3 Management of Soil Properties in Chile

3.1 Chemical Properties

Soil chemical properties are critical in determining nearly all the major soil properties that control plant nutrient availability, the fate of many soil pollutants, microbial reactions in soils, etc. In Chile, climate conditions and parent materials tend to combine to create a pattern of soil chemical properties that varies along the considerable length of the country. Thus, soil chemical properties in the major soil zones, including soil reaction, soil salinity and nutrient availability, are described here. In addition, some management practices for improving crop production are discussed.

3.1.1 Soil Reaction

Soil reaction (pH) in Chilean soils is directly related to the parent material (parental factor), but is also highly influenced by the precipitation regime (climate factor) and vegetation (organism factor). Based on the combined effects of these three soil formation factors, the soil reaction in Chile may be roughly divided into alkaline in the Hyper-arid to Semi-arid zone and acidic in the southern part of the Mediterranean zone. In the Northern Mediterranean zone, a broad range of soil pH can be found as a result of additional influences from the topography. Few studies have been made on the soils in other zones, but the information available to date suggests that the soil reaction in the Rainy and Patagonian zones ranges from acidic to basic, whereas in the Antarctic zone and in the Insular zone it ranges from acidic to neutral.

Figure 3.1 shows soil pH ranges at 0–20 cm depth in 710 pedons in the major soil zones in Chile, based on a number of soil surveys carried out in agricultural areas during the last 40 years by different government agencies (SAG 1974; CIREN 1996a, b, 1997a, b, 1999, 2002, 2003, 2005a, b, 2007; Ahumada et al. 2004). In the Hyper-arid to Semi-arid zone, all the soils described in these studies displayed soil pH_{water} higher than 6.0, and 51 % of the soils had moderately alkaline soil reaction ($pH_{water} \geq 7.9$). In the Mediterranean zone, 52 % of the pedons had moderately acidic (pH_{water} 5.6–6.0) to slightly acidic (pH_{water} 6.1–6.5) soil reaction, with few extreme soil pH soils, for instance only 5 % very strongly acidic and 4 % moderately alkaline soils were included. Considering only two soil surveys carried out in the Rainy and Patagonian zone (CIREN 2005b; SAG 1974) with a limited number of soil descriptions ($n = 23$ pedons) for the extensive area defined, it is possible to find a broad range of soil pH_{water}, but with a dominance of slightly acidic soils (39 %).

The amount of precipitation falling in Chile follows a clear tendency to increase from the Hyper-arid to Semi-arid zone (latitude UTM 7,000 km south; mean annual precipitation (MAP) <150 mm year^{-1}) to the southern part of the Mediterranean zone (latitude UTM 5,400 km south; MAP 1,100–2,400 mm year^{-1}), whereas it decreases towards the Rainy and Patagonian zone to around 200 mm year^{-1} at latitude UTM 4,800 km south, as shown in Fig. 3.2. Overall, the relationship between MAP obtained from Chilean meteorological stations ($n = 74$) and latitude (UTM) is best fitted to a four-order polynomial equation, with a determination coefficient (R^2) of 0.78. Soil pH follows a similar tendency to precipitation regime, with the relationship between soil pH_{water} at 0–20 cm and latitude (UTM) analysed in 710 pedons from the hyperarid to semiarid zone to the Rainy and Patagonian zone being best fitted to four-order polynomial equation with R^2 of 0.56. Thus as Fig. 3.2 shows, soil pH_{water} at 0–20 cm decreases from alkaline values in the hyperarid to semiarid zone to acidic in the southern part of the Mediterranean zone. Where the MAP decreases again, particularly in the east of the Rainy and Patagonian zone, soil pH increases, in some cases to moderately alkaline values. In this zone, calcium carbonate ($CaCO_3$) observed in surface soil and increasing with depth, originates from dust rather than from pedogenic weathering according to Bockheim and Douglass (2006).

M. Casanova et al., *The Soils of Chile*, World Soils Book Series, DOI: 10.1007/978-94-007-5949-7_3,

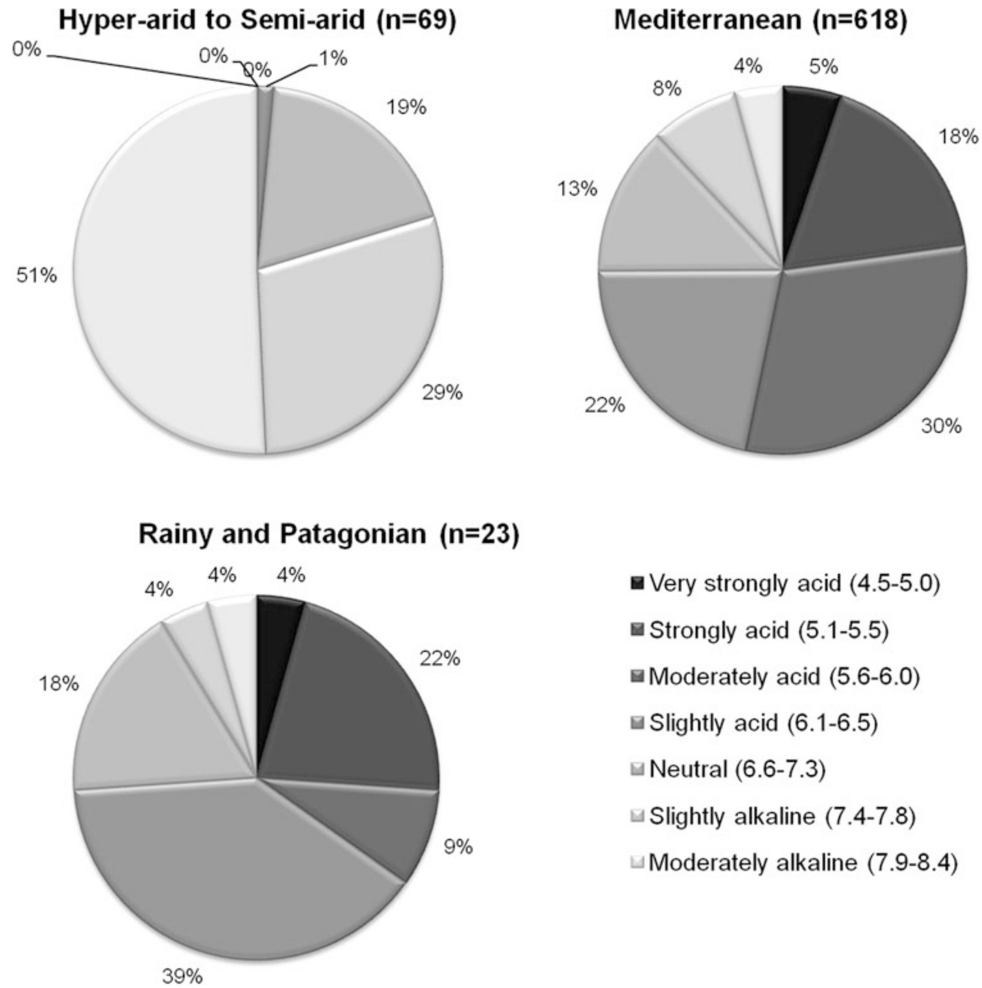

Fig. 3.1 Soil pH_{water} ranges in major soil zones in Chile at 0–20 cm depth; *n* is the amount of pedons analysed

This is because there is minimal evidence of weathering of Ca-bearing minerals in the soil, the amount of $CaCO_3$ in the profile is far in excess of what could be released by weathering, dust collected from the area is enriched in $CaCO_3$ (>4 %), and a source area for the carbonate dust has been identified to the north–west, near Lake General Carrera.

In addition, Fig. 3.2 clearly shows that soil pH reaches its lowest values (around 4.2 at latitude UTM 5,300 km south) in the southern part of the Mediterranean zone, where MAP is over 2,000 mm $year^{-1}$. In contrast, when MAP is lower than 1,000 mm $year^{-1}$, most soils have soil pH above 6.0, while moderately alkaline soils are only found where MAP is lower than 200 mm.

However, in the Hyper-arid to Semi-arid zone, localised areas of acidic soil can be found in the Chilean Altiplano, where pH_{water} of 4.9 (3,000–4,000 m a.s.l.) and 4.2 (4,200–4,500 m a.s.l.) in the surface horizon of Aridisols (Luzio et al. 2002) and Entisols (Norambuena et al. 2011), respectively, have been described.

In the northern part of the Mediterranean zone, localised pockets of acidic soils may also exist, with soil reaction ranging between very strongly acidic (pH 4.5–5.0) and strongly acidic (pH 5.1–5.5). These soils correspond to Inceptisols and Alfisols in terrace or hillslope positions and generally display pH <5.0 and low base saturation (BS <50 %) (Table 3.1).

As shown in Fig. 3.3, in the southern part of the Mediterranean zone most soils have soil pH_{water} below 6.5. In the Central Valley and Coastal Range of the southern part of this zone there is a group of soils, locally named red clayey soils and classified as Ultisols, which display an argillic horizon (B_t) with pH in the range very strongly acidic to strongly acidic and with low Al saturation on the exchange complex (Sadzawka 2006a). In this zone, there are also a number of Andisols, Inceptisols and Alfisols with soil pH_{water} ranging between strongly acidic and moderately acidic.

In soils in the southern part of the Mediterranean zone, the base-forming cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) have usually left the colloidal complex and show high acidity levels, with the appearance of Al, Mn and H phytotoxicity (Borie and Rubio 1999). The Al phytotoxicity in particular

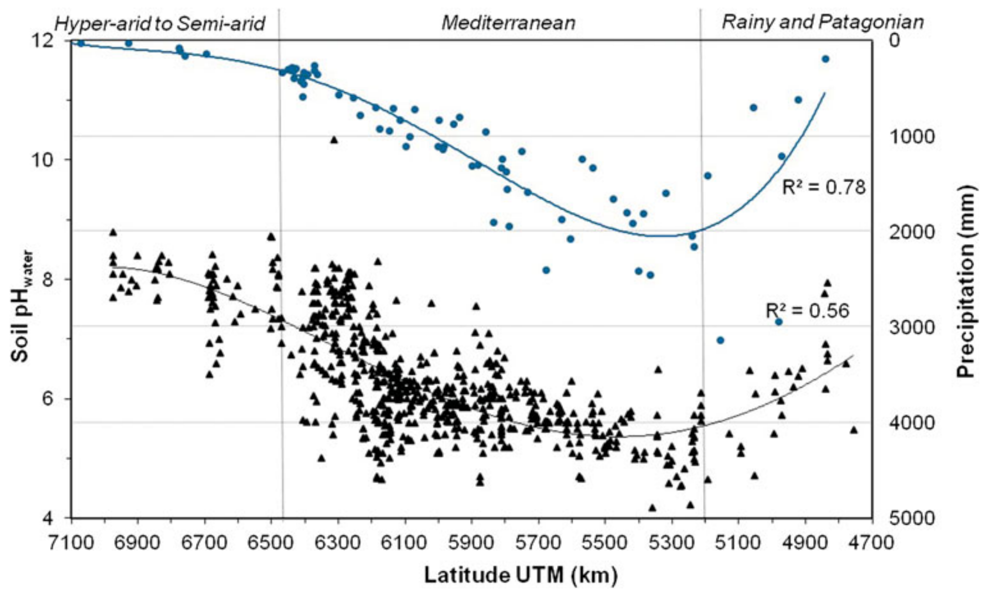

Fig. 3.2 Soil pH_{water} (*triangles*) at 0–20 cm depth between the Hyper-arid to Semi-arid zone and the Rainy and Patagonian zone for 710 pedons. *Circles* are mean annual precipitation from 74 meteorological stations

is an important constraint for plant production in these areas of Southern Chile (Borie and Rubio 1999). For instance, cereals such as wheat and barley growing in very strongly acidic soils with high Al levels display symptoms such as decreased root length (Gallardo et al. 1999, 2005).

Aluminium saturation as a percentage of effective cation exchange capacity (ECEC) has been proposed as a measure of Al phytotoxicity in acidic soils in Chile (Sadzawka 2006a). In soils with Al saturation of ECEC values higher than 5 %, the Chilean Incentives System to Recover Degraded Soils (ISRID) recommends the application of lime (Mora et al. 1999, 2002).

Figure 3.3 shows the negative relationship between measured Al saturation of ECEC and measured soil pH_{water} at 0–20 cm in 169 pedons in the southern part of the Mediterranean zone (CIREN 1999, 2002, 2003). It is clear from the diagram that as soil pH_{water} decreases Al saturation of ECEC increases, fitting a third-order polynomial equation with R^2 of 0.59. In addition, 49 % of analysed samples showed Al saturation of ECEC >5 %, whereas 90 % of soil samples with soil pH_{water} <5.5 had Al saturation of ECEC >5 %.

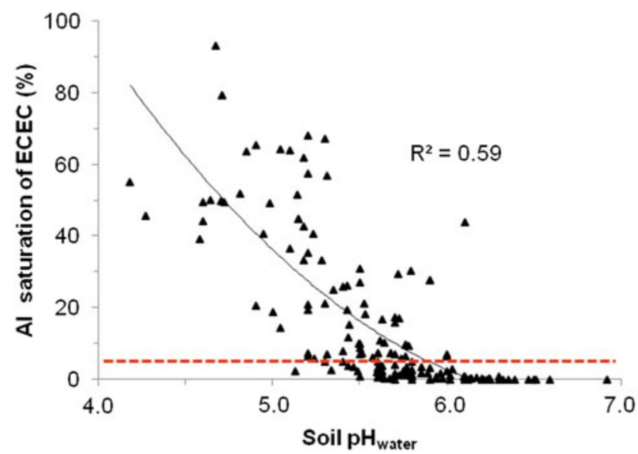

Fig. 3.3 Relationship between Al saturation of the cation exchange capacity (ECEC) and soil pH_{water} at 0–20 cm in soils in the Mediterranean zone (n = 169). *Red segmented line* shows Al saturation of ECEC = 5 %

Table 3.1 Classification, location and soil properties at 0–20 cm depth of some acidic soils in the Mediterranean zone (CIREN 1996b, 1997a, b)

Pedon	Latitude UTM (km)	Soil order	Position	pH	BS (%)
Mantagua	6,353	Alfisol	Marine terrace	5.0	35
Carrizal	6,186	Inceptisol	Recent alluvial terrace	4.7	31
Loma Grande	6,148	Inceptisol	Piedmont	5.0	62
Los Lingues	6,174	Alfisol	Remnant alluvial terrace	4.9	58
Pumanque	6,172	Inceptisol	Hillslope	4.7	22
Quinchamalal	6,184	Alfisol	Piedmont	4.7	22
Piuchén	6,184	Alfisol	Hillslope	5.0	–

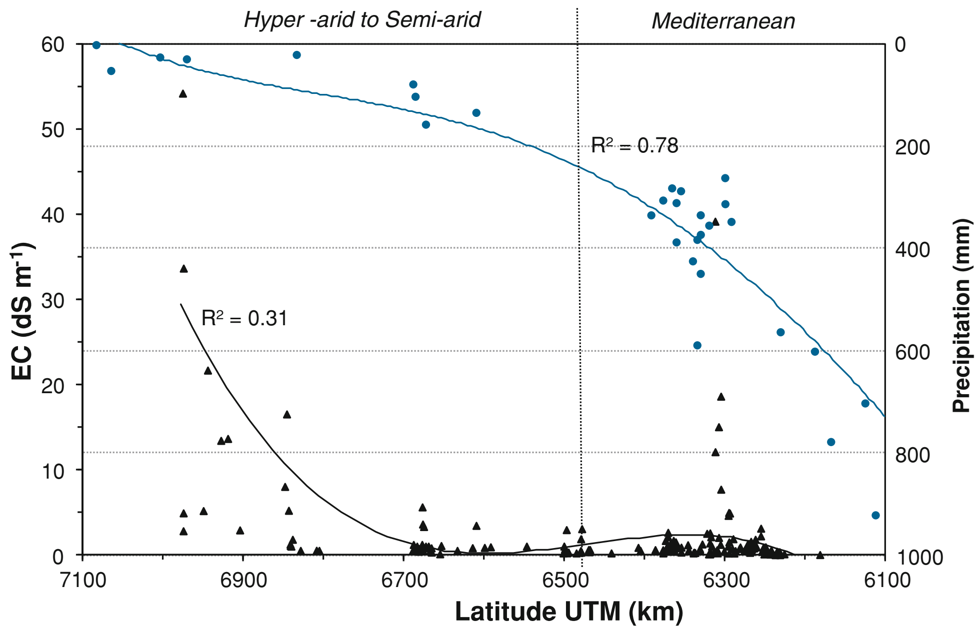

Fig. 3.4 Soil electrical conductivity (EC) at 0–20 cm depth between the Hyper-arid to Semi-arid zone and Mediterranean zone. *Triangles* are EC in pedons (n = 173) and *circles* are mean annual precipitation obtained from 30 meteorological stations

3.1.2 Soil Salinity and Sodicity

Soil salinity is well-known to be a serious problem in many parts of the world. Out of the 21 countries worldwide with over 15 % of their land affected by salinity, excluding secondary salinisation caused by poor management of irrigation schemes, three (Paraguay, Argentina and Chile) lie in South America (FAO 2000). Broad statistical estimates (TERRASTAT 2003) indicate that an area of 759,000 km^2 in Chile is affected by salinity and a further 33,000 km^2 by sodicity. Most of this area occurs in Northern Chile, characterised by a succession of North–South aligned ranges and basins occupied by numerous saline lakes and salt crusts, collectively called *salars* (see Chap. 2). Fossil salt crusts are found to the west in the extremely arid Central Valley, while active salars receiving permanent inflows fill many intravolcanic basins to the east in the semiarid Andes (Risacher et al. 2003).

In the Hyper-arid to Semi-arid zone and in the northern part of the Mediterranean zone, salts accumulate naturally due to insufficient rainfall (<500 mm year^{-1}) to remove them from the upper soil layer, as shown in Fig. 3.4.

In the Hyper-arid to Semi-arid zone and the northern part of Mediterranean zone, 69 and 89 % of the total pedons characterised, respectively, are non-saline (EC <2 dS m^{-1}). However, there are several areas that suffer from some degree of salinity (Table 3.2). Most of the soils with extremely saline conditions (EC >8 dS m^{-1}) are located in the Hyper-arid to Semi-arid zone. However, in the northern part of the Mediterranean zone there are some pockets of moderately to strong saline soils that arise from confinement, created by a physical barrier to water flow out of a depression in the landscape.

3.1.3 Nutrient Availability

3.1.3.1 Nitrogen

The first major requirement in agricultural soils is adequate nitrogen (N) for healthy crop growth. In Chile, many N sources are available for supplying N to annual crops and fruit trees. The quantity of N available to plants depends largely on the amounts applied as fertilisers and mineralised from organic N in soils. Although N fertilisation rates have been increasing in Chile in recent decades, in many cases, these have not been proportional to the increase in crop yields. For instance, the current N application rate averaged over all crops is ~120 kg ha^{-1} (World Bank 2008), which is high in comparison to that in other Andean countries (Fig. 3.5). One possible reason for the high N application rates in Chile is that most farmers do not carry out any soil testing or N balance to determine fertiliser/manure applications, or do not select an appropriate N source according to soil characteristics. Overfertilisation is associated with a high risk of N contamination of water bodies (Alfaro et al. 2006; Claret et al. 2011; Salazar and Nájera 2011) or gaseous losses (Casanova and Benavides 2009; Pérez et al. 2010).

During the 1970s, a number of different research groups carried out N analyses in order to determine available N and used this value to calculate recommended N fertilisation rates (Tejeda and Gogan 1970; García and Gandarillas

Table 3.2 Range of soil electrical conductivity (EC) at 0–20 cm depth in Hyper-arid to Semi-arid zone ($n = 68$ pedons) and northern part of Mediterranean zone ($n = 105$ pedons)

Class	EC (dS m^{-1})	Hyper-arid to Semi-arid zone (%)	Northern Mediterranean zone (%)
Non-saline	0–2	69	85
Very slightly saline	2–4	12	8
Slightly saline	4–8	6	4
Moderately saline	8–16	4	3
Strongly saline	>16	9	1

1974). However, it is now generally accepted that N fertilisation rates for crops should be calculated from the N balance before crop sowing (Rodríguez et al. 2001). With this approach, the amount of available N in soil during the growing season is estimated from potential crop yield and quantity and the biochemical quality of crop residues produced and returned to the soil during preceding seasons (Hirzel 2011). Matus and Rodríguez (1994) found that N supplied to soils by mineralisation was close to the soil mineral N content measured at two sites in the Northern Mediterranean zone and two sites in the Southern Mediterranean zone. Table 3.3 shows a simplified estimate of N supply in soils considering net N mineralisation during the growing season in the Mediterranean zone according to soil management and crop residue incorporation, which correlates with previous values reported for this zone (Matus and Rodríguez 1994; Rodríguez et al. 2001).

Lower net N mineralisation rates than in agricultural soils have been reported in studies on evergreen and deciduous forest soils classified as Andisols in the southern part of the Mediterranean zone. For instance, Pérez et al. (2003a) found net N mineralisation values for forest soils in the range 12–30 kg N ha^{-1} $year^{-1}$, Cárcamo et al. (2004) reported values lower than 6 kg N ha^{-1} $year^{-1}$, and recently Staelens et al. (2011) reported a range of 1.7–11.3 kg N ha^{-1} $year^{-1}$. This lower N mineralisation in forest soils compared with agricultural soils is directly related to higher C/N ratio in litterfall reaching the topsoil in forest soils, where immobilisation processes dominate. For instance, Pérez et al. (2003b) studied an evergreen forest in the southern part of the Mediterranean zone and reported litterfall C/N ratio ranging between 41 and 113, whereas Klein et al. (2008) in a *Nothofagus pumilio* forest in the Rainy and Patagonian zone found a litterfall C/N ratio of 58.

In the Mediterranean zone, some studies have been carried out to estimate N addition to soil by rainfall and dry deposition. Although these studies showed values lower than 10 kg N ha^{-1} $year^{-1}$ (Table 3.4), these forms of N addition should be considered in the N budget to reduce application of commercial N fertiliser.

Other alternatives have been studied to calculate optimal N application rate and avoid negative environmental impacts. Some studies have used ^{15}N to assess the recovery of N applied by fertilisation of crops (Pino et al. 2002a) and fruit trees (Pino et al. 2002b), and also to determine biological N fixation in legumes (Campillo et al. 2002, 2005;

Fig. 3.5 Current fertiliser use (cultivated land) in Andean countries including Chile, $P–P_2O_5$ and $K–K_2O$ (adapted from World Bank 2008)

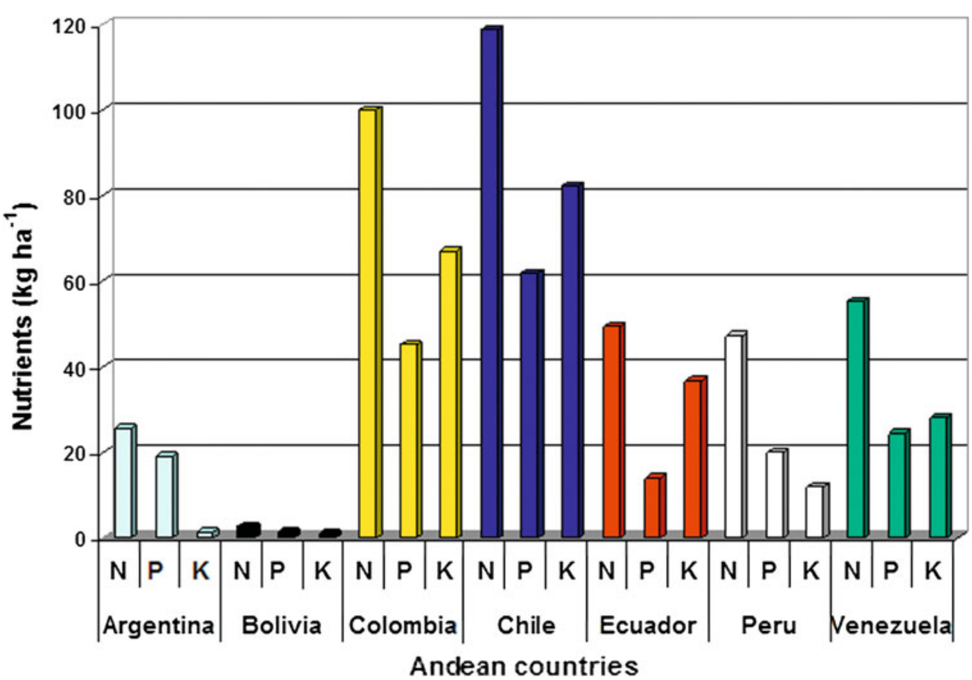

Table 3.3 Estimation of N supply in soils in the Mediterranean zone during the growing season

Soil use management	Nitrogen supply (kg N ha^{-1} $year^{-1}$)
Crop rotation with low yields (>4 year after pasture)	40–60
Crop rotation with high yields (>4 year after pasture)	60–80
Crop rotation (2–4 year after pasture)	80–100
Degraded pasture (1 year after pasture)	100–120
Good pasture (1 year after pasture)	120–150

Table 3.4 Bulk deposition of nitrogen to soils in the Mediterranean zone of Chile

Vegetation	Bulk deposition (kg N ha^{-1} $year^{-1}$)	References
Sclerophyll forest	8.2	Cisternas and Yates (1982)
Evergreen forest	3.3	Godoy et al. (1999)
Pasture	6.9	Oyarzún et al. (2002)
Evergreen forest	3.4	

Pino 2002) and nitrification rates in soils (Huygens et al. 2011). On the other hand, few efforts have been made to test the applicability of computer models for accurate N rate calculations. For example, evaluation of the SimUlation of Nitrogen Dynamics In Arable Land (SUNDIAL) model in Mediterranean zone soils by Zagal et al. (2003) showed that dose rates and fertilisation strategy used by the farmers coincided with those calculated by the model.

3.1.3.2 Phosphorus

Volcanic ash-derived soils cover nearly 50–60 % of arable land in Chile and include Andisols and Ultisols located mainly in the southern part of the Mediterranean zone. These soils are rich in organic matter, possess high specific area, and have pH-dependent CEC. Their surface potential and charge distribution vary substantially with pH and, to a lesser extent, with the concentration of equilibrating solution. Although these soils have many advantages for crop production, one of their main constraints is high phosphate retention, which commonly reaches values over 90 %. When any phosphate is added to the soil, there is immediate competition between plant roots and the soil, and much of the phosphate fertiliser added is retained by soil colloidal surfaces.

Inorganic P retention depends on many physical and chemical properties such as chemical adsorption (Carrasco et al. 1993), but in the Mediterranean zone also soil mineralogy and soil pH. Andisols and Ultisols, with a common mineralogical sequence of evolution but formed under different climate conditions and time, are composed principally of allophane (amorphous aluminium silicate of variable Al to Si ratio), at the surface of which Al- and Fe-humic complexes predominate, presenting high retention capacity because of their greater surface area (Besoaín et al. 2000; Escudey et al. 2001). For instance, Fig. 3.6 shows the strong positive relationship ($R^2 = 0.80$) between phosphate retention and ammonium-oxalate extractable $Al_{ox} + ½Fe_{ox}$ established for Chilean volcanic soils. In most cases, when $Al_{ox} + ½Fe_{ox} > 3$ % phosphate retention in soils is around 100 %.

In Andisols and Ultisols of the Mediterranean zone, phosphate retention is evidenced by low P availability to plants (Montenegro 1989). Thus, the ISRID scheme has focused its efforts on supporting farmers to apply phosphate fertilisers. Plants can present different adaptations to obtain phosphates in high phosphate retention soils. For instance, Sadzawka (1989) examined wheat and lupin growing in a phosphate-deficient Andisol and found that lupin was more efficient in P uptake than wheat because the acidified rhizosphere increased the solubility of P compounds in the soil.

In addition, after the initial rapid allophanic adsorption, any added P is also subjected to reactions resulting in the formation of organic-P forms (Borie and Zunino 1983). Thus, in these soils a large proportion of P is found in organic forms which are not available to plants (Escudey et al. 2001; Borie and Rubio 2003). However, Borie et al. (1983) found that soil fungal populations were particularly active in solubilising these organic phosphates. On the other hand, compared with agricultural soils, forest soils show a higher P cycling rate due to higher fungal activity, root phosphatase activity and organic acid excretion, resulting in higher P bioavailability (Borie and Rubio 2003).

3.1.3.3 Cations

Potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) in a typical soil are present in the solution phase (intensity), but are predominantly adsorbed on the soil's exchange complex (quantity). In Chilean soils, cation availability depends mainly on type and amount of clay minerals, CEC and climate factors such as rainfall amounts (Ruíz and Sadzawka 1986; Gacitúa et al. 2008). In particular, CEC and ECEC have been used to evaluate the capacity of soils to supply plants with K^+, Ca^{2+} and Mg^{2+}. Sadzawka (2006b) related the CEC and the ECEC status to soil order within the Mediterranean zone and found that Histosols and Vertisols presented the highest CEC values, related to the higher amount of exchange sites associated with organo-mineral complexes and clay, respectively (Table 3.5).

Rainfall effects are important for cation availability in some Chilean soils, for example in the Southern

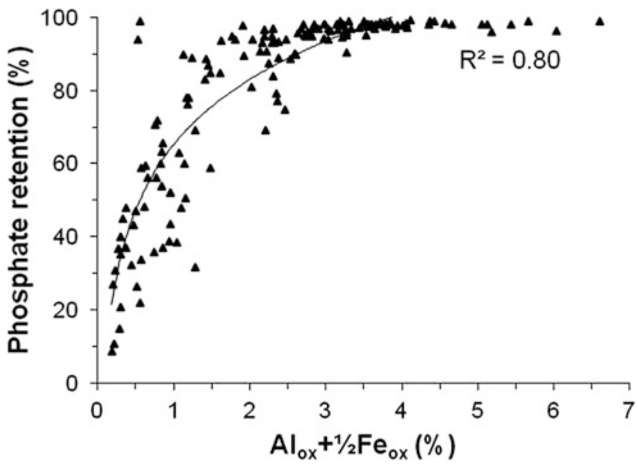

Fig. 3.6 Relationship between phosphate retention and Al_{ox} + ½Fe_{ox} in volcanic ash-derived soils in the Mediterranean zone of Chile (n = 162)

Table 3.5 Cation exchange capacity (CEC) and effective cation exchange capacity (ECEC) at 0–20 cm in different soil orders in the Mediterranean zone of Chile (from Sadzawka 2006b)

Soil order	CEC		ECEC	
	Range ($cmol_c\ kg^{-1}$)	Average	Range ($cmol_c\ kg^{-1}$)	Average
Entisols	4–36	11	2–13	7
Inceptisols	4–87	16	1–35	7
Alfisols	4–49	19	2–26	10
Mollisols	5–64	22	4–56	17
Ultisols	17–60	23	2–9	5
Andisols	7–76	37	1–18	6
Vertisols	17–75	41	15–67	33
Histosols	71–72	72	–	–

Mediterranean zone cation leaching is recognised as a major factor in limiting productivity (Bernier and Alfaro 2006). Most soils in this zone display BS <50 %, and crops usually respond positively to fertiliser application (Montenegro and Rodríguez 1985). Another soil factor that can cause plant nutrient deficiency, mainly of potassium, in the Northern Mediterranean zone is fixation in soils with high 2:1 clay contents (Ruíz and Sadzawka 1986).

3.1.3.4 Sulphur

Sulphur (S) deficiency of crops, which has been reported with increasing frequency over the past two decades on a worldwide scale, is a factor that reduces yield and affects the quality of harvested products (Scherer 2009). In Chile, S applications to soils are mainly recommended for some crops, such as sugarbeet, in the Southern Mediterranean zone, whereas in the hyperarid to semiarid and Northern Mediterranean zones irrigation water contains enough sulphates (SO_4^{2-}) to cover crop requirements. In the Southern Mediterranean zone, adsorption of SO_4^{2-} by soils is an important factor in controlling its mobility and availability to plants. Martínez et al. (1998) found that SO_4^{2-} adsorption decreased with increasing pH of the equilibrium solution and that the ionisation fraction values of organic acids at equilibrium pH were correlated with the amounts of SO_4^{2-} adsorbed.

3.1.3.5 Micronutrients

In Chile, micronutrient availability for plant nutrition is directly related to soil reaction. As in other countries (Rashid and Ryan 2004), in the Hyper-arid to Semi-arid zone and in the Northern Mediterranean zone micronutrients such as iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu) in particular can present deficiencies due to high pH levels. Figure 3.7 shows a number of micronutrients and their relationships to soil pH_{water} at 0–20 cm depth in soils from the hyperarid to semiarid zone and the Northern Mediterranean zone, based on analyses carried out in the Laboratory of Soil and Water Chemistry at the University of Chile using the DTPA extraction method. In these examples, the relationships between micronutrients and soil reaction were best fitted using second-order polynomial equations.

Figure 3.7 shows a clear tendency for declining Fe availability as pH increases. The lower Fe values in soils are most often observed in high pH and calcareous soils located in the Hyper-arid to Semi-arid zone. Similarly, the availability of Zn and Mn decreases with increased soil pH, with most pH-induced Zn and Mn deficiency occurring in the same zones of Chile. For instance, at the Antumapu Experimental Station, which belongs to the Faculty of Agronomy at the University of Chile (33°S), soils pH is around 8.0 and plant species sensitive to low contents of Fe and Mn, such as *Citrus* sp., usually present deficiency symptoms (Fig. 3.8). In calcareous soils of the Hyper-arid to Semi-arid zone, farmers add acid or acid-forming material to dissolve or neutralise $CaCO_3$ and thus decrease pH and increase micronutrient availability (Sierra et al. 2007). However, differing results have been found depending on the pH buffering capacity of the soil.

In contrast, Cu availability does not show a clear correlation with pH (see Fig. 3.7), with high Cu contents even at pH higher than 7.0. This may be related to Cu contamination of irrigated soils due to copper mining activities, which are a potential source of contamination of surface waters with toxic trace elements, as discussed later in the section on Chemical Soil Degradation (Sect. 4.2.2).

Another important micronutrient in Chile is boron (B), with soil nutritional problems in the Hyper-arid to Semi-arid zone being generally related to B toxicity and in the

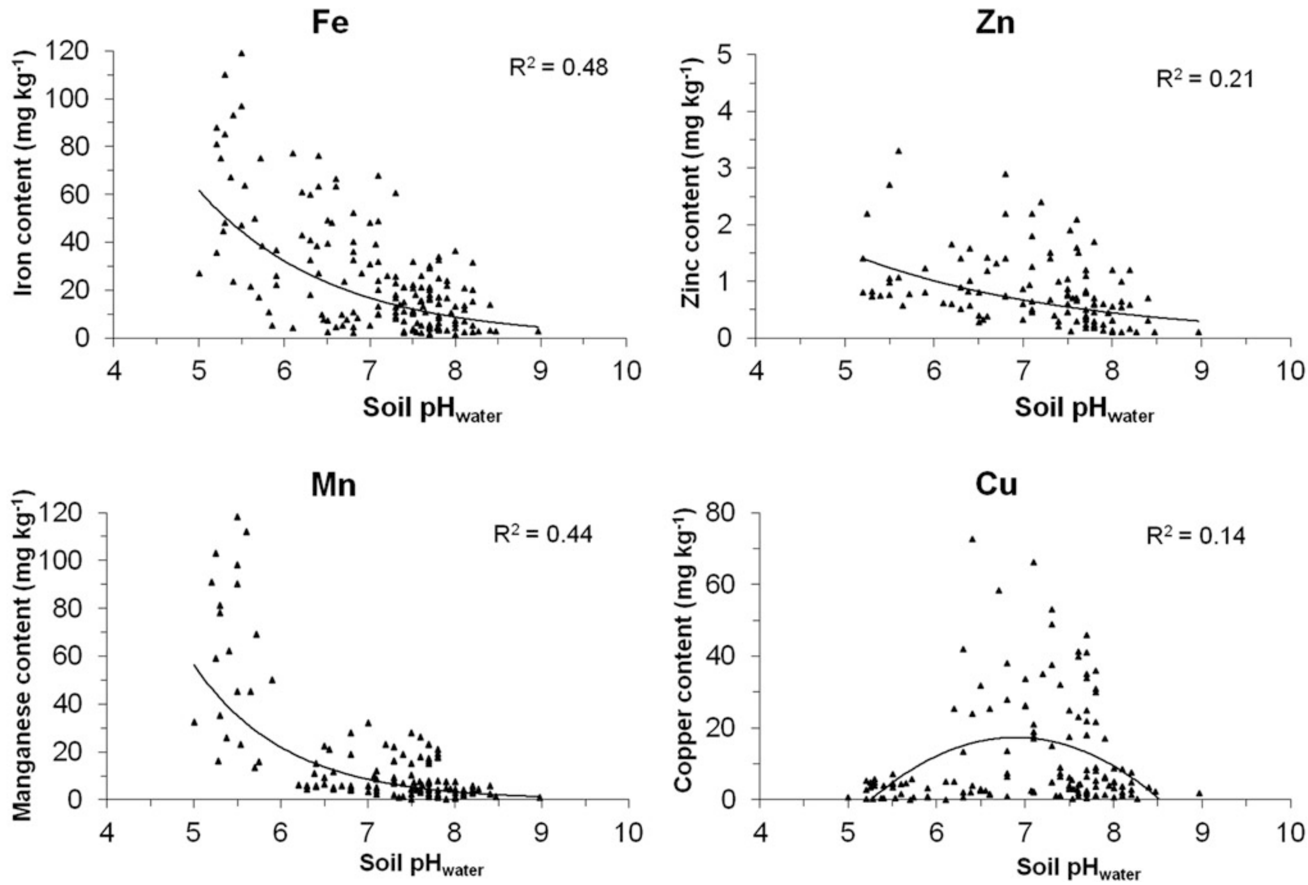

Fig. 3.7 Micronutrient contents (DTPA method) and their relationships with soil pH_{water} at 0–20 cm depth in agricultural soils in the Hyper-arid to Semi-arid zone and Northern Mediterranean zone of Chile. Fe (n = 150), Zn (n = 120), Mn (n = 130) and Cu (n = 145)

Mediterranean zone to B deficiency. Figure 3.9 shows B content and its relationship to soil pH_{water} at 0–20 cm depth in soils from the Hyper-arid to Semi-arid zone and the Northern Mediterranean zone. The analyses were carried out in the Laboratory of Soil and Water Chemistry at the University of Chile using a hot water extraction method. Although there is a tendency for B content to decrease as pH increases, particularly over pH 7.5, in the soil pH range 5.0–7.5 a broad range of values can be found. In some cases, the highest B contents occurring in soils are related to high B inputs with irrigation water.

3.2 Physical Properties

In Chilean soils, soil physical properties are strongly related to OM content and are thus dependent on climate and topography. However, parent material becomes relevant in the case of volcanic ash-derived soils. Thus, the soil physical properties: bulk density, particle size distribution, water retention, structure stability and pore function in soils of the major soil zones are discussed below (see Sect. 2.2).

Fig. 3.8 Leaf symptoms of Fe and Mn deficiency in orange trees in the Mediterranean zone of Chile

3.2.1 Bulk Density

Although soil bulk density (Db) is a physical property that is very dependent on soil texture (Brady and Weil 2000), OM input decreases Db because it promotes soil aggregation and abundant coarse pore formation, but also because

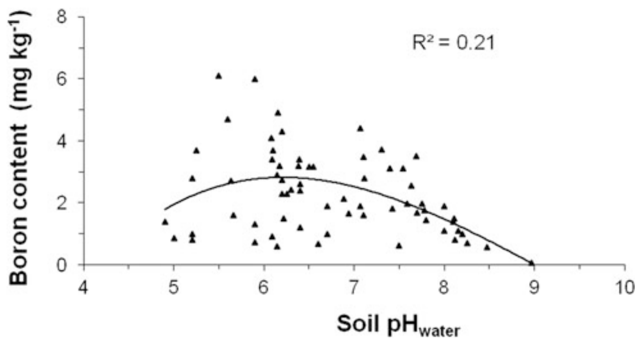

Fig. 3.9 Boron content at 0–20 cm depth and its relationship with soil pH_{water} in agricultural soils from the Hyper-arid to Semi-arid zone and Mediterranean zone ($n = 66$)

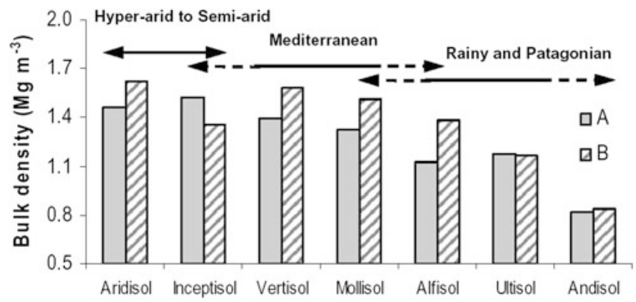

Fig. 3.10 Bulk density values for representative soils (according Soil Survey Staff 2006) along transect (north to south) in Chile. The values of surface (*A horizon*) and subsurface (*B horizon*) are included

of the low Db values of the OM itself (Hillel 2004). In this regard, it is possible to define a decreasing Db gradient from north to south in Chile according to dominant soil orders in the major soil zones (Fig. 3.10).

In general, for normal deposited materials, soil Db increases with depth in the soil profile (Hartge 2000). However, this tendency is altered when, for example, a plough pan is created due to excessive machinery traffic (Ellies 1986) or when in natural polygenetic conditions different materials are deposited in alternate events, resulting in variable Db in different soil horizons. In Andisols, the shape of the mineral particles produces very porous soils with high mechanical stability (Ellies 1988), maintaining low Db values with depth, as shown in Fig. 3.11 for representative soils from the Southern Mediterranean zone (data from CIREN 2003).

Inceptisols can be either fresh, coarse volcanic materials or unevolved fine materials as poorly developed soils due to weather conditions or type of parent material, with 10–40 % clay content. In any case, they have low Db values in the first 40 cm because of their high OM content (between 12 and 20 % in topsoil and 4–12 % at 40 cm depth). At the other extreme of soil evolution, Ultisols show high variability of Db values, depending on the parent material (old volcanic ash or metamorphic rocks from the Coastal Range).

Andisols in Chile are locally differentiated into *trumao* and *ñadi*, which are well-drained and poorly drained volcanic soils, respectively. The *ñadis* (in general, a Placaquand) are restricted in depth for a B_{hsm} horizon overlying the glacial deposit, determining the lower depth of these soils (80 cm on average). The poorly drained conditions, with high amounts of water during the year, promote the accumulation of OM in the profile (OM in topsoil >20 %), giving the lowest Db values among all soils. On the other hand, *trumaos* are deeper and slightly denser than *ñadis*, but always with Db values lower than 0.9 Mg m^{-3} according to Soil Survey Staff (2006).

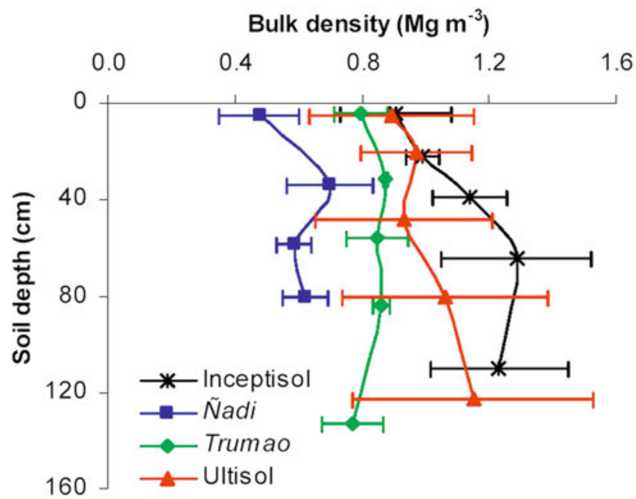

Fig. 3.11 Bulk density values and their variability (±SD) in function of depth for soils influenced by volcanic ashes along Mediterranean, Rainy and Patagonian zones. *Trumao* and *ñadi* are Andisols (see the text)

The OM gradient along the major soil zones (see Sect. 2.2) determines a dependency of Db on soil OM content, as is shown in Fig. 3.12 for representative soils under natural or low intensity use conditions.

In conclusion, from north to south there is an increase in OM content due to climate conditions (Padarian 2011) and a decrease in Db values due to the higher amount of OM and the ash-derived mineralogy (Besoaín 1985a). The latter determines the existence of low Db values with relatively low OM contents, moving away from the linear tendency in Fig. 3.12.

Particle density (Dr) varies between normal values in the soils with crystalline mineralogy (2.55–2.75 Mg m^{-3}), while in volcanic ash-derived soils (Andisols and Ultisols from the Rainy and Patagonian zones) the values can be more variable, depending on the OM and iron oxide contents. In Andisols, the values vary between 1.90 and 2.50 Mg m^{-3} (Nissen et al. 2005), owing to the high OM content, but in Ultisols the Dr values are higher (2.50–2.80 Mg m^{-3}), owing to the high iron oxide contents (Besoaín 1985a).

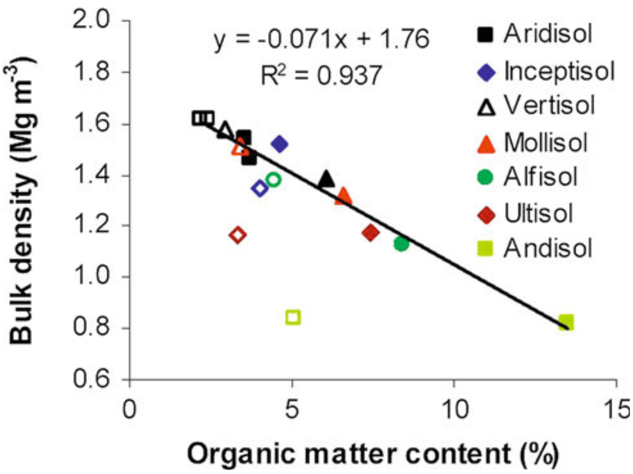

Fig. 3.12 Bulk density values along a soil organic matter gradient for representative soils from different soil orders according to Soil Survey Staff (2006). Full figures are from *A horizon* and empty figures are from *B horizon*. Line adjust excludes the subsurface values of Ultisol and Andisol

Fig. 3.13 Upper 100 cm in a Fluventic Haploxeroll (*left*, Isla Huechún soil series) and in an Entic Haploxeroll (*right*, Codigua soil series), both located in the same alluvial terrace of Mediterranean zone, separated by 20 m. Differences between soils determine a water availability of 16.7 and 6.6 cm, respectively (Ibáñez 2009)

3.2.2 Particle Size Distribution and Water Retention

As can be expected in a country of steep topography with active geological processes, the variability in soil texture is very high, and soils with different textural classes occur within a short distance and in the same physiographical position (Fig. 3.13). This prevents generalisations about the particle size distribution throughout Chile, and it is necessary to interpret the landscape in order to draw conclusions on some possible distributions (Birkeland 1999). In general, the Coastal Range is dominated by fine textured soils (derived from a granitic batholith between the hyperarid to semiarid and Mediterranean zones or from metamorphic rocks in the Mediterranean and Rainy and Patagonian zones). However, owing to erosion processes it is possible to find coarse-textured soils in the same formation and/or in creeks. In the valleys with permanent watercourses (Hyper-arid to Semi-arid zone) and in the Central Valley of the Mediterranean zone, the alluvial terraces are stratified and highly variable in textural classes, but from Chillán city (36°30′S) to the south, medium-textured soils (loam, silty loam, silty) dominate because of the dominance of allophane in volcanic ash-derived soils (Besoaín 1985b).

On the other hand, in the Hyper-arid to Semi-arid and Mediterranean zones the water retention depends on soil texture (Fig. 3.14), while medium to low OM content does not influence this property, giving higher differences between the field capacity and the permanent wilting point (defined by convention as the water retained at pore water pressure of −33 and −1,500 kPa, FC and PWP, respectively) at higher clay contents. Below the adjusted line for PWP (Fig. 3.14), the soil is excessively dry and plants do not have enough energy to absorb water from soil; above FC, there is free drainage of water through coarse pores, ensuring sufficient air-filled porosity for root respiration.

The dispersion around the adjusted lines in Fig. 3.14 depends not only on OM content, but also on clay mineralogy, soil structure, cations, salinity, etc. In general, for these kinds of soils there is a good correlation between water availability and clay content (Fig. 3.15).

Towards the south of Chile, the OM content increases, eliminating the dependency of water retention on clay content. However, the presence of volcanic soils with amorphous minerals creates a problem for correct determination of soil texture (Kimble and Nettleton 1984) because of the high charge of allophane and the risk of destroying particles if ultrasound is used. In this regard, there is a high variation in texture for the Andisols, depending on size of parent material (ashes or lapillis) and time of pedogenesis.

Figure 3.16 shows soil sand distribution in depth observing that Andisols from Chiloé Island present a lower variation and coarser textures than continental Andisols. On the other hand, *ñadis* can show a wide range of textures, depending on local conditions.

Inceptisols from Rainy and Patagonian zone show different textural classes, depending if they are fresh volcanic materials with low evolution or old parent materials eroded or non-evolved as a consequence of aquic conditions (for more details see Sect. 2.2). Ultisols from same zones are fine textured soils, dominating clay loam textures in surface

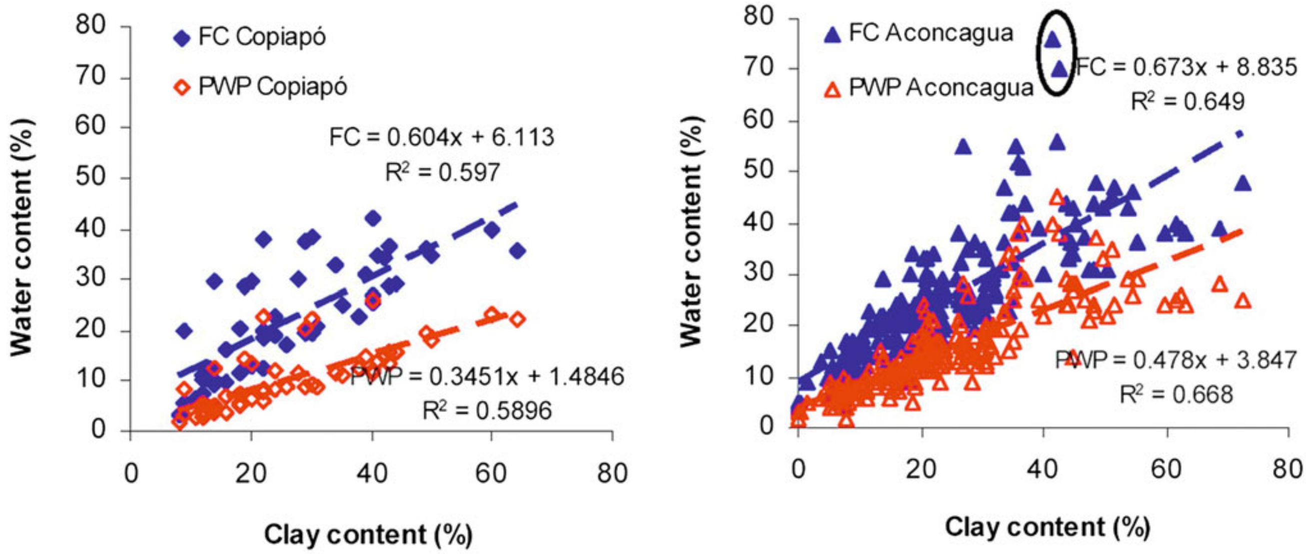

Fig. 3.14 Clay and gravimetric water contents at field capacity (*FC* −33 kPa) and permanent wilting point (*PWP* −1,500 kPa) for Copiapó Valley (Hyper-arid to Semi-arid zone) and Aconcagua Valley (Mediterranean zone). Values into the ellipse of Aconcagua Valley (upper horizons of Histosols) were excluded from the line adjust

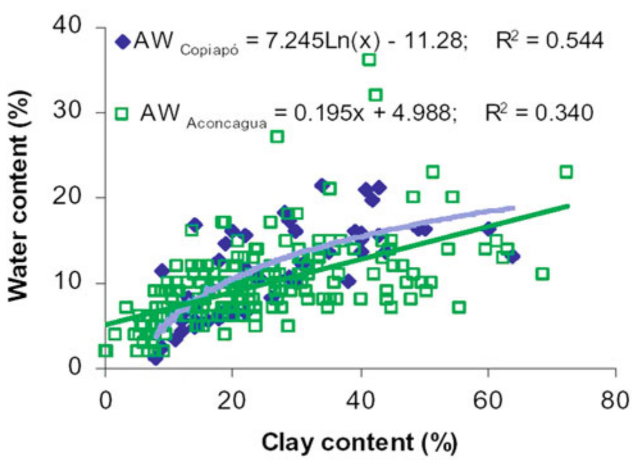

Fig. 3.15 Available water (AW) calculated as the difference in water content at FC and PWP from Fig. 3.14

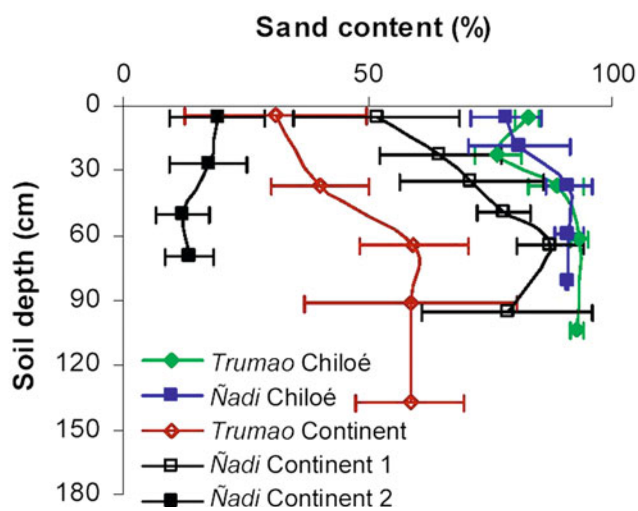

Fig. 3.16 Sand distribution in depth for well-drained Andisols (*trumao*) and poorly drained Andisols (*ñadi*) from continental land and Chiloé Island. *Ñadi* 1 corresponds to typical ash-derived soil and *ñadi* 2 correspond to more organic Andisol (Rainy and Patagonia zone)

and clay textures in depth. Nevertheless, the OM contents and the productive use in both soil orders determine different structural conditions, preventing to find a dependency between clay content and water retention (Fig. 3.17) as in northern regions.

Therefore, regardless of whether there is an effect on other soil properties, there is an increase in water retention from north to south in Chile, mainly owing to increased OM content and the dominance of short-range order minerals (Table 3.6). The only exception is the Andisols in the Rainy and Patagonian zone, which have lower water retention because of their lower pedogenic development.

3.2.3 Structural Stability

The physical and mechanical stability of soils ensures their functioning to maintain adequate productivity. Different approaches exist to evaluate the structural stability of soils, mainly focused on water stability and mechanical strength tests to characterise the behaviour of soils when wetted or submitted to external loads (Nimmo and Perkins 2002; Fredlund and Vanapalli 2002; Hartge and Horn 2009).

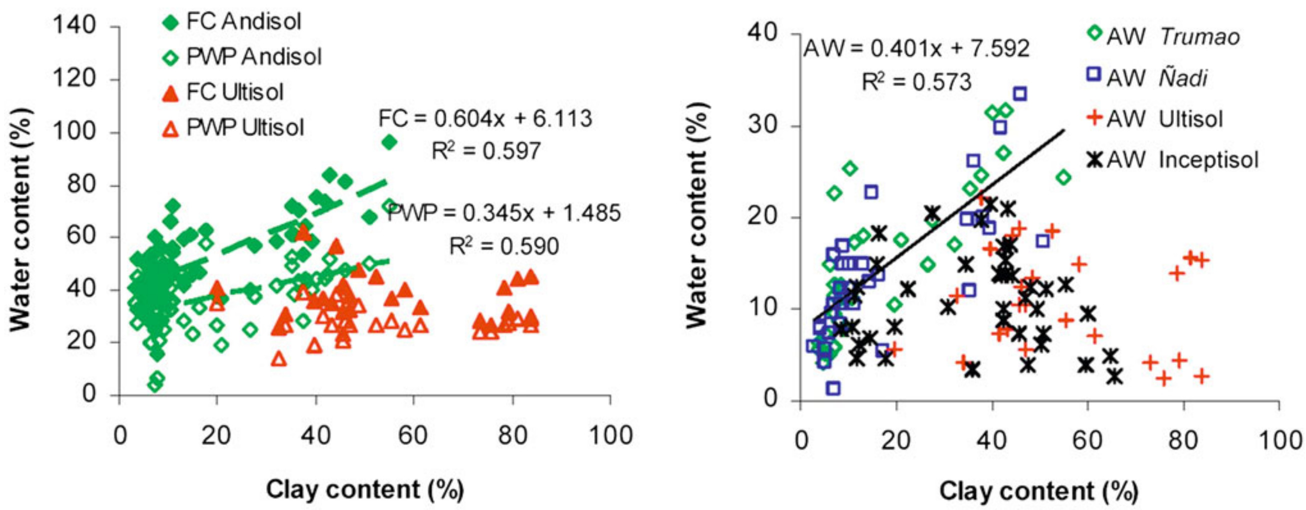

Fig. 3.17 Gravimetric water contents at field capacity and permanent wilting point (*left*) and available water, AW (*right*), for representative soils from Rainy and Patagonian zones. The line adjust of AW considers both kind of Andisols (*trumaos* and *ñadis*)

In relation to stability to water, the SOM content is essential to ensure adequate structure stability because it prevents the fast wetting of aggregates, avoiding air slaking (Chenu et al. 2000). On the other hand, it promotes unions among particles, increasing the contact points (Hartge 2000). According to this, it is obvious that there will be higher stability of Chilean soils influenced by volcanic materials as a consequence of their higher SOM contents, compared with soils from northern zones (Fig. 3.18). However, there is a significant influence of mineralogy and particle shape in volcanic ash-derived soils (Ellies 1988), which explains their high physical and mechanical stability even at low Db values.

The soils in Fig. 3.18 have natural vegetation or low intensity of use, so the results are close to non-altered conditions. The stability of the surface horizon is higher than that of lower horizons as a result of higher SOM content and more intense aggregation processes. On the other hand, there is a strong increase in aggregate stability (decrease in water dispersion) from Region VIII to the south, related to the increase in SOM content and the appearance of Andisols in the Central Valley (Padarian 2011). However, when soils are submitted to intense use, aggregate stability can decrease at critical levels due to SOM losses (Ellies et al. 2000). On the other hand, excessive SOM content can increase hydrophobic behaviour of

Table 3.6 Location, classification and properties for upper horizon of different soils along Chile, according to CIREN (1997a, b, 2003, 2005b, 2007)

Pedon	Region	Soil order	Textural class	Gravimetric water retention (−33 kPa) (%)	Gravimetric water retention (−1,500 kPa) (%)
Amolanas	III	Aridisol	Sandy loam	11.6	5.0
La Capilla	III	Aridisol	Clay loam	25.4	11.8
Encón	V	Inceptisol	Sandy loam	9.0	4.0
Pocuro	V	Mollisol	Loam	23.0	13.0
La Palma	V	Inceptisol	Sandy loam	21.0	9.0
Talca	VII	Alfisol	Loam	20.0	11.0
La Pelada	X	Inceptisol	Sandy loam	30.8	12.6
Los Ulmos	X	Ultisol	Clay	45.4	26.8
Puerto Fonck	X	Andisol	Sandy loam	48.1	29.3
Simpson	XI	Inceptisol	Sandy loam	31.8	19.1
Pollux	XI	Andisol	Sandy loam	31.9	22.0

See sandy loam Inceptisols by comparison

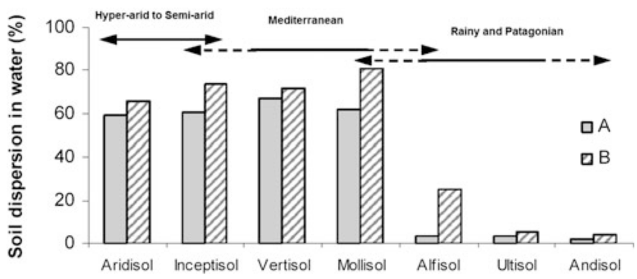

Fig. 3.18 Aggregate stability evaluated as a dry and wet sieving test (Hartge and Horn 2009), where the lowest value (lowest dispersion) denote the higher stability, along transect from north to south in Chile. Values of A and B *horizons* are included

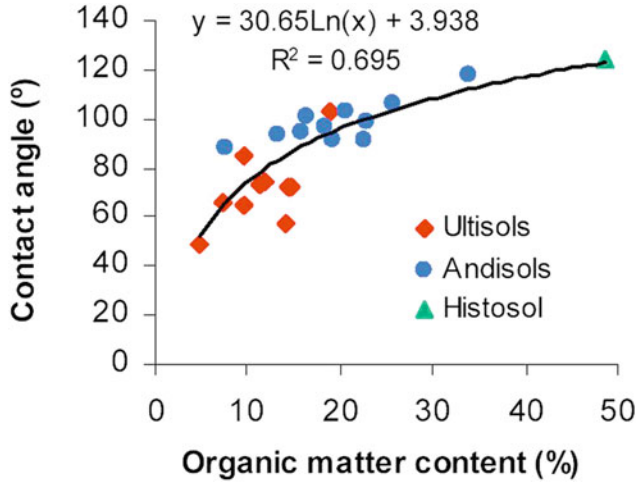

Fig. 3.19 Contact angle of soils from Rainy and Patagonian zone and their dependence on soil organic matter contents (adapted from Orellana 2010)

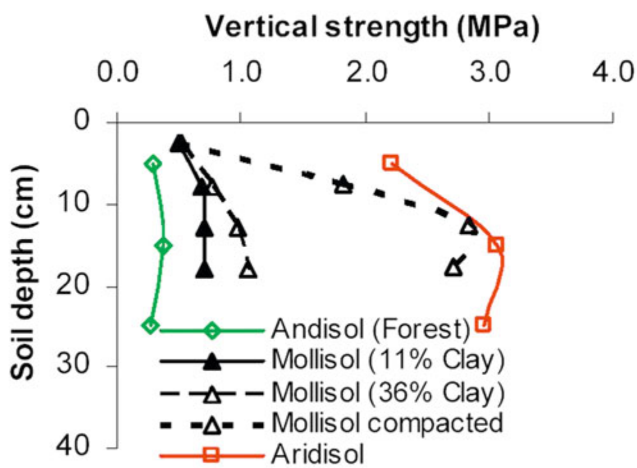

Fig. 3.20 Vertical strength evaluated by cone penetrometer in the ploughed horizon of different soil orders in Chile, 24 h after irrigation. Compacted Mollisol has a clay content of 30 %

the soil, resulting in an increased risk of soil erosion (see Sect. 4.2). Figure 3.19 shows the contact angle between water and solid particles, as a hydrophobicity index, for different soils influenced by volcanic ash materials.

Soils with contact angles higher than 90° are hydrophobic (Hallet 2008), a typical condition of Chilean Andisols (Ellies et al. 2005). Other soils in Chile have contact angles lower than 60°, explaining their high dispersibility in water (Fig. 3.18). The common trend for Andisols and Ultisols (Fig. 3.19) denotes a possible common origin for both groups of soils, or at least rejuvenation processes in Ultisols by inputs of new volcanic ash (Besoaín 1985a).

Mechanical stability depends on particle size distribution, soil aggregation, SOM content, bulk density, pore water pressure and other factors related to internal tension, but also on external factors such as type of load (weight of machinery, contact pressure), number of passes and use (Horn 2003). Figure 3.20 shows mechanical strength for different soils from Chile, evaluated with a cone penetrometer in vertical measurements and 24 h after a rain or irrigation.

The nature of Aridisols, with low SOM content and abundant cementing agents, explains their high mechanical strength despite their low stability in water. Intense use can increase the strength of some soils to critical levels, as it is a highly variable soil property. However, even with high intensity of use, Andisols do not reach values of mechanical strength higher than 100 kPa evaluated in wet conditions (Ellies et al. 2000), maintaining a relatively constant behaviour in mechanical properties under wet and dry conditions (Ellies 1988).

3.2.4 Pore Functionality

Basic soil physical properties such as Db and texture allow soil behaviour to be inferred within certain limits, but sometimes it is necessary for a more detailed characterisation to understand specific phenomena, for example gas and water transport, which are dependent on soil structure. In this regard, hydraulic conductivity (K) and pore size distribution are useful for making a correct diagnosis of the structural conditions (Ellies et al. 1997). Many efforts have been made by researchers in Chile to define an appropriate methodology to measure soil K (Pfeiffer et al. 2008; González et al. 2005; Luna 2003). In fact, Fodor et al. (2011) found that the effect of the evaluation method applied for assessing K can be just as significant as the effect of other factors, such as the scale effect, as well as the spatial and temporal variation. Table 3.7 presents values of saturated hydraulic conductivity (K_s) and its variation in Chilean soils.

Table 3.7 Saturated hydraulic conductivity (K_s) mean values for representative Chilean soils

Pedon	Region	Soil classification	$K_s \pm$ SD (m d^{-1})	CV (%)	Clay content (%)
Elisa de Bordos	III	Aridisol	8.51 ± 2.21	18.8	12
La Capilla	III	Typic Haplocambid	3.22 ± 0.92	28.6	31
Isla de Huechún	MR	Fluventic Haploxeroll	2.99 ± 1.80	60.2	22
Santa María	V	Typic Haploxeroll	7.23 ± 1.36	18.8	23
La Lajuela	VI	Ultic Haploxeralf	2.11 ± 0.92	43.6	15
La Obra	VII	Aquultic Haploxeralf	7.10 ± 0.92	13.0	27
Valdivia	X	Typic Hapludand	1.50		25
Malihue	X	Typic Hapludand	7.90		31

La Obra soil from Pfeiffer et al. (2008) and both Hapludand from Ellies et al. (1995). Clay content for Ap horizon is included

The data presented in Table 3.7 were obtained from sites with medium to low intensity of use, and showed low variability according to Jury et al. (1991). As expected, there was no correlation between soil orders or clay content and K_s, a property which is highly variable and dependent on management practices that affect the structure. Nevertheless, Ellies et al. (1997), working in a wide range of volcanic soils, determined a high correlation between coarse porosity (>50 µm) and K_s, showing also that if aggregate stability is high, temporal variation in K_s is low.

Depending on slope gradient and aspect, Casanova et al. (2000, 2003) measured different field non-saturated hydraulic conductivity (K_{ns}) values using a tension disc infiltrometer and established a direct relationship with clay content on Inceptisols from a toposequence in Central Chile. They concluded that with increasing site inclination, K_{ns} increases as result of higher lateral flow, which favours the process of soil slippage. On the other hand, Casanova et al. (2009) reported different K_{ns} values measured in soil monoliths (Table 3.8) and observed that in all soils K_s values were strongly negatively correlated to slope gradient. They attributed this to refraction of water flow, considering the greater frictional or viscous resistance generated by inclination.

Table 3.8 does not include all soils studied by Casanova et al. (2009). Evaluating four soils with different clay contents, they found a direct relationship between clay content and K_s, but it is not possible to generalise this dependence for Chilean soils, as noted for Table 3.7. Recently, Dörner et al. (2010) reported that K_s decreased for Andisols during water infiltration as a function of land use due to particle release, transport and re-sedimentation, which probably affects the pore continuity.

Except for the Andisols, it is not possible to relate K to coarse porosity, because the ability to conduct water also depends on aggregate stability to water. However, the ability to renew pore air is related to soil texture (Ferreyra et al. 2011) and structure (Poblete 2011), the latter particularly when evaluated as changes in coarse porosity as result of soil management (Fig. 3.21).

Table 3.8 Saturated hydraulic conductivity (K_s) estimated by tension disc infiltrometer in two soil monoliths arranged at different slope gradients

Soil classification	Slope gradient (%)	K_s (mm h^{-1})	Clay content ± SD (%)
Fluventic Haploxerolls	0	1.9	52.5 ± 2.11
	15	1.8	
	20	1.0	
	25	0.8	
Typic Xerochrepts	0	15.0	3.4 ± 0.10
	15	9.5	
	20	6.6	
	25	3.0	

Adapted from Casanova et al. (2009)

Again, it is not possible to generalise regarding the behaviour of air flux for Chilean soils, because the results depend on management (which affects the structure, see Fig. 3.21) and soil composition. In general, many soils under agricultural use have some degree of compaction (Ferreyra 2009), but the ability to conduct fluids will depend on the tortuosity, which can be affected by texture and the presence of coarse particles (Seguel et al. 2011).

In the case of soils under the influence of volcanic materials in the Rainy and Patagonian zone, Seguel and Horn (2006) measured values of air flux between 43 and 280 cm h^{-1} for aggregate beds simulating a ploughed horizon in Andisols equilibrated at −6 kPa, while Leiva (2009) measured a wider range of air flux in an Ultisol, with values being closely related to water conductivity.

Finally, Fig. 3.22 shows the dependence of drainage porosity on clay content for different soils in Chile. According to this, Chilean soils could present problems of

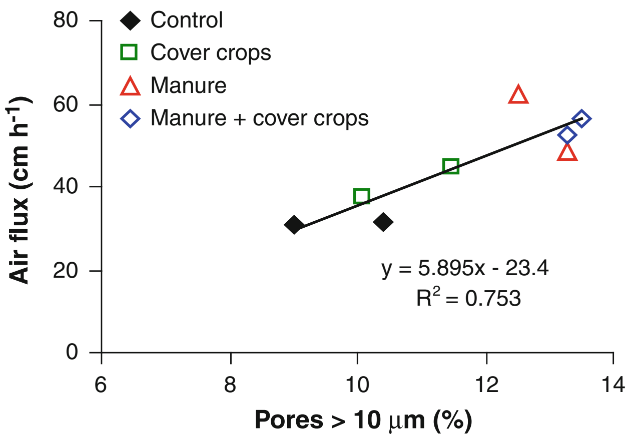

Fig. 3.21 Convection air flux depending on proportion of coarse pores in a compacted Aridisol subjected to different managements during 4 years

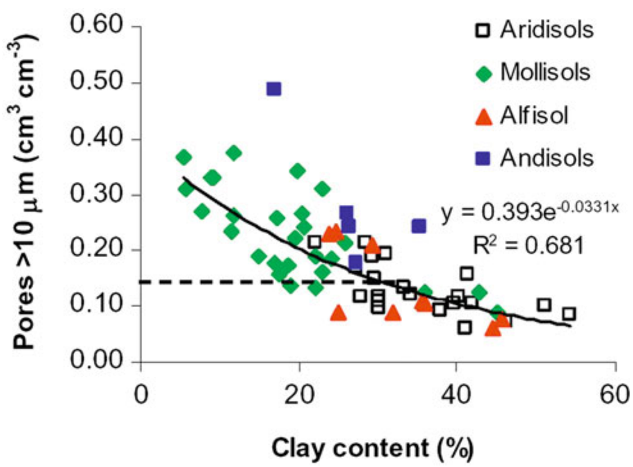

Fig. 3.22 Volume of pores >10 μm in relation with clay content for different soil orders from Chile. Andisols (taken from Ellies and Mac Donald 1984) were excluded from the line adjust. The *horizontal line* demarcates a critical level (0.15 cm^3 cm^{-3}), after Richards (1983)

low air porosity content with about 30 % clay, a very critical level in Aridisols and Alfisols, but not important in Andisols.

3.3 Biological Properties

Low diversity ecosystems are expected to be more vulnerable to global climate change, although they have received less attention than high diversity ecosystems (Wall 2007). As described in Chap. 1, natural barriers (Pacific Ocean, Antarctic, Andes Mountains and Atacama Desert) give an island connotation to the territory of Chile, resulting in moderate biodiversity compared with other South American countries. Badal (2008) concluded that given the smoothness of thermal regimes, the low incidence of extreme temperatures and the generally uniform Chilean weather, the most decisive factor in determining the evolution of the vegetation is the moisture in summer.

Soil biological properties such as soil organic matter (SOM) and soil biodiversity can affect several critical soil functions that support food production and environmental quality. It is well-known that SOM contains large reserves of soil organic carbon (SOC), a major factor controlling global warming. In addition, SOM contains large amounts of plant nutrients (especially N and S) and affects other chemical and physical soil properties, such as cation exchange and water-holding capacity. The activity of the soil biota is also responsible for nutrient transformations in soils and underpins a number of other fundamental chemical and physical soil properties.

These biological properties are revisited in this section, which examines in particular how these soil properties are affected by the soil moisture regime and vegetation in Chile.

3.3.1 Soil Organic Carbon

SOC content is directly related to precipitation regime (climate factor) and vegetation (organism factor). These two soil formation factors mean that soils in Chile may be roughly divided into soils with low SOC stocks (SOC ≤2.5 %) in the hyperarid to semiarid and Northern Mediterranean zones and soils with medium–high (SOC >2.5 %) stocks in the Southern Mediterranean and Rainy and Patagonian zones. For instance, desert and rainy forest landscapes are correlated with low and high SOC levels, respectively, as SOC may be lower than 0.5 % in the Hyper-arid to Semi-arid and in the range 5–20 % in forest soils classified as Andisols in the Rainy and Patagonian zone (Aguilera 2000). Figure 3.23 shows SOC in major soil zones in Chile at 0–20 cm based on a number of soil surveys carried out on 708 pedons in agricultural areas during the last 40 years by different government agencies (SAG 1974; CIREN 1996a, b, 1997a, b, 1999, 2002, 2003, 2005a, b, 2007; Ahumada et al. 2004). In the Hyper-arid to Semi-arid zone all the soils examined in these studies displayed SOC values lower than 5.0 and 96 % of the soils had SOC ≤2.5 %. The Mediterranean zone can be roughly divided into two zones related to the precipitation regime, a Northern or dry Mediterranean zone that has precipitation of 300–1,200 mm $year^{-1}$ and a Southern or wet Mediterranean zone that has precipitation of 1,200–2,500 mm $year^{-1}$. In the Northern Mediterranean zone, 81 % of the pedons analysed had SOC ≤2.5 %, 16 % of pedons had values in the range 2.6–7.5 %, and the highest SOC (20 %) was found in a

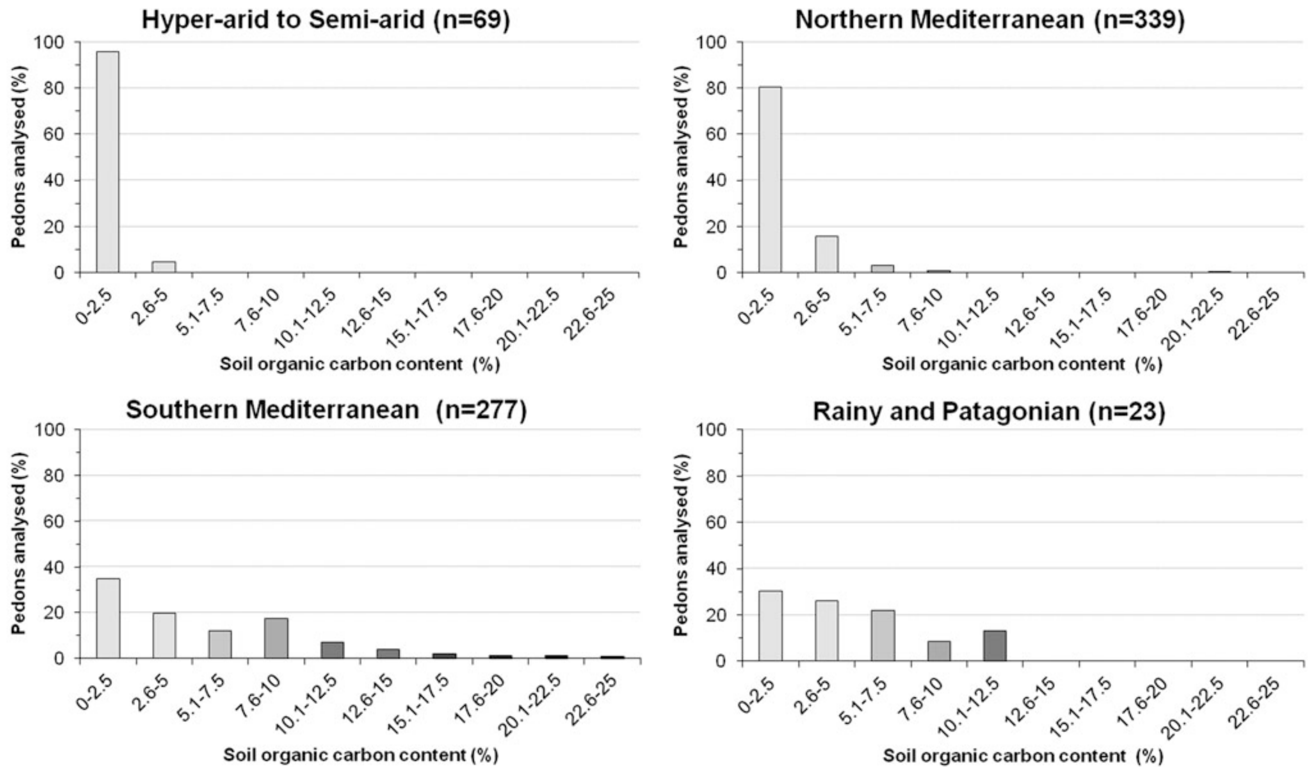

Fig. 3.23 Soil organic carbon ranges in major soil zones in Chile at 0–20 cm depth (n = number of pedons analysed)

Histosol in a lacustrine landform. In contrast, in the Southern Mediterranean zone, soils had high SOC contents, with 45 % of the soils having SOC higher than 5 and 16 % of soils having SOC contents higher than 10 %. Considering only two soil surveys carried out in the Rainy and Patagonian zone (CIREN 2005b; SAG 1974) with a limited number of soil descriptions ($n = 23$ pedons) for the extensive area defined, it is possible to find a broad range of SOC contents, with 56 % of the soils having SOC $\leq$5 %, 31 % with SOC in the range 5.1–10 % and 13 % of soils with SOC in the range 10.1–12.5 %.

Similarly, as was discussed for soil reaction (Sect. 3.1.1), SOC levels follow the same tendency as precipitation regime. The relationship between SOC stocks at 0–20 cm analysed in 708 pedons between the hyperarid to semiarid zone and the Rainy and Patagonian zone and latitude (UTM) were best fitted to a fourth-order polynomial equation, with R^2 of 0.57. For instance, Fig. 3.24 shows that SOC stocks are directly related to precipitation regime, increasing from levels lower than 2 % in the Hyper-arid to Semi-arid zone to levels higher than 10 % in the southern part of the Mediterranean zone. Furthermore, when the MAP decreases in the Rainy and Patagonian zone, SOC decreases to values around 2 %.

In the *espinal* agroecosystem, the SOC content usually shows a high variability in the upper soil. A possible explanation is that this zone is usually covered by Mediterranean annual prairie, including native *Acacia caven* trees in some patches (see Fig. 3.25). This contributes to microvariation in SOC by creating islands of fertility (Salazar et al. 2011). For example, Olivares et al. (1988) reported greater amounts of SOC and N stocks beneath *A. caven* canopy than in open grassland, which may explain the higher spatial variability in soil properties in the Mediterranean annual prairie. Similarly, Muñoz et al. (2007) in a study in the *espinal* Chilean agroecosystem found that *A. caven* canopy increased SOC stocks in the 0–40 cm layer by 25 % compared with intercanopy.

In soils of the southern part of the Mediterranean zone, Aguilera et al. (1997) noted that Andisols have higher SOC levels than Ultisols, but the fraction distribution in the latter suggests a shift of the more stable fractions to a more labile state. Those authors suggested that the content of humines and humic and fulvic acids may indicate that the OM in Chilean volcanic soil is highly humified.

Some studies have been carried out to determine the effects of agricultural practices on soil carbon fractions. For instance, Zagal et al. (2002a) examined an Andisol from the southern part of the Mediterranean zone and found a clear tendency for light OM fractions to decrease when soil use was intensified.

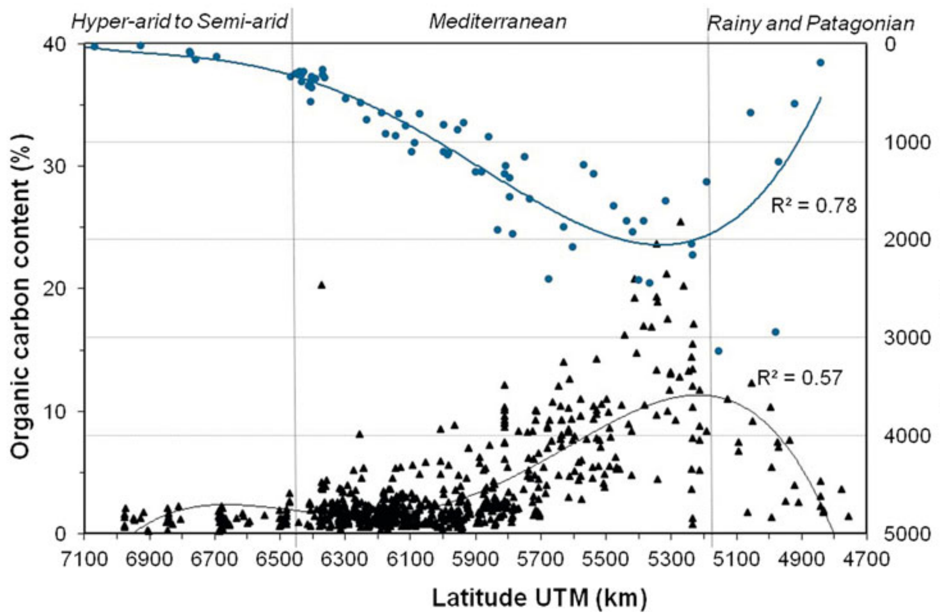

Fig. 3.24 Soil organic carbon (SOC) content at 0–20 cm in pedons between the Hyper-arid to Semi-arid and the Rainy and Patagonian zones. *Triangles* are SOC content in pedons ($n = 708$) and *circles* are mean annual precipitation obtained from 74 Chilean meteorological stations

Fig. 3.25 *Espinal* agroecosystem in the Mediterranean zone of Chile

In addition, the amount of SOM is a key indicator of soil fertility, and has been associated with the capacity of the soil to supply essential elements for plant production. For instance, Matus and Maire (2000) found that in the northern part of the Mediterranean zone, there was a close relationship between soil OC content and nitrogen mineralisation rate. Similarly, Rivas et al. (2007) noted that pristine temperate forest soils in the southern part of the Mediterranean zone receive low N additions by atmospheric deposition, so tree growth depends primarily on the internal recycling of nutrients present in the OM. In addition, Borie et al. (2002) noted that the natural N input processes in these soil systems are carried out by N-fixing microbes such as *Rhizobium* spp. and *Azotobacter* spp., endomycorrhizal activity and microbial synthesis of humic polymers.

3.3.2 Soil Biodiversity

Soil biodiversity reflects the mix of living organisms in the soil, which interact with one another and with plants and small animals, forming a web of biological activity. Biological activity in soils increases or decreases depending on land use and soil management and changes in activity have been evaluated for Chilean soils through different parameters, such as occurrence of species, soil respiration, radioactive tracer techniques, biochemical variables and glomalin content.

Castillo et al. (2010) reported that the diversity of arbuscular mycorrhizal (AM) fungal species is highly variable in agricultural soils in the southern part of the Mediterranean zone, and that the occurrence or absence of AM fungi is likely to depend on the various agronomic inputs that farmers have applied to crops over the years.

Soil respiration, expressed as carbon dioxide (CO_2) emissions, is one measure of biological activity and decomposition which reflects the capacity of soil to support life. Table 3.9 shows some soil respiration rates reported for agricultural and forest soils in Chile. There have also been some soil respiration studies on agricultural soils, for instance Zagal et al. (2002b) examined an Andisol in the Mediterranean zone (36°31′S) and found that the OM content of the different crop rotations correlated significantly with microbial activity.

This CO_2 production considered as carbon (C) mineralisation can be also evaluated using radioactive tracer techniques such as glucose ^{14}C, cellulose ^{14}C and organic residues ^{14}C. Zunino et al. (1982) analysed agricultural soils classified as Andisols in the southern part of the

Table 3.9 Soil respiration rate in different agricultural and forest soils in the Mediterranean zone of Chile

Vegetation	Respiration rate	References
Crop rotation	420–1,046 μg $C–CO_2$ g^{-1} 30 d^{-1}	Zagal et al. (2002a, 2002b)
Crop rotation	104–353 μg $C–CO_2$ g^{-1} 10 d^{-1}	Zagal and Córdova (2005)
Espinal forest	2.8–11.8 mg $C–CO_2$ 100 g^{-1} d^{-1}	Carmona et al. (2006)
Conifer forest	55.7 mg $C–CO_2$ 100 g^{-1} d^{-1}	
Nord-patagonia forest	10.4–65.6 mg $C–CO_2$ 100 g^{-1} d^{-1}	
Sclerophyll forest	0.5–0.8 g $C–CO_2$ m^{-2} h^{-1}	

Table 3.10 Glomalin content in topsoil in different ecosystems in the Mediterranean zone of Chile

Soil order	Vegetation	Glomalin (mg g^{-1})	References
Alfisol	Crop rotation (no-tillage)	1.8–3.6	Borie et al. (2000)
Alfisol	Pasture	1.6–2.1	
Andisol	Mixed forest	44–46	Seguel et al. (2008)
Andisol	Crop rotation	65	Morales et al. (2005)
Andisol	Evergreen forest	88–114	
Ultisol	Crop rotation	9–10	

Mediterranean zone and found that during 4 months, 70–79 % of the C in added glucose and cellulose had evolved as CO_2.

Other studies have determined soil biological properties through biochemical variables. Recently, Lillo et al. (2011) in a study in the high mountain areas (1,140–1,700 m a.s.l.) of the southern part of the Mediterranean zone determined soil biological properties such as fluorescein diacetate hydrolysis, carbon and nitrogen microbial biomass, β-glucosidase, carboximethylcellulase, acid phosphatase, urease and arylsulphatase. They found that these biochemical parameters were sensitive to changes in altitude, with the highest biological activities observed at the lower altitudes. Peirano et al. (1992) in an Andisol in the same zone found a direct relationship between microbial biomass and SOM.

Some studies have evaluated the production of glomalin, a glycoprotein produced by AM fungi, as an indicator of soil biological activity. Borie et al. (2000) studied an Alfisol in the southern part of the Mediterranean zone and found a close relationship among glomalin content, SOC and mycorrhizal hyphal density. Table 3.10 shows soil glomalin content in different ecosystems in Chile.

It is also possible that increasing soil biodiversity by soil inoculation with microorganisms may have some positive effects on crop yield. For instance, Redel et al. (2006) in a study of a strongly acidic Andisol in the southern part of the Mediterranean zone found that when wheat and lupin were inoculated with an exogenous AM fungus, the mineral uptake of Al decreased, which might contribute to reducing toxicity problems in acidic soils.

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