to afforest degraded soils in the Hyper-arid to Semi-arid zone, including some trees (*Prosopis tamarugo*) and bushes (*Atriplex nummularia* and *Atriplex repanda*) (Olivares and Gastó 1981; Ormazábal 1991).

Aronson et al. (2002) noted that agroforestry systems are a promising approach to rehabilitating damaged agroecosystems, sustaining profitable agricultural production, restoring soil fertility on degraded lands and biological conservation. Similarly, Aronson et al. (1993) highlighted the beneficial effects of including nitrogen-fixing legume to optimise the amount of atmospheric N fixed in a degraded arid or semi-arid land ecosystem, to promote the development of associated plants, and to improve soils and enhance possibilities for the spontaneous or assisted return of native plants and animals. Ovalle et al. (1999) added that water resources in the Mediterranean zone, especially precipitation and runoff, must be better managed. Considering the latter point, Salazar et al. (2006) reported that the use of runoff water harvesting combined with agroforestry systems in the central zone of Chile can be beneficial for increasing SOC and N stocks, which indicates that these land management practices can be used for restoration of degraded soils and potential SOC sequestration in degraded *espinal* ecosystems. Figure 4.29 shows a field experiment combining agroforestry with water harvesting at the Germán Greve Silva Experimental Station, University of Chile, which started in 1996 in the Mediterranean zone (Salazar and Casanova 2011). It can be seen that after 14 years, the system has been able to survive under extreme scarcity of water.

In the same study, Salazar et al. (2011) reported that after 12 years, the treatments with water harvesting had higher OM contents (Fig. 4.30) than the control, which comprised degraded natural pasture. This suggests that this practice had positive effects in improving the water content in the soil, stimulating biomass production of trees (*Acacia saligna*) and the decomposition of litter and favouring the process of root turnover. They used *A. saligna* as N-fixing trees, and also found that agroforestry combined with water harvesting showed the highest accumulation of N content as a result of increased litter and root turnover (see Fig. 4.30).

It is important to note that some management practices that aim to restore degraded soils may have unexpected negative effects in the short term. For instance, Pérez-Quezada et al. (2011), in a field experiment in the Hyper-arid to Semi-arid zone, evaluated the conversion of ecosystems from natural conditions with arid shrub land (moderately disturbed by grazing) to afforested conditions (2-year-old plantation of *A. saligna*). They found that stocks of ecosystem C decreased from 32.4 in the natural places to 19.8 Mg ha^{-1} at the afforested sites, mainly due to loss of C from the soil C pool at 0–50 cm depth during site preparation for afforestation (Fig. 4.31).

In one of the few studies carried out in the Rainy and Patagonian zone, Klein et al. (2008) analysed SOC and the organic soil horizons in five stands at different stages of development (Fig. 4.32): intact native forest (NI); a 3-year-old shelterwood stand (S3); an 8-year-old shelterwood stand (S8); a 14-year-old stand that was initially treated with shelterwood and subsequently final cut (10 year after the first intervention) (S14), and a 25-year-old stand subjected to a exploitative intervention (E25). Short-term effects of shelterwood cuts on SOC were only detected in the upper 10 cm of the mineral upper horizons, where comparison of the SOC per unit area between the NI and S3 stands indicated a significant net C loss of 5 Mg ha^{-1}, whereas long-term effects of shelterwood cutting on SOC could not be verified for this type of forest.

Fig. 4.29 Agroforestry under water harvesting field experiment located in the Mediterranean zone. Initial conditions in 1996 (*left*) and 2010 situation (*right*)

It is important to note that the development of computer simulation models has also provided tools to predict the effects of management practices to recover OM and biodiversity in soils affected by biological degradation processes. However, in Chile few soil carbon model applications have been carried out. In one study, Stolpe et al. (2008), using the *Century* model, predicted that less intensive management could gradually increase soil organic C (3.19 to 3.86 Mg ha^{-1} in 100 years) in degraded *espinal*, thereby improving the general quality of the soil and agroecosystem. In another modelling approach, Salazar et al. (2011) used the *ICBM/N* model and predicted that in a degraded *Mediterranean annual prairie* system, there was a slight trend for decreasing OM over time, which may indicate a negative OM balance, whereas a degraded *Mediterranean annual prairie* system with introduced *A. saligna* trees increased the OM stocks.

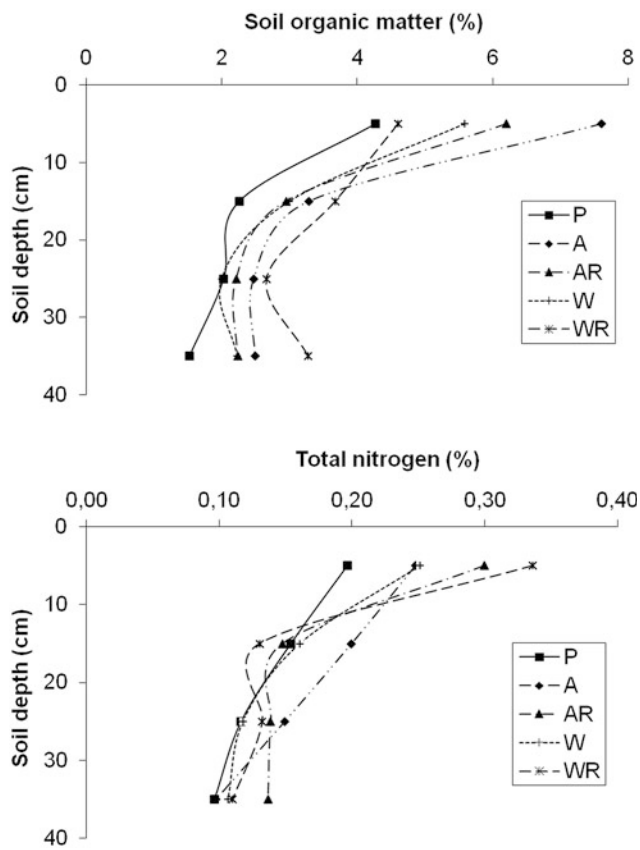


Fig. 4.30 Soil organic matter content and total nitrogen content in different soil layers (year 2008) for the treatments control (P), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR) from Villarroel (2012)

4.3 Desertification

Ecosystems in semi-arid and arid regions around the world appear to be undergoing various processes of degradation commonly described as desertification, probably caused by land misuse, soil mismanagement and a harsh climate. Desertification is a stage of extreme degradation that includes environmental and socio-economic aspects. It involves soil degradation as an inseparable term of deficient sustainability of ecosystem, which covers a wide variety of interactive phenomena, both natural and anthropogenic. In this sense, basic investigation has to precede monitoring, because it is not possible to know what to monitor if basic processes are unknown and, the impacts on inhabitants are ignored.

Much of the agricultural production in Chile derives from areas subject to the effects of desertification: the irrigated valleys in the northern Hyper-arid to Semi-arid zone of the country down to Region IV, and south of Santiago down to Region VII (Fig. 4.33). The areas considered vulnerable amount to about 45 % (340,000 km^2) of the national land surface, affecting 1.5 million inhabitants (Beekman 2007).

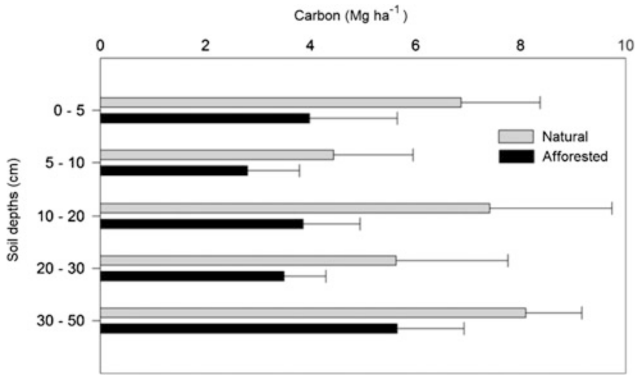


Fig. 4.31 Soil carbon content at five soil depth intervals in natural and afforested conditions of an arid Mediterranean shrubland in Chile (Pérez-Quezada et al. 2011)

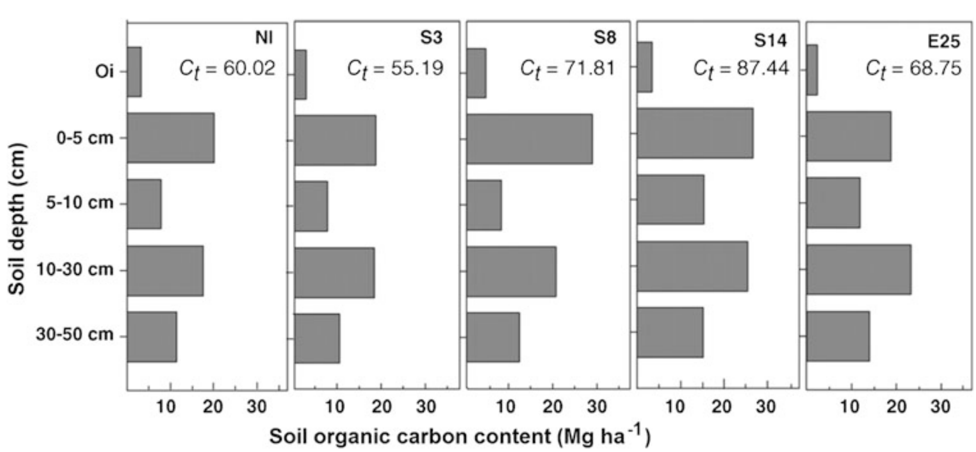
In ecosystems subject to desertification, the vegetation cover is highly variable, with large patches of bare ground where solar radiation reaches the surface without interference. Therefore, plant cover is an important factor for combating desertification, because it protects the soil surface from raindrop impact, enhances infiltration and retards runoff (also reducing spatial variability in both), resulting in arresting land degradation. Optimal production, as dictated by the farmer's particular needs, comprises a well-planned combination of productive system components, so agroforestry emerges as the best option to establish diverse, stable and productive systems. Using either native or exotic species is a potent and efficient tool for biological recovery, allowing higher productivity than pristine vegetation under the same ecological conditions. The presence of trees modifies site microclimate in terms of temperature, relative humidity and wind speed, among other factors. With respect to spatial niche differentiation in agroforestry systems, the general expectation is that deep-rooted trees will not compete with, but rather complement, shallow-rooted annual crops (Daudin and Sierra 2008). Consequently, yield advantages for components in agroforestry systems within semi-arid environments occur only when profile soil water status remains high throughout the growing season, or when the trees are managed with a reduced transpiration surfaces (McIntyre et al. 1997). However, in the case of arid and semi-arid rainfed farming, there is insufficient rainfall to maintain such plant cover.

4.3.1 Coquimbo Region and Patagonia, Two Emblematic Cases of Desertification in Extremes Zones of Chile

Desertification is particularly important in Region IV, which is recognised at planetary level and characterised by a steeply landscape and a semi-arid climate. Rural development in this region takes place under constant tension between use of the natural resources and economic activity. Favourable agro-ecological and climate conditions in the valleys have stimulated the rapid expansion of fruit production, notably table grapes and grapes for processing into liquor (*pisco*), both with outward orientation. However, the dynamism of the fruit sector has not translated into an improvement of quality of life for most people in the region. Moreover, the complex and diverse land tenure (Agricultural Communities) in rainfed conditions contribute to increase this tension. On the whole, this situation may be further exacerbated by the interactions among adverse climate factors, with recurrent drought episodes, few torrential and destructive rain events, and a historical reduction in the amount of rainfall (Fig. 4.34). These features mean that this region is extremely prone to runoff and soil erosion, especially when the soil is unprotected by vegetation. Natural regeneration of plants in many arid zones occurs only for every 5 or 7 years (or less frequently), when two successive years of favourable conditions occur (Hahm and Wester 2004).

Land degradation in this zone has been attributed to increased population pressure on natural resources and to

Fig. 4.32 Soil organic carbon (C) in the different forest stands. The number in each graph indicates the sum of total C for the entire soil profile. Sampling number was 40 for the O_i layers and 20 for the mineral soil layers (Klein et al. 2008)



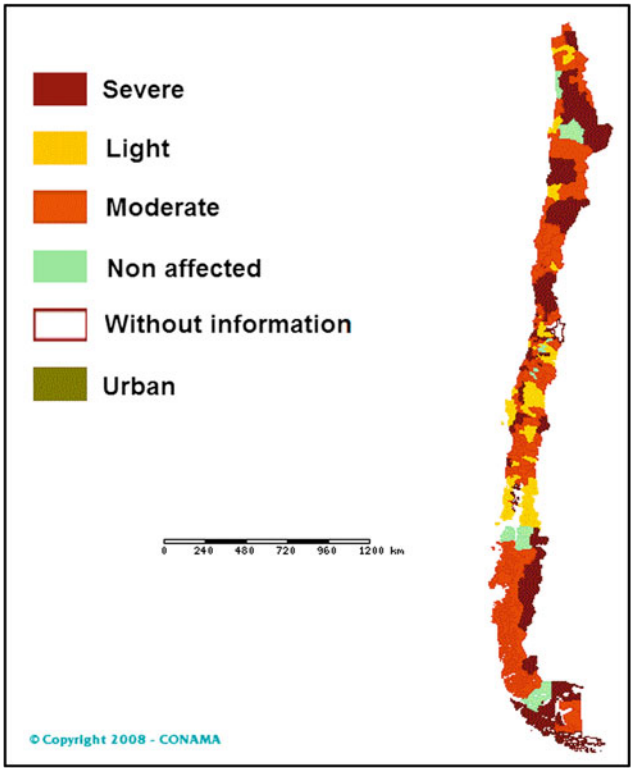


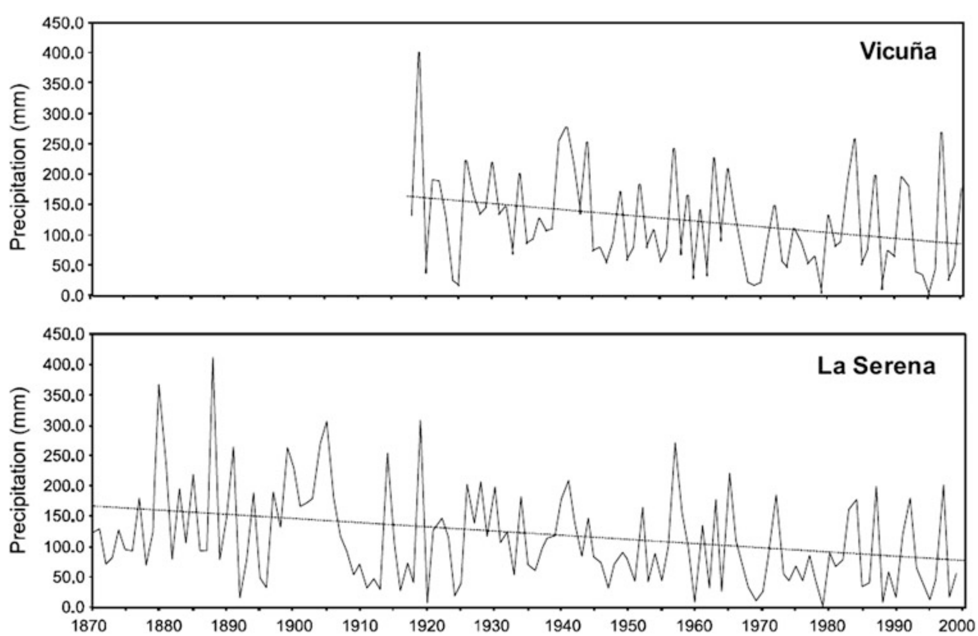
Fig. 4.33 Desertification map of Chile (http://www.mma.gob.cl). Accessed 20 March 2012

the droughts that have affected the region for many decades. Even earlier, natural resources had been severely depleted; at present, further degradation is taking place at rates that could lead to an environmental collapse in the near future. For example, Bahamondes (2003) reported that certain threatening agricultural practices have not diminished notably the large goat population and the gathering of firewood.

Agricultural communities are social organisations of small farmers, joined by family bonds or friendship, living on communitarian ownership, which is basically an undivided and indivisible expanse of land. These communities have their origin in land grants to generally licensed military personnel of the Spanish armies (sixteenth–seventeenth centuries). Many of these lands were subdivided by inheritance and finished up as *minifundia*, while a few remained undivided, either as *haciendas* or as communities. Grazing privileges on the ranges and slopes, which often constitute by far the largest proportion of the community lands, are enjoyed by all members.

Although most of the 180 agricultural communities identified in Chile have holdings between 500 and 10,000 ha and their total area covers almost 1 million ha (25 % of the Region IV), only a small proportion is classified as permanently suitable for agriculture and stock rearing. In fact, only 1,000 ha are irrigated, and a further 9,000 ha are of limited use because of insufficient water. Furthermore, almost 900,000 ha can only be used as rangeland. For the 70,000 inhabitants of the agricultural communities, per capita land with some agricultural potential is extremely low: 0.017 ha of permanent agricultural land, 0.13 ha of cropland with limitations and 0.69 ha of land suitable for dry-farming or grazing. The proportions of these different categories of land vary greatly. All agricultural communities have the same problem of having to subsist on a small area of land of low agricultural value, most of which is covered by unproductive shrub on which

Fig. 4.34 Average annual precipitation (1869–1999) in Vicuña and La Serena (Young et al. 2010) at Region IV of Chile



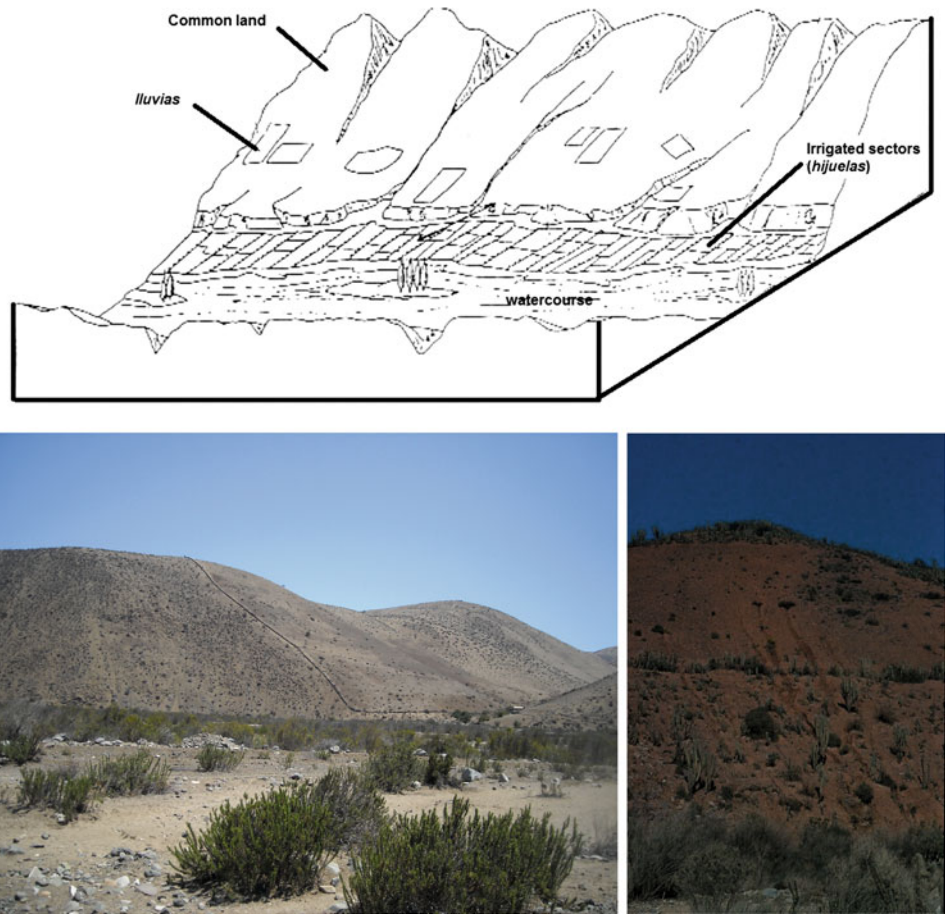


Fig. 4.35 Scheme of land possession types in rainfed zone of Region IV (*above*). Very steeply cropped land (*lluvias*) with erosion features (*below*)

even the goats have difficulties surviving in many years. The widespread failure of crop and animal production, especially since the 1968 drought, has forced a large sector of the rural population to put even greater pressure on the region's natural resources. However, it seems clear that the present rates of extraction of wild plants and firewood cannot be sustained by the ecosystem in the future.

Within the agricultural communities, members generally have the possibility to be the owners of small private plots that are permanently assigned to families, while larger tracts of dryland for crops are often rotated. For several decades, it has been traditional that rainfed soils on steep slopes are widely used in the production of cereals (wheat, barley) and umbelliferae (cumin, anise). This activity net of subsistence has contributed to the degradation of the scarce land available, with an abandonment of agricultural land at certain sites, locally called *lluvias* (Fig. 4.35), where the soil has lost its natural fertility or has reached levels of severe erosion. Cultivation is followed by at least 1 year of fallow (Fig. 4.36) and after harvesting the stubble fields are grazed by farm animals (goat overgrazing).

Land abandonment constitutes a depreciation of environmental capital stock and has many, mostly negative, socioeconomic and environmental consequences. While it can be argued that the *lluvias* are a management system that is not recommended and which should be excluded, it is equally true that farmers are continuing with this practice and will continue in the future, giving validity to the tragedy of the commons hypothesis (Hardin 1968).

In Region IV, plant productivity has decreased over time, caused by a negative water balance (Kalthoff et al. 2006) and intense soil degradation. In the inner rainfed area, plant productivity is low due to lack of adequate water, which induces a short growing season. However, the socio-economic effects of an imminent climate change will be reflected most clearly in the existing marginal system of communities, because farmers with access to supplementary water and financial support will be able to respond better than those poor farmers.

Soil and water conservation in Hyper-arid to Semi-arid zone of Chile is a priority. Integrated management of these cultivated hillsides has been poorly addressed by the national investigations, but abundant documentation relating to the management of runoff in these conditions has been produced (Verbist 2011; Verbist et al. 2009; Sangüesa et al. 2010).

A field study examining an agroforestry and/or rainwater harvesting combination with *A. saligna* was carried out in a

Fig. 4.36 Rills erosion in a *lluvia* (*above*) and in a hillside being grazed by goats (*below*), Region IV

Fig. 4.37 Soil and water conservation practices in deeply degraded soils in Region IV, initial (April-2011, *above*) and later (October-2011, *below*) scenarios. Microcatchments, stone-lines and erosion plots

rainfed area of central Chile, between 1996 and 2004. The field experiment, located at Germán Greve Silva Experimental Station of the University of Chile (Santiago), assessed the influence of this synergic combination on some soil fertility parameters at four depths (Salazar 2003; Leiva 2005; Salazar et al. 2006) of a Typic Haploxeroll (see Sect. 4.2.2). Soil physical properties were evaluated later by Bauzá (2009) and Moreno (2012) to obtain improved values. The lack of significant statistical differences observed was attributed to poor contribution of OM, leading to the conclusion that in more arid conditions, addition of organic amendments is essential to benefit plant growth and improve soil quality.

Traditionally, research has tended to propose or suggest techniques that aim to change the use and management of soils (Salazar and Casanova 2011). Even though there are many options being offered, farmers have preferred to maintain their traditional use and management. Therefore, an initiative (Casanova et al. 2011) in Region IV is starting a trial that aims to establish a demonstration area to show different options (*Acacia saligna*, *Atriplex numularia* and *Prosopis chilensis* trees, with and without organic amendments) in soil and water conservation to local farmers (Fig. 4.37). Clearly, although an important biophysical potential for intensification and enhancement of arid zones exists, it is necessary to give more attention to socio-economic variables of the system. Many authors (Abdelkdair and Schultz 2005; Montambault and Alavalapati 2005) argue that the integration of agroforestry system with rainwater harvesting will require active participation by farmers in all planned trials.

Finally, it should be emphasised that at least three important institutions are working in this desertified region of Chile:

a. CEZA (Centre of Arid Zones Studies, University of Chile: http://agronomia.uchile.cl/centros/ceza/index.html)
b. CEAZA (Advanced Centre of Arid Zones Studies: http://www.ceaza.cl)
c. CAZALAC (Water Centre for Arid and Semi-Arid Zones in Latin America and the Caribbean: http://www.cazalac.org/eng/index.php).

Desertification in the Patagonia (eastern side of the Andes) is also a significant environmental problem, both due to its severity and to the area it covers. The areas

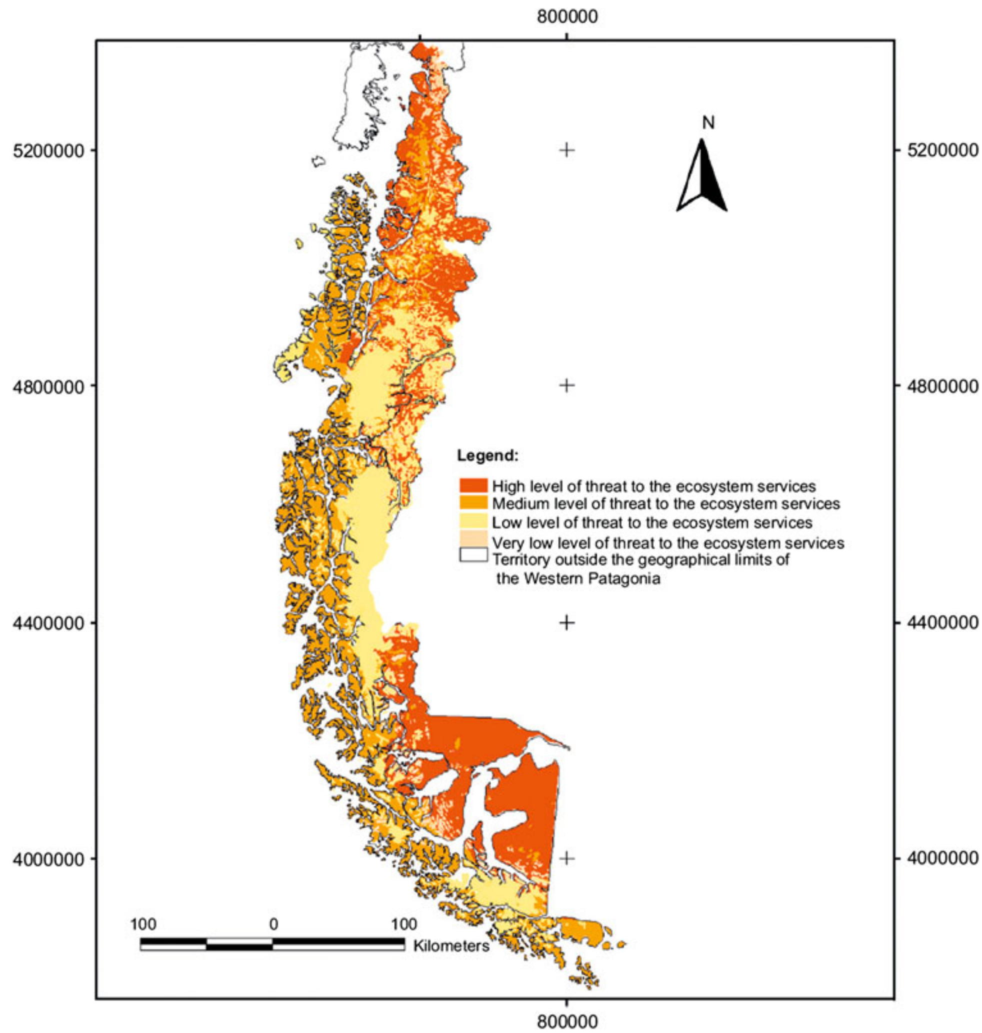


Fig. 4.38 Level of threat to the regional territory and the National System of Protected Areas from Western Patagonia (Martínez-Harms and Gajardo 2008)

classified as irreversible for the development of agricultural and livestock production activities cover 58 % of the whole area, i.e. 73,544,300 ha of Argentinian territory (Mazzonia and Vásquez 2010). Overgrazing by sheep is assigned as the main cause of desertification in the zone, because grazing, by removing perennial grasses and pulverising the surface soil can have a major impact on soil erosion (Chartier and Rostagno 2006). However, hydrocarbon extraction and mining activities have also been incorporated into the system, with the subsequent clearing of extensive areas. For western Patagonia, Holz and Veblen (2011) report that although in both pre-historic and modern times climate variability is the dominant control on years of widespread fires, aboriginal farmers and Euro-Chilean settlers have amplified fire activity (particularly during the twentieth–twenty-first centuries) and shifted the region's fire regimes to new behaviours, which threaten the soil severely (Vött and Endlicher 2001). Moreover, results obtained by Martínez-Harms and Gajardo (2008) show an unbalanced coverage of the National System of Protected Areas in Chilean Patagonia. These authors conclude that despite the high amount of regional area allocated to conservation, key territorial units in the provision of ecosystem services, which are vulnerable to human action, remain without a conservation category (Fig. 4.38).

4.3.2 Easter Island, an Example of Collapse by Soil Degradation

Nowadays, the soils of the Easter Island show the effects of intensive soil degradation processes, particularly soil erosion. In the Island the sheet erosion is evident, with abundant gullies in the northern area. In the 1940s, Díaz (1949) found that soil erosion was an important soil degradation constrain that affected soils with slope >10 %, occupied mainly with pastures covering 50 % of this degraded areas. While in the 1990s, Honorato and Cruz (1999) reported that 20 % of the soils of the island present erosion processes, mainly located in hilly areas (slope >15 %) around the main volcanoes. They noted that other studies in the island estimated severe erosion processes in 57 % of the total area.

However, the causes of these soil degradation processes are not totally clear yet. Louwagie et al. (2006) suggested that physical soil degradation is witnessed by increased erosion on the island since the introduction of grazing sheep (from 1872 to 1985) and cattle (in the 1970s) with ensuing overgrazing, especially on slope positions. Mieth and Bork (2005) added that after the woodland clearance around AD 1,300–1,400 the soils were exposed to the harsh climate conditions, where surface impacts after the destruction of the vegetation realised by agriculture in open land and by the construction of new settlements enabled migrating sheet erosion. Diamond (2007) noted that new information on Easter Island is helping to identify the cause of the massive deforestation that occurred prior to European arrival, but unanswered questions still remain. Even Mieth and Bork (2005) hypothesised that soil erosion may have played a dominant role in the breakdown of Easter Island stone culture.

Mieth and Bork (2005) in the area around Poike volcano, estimated a rate of 8.6 Mg ha^{-1} yr^{-1} of soil transported by erosion. They suggested that gullies in this area were caused by excessive overgrazing, while in its formation the soil rate loss was around 190 Mg ha^{-1} yr^{-1}. Although the same authors highlighted the effects of strong winds over soil surface in the badlands in the Cumming Cape, they noted that water erosion is the main degradation process in this portion of the Easter Island.

4.4 Future of Soil Conservation in Chile

At the present time, combination of climate changes and land cover changes is particularly threatening for soil conservation in Chile. The average net annual deforestation rate (1975–2008) for Central Chile was estimated by Schulz et al. (2010) to be −1.7 %, with a reduction in dryland forest and conversion of shrubland to intensive land uses (farmland) as major trends in this highly dynamic landscape. Moreover, Chile stands to be one of the planet's most vulnerable countries to climate change due to glacial melt and shifts in rainfall patterns. All glaciers in Chile had a net retreat between 1955 and 2007, with mean frontal rates of −22 m yr^{-1} (Le Quesne et al. 2009). According to ENERSIS-Fund (García and Ormazábal 2008), 45 % of the original forest area in continental Chile was lost during the sixteenth century due to factors mainly such as fuel-wood extraction, carbon and wood, fires and land clearing for agriculture production and livestock.

The most direct effect of climate change on erosion by water can be expected to be the effect of changes in rainfall erosivity. Ellies (2000) reported that in central and southern Chile, 5–8 % of the annual precipitation (from 500 to 2,500 mm yr^{-1}) has a high kinetic energy, with a range of erosivity ranging between 27 and 35 MJ ha^{-1} mm^{-1}. Bonilla and Vidal (2011) and Santibañez et al. (2008) described this factor for other important areas of Chile (Fig. 4.39).

Annual precipitation is forecast to change by more than 30 % in some areas of the country by 2040, an amount that illustrates Chile's vulnerability under a future scenario with increased (double) atmospheric CO_2 levels. The central Chile, for example, may see a significant reduction in precipitation, while the Altiplano zone in the far north will experience higher precipitation levels due to tropical cyclone activity. Precipitation will decrease by about 20–25 % between Antofagasta (20 °S) and Puerto Montt (45 °S), but will increase from Chiloé Island to the south. As a consequence of these trends, aridity will increase in north and central Chile down to the Region VIII (CONAMA 2010).

The Chilean government has subsidised soil conservation activities through a major national programme (ISRD). This aimed to improve the productivity of Chilean soils, focusing on the restoration of degraded soils that cannot be used anymore in a sustainable and productive way. The first programme ran from 1999 to 2010, controlled by the Agriculture Ministry, and today a new programme (ISRD-S) is being introduced.

In the ISRD programme, all cash payments were awarded through an invitation to tender, covering about 50–80 % of the total costs of soil conservation practices, including agricultural inputs, labour and technical material. Six different subprogrammes were developed: regeneration of a permanent plant cover, crop rotations rehabilitation and soil conservation by physical structures. After 15 years, almost 31 million dollars were assigned to an annual average of 3,548 users and 102,000 ha.

At the end of ISRD (2010), from a territorial point of view a zone from Region VII to the extreme south concentrated 85 % of invested resources, and Region X alone received almost 32 % of the investment.

However, there is no legislation which regulates land use by land owners in Chile. The government has developed decrees to promote sustainable land use, but its application is not mandatory. In fact, direct legal aspects of soil degradation have in the past been generally neglected at the national level (Cavieres 2000). Today, it appears to be economically beneficial for some land users to exploit soils, transferring the capital loss to society. There is thus an urgent need to enact a Chile Soil Law as soon as possible, including the protection, conservation and recovery of these resources as main objectives. While such legislation is lacking, the State is not fulfilling its constitutional obligation to ensure the protection of one of fundamental natural resources of the nation (Escárate et al. 2005).

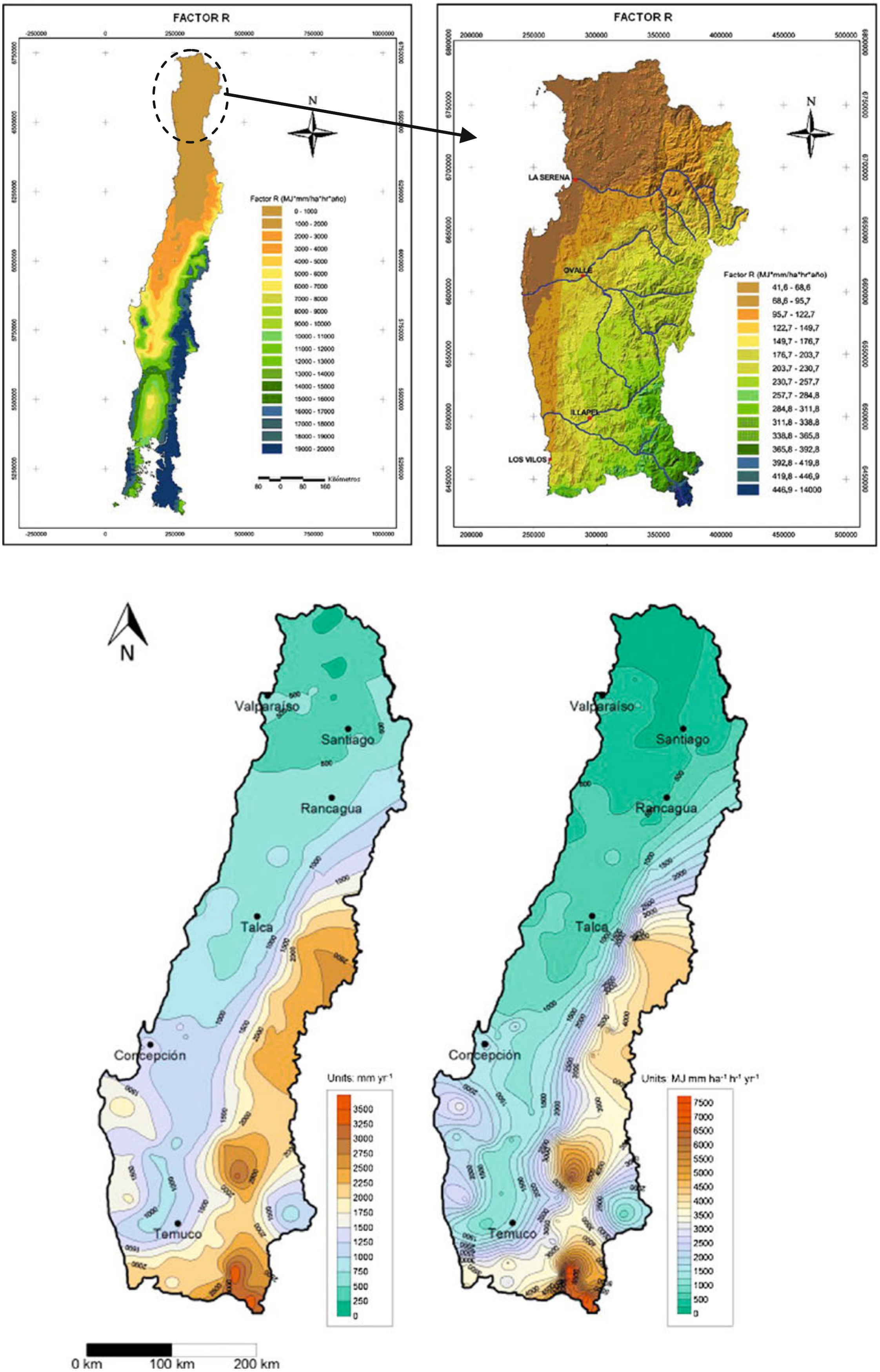


Fig. 4.39 Rainfall erosivity map in Chile (Santibáñez et al. 2008, *above*; Bonilla and Vidal 2011, *below*)

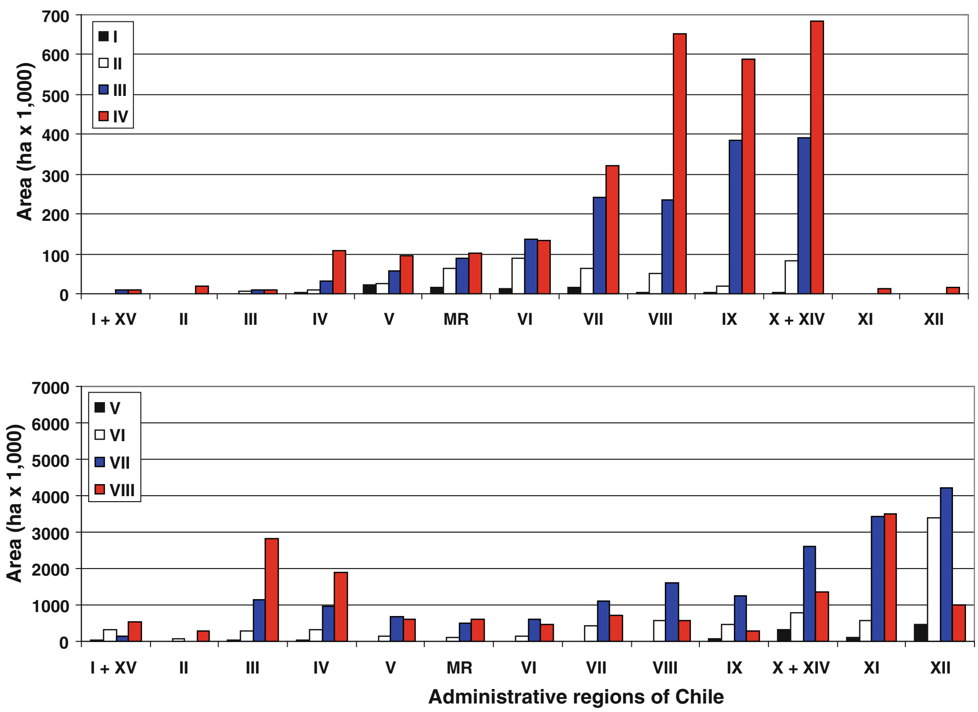


Fig. 4.40 Land capability classes of Chile (http://www.ine.cl, accessed 22 may 2011)

With human-induced soil degradation, soil resilience represents an expression of soil to resist or recover from such perturbation, a concept that must be considered when rejecting or stimulating soil management practices (Casanova 2000). The Hyper-arid to Semi-arid zone is known to be more sensitive to soil degradation than other climate zones of Chile and requires in general considerable management inputs and appropriate conservation practices. From the point of view of the soil scientist, different soils of central Chile have a widely varying susceptibility to degradation due to the vast range of physical, chemical and mineralogical properties involved, requiring specific measures against erosive and/or non-erosive degradation. Alfisols, for example, are subject to low productivity and soil degradation and have several characteristics which make management difficult, including low water-holding capacity, low aggregate stability and high soil strength when dry. In the southern part of the territory, while fresh volcanic deposits with low cohesiveness may be particularly prone to degradation, their progressive development towards mature Andisols generally shows more resilience.

The land capability classes (LCC) along Chile illustrated in Fig. 4.40 represent a trend from north to south of generally better soil quality. As mentioned above, this natural heritage of the country must be protected considering its integration to other natural resources, sustainable productive activities and the socio-economic particularities of stakeholders.

Finally, it is possible to think that it is high time for action, i.e. to pass from rhetoric to practice in soil conservation with sustainable soil use and management programs, including monitoring, impact evaluation, assessment experiments (participative, innovative and adapted to local reality), natural resources inventory (base lines and databases), reliable data generation and above all a solid and comprehensive training of all the actors involved. Although considerable progress in erosion modelling has been made, model validation for major soil zones and ecoregions is often lacking (Casanova et al. 2010b).

References

Abdelkdair A, Schultz R (2005) Water harvesting in a runoff-catchment agroforestry system in the dry lands of Ethiopia. Agroforest Forum 63:291–298

Alister C, Lopez R, Kogan M (2005) Simazine dynamics in a vineyard soil at Casablanca Valley, Chile. Pest Manag Sci 61:1083–1088

Alvear M, Rosas A, Rouanet JL, Borie F (2005) Effects of three soil tillage systems on some biological activities in an Ultisol from southern Chile. Soil Till Res 82:195–202

Aronson J, Rigel A, Shmida A (1993) Reproductive allocation strategies in desert and Mediterranean populations of annual plants grown with and without stress. Oecology 93:336–342

Aronson J, Ovalle C, Avendaño J, Longeri L, Del Pozo A (2002) Agroforestry tree selection in central Chile: biological nitrogen fixation and early plant growth in six dryland species. Agroforest Syst 56:155–166

Arroyo MTK, Pliscoff P, Mihoc M, Arroyo-Kalin M (2005) The Magellanic moorland. In: Fraser LH, Keddy PA (eds) The world's largest wetlands: ecology and conservation. Cambridge University Press, London, UK

Bachmann J, Contreras K, Hartge KH, MacDonald R (2006) Comparison of soil strength data obtained in situ with penetrometer and with vane shear test. Soil Till Res 87:112–118

Badilla-Ohlbaum R, Ginocchio R, Rodríguez P, Céspedes A, González S, Allen H, Lagos G (2001) Relationship between soil copper content and copper content of selected crop plants in central Chile. Environ Toxicol Chem 20:2749–2757

Baginsky C, Seguel O, Contreras A (2010) Impact of the utilization of crop and organic amendments in the soil functionality. University of Chile, Agronomic Science Series N° 17. Santiago, Chile (in Spanish)

Bahamondes M (2003) Poverty-environment patterns in a growing economy: farming communities in Arid Central Chile, 1991–99. World Dev 31(11):1947–1957

Barra R, Popp P, Quiroz R, Bauer C, Cid H, von Tümpling W (2005) Persistent toxic substances in soils and waters along an altitudinal gradient in the Laja River Basin, Central Southern Chile. Chemosphere 58:905–915

Barrow CJ (1991) Soil degradation: development and breakdown of terrestrial environments. Cambridge University Press, Cambridge

Bastías EI, González-Moro MB, González-Murúa C (2004) *Zea mays* L. *amylacea* from the Lluta Valley (Arica-Chile) tolerates salinity stress when high levels of boron are available. Plant Soil 267:73–84

Bauzá F (2009) Physical properties evaluation in a soil with agroforestry and water harvesting in the inner rainfed of the Central Zone of Chile. Dissertation, University of Chile (in Spanish with English summary)

Beekman GB (2007) Climate and national action programs in Latin America. In: Sivakumar MVN, Ndiang'ui N (eds) Climate and land degradation. Springer, Berlin

Benavides C (1992) Soil as a physic system. In: Vera W (ed) Soils, an actualised vision of the resource. University of Chile, Faculty of Agrarian and Forestry Sciences, Santiago, Chile (in Spanish)

Benavides C (2011) Tolerance to salinity in olives, physic conditions of the olive's soils and leaching soils in areas with salinity risk: basic considerations for the Atacama Region. In: Fichet T, Razeto B, Curkovic T (eds) The olive: agronomic study in the Atacama Region. University of Chile, Faculty of Agronomic Sciences, Santiago, Chile (in Spanish)

Bernier R, Alfaro M (2006) Soil acidity and liming effect. Agriculture and Livestock Research Institute (INIA), INIA Bull 151, Osorno, Chile (in Spanish)

Biester H, Kilian R, Franzen F, Woda C, Mangini A, Schöler HF (2002) Elevated mercury accumulation in a peat bog of the Magellanic Moorlands, Chile (53°S) an anthropogenic signal from the Southern Hemisphere. Earth Planet Sci Lett 201:609–620

Boix-Fayos C, Martínez-Mena M, Arnau-Rosalén E, Calvo-Cases A, Castillo V, Albaladejo J (2006) Measuring soil erosion by field plots: understanding the sources of variation. Earth Sci Rev 78:267–285

Boix-Fayos C, Martínez-Mena M, Calvo-Cases A, Arnau-Rosalén E, Albaladejo J, Castillo V (2007) Causes and underlying processes of measurement variability in field erosion plots in Mediterranean conditions. Earth Surf Process Landf 32:85–101

Bonilla C, Vidal KL (2011) Rainfall erosivity in Central Chile. J Hydrol 410:126–133

Bonilla C, Reyes JL, Magri A (2010) Water erosion prediction using the revised universal soil loss equation (RUSLE) in a GIS framework, central Chile. Chil J Agric Res 70:159–169

Botti C (2000) Horticultural trees for arid zones. University of Chile, Faculty of Agronomic Sciences, Department of Agriculture Production, Santiago, Chile (in Spanish)

Botti C, Palzkill D, Muñoz D, Prat L (1998a) Morphological and anatomical characterization of six jojoba clones at saline and non-saline sites. Ind Crop Prod 9:53–62

Botti C, Prat L, Palzkill D, Cánaves L (1998b) Evaluation of jojoba clones grown under water and salinity stresses in Chile. Ind Crop Prod 9:39–45

Brito J, Peña L (1980) Determination of water erosion prediction universal equation R factor in the province of Ñuble. Agric Tecnica (Chile) 40(2):152–156 (in Spanish with English summary)

Campillo R, Rodríguez J (1984) Acidifying effects of urea transformations of two Andisols of the Lake Regions. Agric Tecnica (Chile) 44(2):131–138

Campillo R, Sadzawka MA (2006) Soil acidification. In: Campillo R (ed) Natural resources management in the incentives system to recovery degraded soils in the Araucanía. Series N°38. Agriculture and Livestock Research Institute, INIA, Regional Research Centre in Carillanca, Temuco, Chile (in Spanish)

Campillo R, Urquiaga S, Undurraga P, Pino I, Boddey RM (2005) Strategies to optimize biological nitrogen fixation in legume/-grass pastures in the southern region of Chile. Plant Soil 273: 57–67

Candan F, Broquen P (2009) Aggregate stability and related properties in NW Patagonian Andisols. Geoderma 154:42–47

Cartes E, Rubilar R, Mardónez O (2009) Comparison of water erosion on plantation and native forests in granitic soils of Bio–Bio's Region, Chile. XIII World Forestry Congress. 18–23 Oct Buenos Aires, Argentina (in Spanish)

Casanova M (2000) Stimulated and rejected managements in soil use. Chil Soc Soil Sci Bull 14:60–76 (in Spanish)

Casanova M, Leiva C, Seguel O, Salazar O, Luzio W (2006) Soil degradation and desertification. In: Luzio W, Casanova M (eds) Advances in knowledge of the Chilean soils. Santiago, Chile (in Spanish)

Casanova M, Haberland J, Seguel O, Luzio W (2007) Effect of gradient and slope aspect in the erosion of rainfed hillsides of central Chile. In: Proceeding XVII Latin-American congress of soil science (León-México) (in Spanish, with English summary)

Casanova M, Seguel O, Luzio W, Nario A, Videla X, Parada AM (2009) Assessment of soil degradation in hillsides. A contribution to a sustainable viticulture. University of Chile and Chilean Commission of Nuclear Energy. Santiago of Chile (in Spanish)

Casanova M, Dercon G, Zapata F (2010a) Soil erosion in Latin America and Caribbean. In: Casanova M, Ruiz G, Zagal E (eds) Proceeding XVI international soil conservation organization congress (ISCO). November, Santiago of Chile (in Spanish)

Casanova M, Dercon G, Zapata F (2010b) Soil erosion assessment: traditional methods. In: Casanova M, Ruiz G, Zagal E (eds) Proceeding XVI international soil conservation organization congress (ISCO). November, Santiago of Chile (in Spanish)

Casanova M, Seguel O, Salazar O, Homer I (2011) Demonstrative unit associated to 'Incentive system for agroenvironmental sustainability of agricultural and livestock soils'. University of Chile-Agriculture Ministery (Agriculture and Livestock Service, SAG)

Castro CP, Soto MV, Fernández R, Märker M, Rodolfi G (2009a) Impact of today geodynamic of Nantoco Valley, basin of Copiapó River, associated to productive reconversion. Rev Geogr Norte Gd 42:81–99 (in Spanish with English summary)

Castro M, Iturrieta R, Fassio C (2009b) Rootstock effect on the tolerance of cv. Hass avocado plants to NaCl stress. Chil J Agric Res 69:316–324

Cavieres A (2000) Criteria for development of a framework law for soil conservation. Chil Soc Soil Sci Bull 14:107–116 (in Spanish)

Cerda P, Jimenez K (2003) Relationship between soil loss, use and management on hillsides commune of La Cruz. Dissertation, University of Santiago, Chile (in Spanish)

Chartier MP, Rostagno CM (2006) Soil erosion thresholds and alternative states in northeastern Patagonian rangelands. Rangeland Ecol Manage 59:616–624

CIREN (2003) Soil survey of the Region X of Chile. Natural Resources Information Centre, Publication N° 123. Santiago, Chile (in Spanish)

CIREN (2007) Soil survey, Region III of Chile (Copiapó and Huasco valleys). Natural Resources Information Centre, Publication N°135. Santiago, Chile (in Spanish)

CONAMA (2010) National Climate Change Action Plan 2008–2012. National Environmental Commission (Chile) Department of Climate Change

Contreras H (1986) Water, life and development. Water use and conservation manual in Rural Zones of Latino America and Caribbean. UNESCO-ROSTLAC. Project DR-PRM. (in Spanish)

Contreras K (2006) Evaluation of the soil structural state using simple parameters: the stress at rest coefficient. Dissertation, Austral University of Chile (in Spanish with English summary)

Cortés A (2011) Physical stabilization of raised beds with avocado trees through organic amendments/cover crops (Region IV, Chile). Dissertation, University of Chile (in Spanish with English summary)

Cuevas J, Ellies A (2001) Pressure transmission and porosity changes generated by traffic in a Hapludand with different soil moisture conditions. R C Suelo Nutr Veg 1(2):48–57 (in Spanish with English summary)

Cuitiño H (1999) Qualitative assessment of water erosion on bare soils of pre-Andean and Central Valley of Region VII. Dissertation, University of Talca, Chile (in Spanish)

Daudin D, Sierra J (2008) Spatial and temporal variation of below-ground N transfer from a leguminous tree to an associated grass in an agroforestry system. Agric Ecosyst Environ 126:275–280

De Gregori I, Fuentes E, Rojas M, Pinochet H, Potin-Gautier M (2003) Monitoring of copper, arsenic and antimony levels in agricultural soils impacted and non-impacted by mining activities, from three regions in Chile. J Environ Monit 5:287–295

Delatorre J, Pinto M (2009) Importance of ionic and osmotic components of salt stress on the germination of four quinua (*Chenopodium quinoa* Wild.) selections. Chil J Agric Res 69:477–485

Delatorre J, Arenas J, Campos H (1995) Morphologic comparison of nine quinua ecotypes collected in the Altiplano in the Iquique province. Rev Agric Desierto 1:5–14 (in Spanish)

Diamond J (2007) Easter Island revisited. Science 317:1692–1694

Díaz C (1949) Association of soils of the Easter Island. Agric Tecnica (Chile) 9:115–126 (in Spanish)

Dörner J, Dec D, Peng X, Horn R (2009) Change of shrinkage behavior of an Andisol in southern Chile: effects of land use and wetting/drying cycles. Soil Till Res 106:45–53

Dube F, Thevathasan NV, Zagal E, Gordon AM, Stolpe N, Espinosa M (2011) Carbon sequestration potential of silvopastoral and other land use systems in the Chilean Patagonia. In: Kumar BM, Nair PKR (eds) Carbon sequestration potential of agroforestry systems: opportunities and challenges, advances in agroforestry, p 8

Elizalde R (1970) The survival of Chile. Renewable natural resources conservation, 2nd edn. Chilean Ministry of Agriculture, Chile (in Spanish)

Ellies A (1978) Some aspects of hidrophobicity in soils derived from volcanic ashes. Chil Soc Soil Sci Bull 2(2):344–365 (in Spanish)

Ellies A (1986) Effects of the mechanic consolidation in some Distrandepts and Palehumults of South Chile. Cienc Suelo (Argentina) 2:91–97 (in Spanish)

Ellies A (1988) Mechanical consolidation in volcanic ash soils. In: Drescher J, Horn R, de Boodt M (eds) Impact of water and external forces on soil structure. Catena supplement 11. Cremlingen-Destedt, Germany

Ellies A (1999) Structural changes and stress distribution in soils under machinery traffic. Bosque 20:37–45 (in Spanish)

Ellies A (2000) Soil erosion and its control in Chile—an overview. Acta Geol Hispan 35:279–284

Ellies A (2001) Changes in soil physical properties by drainage. Chil Soc Soil Sci Bull 17:66–72 (in Spanish)

Ellies A, Grez G, Ramírez C (1995a) Changes in wetting properties of soils under different managements. Turrialba 45:42–48 (in Spanish)

Ellies A, Grez R, Ramírez C (1995b) Wettening potential and stability of aggregates in soils with different management. Agric Tecnica (Chile) 55:220–225 (in Spanish with English summary)

Ellies A, Smith R, Horn R (1996) Stress transmission into the profile of some soils. Agro Sur 24:149–158 (in Spanish)

Ellies A, Horn R, Smith R (2000) Effect of management of volcanic ash soil on structural properties. Int Agrophys 14:377–384

Escárate K, Casanova M, Luzio W (2005) Conflict between constitutional guarantees for the soil conservation: a critical review of Chilean legislation. R C Suelo Nutr Veg 5(2):1–8 (in Spanish with English summary)

Espinosa G, Hajek E, Fuentes E (1985) Geographic distribution of landslides associated to disasters in Chile. Amb Des 1(2):81–90 (in Spanish)

Farías E (2009) Changes in soil physical properties on hillsides cropped with vineyard. Dissertation, University of Chile (in Spanish with English summary)

Ferreyra R, Aljaro A, Ruiz R, Rojas L, Oster JD (1997) Behavior of 42 crop species grown in saline soils with high boron concentrations. Agric Water Manage 34:111–124

Ferreyra R, Sellés G, Pinto M, Morales M, Seguel O (2011) Effect of soil air capacity on water relations and vegetative growth of *Thompson Seedless* grafted on different rootstocks: preliminary results. Acta Hortic 889:145–150

Flores C, Morgante V, González M, Navia R, Seeger M (2009) Adsorption studies of the herbicide simazine in agricultural soils of the Aconcagua Valley, Central Chile. Chemosphere 74: 1544–1549

Flores JP, Martínez E, Espinosa M, Muñoz P (2011) Determination of actual and potential erosion Chile territory through geomatics techniques, remote sensing and GIS. Chil Soc Soil Sci Bull 24:21–28 (in Spanish)

Flores-Aqueveque V, Vargas G, Rutllant J, Le Roux J (2009) Seasonality of erosion and eolian particle transport in the coastal Atacama Desert, Chile (23°S). Andean Geol 36(2):288–310

Fuentes I (2010) Mechanical behavior of soil matrix and their individual aggregates depending on soil water tension in three soils of central Chile. Dissertation, University of Chile (in Spanish with English summary)

Fuentes JP, Varnero MT (2011) Carbon quality and biologic properties as soil perturbation indicators in the Mediterranean area of Chile. Chil Soc Soil Sci Bull 24:83–94 (in Spanish)

Fuentes I, Seguel O, Casanova M (2011) Soil physical degradation in the Central Zone versus volcanic soils from South Chile. Chil Soc Soil Sci Bull 24:75–81 (in Spanish)

García N, Ormazábal C (2008) Native trees of Chile. ENERSIS-Huinay Fundation, Chile (in Spanish)

Gayoso J, Alarcon D (1999) Forest soil conservation guide. Austral University of Chile, Valdivia

Ginocchio R (2000) Effects of a copper smelter on a grassland community in the Puchuncaví Valley, Chile. Chemos 41:15–23

Ginocchio R (2011) Consequences of mining activity in soils of Chile. Chil Soc Soil Sci Bull 24:97–105 (in Spanish)

Ginocchio R, Rodríguez P, Badilla-Ohlbaum R, Allen H, Lagos G (2002) Effect of soil copper content and pH on copper uptake of selected vegetables grown under controlled conditions Environ Toxicol Chem 21:1736–1744

Ginocchio R, Carvallo G, Toro I, Bustamante E, Silva Y, Sepúlveda N (2004) Micro-spatial variation of soil metal pollution and plant recruitment near a copper smelter in Central Chile. Environ Pollut 127:343–352

Ginocchio R, Sánchez P, de la Fuente L, Camus I, Bustamante E, Silva Y, Urrestarazu P, Torres J, Rodríguez P (2009) Agricultural soils spiked with copper mine wastes and copper concentrate: implications for copper bioavailability and bioaccumulation. Environ Toxicol Chem 25:712–718

González S (2000) Soil contamination: heavy metals. Chil Soc Soil Sci Bull 14:42–59 (in Spanish)

González S, Bergqvist E (1986) Heavy metal pollution in an area of the coastal dryland of the Region V. Agric Tecnica (Chile) 46(3):299–306 (in Spanish with English summary)

González S, Ite R (1992) Soil metal accumulation in the area under industrial chimney influence (Valparaíso Province, Region V). Agric Tecnica (Chile) 50:214–219 (in Spanish with English summary)

González S, Bergqvist E, Ite R (1984) Heavy metal pollution of an area near a copper smelter in Chile. Catemu, V Region. Agric Tecnica (Chile) 44(1):63–68 (in Spanish with English summary)

González I, Muena V, Cisternas M, Neaman A (2008) Copper accumulation in a plant community affected by mining contamination in Puchuncaví Valley, central Chile. Rev Chil Hist Nat 81:279–291

Goudie A (2008) The history and nature of wind erosion in deserts. Annu Rev Earth Planet Sci 36:97–119

Gualterio H (2006) Trends in land degradation in South America. In: Stefanski R, Pasteris P (eds) Management of natural and environmental resources for sustainable agricultural development. World Meteorological Organization, Workshop Proceedings. Portland, Oregon. (http://www.wmo.int/Templates/wmo.vcf)

Gut B (2008) Trees in Patagonia. Birkhäuser Verlag AG, Basel

Hahm J, Wester D (2004) Effects of surface-applied biosolids on grass seedling emergence in the Chihuahuan desert. J Arid Environ 58:19–42

Hardin G (1968) The tragedy of commons. Science 162:1243–1248

Heredia W, Peirano P, Borie G, Zunino H, Aguilera M (2007) Organic carbon balance in Chilean volcanic soils after human intrusion and under different management practices. Acta Agric Scand B-S P 57:329–334

Higueras P, Oyarzún R, Oyarzún J, Maturana H, Lillo J, Morata D (2004) Environmental assessment of copper-gold-mercury mining in the Andacollo and Punitaqui districts, northern Chile. Appl Geochem 19:1855–1864

Hillel D (2004) Environmental soil physics. Academic Press, San Diego

Holz A, Veblen T (2011) The amplifying effects of humans on fire regimes in temperate rainforests in western Patagonia. Palaeogeogr Palaeoclimatol Palaeoecol 311(1–2):82–92

Homer I, Casanova M (2011) Conservation tillage on hillsides. Chil Soc Soil Sci Bull 24:59–73 (in Spanish)

Honorato R, Cruz G (1999) Erodability and soil erosion of Easter Island. Cien Invest Agric (Chile) 26:27–36 (in Spanish with English summary)

Honorato R, Barrales L, Peña I, Barrera F (2001) USLE erosion model evaluation on six locations between IV and IX Region of Chile. Cien Invest Agric 28:7–14 (in Spanish with English summary)

Hooda PS (2010) Trace elements in soils. Wiley, Chichester

Horn R (2003) Stress-strain effects in structured unsaturated soils on coupled mechanical and hydraulic processes. Geoderma 116:77–88

Hugo G (2008) Trends in land degradation in South America. In: Stefanski R, Pasteris P (eds) Management of natural and environmental resources for sustainable agricultural development. World Meteorological Organization, Workshop Proceedings. Portland, Oregon. (http://www.wmo.int/Templates/wmo.vcf)

Inostroza-Blancheteau C, Soto B, Ulloa P, Aquea F, Reyes-Díaz M (2008) Resistance mechanisms of aluminum (Al^{3+}) phytotoxicity in cereals: physiological, genetic and molecular bases. J Soil Sci Plant Nutr 8:57–71

IREN (1966) Dunes inventory of Chile (29°48′–4°50′S). National Research of Natural Resources Institute and Agriculture Ministry, Department of Soil and Water Conservation, Santiago

IREN-CORFO (1979) Fragility of natural ecosystems of Chile. National Research of Natural Resources Institute- Development Corporation. Santiago

Joel A, Messing I, Seguel O, Casanova M (2002) Measurement of surface water runoff from plots with two different sizes. Hydrol Process 14(7):1467–1478

Kabata-Pendias A (2011) Trace elements in soils and plants, 4th edn. CRC Press, Boca Raton

Kalthoff N, Fiebig-Wittmaack M, MeiBner C, Kohlera M, Uriarte, Bischoff-Gau BI, Gonzáles E (2006) The energy balance, evapotranspiration and nocturnal dew deposition of an arid valley in the Andes. J Arid Environ 65:420–443

Keller K (2011) Evaluation of the water dynamics in soils with organic manure applications under drip irrigation. Dissertation, University of Chile (in Spanish with English summary)

Kelm U, Helle S, Matthies R, Morales A (2009) Distribution of trace elements in soils surrounding the El Teniente porphyry copper deposit, Chile: the influence of smelter emissions and a tailings deposit. Environ Geol 57:365–376

Klein D, Fuentes JP, Schmidt A, Schmidt H, Schulte A (2008) Soil organic C as affected by silvicultural and exploitative interventions in *Nothofagus pumilio* forests of the Chilean Patagonia. Forest Ecol Manag 255:3549–3555

Lagos M (2005) Protocol for selection of alternatives for soil conservation. Technical Series N° 18. Agriculture and Livestock Service, SAG. Santiago, Chile (in Spanish)

Lagos E (2006) Characterization of precipitation-runoff process using a rain simulator. Dissertation, University of Talca, Chile (in Spanish with English summary)

Lavín A (1988) Boron toxicity induced by ulexite applications in some drip irrigated fruit crops at Cauquenes, Chile. Agric Tecnica (Chile) 48(2):167–170 (in Spanish with English summary)

Le Quesne C, Acuña C, Boninsegna JA, Rivera A, Barichivich J (2009) Long-term glacier variations in the Central Andes of Argentina and Chile, inferred from historical records and tree-ring reconstructed precipitation. Palaeogeogr Palaeoclimatol Palaeoecol 281:334–344

Leiva C (2005) Soil assessment at seven years of agroforestry and water harvesting management in the inner rainfed of central Chile. Dissertation, University of Chile (in Spanish with English summary)

Lemus M, Navarro G (2003) Manual for development of soil conservation works. Diversion channel—infiltration trench system. National Forestry Corporation, Chile Government (in Spanish)

León O, Carrasco MA (2011) Soil chemical degradation. Chil Soc Soil Sci Bull 24:115–122 (in Spanish)

Louwagie G, Stevenson CM, Langohr R (2006) The impact of moderate to marginal land suitability on prehistoric agricultural production and models of adaptive strategies for Easter Island (Rapa Nui, Chile). J Anthropol Archaeol 25:290–317

Luzio W, Casanova M, Seguel O (2010) Soils of Chile. In: Luzio W (ed) University of Chile. Maval Press, Santiago (in Spanish)
Macaya C, Gallardo M (2007) Rehabilitation manual of soils subjected to extraction of subsoil in agricultural areas. Report, Agriculture and Livestock Service (SAG, Chile) (in Spanish)
Martínez EA, Veas E, Jorquera C, San Martín R, Jara P (2009) Re-introduction of quinoa into Arid Chile: cultivation of two lowland races under extremely low irrigation. J Agron Crop Sci 195:1–10
Martínez-Harms MJ, Gajardo R (2008) Ecosystem value in the Western Patagonia protected areas. J Nat Conserv 16:72–87
Mathieu R, Cervelle B, Remy D, Pouget M (2007) Field-based and spectral indicators for soil erosion mapping in semi-arid mediterranean environments (Coastal Cordillera of central Chile). Earth Surf Proc Land 32:13–31
Mazzonia E, Vasquez M (2010) Desertification in Patagonia. In: Latrubesse EM (ed) Natural hazards and human-exacerbated disasters in Latin America. Developments in Earth Surface Processes, vol 13. Elsevier, UK
McBride MB (1994) Environmental chemistry of soils. Oxford University Press, New York
Mcintyre B, Riha S, Ong C (1997) Competition for water in a hedge-intercrop systems. Field Crop Res 52:151–160
Mieth A, Bork HR (2005) History, origin and extent of soil erosion on Easter Island (Rapa Nui). Catena 63:244–260
MINVU (2010) Soil consume in cities and regions. Estimations from building statistics and satellite images. Observatories of the commission on housing and urban studies. Ministry of Building and Urbanism, Chile (in Spanish)
Molina M, Aburto F, Calderón R, Cazanga M, Escudey M (2009) Trace element composition of selected fertilizers used in Chile: phosphorus fertilisers as a source of long-term soil contamination. Soil Sediment Contam 18:497–511
Montambault J, Alavalapati J (2005) Socioeconomic research in agroforestry: a decade in review. Agroforest Syst 65:151–161
Montenegro G, Fredes C, Mejías E, Bonomelli C, Olivares L (2009) Content of heavy metals in soils near a Chilean copper mining tailing. Agrociencia (Mexico) 43:427–435
Moreno R (2012) Seasonal assessment of soil water content and penetration resistance in an agroforestry system associated to water harvesting in the inner rainfed of central Chile. Dissertation, University of Chile (in Spanish with English summary)
Muena V, González I, Neaman A (2010) Effects of liming and nitrogen fertilization on the development of Oenothera affinis in a soil affected by copper mining. J Soil Sci Plant Nutr 10:102–114 (in Spanish with English summary)
Muñoz C, Ovalle C, Zagal E (2007a) Distribution of soil organic carbon stock in an Alfisol profile in Mediterranean Chilean ecosystems. J Soil Sci Plant Nutr 7:15–27 (in Spanish with English summary)
Muñoz C, Ovalle C, Zagal E (2007b) Influence of trees on soil organic matter in Mediterranean agroforestry systems: an example from the 'Espinal' of central Chile. Eur J Soil Sci 58:728–735
Muñoz C, Monreal CM, Schnitzer M, Zagal E (2008) Influence of *Acacia caven* (Mol) coverage on carbon distribution and its chemical composition in soil organic carbon fractions in a Mediterranean-type climate region. Geoderma 144:352–360
Nario A, Capri E, Balderacchi M, Pino I, Parada AM, Videla X, Luzio W, Casanova M, Seguel O (2009) Pesticide risk management using indicators for vineyards in the central valley of Chile. Integr Environ Assess Manag 5:476–482
Neaman A, Reyes L, Trolard F, Bourrié G, Sauvé S (2009) Copper mobility in contaminated soils of the Puchuncaví Valley, central Chile. Geoderma 150:359–366
Nissen J, Quiroz C, Seguel O, Mac Donald R, Ellies A (2006) Non-saturated water movement in Andisols. J Soil Sci Plant Nutr 6:9–19 (in Spanish with English summary)
Olivares A, Gastó J (1981) *Atriplex repanda*, organization and management of ecosystems with bushes for forage. Agriculture Sciences N°7, University of Chile, Santiago, Chile (in Spanish)
Orellana I (2010) Comparison of two methods to measure the wetting capacity of soils. Dissertation, Austral University of Chile (in Spanish with English summary)
Ormazábal CS (1991) Silvopastoral systems in arid and semi-arid zones of northern Chile. Agroforest Syst 14:207–217
Osorio A, Césped R (2000) Effect of micro-irrigation methods on the salinity of the soil profile in a grape vineyard. I. Electrical conductivity of sodium, chloride and boron at several points of the profile. Chil J Agric Res 60:178–194, 42 (in Spanish with English summary)
Ovalle C, Squella F (1988) Pasture lands with annual prairie in the area with Mediterranean climate influence. In: Ruiz I (ed) Prairies for Chile. Agriculture and Livestock Research Institute, INIA, Santiago, Chile (in Spanish)
Ovalle C, Aronson J, del Pozo A, Avendaño J (1990) The espinal: agroforestry systems of the Mediterranean-type climate region of Chile. Agroforest Syst 10:213–239
Ovalle C, Aronson J, del Pozo A, Avendaño J (1999) Restoration and rehabilitation of mixed espinales in central Chile: 10 year report and appraisal. Arid Soil Res Rehabil 13:369–381
Oyarzún C (1993) Evaluation of the USLE for the prediction of soil erosion in forested areas of the Bio–Bio river basin. Bosque 14(1):45–54
Oyarzún R, Arumí JL, Alvarez P, Rivera D (2008) Water use in the Chilean agriculture: current situation and areas for research development. In: Sorensen ML (ed) Agricultural water management research trends. Nova Publishers, New York
Paruelo JM, Jobbágy EG, Oesterheld M, Golluscio RA, Aguiar RA (2007) The grasslands and steppes of Patagonia and the Río de la Plata Plains. In: Veblen TT, Young KR, Orme AR (eds) The physical geography of South America. Oxford University Press Inc, Oxford
Peña L (1983) Determination of R, K and C factors of the universal equation of estimation erosion for pre Andean Region VII. Agric Tecnica (Chile) 43(2):151–158 (in Spanish with English summary)
Peña L (1985) Water erosion in hilly trumaos. In: Tosso J (ed) Volcanic soils of Chile. Agriculture Ministry, Agriculture and Livestock Research Institute (INIA) Santiago, Chile (in Spanish)
Peña L (1992) Erosion and soil conservation. In: Vera W (ed) Soils, an actualised vision of the resource. University of Chile, Faculty of Agrarian and Forestry Sciences. Santiago, Chile (in Spanish)
Peña-Cortés F, Ailio C, Gutiérrez P, Escalona-Ulloa M, Rebolledo G, Pincheira-Ulbrich J, Rozas D, Hauenstein E (2008) Dunes morphology and dynamic in coastal ridge of Araucania Region in Chile. Antecedents for land conservation and land management. Rev Geogr Norte Gd 41:63–80 (in Spanish with English summary)
Peralta M (1976) Use classification and conservation of soils. Ministry of Agriculture, Chile (in Spanish)
Pérez C, González J (2001) Diagnosis on the state of soil resource degradation in the country. CRI-Quilamapu, Agricultural and Livestock Research Institute (INIA), Chillán–Chile (in Spanish)
Pérez-Quezada JF, Delpiano CA, Snyder KA, Johnson DA, Franck N (2011) Carbon pools in an arid shrubland in Chile under natural and afforested conditions. J Arid Environ 75:29–37
Pfeiffer M, Mascayano C, Aburto F (2010) Soils of Chilean Patagonia in glacial and periglacial environments. Eurasian Soil Sc 43(13):1–9

Pizarro R, Morales C, Vega L, Balocchi F (2009) Design manual for works of recovery and conservation of water and soil. University of Talca, INNOVA-Chile (in Spanish)

Pizarro J, Vergara P, Rodríguez J, Valenzuela A (2010) Heavy metals in northern Chilean rivers: spatial variation and temporal trends. J Hazard Mater 181:747–754

Poblete L (2011) Modification of soil physical properties of a fine textured soil from Region III of Chile cultivated with grape through the use of organic matter on the row-planting. Dissertation, University of Chile (in Spanish with English summary)

Ramírez C, Ellies A, Mac Donald R, Seguel O (2003) Floristic and organic matter changes from native forest to anthropogenic prairies in volcanic soils (Region IX, Chile). J Soil Sci Plant Nutr 3(1):1–12

Rodríguez N (2011) Conditioning for the recultivation of a sandy loam soil disturbed by sand extraction. Dissertation, University of Chile (in Spanish with English summary)

Rodríguez M, Suárez J (1946) The conservation of soil of Chile. General Direction of Agriculture, Chile (in Spanish)

Rodríguez N, Ruz E, Valenzuela A, Belmar C (2000) Effect of tillage on soil erosion losses with a wheat-oat rotation and pasturing in the Andean foothills of the south-central region of Chile. Agric Tecnica (Chile) 60(3):259–269 (in Spanish with English summary)

Romero H, Órdenes F (2004) Emerging Urbanization in the Southern Andes. Environmental impacts of urban sprawls in Santiago of Chile on the Andean piedmont. Mt Res Dev 24(3):197–201

Romo-Kröger CM, Morales JR, Dinator MI, Llona F, Eaton LC (1994) Heavy metals in the atmosphere coming from a copper smelter in Chile. Atmos Environ 28:705–711

Ruiz G (2005) Manual of good soil management practices on hillsides, technical specifications. Technical series N° 20. Chilean Ministry of Agriculture, Agriculture and Livestock Service, SAG. Santiago, Chile (in Spanish)

Ruiz G (2011) System of incentives for agri-environmental sustainability of agricultural soils. Chil Soc Soil Sci Bull 24:31–36 (in Spanish)

Sadzawka MA (2006) Physical-chemical soil properties in the soils I: reaction (pH), acidity and alkalinity. In: Luzio W, Casanova M (eds) Advances in the knowledge of the Chilean soils. University of Chile—Chilean Ministry of Agriculture, Agriculture and Livestock Service (SAG), Maval Press, Santiago, Chile (in Spanish)

Sagardía S, Seguel O, Casanova M (2008) Effect of exudations from *Chaitophorus leucomelas* Koch, parasite of *Populus* sp., on the soil hydraulic properties. In: IV Chilean Congress of Forest Sciences. Talca, Chile, 1–3 Oct, (in Spanish)

Salazar O (2003) Chemical assessment of a soil under agroforestry associated to water harvesting essay in the inner rainfed of central Chile. Dissertation, University of Chile (in Spanish with English summary)

Salazar O, Casanova M (2011) Runoff water harvesting as a strategy for increasing agricultural production on hillslope areas in arid and semi-arid zones. In: Carrey DM (ed) Water recycling and water management. Nova Science Publishers, New York

Salazar O, Casanova M, Benavides C, Luzio W, Vera W (2006) Chemical properties of a soil under agroforestry and water harvesting in the inner rainfed zone of central Chile. Terra 24:471–476 (in Spanish with English summary)

Salazar O, Casanova M, Kätterer T (2011) The impact of agroforestry combined with water harvesting on soil carbon and nitrogen stocks in central Chile evaluated using the ICBM/N model. Agric Ecosyst Environ 140:123–136

Sandoval M, Castillo C, Zagal E, Stolpe N (2007) Hydraulic parameters determined in Andisol under different crop rotations after ten years. R C Suelo Nutr Veg 7(2):32–45 (in Spanish with English summary)

Sangüesa C, Arumí J, Pizarro R, Link O (2010) A rainfall simulator for the in situ study of superficial runoff and soil erosion. Chil J Agric Res 70(1):178–182

Santibáñez F, Santibáñez P, Hernández J, Montaner D (2008) Vulnerability analysis of forestry and agricultural sector, water and soil of Chile against climate change scenarios. AGRIMED-University of Chile

Schulz J, Cayuela L, Echeverria C, Salas J, Rey JM (2010) Monitoring land cover change of the dryland forest landscape of Central Chile. Appl Geogr 30:436–447

Schüller P, Ellies A, Kirchner G (1997) Vertical migration of fallout in agricultural soils from Southern Chile. Sci Total Environ 193:197–205

Schüller P, Sepúlveda A, Trumper R, Castillo A (2000) Application of the ^{137}Cs technique to quantify soil redistribution in Paleohumults from Central-South Chile. Acta Geol Hispan 35(3–4):285–289

Schüller P, Ellies A, Castillo A, Salazar I (2003) Use of the 137Cs technique to estimate tillage- and water-induced soil redistribution rates on agricultural land under different use and management in central-south Chile. Soil Till Res 69:45–51

Schüller P, Bunzl K, Voigt G, Ellies A, Castillo A (2004a) Global fallout ^{137}Cs accumulation and vertical migration in selected soils from South Patagonia. J Environ Radioact 71(43–60):44

Schüller P, Walling D, Sepúlveda A, Trumper R, Rouanet JL, Pino I, Castillo A (2004b) Use of Cs-137 measurements to estimate changes in soil erosion rates associated with changes in soil management practices on cultivated land. Appl Radiat Isot 60:759–766

Schüller P, Iroumé A, Walling D, Mancilla H, Castillo A, Trumper R (2006) Use of ^{7}Be to document soil redistribution following forest harvest operations. J Environ Qual 35:1756–1763

Schüller P, Walling D, Sepúlveda A, Castillo A, Pino I (2007) Changes in soil erosion associated with the shift from conventional tillage to a no-tillage system, documented using Cs-137 measurements. Soil Till Res 94(1):183–192

Schüller P, Iroumé A, Walling D, Castillo A (2010) Use of beryllium-7 to study the effectiveness of woody trash barriers in reducing sediment delivery to streams after forest clearcutting. Soil Till Res 110:143–153

Seguel O, Farías E, Luzio W, Casanova M, Pino I, Parada MA, Videla X, Nario A (2009) Changes in soil physical properties on hillsides vineyard (*Vitis vinifera*). ISTRO 18th Triennial conference. Izmir, Turkey, 15–19 June

Seguel O, Baginsky C, Contreras A, Covarrubias J, González C, Sandoval M (2011) Changes in physical properties of a Typic Haplocambid by annual crop culture. J Soil Sci Plant Nutr 11(1):1–15

Sepúlveda A, Schüller P, Walling D (2008) Use of ^{7}Be to document soil erosion associated with a short period of extreme rainfall. J Environ Radioact 99:35–49

Sierra C, Césped R, Osorio A (2001) Characterization of soil and water salinity in the river in the Copiapó Valley. Agriculture and Livestock Research Institute (INIA), INIA Bull 70, Chile (in Spanish)

Silva M, Lozano U (1986) Description of the main pasture species between arid Mediterranean area and the rainy area. University of Chile. Faculty of Agrarian and Forest Sciences, Department of Animal Production. Educational Publication N° 9. Santiago, Chile (in Spanish)

Silva H, Sagardía S, Seguel O, Torres C, Tapia C, Franck N, Cardemil L (2010) Effect of water availability on growth and water use efficiency for biomass and gel production in Aloe Vera (*Aloe barbadensis* M.). Ind Crop Prod 31:20–27

Sotomayor EM, De la Riva FP, Leiva AJ (1994) Olive adaptation to the edaphoclimatic conditions in the Lluta Valley, Arica-Chile. Acta Hortic 356:189–192

Stocking MA, Murnaghan N (2001) Handbook for the field assessment of land degradation. Earthscan, London

Stolpe N (2005) A comparison of the RUSLE, EPIC and WEPP erosion models as calibrated to climate and soil of south-central Chile. Acta Agric Scand B 55:2–8

Stolpe N, Muñoz C, Zagal E, Ovalle C (2008) Modeling soil carbon storage in the 'Espinal' agroecosystem of central Chile. Arid Land Res Manag 22:148–158

Tchernitchin A, Lapin N, Molina L, Molina G, Tchernitchin N, Acevedo C, Alonso P (2006) Human exposure to lead in Chile. Rev Environ Contam Toxicol 185:93–139

Torres A, Acevedo E (2008) The salinity problem of the water and soil resources in Lluta and Azapa Valleys in northern Chile. Idesia 26:31–44 (in Spanish with English summary)

Traub M (2010) Use of an organic emulsion as an erosion control management in cultivated hillside with vineyards, Region VI of Chile. Dissertation University of Chile (in Spanish with English summary)

Undurraga P, Zagal E, Sepúlveda G, Valderrama N (2009) Dissolved organic carbon and nitrogen in Andisol for six crop rotations with different soil management intensity. Chil J Agric Res 69: 445–454

UNEP (2007) Global environment outlook-4. (Geo-4), United Nations Environment Programme, Nairobi

Valenzuela J, Narvaez C (1983) Some factors associated with boron excess in the Elqui Valley vineyards. Agric Tecnica (Chile) 43(2):145–149 (in Spanish with English summary)

Vargas R, Tokugawa K, Francke S, Makita M (1998) Erosion control manual. Agriculture Ministry of Chile (CONAF) and Japanese International Cooperation Agency (JICA)

Varnero MT, Rojas C, Macaya C, Orellana R (2005) Effects of grass carpet production on agriculture soils. Chil Soc Soil Sci Bull 21:84 (in Spanish)

Verbist K (2011) Climatic and soil physical constraints for efficient rain water harvesting in degraded lands of Chile. Dissertation, University of Ghent, Belgium

Verbist K, CornelisWM, Gabriels D, Alaerts K, Soto G (2009) Using an inverse modelling approach to evaluate the water retention in a simple water harvesting technique. Hydrol Earth Syst Sci 13:1979–1992

Villarroel R (2012) Chemical properties of a soil from Chilean central rainfed under an agroforestry system associated to water harvesting, 12 years old. Dissertation, University of Chile (in Spanish with English summary)

Vött W, Endlicher A (2001) Landscape degradation in the Region XI of Chile within the framework of growing environmental problems in Western Patagonia—a geological and geostatistical approach. Die Erde 132:239–268

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses—a guide to conservation planning. Agriculture handbook N° 537. U.S. Department of Agriculture, Washington D.C., USA

Youlton C, Espejo P, Biggs J, Norambuena M, Cisternas M, Neaman A, Salgado E (2010) Quantification and control of runoff and soil erosion on avocado orchards on ridges along steep-hillslopes. Cien Invest Agric 37(3):113–123

Young G, Zavala H, Wandel J, Smit B, Salas S, Jimenez E, Fiebig M, Espinoza R, Diaz H, Cepeda J (2010) Vulnerability and adaptation in a dryland community of the Elqui Valley, Chile. Clim Chang 98:245–276

Zapata F (2003) Handbook for the assessment of soil erosion and sedimentation Using environmental radionuclides. Kluwer Academic Publishers, Dordrecht

Zapata F, Dercon G, Casanova M (2010) Soil erosion assessment: isotopic methods. In: Casanova M, Ruiz G, Zagal E (eds) Proceeding XVI international soil conservation organization congress (ISCO), November, Santiago of Chile