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RESEARCH PAPER

Physical assessment of a Mollisol under agroecological management in the Quillota Valley, Mediterranean Central Chile

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Abstract

M. Casanova, B. Ticona, O. Salazar, E. Gratacós, M. Pfeiffer, G. Ávila, Y. Tapia, O. Seguel, and C. Sabaini. 2020. Physical assessment of a Mollisol under agroecological management in the Quillota Valley, Mediterranean Central Chile. Int. J. Agric. Nat. Resour. 261-279. A number of agroecological practices have been proposed for assessing soil quality. Several physical soil properties have been shown to be important for determining soil quality by using the sustainability index (SI) and the cumulative rating approach. The main aim of the study was to determine the effects of different agroecological managements on the physical properties of a Mollisol in the Mediterranean central Chile. In addition, some physical properties were selected to compare the soil quality among different agroecological management practices and highly mechanized intensive systems by using the SI and cumulative rating approaches. An experimental field was defined in an area of 3.5 ha in 2014. Four sites with different agroecological practices were selected in 2019 to assess soil physical properties: rainfed Mediterranean annual prairie - no tillage (1-S), irrigated perennial prairie with deep-root species - no tillage (2-N), irrigated annual and perennial prairie - conventional tillage (4-S), irrigated vegetables and flowers - minimum tillage (4-N); an avocado orchard with traditional management was used as the control. Soil organic carbon and the following soil physical properties were selected to assess SI and CR: bulk density, total porosity, void ratio, air capacity, fast-drainage pores, relative field capacity, hydraulic conductivity, structural stability index and unavailable water pores. The applicability of the selected physical indicators to the SIs of agroecological management practices compared with the control was demonstrated. The cumulative rating index (CR) for each land use showed that all agroecological practices constituted sustainable soil management ($25 \leq CR < 30$), whereas the avocado orchard showed the least sustainable management ($30 \leq CR < 40$), and a change in soil use is recommended.

Keywords: Agroecology, cumulative rating approach, soil health, soil quality, sustainability index.

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Introduction

All Mediterranean-type zones worldwide appear to be hotspots of climate change and dwindling biodiversity (Myers *et al*., 2000; García *et al*., 2011). Because of their pleasant climate, Mediterranean regions have long been popular sites for human settlement, and the population density is high. Thus, Mediterranean regions are among the longest and most intensively exploited agricultural areas with increasing population pressure, which render their soils already depleted or more fragile. Furthermore, the scope and severity of human impacts in Mediterranean regions are currently accentuating the effects of climate change. These impacts could obliterate the efficient capacity for soil ecological resilience, which has managed to withstand other drastic and rapid changes in the past.

As in other Mediterranean zones, agriculture in central Chile is currently conducted under vulnerable conditions and is characterized by different forms of soil degradation (e.g., soil organic matter decline), water scarcity or overuse, disrupted nutrient cycles, land use change, high dependence on biomass and energy imports, and a prevalence of highly specialized and low-diversity agroecosystems. This scenario of vulnerability is also described by Aguilera *et al.* (2020), who urged the rapid adoption of systemic measures to increase the resilience of production systems and precision agroecological practices with high adaptation potential through the generation of local knowledge based on the integration of scientific and traditional ecological knowledge. Similarly, Ryan and Peigné (2017) concluded that agroecology, as a scientific discipline, will help facilitate efforts to respond to the actual challenges of agricultural production due to of increasingly applied systems thinking and interdisciplinary research approaches.

A wide range of agroecological practices have already been tested worldwide (Mendez *et al*., 2015; TWN and SOCLA, 2015) and in Chile (Montalba *et al*., 2017; Delpino-Chamy *et al*., 2019) to increase agroecosystem diversity and complexity and to act as a foundation for soil quality, plant health and crop productivity. However, there is a need to assess how these practices impact soil conditions, which are vital for crop production. In particular, soil physical conditions are prone to changes in the field due to management practices that play an integral role in controlling chemical and biological processes (Fuentes *et al*., 2014). Several physical soil properties (e.g., aggregate stability, available water capacity, and soil strength) have been shown to be important for determining yield and have been utilized as soil health or soil quality tests (Idowu *et al*., 2008; Schindelbeck *et al*., 2008).

The hypothesis of this study was that agroecological management improves the ability of soil to store water and improve the air capacity that is necessary for plant growth when compared to conventional management of avocado. Therefore, our objective was to determine the effects of agroecological practices on the physical properties of a Mollisol, which was initially an intensely managed avocado orchard in Mediterranean central Chile. In addition, we identified some physical soil properties for comparing soil quality among agroecological management practices and highly mechanized intensive systems by using the sustainability index (SI) and cumulative rating (CR) approaches.

Material and Methods

The CERES (Regional Center of Research and Innovation for the Sustainability of Agriculture and Rural Territories) is an experimental field that is located near Quillota City, Valparaiso Region, Chile (32°53'SL; 71°12'WL) at 220 masl (Figure 1). It was created to develop agroecological technologies, was established in 2014 and encompasses ≈3.50 ha, but 2.25 ha was designated for polyculture farming. In the previous management of agroecological practices, two subsoils at 0.6 m depth were constructed in perpendicular directions, and three consecutive (June 2015–January 2016–May 2016) high biomass prairies were then sown and incorporated into these soils (Figure 1).

From the different designed agroecological practices, four sites (e.g., 1-S, 2-N, 4-S and 4-N) were selected to assess the physical properties of soil using an avocado (*Persea americana* Mill.) orchard (5.50 ha) with traditional management, that was close to the experimental field and was used as the control (Table 1).

The study area is characterized by deep soils of colluvial origin that are on a slightly inclined plane (piedmont), which exhibit moderate permeability and good drainage and are classified as fine-loamy, mixed, thermic fluventic haploxerolls (CIREN, 1997). Morphological soil profile descriptions for each treatment were initially conducted in pits by collecting soil samples at 0–20, 20–40 and 40–60 cm depths (4 replicates) for laboratory characterization. In general, the dominant climate is Csb2 (Köppen system), i.e., temperate warm with Mediterranean influence with winter rains and an extended dry season (8 months), the average annual temperature is 13°C, annual rainfall is 430 mm and annual potential evapotranspiration is 1,350 mm.

Figure 1. Time evolution of the study area and distribution of five assessed sites (T0, 1-S, 4-S, 2-N and 4-N) in Mediterranean central Chile (Google Earth images, between 2015 and 2019).

Table 1. Treatments defined according to the agroecological practices applied in Mediterranean central Chile.

Treatment	Vegetal cover	Management	Tillage	Irrigation system
Control	Conventional irrigated avocado orchard	Chemical fertilization.	No tillage	Microsprinkler
1-S	Rainfed Mediterranean annual prairie, growing in winter	Cutting and residues left in the field.	No tillage	---
2-N	Irrigated perennial prairie with deep roots species	Cutting, residues removed to compost production.	No tillage	K-line sprinkler
4-S	Irrigated annual and perennial prairie (new apple trees)	Winter sowing, cutting and residues left in the field.	Conventional	Microsprinkler
4-N	Irrigated vegetables and flowers	Residues removed to compost production, which is later applied to seedbeds.	Minimum	Drip/trickle

Measured soil physical properties

Soil bulk densities (determined from cylinders and clods); particle densities (Pd, determined with pycnometers); textures (Bouyoucos densimeter) and pF curves (determined with sand beds and pressure-plate devices; at 0.2, 6, 33, 100 and 1,500 kPa) were calculated by following standard Chilean methodologies (Sandoval *et al.*, 2012). Soil saturated hydraulic conductivities, Ks1 and Ks5, were measured at 1 and 5 h, respectively, in undisturbed samples with an Eijkelkamp laboratory constant-head permeameter (Eijkelkamp, 2011).

Soil macroaggregate stability was determined as the mean diameter variation (MDV) by sieving soil samples in wet and dry conditions (Eq. 1, Supplemental Material 1), where n_{i1} is the dry sieved aggregate fraction (%), n_{i2} is the wet sieved aggregate fraction (%) and d_i is the weighted diameter of the aggregates (mm). On the other hand, soil microaggregate stability was assessed as the dispersion ratio (DR) by using Eq. 2 (Supplemental Material 1), which is defined as the ratio of the amount of clay+silt obtained in distilled water-dispersed samples (sd, soft dispersion) to that obtained in sodium hexametaphosphate dispersed samples (dd, drastic dispersion). High values indicate high dispersion of microaggregates and low soil stability.

The Atterberg limits (plastic and liquid) of soils were determined following the Test D-4318, standardized by the American Society for Testing and Materials (Das, 2016). The hydrophobicity or repellency index (R) was measured with a microinfiltrometer device (Hallett and Young, 1999; Cosentino *et al.*, 2010) from the sorptivity of aggregates (3 to 5 mm diameter) to deionized water and ethanol (95% vol.). Liquids were supplied to the aggregates through a micropipette tip with a 140 μm radius from a source at a constant hydraulic head (ψ=-1 cm) and according to Eq. 3 (Supplemental Material 1), where the constant (1.95) accounts for the difference in surface tension and viscosities of ethanol and water. $S_{ethanol}$ is the sorptivity for ethanol (mm $s^{-1/2}$), and S_{water} is the sorptivity for water (mm $s^{-1/2}$) of soil aggregates.

At the field level, soil penetration resistance (PR, N cm^{-2}) was measured with a digital force gauge (Enpaix EFG500) and conical tip (1 cm diameter/5 cm length) 24 h after irrigation at each site and included six replicates at each soil depth.

Finally, soil organic matter content (SOM) was determined through dry calcination at 360 °C for 16 h (Sadzawka *et al.*, 2006).

Estimated soil physical properties

Soil porosity, which is dependent on management treatments, was evaluated by examining several properties:

Total porosity (S) was obtained by using the cyBd and Pd values shown in Eq. 4 (Supplemental Material 1).

*Textural (*TP*) and structural (*SP*) porosities*: SP includes macropores (structural pores) that result from tillage, traffic, weather and biological activity, while TP includes micropores (textural pores) that result from the arrangement of elementary soil particles (Nimmo, 2004). Structural pores are subjected to short-term variations such as compaction by wheeling, whereas compaction does not affect textural porosity (Pereira *et al.*, 2019). Using soil density values, TP and SP were estimated using Eqs. 5 and 6 (Supplemental Material 1).

Void ratio (e): expresses changes in soil porosity for the same mass of soil regardless of the bulk density (Eq. 7, Supplemental Material 1). The e value may range from 0.25 to 0.80 for subsoils and from 0.80 to 1.40 for surface soils (Lal and Shukla, 2004).

Pore size distribution was derived from pF curves (Hartge and Horn, 2009; Pagliai and Vignozzi,

2002) as fast-drainage pores (FDP, >50 μm and water retention between 0.2 and 6 kPa); slow drainage pores (SDP, 10–50 μm and water retention between 6 and 33 kPa); available water pores (AWP, 0.2–10 μm and water retention between 33 and 1,500 kPa) and unavailable water pores (UWP, <0.2 μm, water retention at 1,500 kPa).

Air capacity (AC): determined by the difference between soil water content at saturation (Ws) and at field capacity (Eq. 8, Supplemental Material 1) and is an indicator of soil ability to store root-zone air (i.e., degree of soil aeration).

Relative field capacity to saturation (RFC): indicates the soil ability to store water and air relative to the total pore volume of the soil and was estimated using Eq. 10 (Supplemental Material 1).

Structural conditions were evaluated through the risks of the structural degradation index (StI, Eq. 9, Supplemental Material 1). Since StI is based on OC and texture, it is directly related to the resilience of the structure (Reynolds *et al*., 2009).

From the Atterberg limit results, the plastic index (PI, %) was obtained as the difference between LL and PL (Eq. 11, Supplemental Material 1), which is often used as an indicator of soil workability. Furthermore, the consistency index (Ic) was derived from these limits (Eq. 12, Supplemental Material 1), which indicates soil firmness and changes in gravimetric water content that allow the soil to vary from liquid to hard states. Therefore, an optimal range of water content (Wo) for agricultural use was estimated. The difference between PL (optimum conditions for plowing) and field capacity (W_{fc} or W_{33}) or permanent wilting point (W_{PWP} or W_{1500}) also provides a useful indication of soil workability (Kirby, 2002). If PL is close to W_{fc} or is much higher than W_{PWP}, soil will be suitable for working soon after drainage or when there is sufficient stored water, respectively. On the other hand, the activity values (Am; Eq. 13, Supplemental Material 1) were also calculated to infer some of the mineralogical properties of soils.

All of these measurements and estimations were considered to be the total data set (TDS), and principal component analysis (PCA) was used to select more effective soil physical indicators of management sustainability and conform to a minimum data set (MDS).

Relationships within the TDS were investigated by using parametric correlation analysis and by computing Pearson correlation coefficients. To assess soil sustainability in different agricultural management systems, a cumulative rating (CR) approach was also utilized (Shukla *et al*., 2006). Selected soil physical indicators were categorized on the basis of critical levels from none to extreme limitation on a scale of 1 to 5, respectively, by using a relative weighting factor (RWF) based on the limitations for crop production (Landon, 1984; Lal, 1994; Nwosu and Okon, 2020). Finally, the physical soil sustainability values for each site and soil depth were calculated by summing the RWFs (Table 2).

Table 2. Sustainability of a land use in relation to the cumulative rating index (CR, 10 indicators), according Lal (1994).

Cumulative rating index	Sustainability
<20	Highly sustainable (HSU)
≥ 20–<25	Sustainable (SUS)
≥ 25–<30	Sustainable with high inputs (SHI)
≥ 30–<40	Sustainable with another land use (SAU)
≥ 40	Unsustainable (USU)

Results and Discussion

The soils at the surface and at different depths are mainly medium textured, and the particle density (Pd) varies within a narrow range (Supplemental Material 2). A positive, significant correlation of bulk density (Bd), as determined from cylinders and clods, was observed with sand contents but the correlation was negative with soil clay and silt contents (Supplemental Material 3).

Both soil bulk densities showed similar trends in soils when agroecological practices were developed, which exhibited increases with depth and showed higher variations in surface areas. Reynolds *et al.* (2009) reported that the Bd (Mg m^{-3}) ranges for most soil textures were optimal ($0.90 \leq Bd \leq 1.20$), near optimal ($0.85 \leq Bd < 0.90$ and $1.20 < Bd \leq 1.25$) and at critical limits ($0.85 < Bd$ and $Bd > 1.25$).

Soils under traditional management (i.e., T0, avocado trees) maintained the highest Bd values, regardless of the determination method (Supplemental Material 2), suggesting increasing soil compaction at depth. In the same manner, in the upper soil horizons of all sites, penetration resistance levels (PR, N cm^{-2}) varied from medium ($50 < PR < 125$) to very dense ($200 < PR < 300$) according to Hazelton and Murphy (2016). However, in the subsurface soils of some sites (e.g., T0, 2-N and 4-N), the degree of soil consolidation was classified as extremely dense ($PR > 300$) (Supplemental Material 2).

It is known that Bd indirectly provides a measure of soil porosity and has an inverse relationship; in this sense, we found a strong negative correlation (Supplemental Material 3) between both of these properties. Likewise, void ratios (e), which have an advantage over total porosity (S) because their changes only result from changes in pore volumes with the volume of solids remaining unaltered and soil compaction findings, particularly for soil profiles of the avocado orchard, were corroborated (Figure 2). In fact, Li and Zhang (2009) report that

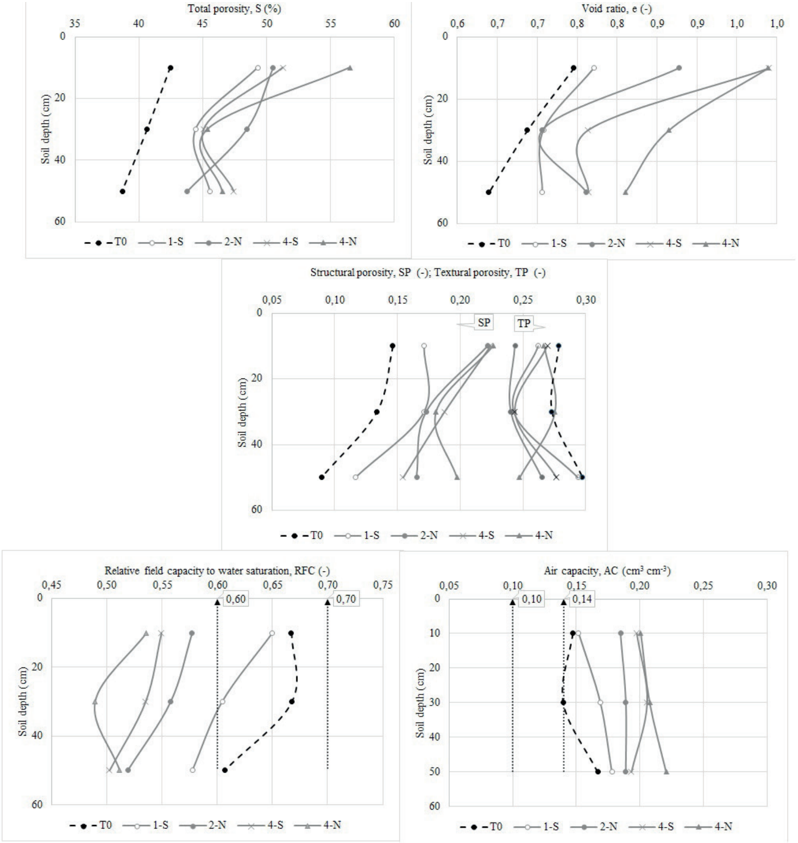

Figure 2. Assessment of soil porosity with depth following six methods, with conventional avocado orchard management (T0) and with agroecological management sites (1-S, 2-N, 4-S and 4-N) in Mediterranean central Chile.

e values become smaller (i.e., reduction of open pore space available for water flow) as compaction increases; then, soil permeability is directly proportional to e. Nevertheless, these results also indicate that for sites with agroecological management, subsoiling operations are effective only at the soil surface, considering that looser soils are those with higher e values than dense soils.

Textural porosity (TP) is only slightly affected by soil management, whereas structural porosity (SP) is sensitive to management factors such as tillage, compaction and cropping. Both Richard *et al.* (2001) and Kutilek *et al.* (2006) detected that soil compaction by intense management occurred mainly at the expense of SP. In this sense, similar trends among S, e and SP (but not TP) at all sites assessed in our study were observed (Figure 2). According to Pitts (1985), for the range of e values between 0.35 and 1.00, the soil skeleton remains stable (for most of the assessed sites), but if e values >1.00 are recorded, then the soil may be collapsible (for only the surface soils of 4-N and 4-S sites).

Air capacity (AC, cm^3 cm^{-3}) values were also estimated. Reynolds *et al.* (2015) concluded that high AC values (≥0.20) are considered ideal for maintaining atmospheric concentrations of O_2 and CO_2 in fine-textured soil; AC≈0.14 is equivalent to the lower optimal limit for adequate aeration of fine-textured soil and AC≈0.09 corresponds to the lower critical limit where fine-textured soil becomes susceptible to periodic anaerobiosis. At irrigated sites (e.g., 2-N, 4-N and 4-S), the AC values obtained were optimal and varied between 0.19 and 0.22 cm^3 cm^{-3} (Figure 2), but at T0 and 1-S (rainfed site), the AC values fluctuated between 0.14 and 0.18 cm^3 cm^{-3}, which were closer to values indicating poor aeration. Recently, Castellini *et al.* (2019b) suggested that optimal AC values are in the range of 0.10–0.26 cm^3 cm^{-3}, while higher or lower values represent inadequate soil aeration conditions.

RFC values indicate a soil's primary limitation with respect to water (droughtness) and air storage, and the optimal range (0.6≤RFC≤0.7) was defined by Reynolds *et al.* (2009). Lower values (RFC<0.6) can reduce microbial activity and nitrate production because of insufficient water (water-limited soil), whereas greater values (RFC>0.7) may indicate reduced microbial activity because of insufficient air (aeration-limited soil). In agreement with Castellini *et al.* (2019a), with RFC being a key soil physical quality indicator, Supplemental Material 3 shows that there are high negative correlations ($p<0.01$) of RFC with FDP, SDP, UWP and AC but there is a positive correlation ($p<0.05$) with AWP. Figure 2 describes the variations in soil depth at the assessed sites and shows that there are no values that are in the undesirable aeration range.

High to very high values of SOM in the upper horizons were observed, which decreased with depth (60 cm) to medium values (Supplemental Material 2). However, those sites where residues were left in the field (1-S and 4-S sites) showed higher SOM values than other sites. On the other hand, the SOM contents at the surface of the old (20 years) avocado orchard (T0) were higher than those at sites where organic residues were removed (2-N and 4-N).

Similar to the results of other studies (Lichner *et al.,* 2018; Mao *et al*., 2019), vegetation cover strongly influences surface SOM and impacts the level and distribution of soil water repellency (R); in fact, a significant correlation (Supplemental Material 3) between both variables was observed.

Soil water repellency is a common phenomenon that is observed postfire in Mediterranean forest soils but also in agricultural soils in which hydrophobic organic substances are produced during plant decomposition in rotations including legumes (Garcia-Chevesich, 2010; Casanova *et al*., 2013; Fuentes *et al.,* 2015). Considering the thresholds for the water repellency index (R) as defined by Iovino *et al.* (2018), all sites, particularly those with agroecological management, are included in the class of slight repellents (1.95≤R<10) at the soil surface (Supplemental Material 2), while at depth, the general trend changed to wettable soils (R<1.95). The highest R values were measured in sites where harvesting residues were incorporated into soil (1-S and 4-S), and following dry periods, exacerbated water repellency should be expected, and increasing summer droughts could worsen the problem.

Trafficability and workability (i.e., optimum conditions suitable for plowing) are soil capabilities which support the operations of agricultural machinery while avoiding soil degradation risk (Müller *et al*., 2011). Soils that have poor trafficability and a narrow range of water contents in which cultivation is beneficial (Wo) are difficult to manage and are susceptible to compaction (Kirby, 2002).

Optimal soil water contents (Wo, Eq. 12, Supplemental Material 1) for soil cultivation are estimated to occur when soils are stiff and have an Ic (index of consistency) between 0.75 and 1.00; drier soils increase the energy input needed for cultivation, which can be a serious problem for fine-textured soils as plowing can become difficult. For the case of lower than optimal Ic, soil structures can easily be destroyed when the soil is kneaded by trafficking, and cultivation can have serious effects on plant growth and soil biological activity (Baumgartl, 2016). In this sense, a low soil degradation risk is expected when Wo values that are favorable for workability are estimated and differentiated by site. Therefore, during tillage and according to Figure 3, we estimate that the rainfed site (1-S) should have a high Wo (17 to 19%), 4-S site should have a medium Wo value (15 to 17%) and 2-N and 4-N sites should have low Wo values (10 to 15%) in the plowed layer.

For fine-textured soils, it is possible to use clay contents and the plastic index (Eq. 11, Supplemental Material 1) to compute some mineralogical

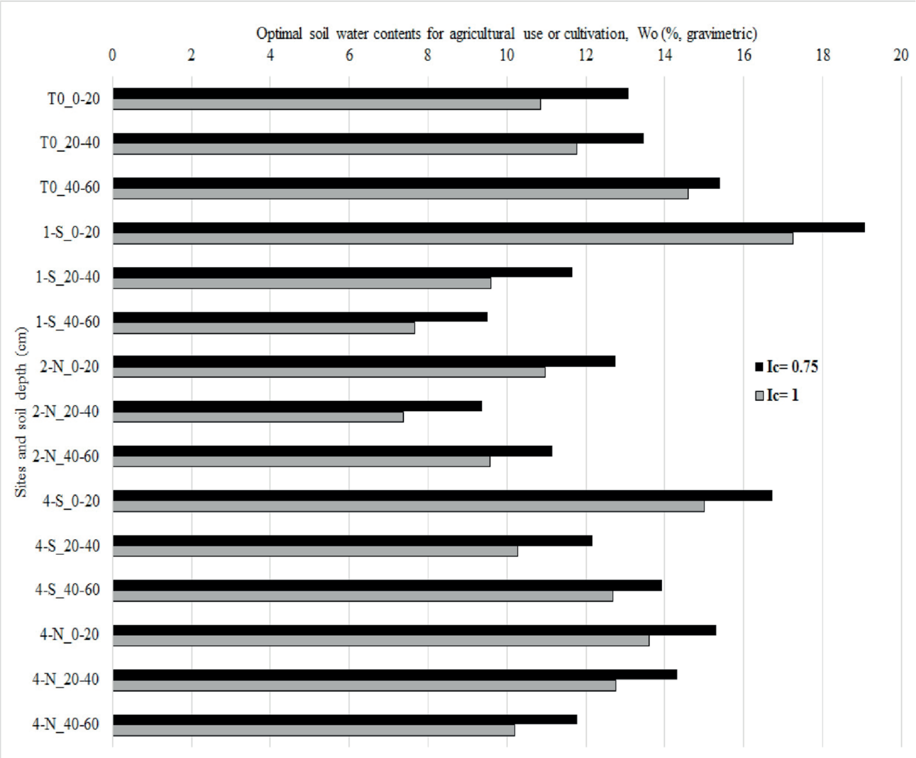

Figure 3. Gravimetric water contents (Wo) for optimum agricultural use (avoiding physical soil degradation risk) that were estimated with index of consistency (Ic) values of 0.75 and 1.00 for each site and soil depth. Agroecological management (1-S, 2-N, 4-S and 4-N) and conventional avocado orchard management (T0) in Mediterranean central Chile.

features of soils because there is a fairly close correlation between clay mineral type and activity (Lambe & Whitman, 1969). Activity of clay (Am) values allow differentiation of active soils with a high capacity for swelling and shrinking ($Am \geq 1.25$), illitic ($0.75 < Am < 1.25$) and kaolinitic soils ($Am \leq 0.75$). The values obtained at all sites (0.18 to 0.40, Supplemental Material 2) confirm the homogeneity of the studied field as well as the kaolinitic mineralogy domain in the soils of Mediterranean central Chile informed by CIREN (1997).

It is often argued that agroecological management tends to favor and enhance soil structure (Lozano *et al*., 2015; Ryan & Peigné, 2017) by using practices that are oriented to preserving soil stability. Pulido Moncada *et al.* (2014) described the structural stability index (StI, Eq. 9 in Supplemental Material 1), which allowed us to classify cultivated soils as structurally degraded ($StI \leq 5\%$), with high structural degradation risk ($5\% < StI < 7\%$), with low structural degradation risk ($7\% \leq StI < 9\%$) and with good conditions for maintaining structural stability ($StI \geq 9\%$). In this sense, 1-S and 4-S sites showed higher values, while 2-N and 4-N sites fell in the degraded range.

In our study and in agroecological management, reductions in macroaggregate stability (higher values of MDV, Figure 4) occurred in depth, which were explained by the small influence of pedogenetic processes (e.g., wetting-drying cycles and SOM dynamics) at these depths. Therefore, more labile organic compounds would promote bonding among soil mineral particles, which would improve macroaggregate stability in the upper horizons. On the other hand, SOM contents were affected by subsoiling and favored its oxidation, which took place mainly in the lower horizons with a subsequent decrease in macroaggregate stability.

Most soils contain microaggregates that are composed of a vast variety of organic and inorganic material that are bound together during pedogenesis by several processes, which enable them to withstand strong stresses, survive slaking in water and persist in soils for decades (Totsche *et al*., 2018). Although little is known regarding how microaggregates and their properties change over time (Ritschel and Totsche, 2019), which strongly limits our understanding of microscale soil structure dynamics, similar behavior between the structure stability index (StI) and dispersion ratio (DR, Eq. 1 in Supplemental Material 1) was observed but not between StI and MDV. Higher DR values (i.e., lower stability), even than those for T0, were detected for sites where harvesting residues were exported (2-N and 4-N), which indicates low resistance of soil microaggregates to breakdown by water; instead, for those sites where residues were left in the field, lower DR (high microaggregate stability) values were observed, but few cases were below the threshold

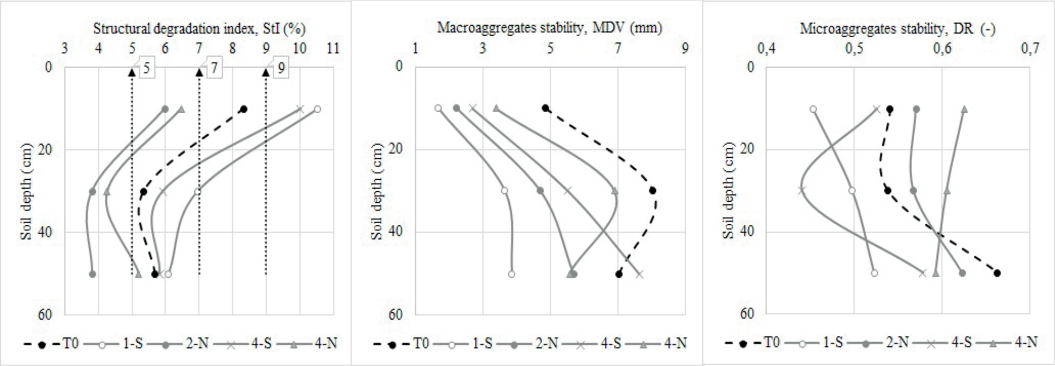

Figure 4. Structural degradation index and aggregate stability with soil depth for each agroecologically managed (1-S, 2-N, 4-S and 4-N) and conventional avocado orchard management (T0) systems in Mediterranean central Chile.

level of DR<0.3 reported for highly stable soils (Brunel *et al*., 2016).

The highest values of fast-drainage pores (FDP≥17%) were detected at the surfaces of sites under different agroecological practices, whilst in T0 were lower than 13% (Figure 5). Moreover, the average difference between available water pores (AWP) and unavailable water pores (UWP) showed contrasts among the soil profiles and followed a trend of $T0_{11\%} > 1\text{-}S_{8\%} > 4\text{-}S_{7\%} > 2\text{-}N_{6\%} > 4\text{-}N_{3\%}$. Significant negative correlations, with *p* values <0.01 (n=60) between the measured properties and FDP were observed (water retention between 6 and 1,500 kPa; MDV; Bd and PR). Additionally, significant positive correlations with *p* values <0.05 (n=60) were detected for Ks1, Ks and Pd (Supplemental Material 3).

There were fewer slow drainage pores (SDPs) in the avocado orchard than in agroecological practice sites (Figure 5). In addition, it is known that for soils with few slow drainage pores (SDPs) and conversely, with abundant FDPs, soil water will decrease very rapidly; in this case, among the studied sites, it was notable that the nonirrigated site (1-S) exhibited an average value of 13% in its soil profile.

Most measured and/or estimated soil properties were included in the principal component analysis (PCA) to extract the smallest number of factors that could explain most of the total variation. Two factors extracted by PCA explained 55% of the total variance in the samples (Figure 6). The first factor accounted for 33%, and the second accounted for 2%. The highest loadings in the first factor group

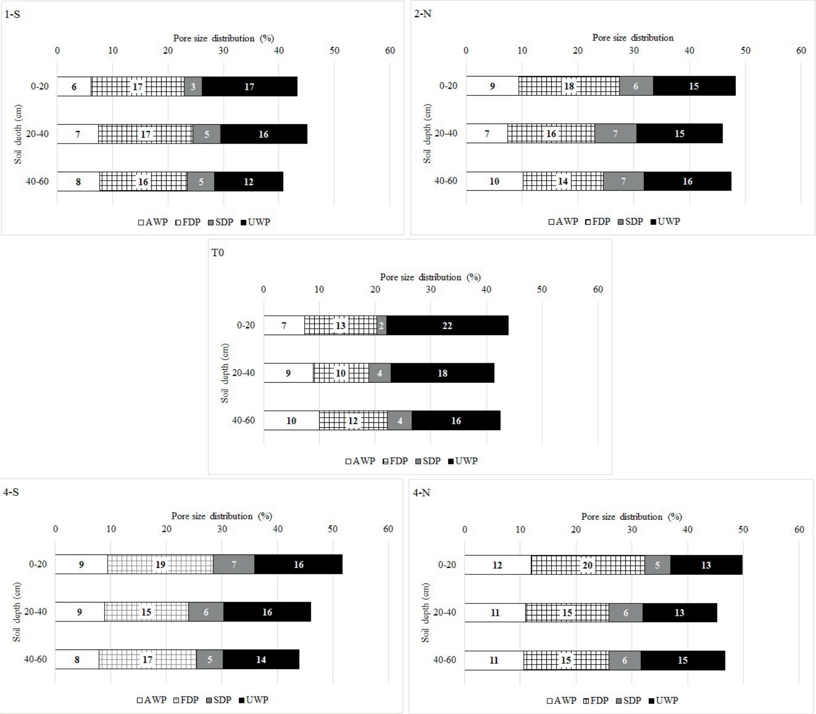

Figure 5. Soil pore size distributions under different agroecological management practices (1-S, 2-N, 4-S and 4-N) and conventional avocado orchard management (T0) in Mediterranean central Chile. (UWP: unavailable water pores, AWP: available water pores, SDP: slow drainage pores, and FDP: fast-drainage pores).

were bulk density (cyBd), total porosity (S), void ratio (e), air capacity (AC), fast-drainage pores (FDP) and relative field capacity (RFC). The second factor had a high factor loading for soil organic carbon (SOC), hydraulic conductivity (Ks5), structure stability index (StI) and unavailable water pores (UWP). Thus, we selected those properties to assess practices and agroecological management sustainability (Table 3).

Considering all soil profiles (0–60 cm), cumulative ratings of 33, 29, 29, 26 and 25 were obtained for T0, 1-S, 2-N, 4-S and 4-N sites, respectively, which indicated that T0 is sustainable only with another use but for the other sites, the current land uses and management systems are sustainable with high inputs (Table 4). Similar results were observed when 0–40 cm soil depths were assessed. Only surface soils (0–20 cm) at the 4-S and 4-N sites showed greater sustainability under current agroecological land use and management.

Conclusions

Our results indicate that subsoiling and other initial operations at sites with agroecological management are effective only at the soil surface (0–20 cm), which emphasizes the lower bulk densities and penetration resistance values obtained with agroecological management, as well as the higher values of porosity indicators when compared to intensive management. In this sense, the potential usefulness of measured

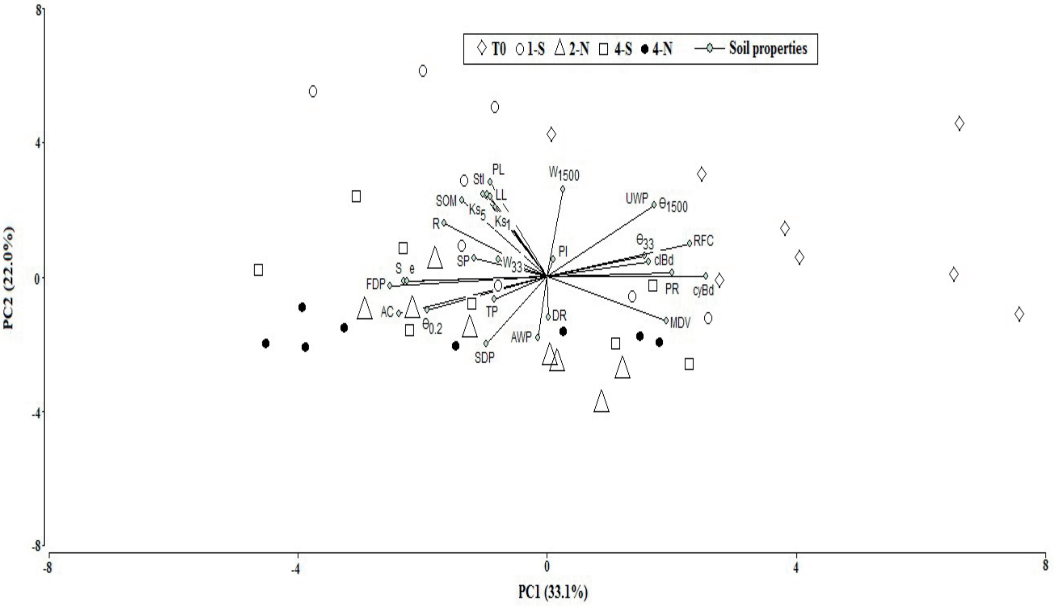

Figure 6. Principal component analysis of soil properties (e.g., AC, air capacity; AWP, available water pores; UWP, unavailable water pores; clBd, bulk density determined from clods; cyBd, bulk density determined from cylinders; DR, dispersion ratio; FDP, fast-drainage pores; R, hydro-repellency index; LL, liquid limit; MDV, mean diameter variation; Pd, particle density; PR, penetration resistance; PI, plastic index; PL plastic limit; PC1, first principal component; PC2, second principal component; RFC, relative field capacity to water saturation; SDP, slow drainage pores; SOC, soil organic carbon; SOM, soil organic matter; SP, structural porosity; TP, textural porosity; S, total porosity; e, void ratio; $\theta_{0.2}$, volumetric water content at 0.2 kPa; θ_{33}, volumetric water content at 33 kPa; θ_{1500}, volumetric water content at 1,500 kPa; W_{33}, gravimetric water content at 33 kPa; and W_{1500}, gravimetric water content at 1,500 kPa) at 0–40 cm soil depth in sites with different agroecological managements (1-S, 2-N, 4-S and 4-N) and conventional avocado orchard management (T0) in Mediterranean central Chile (n=40).

Table 3. Relative weighting factors (RWF) based on threshold values of soil physical indicators by using the cumulative rating (CR) approach; adapted from Landon (1984), Lal (1994), Cass (1999), Hazelton and Murphy (2016), Nwosu and Okon (2020)

Limitation	RWF	AC	S	cyBd	e	RFC	SOC	StI	FDP	UWP	Ks5
		cm^3 cm^{-3}		Mg m^{-3}	-		%				cm h^{-1}
None	1	> 0.20	>0.50	< 1.25	>1.2	≥0.60 to ≤0.70	>5	> 9	> 20	<15	< 2
Slight	2	>0.18 to ≤0.20	>0.45 to ≤0.50	≥1.25 to <1.35	>1.0 to ≤1.2	>0.50 to ≤0.60 ≥0.70 to <0.75	>3 to ≤5	>7 to ≤9	>18 to ≤20	≥15 to <18	≥2 to <6
Moderate	3	>0.15 to ≤0.18	>0.40 to ≤0.45	≥1.35 to <1.55	>0.8 to ≤1.0	>0.40 to ≤0.50 ≥0.75 to <0.80	>1 to ≤3	>6 to ≤7	>15 to ≤18	≥18 to <20	≥6 to <8
Severe	4	>0.10 to ≤0.15	>0.35 to ≤0.40	≥1.45 to <1.55	>0.6 to ≤0.8	>0.35 to ≤0.40 ≥0.80 to <0.90	>0.5 to ≤1	>5 to ≤6	>10 to ≤15	≥20 to <25	≥8 to <12.5
Extreme	5	≤ 0.10	≤ 0.35	≥ 1.55	≤0.6	≤0.35 to ≥0.90	≤0.5	≤ 5	≤ 10	≥25	≥12.5

AC, air capacity; S, total porosity; cyBd, bulk density determined from cylinders; e, void ratio; RFC, relative field capacity to water saturation; SOC, soil organic carbon; FDP, fast-drainage pores; UWP, unavailable water pores; and Ks5, hydraulic conductivity at 5 h.

Table 4. Selected soil physical indicators, their relative weighing factors and the cumulative rating approach (CR, 10 factors) for each site and soil depth in Mediterranean central Chile.

Sites	Depth	AC	S	cyBd	e	RFC	SOC	StI	FDP	UWP	Ks5	Cumulative rating (CR, 10 factors)		
	cm	cm^3 cm^{-3}		Mg m^{-3}	-		%				cm h^{-1}	Horizons	Soil profile (0-60 cm)	Soil profile (0-40 cm)
T0	0–20	4	3	4	4	1	3	2	3	4	5	33 (SAU)	33 (SAU)	35 (SAU)
	20–40	4	3	5	4	1	3	4	4	3	5	36 (SAU)		
	40–60	3	4	5	4	1	3	3	4	2	2	31 (SAU)		
1-S	0–20	3	2	3	4	1	2	1	3	2	5	26 (SHI)	29 (SHI)	29 (SHI)
	20–40	3	3	4	4	1	3	3	3	2	5	31 (SAU)		
	40–60	3	2	4	4	2	3	4	3	1	4	30 (SAU)		
2-N	0–20	2	1	2	3	2	3	4	4	1	5	27 (SHI)	29 (SHI)	28 (SHI)
	20–40	2	2	3	4	2	3	5	3	2	2	28 (SHI)		
	40–60	2	3	4	4	2	3	5	4	2	2	31 (SAU)		
4-S	0–20	2	1	2	3	2	2	1	2	2	5	22 (SUS)	26 (SHI)	25 (SHI)
	20–40	1	2	4	4	2	3	4	3	2	3	28 (SHI)		
	40–60	2	2	4	4	2	3	4	3	1	2	27 (SHI)		
4-N	0–20	1	1	1	3	2	3	4	1	1	5	22 (SUS)	25 (SHI)	25 (SHI)
	20–40	1	2	4	3	3	3	5	4	1	2	28 (SHI)		
	40–60	1	2	4	3	2	3	4	3	1	2	25 (SHI)		

AC, air capacity; S, total porosity; cyBd, bulk density determined from cylinders; e, void ratio; RFC, relative field capacity to water saturation; SOC, soil organic carbon; FDP, fast-drainage pores; UWP, unavailable water pores; and Ks5, hydraulic conductivity at 5 h. (SAU, sustainable with another land use; SHI, sustainable with high inputs; and SUS, sustainable).

physical indicators for integrated assessments of the sustainability of agroecological management practices when compared with highly mechanized intensive systems (conventional avocado orchard) was demonstrated.

Soil organic carbon content and nine physical soil quality indicators (air capacity, bulk density, relative field capacity to saturation, structural stability index, total porosity, void ratio, fast-drainage pores, unavailable water pores and saturated hydraulic conductivity at 5 h) were identified as being important for the sustainable management of natural resources. Therefore, the cumulative ratings index (CR) for each land use showed that all agroecological practices constituted sustainable soil management (25≤CR<30), although with high input requirements, while T0 (avocado orchard) exhibited the least sustainable management (30≤CR<40) with a recommended change in soil use.

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This manuscript summarises the authors' intended contribution at the Workshop on Challenges for Agroecology Development for the Building of Sustainable Agri-Food Systems (CRP), which was due to take place at the Faculty of Agricultural Sciences, University of Chile, Santiago de Chile, on 11–13 November 2019, and which was sponsored by the OECD Co-operative Research Programme: Biological Resource Management for Sustainable Agricultural Systems. Although due to the circumstances the workshop did not take place as a physical meeting and contributions intended to be supported by the OECD CRP are published in this Thematic Issue.

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The opinions expressed and arguments employed in this manuscript are the sole responsibility of the authors and do not necessarily reflect those of the OECD or of the governments of its Member countries.

Resumen

M. Casanova, B. Ticona, O. Salazar, E. Gratacós, M. Pfeiffer, G. Ávila, Y. Tapia, O. Seguel, y C. Sabaini. 2020. Physical assessment of a Mollisol under agroecological management at Quillota valley, Mediterranean Central Chile. Int. J. Agric. Nat. Resour. 261-279. Se ha propuesto un número amplio de prácticas agroecológicas para actuar como base para mejorar la calidad del suelo, la salud de las plantas y la productividad de los cultivos. Se ha demostrado que varias propiedades físicas del suelo son importantes para determinar la calidad del suelo utilizando el índice de sostenibilidad (SI) y el enfoque de calificación acumulativa. El objetivo principal del estudio fue determinar los efectos de diferentes manejos agroecológicos sobre las propiedades físicas de un Mollisol en el mediterráneo de Chile central. Se estableció un campo experimental en un área de 3,5 ha en 2014. Se seleccionaron cuatro sitios con diferentes prácticas agroecológicas para evaluar las propiedades físicas del suelo en 2019: pradera mediterránea anual de secano - cero labranza (1-S); pradera perenne y especies de raíces profundas con riego - cero labranza (2-N); pradera anual y perenne - labranza convencional con riego (4-S); hortalizas y flores con riego - labranza mínima (4-N); y como control se utilizó un huerto de paltos con manejo tradicional. Se seleccionaron el contenido de carbono orgánico y las siguientes propiedades físicas del suelo para evaluar las prácticas o la sostenibilidad del manejo agroecológico: densidad aparente, porosidad total, relación de vacíos, capacidad de aire, poros de drenaje rápido, capacidad relativa de campo, conductividad hidráulica, índice de estabilidad de la estructura y poros de agua no disponibles. Se demostró la utilidad potencial de los indicadores físicos seleccionados para SI de prácticas de manejo agroecológico, en comparación con un sistema intensivo altamente mecanizado (huerto de palto convencional). El índice de calificación acumulativa (CR) para cada uso del suelo mostró que todas las prácticas agroecológicas constituyeron un manejo sostenible del suelo ($25 \leq CR < 30$), mientras que el huerto de paltos fue el manejo menos sostenible ($30 \leq CR < 40$) recomendándose un cambio de uso del suelo.

Palabras clave: Agroecología, calidad de suelos, enfoque de calificación acumulativa, índice de sostenibilidad, salud del suelo.

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Supplemental Material 1.

Equations for measured and estimated physical soil properties.

Properties	Equations formulas	References
Measured		
1. Mean diameter variation	$\mathrm{MDV} = \frac{\sum(n_{i1} \cdot d_i) - (n_{i2} \cdot d_i)}{\sum n_{i1}}$	Hartge and Horn (2009)
2. Dispersion ratio	$\mathrm{DR} = \frac{(\mathrm{silt+clay})_{sd}}{(\mathrm{silt+clay})_{dd}}$	Berryman *et al.* (1982)
3. Hydro-repellency index	$\mathrm{R} = 1.95 \cdot \frac{S_{ethanol}}{S_{water}}$	Tillman *et al.* (1989)
Estimated		
4. Total porosity	$\mathrm{S} = (1 - \frac{\mathrm{cyBd}}{\mathrm{Pd}}) \cdot 100$	Das (2016)
5. Structural porosity	$\mathrm{SP} = (1 - \frac{\mathrm{cyBd}}{\mathrm{clBd}}) \cdot 100$	Cerisola *et al.* (2005)
6. Textural porosity	$\mathrm{TP} = \mathrm{cyBd} \cdot (\frac{1}{\mathrm{clBd}} - \frac{1}{\mathrm{Pd}})$	Cerisola *et al.* (2005)
7. Void ratio	$e = \frac{\mathrm{Pd}}{\mathrm{cyBd}} - 1$	Das (2016)
8. Air capacity	$\mathrm{AC} = W_s - W_{fc}$	Castellini *et al.* (2019a)
9. Structural stability index	$\mathrm{StI} = \frac{\mathrm{SOM}}{\mathrm{clay+silt}} \cdot 100$	Pieri (1992)
10. Relative field capacity to saturation	$\mathrm{RFC} = \frac{W_{fc}}{W_s}$	Reynolds *et al.* (2009)
11. Plastic index	$\mathrm{PI} = \mathrm{LL} - \mathrm{LP}$	Das (2016)
12. Optimal soil water contents for agricultural use	$\mathrm{Wo} = \mathrm{LL} - (\mathrm{Ic} \cdot \mathrm{PI})$	Baumgartl (2016)
13. Activity	$\mathrm{Am} = \frac{\mathrm{PI}}{\mathrm{Clay}}$	Baumgartl (2016)

Supplemental Material 2.

Mean (± standard deviation) values of measured soil properties by site and depth (n= 4)

Soil depth	Properties	Units	Sites				
			T0	1-S	2–N	4–S	4–N
0 - 20 cm	Sand	(%)	44.41± 2.88	46.21± 4.36	37.97± 2.17	42.02± 3.26	38.36± 0.84
	Silt	(%)	32.49± 2.05	29.87± 2.05	33.37± 2.00	33.20± 0.48	36.00± 1.22
	Clay	(%)	23.10± 1.51	23.92± 3.40	28.67± 3.50	24.78± 3.09	25.64± 0.90
	Pd	(Mg m^{-3})	2.66± 0.11	2.69± 0.13	2.60± 0.18	2.78± 0.28	2.87± 0.13
	SOM	(%)	4.60± 0.94	5.61± 0.59	3.71± 0.37	5.76± 1.36	3.99± 0.61
	R	(-)	2.68± 0.64	6.67± 2.65	3.36± 2.53	5.38± 1.53	4.69± 0.96
	cyBd	(Mg m^{-3})	1.53± 0.12	1.36± 0.11	1.28± 0.02	1.34± 0.07	1.25± 0.04
	clBd	(Mg m^{-3})	1.80± 0.07	1.76± 0.13	1.67± 0.09	1.63± 0.06	1.53± 0.26
	DR	(%)	53.77± 4.64	45.22± 7.25	56.97± 4.89	52.68± 7.67	62.64± 5.94
	MDV	(mm)	4.86± 1.94	1.69± 0.86	2.23± 1.14	2.70± 0.94	3.39± 1.31
	LL	(%)	28.69± 1.46	31.86± 1.36	25.12± 1.94	28.74± 2.10	27.25± 0.89
	LP	(%)	19.78± 3.35	24.56± 3.99	18.04± 2.52	21.88± 1.33	20.42± 1.42
	PR	(N cm^{-2})	206.64± 4.99	201.97± 17.67	147.06± 31.71	161.22± 48.94	64.03± 18.70
	θ_{33}	(cm^3 cm^{-3})	0.292± 0.040	0.232± 0.011	0.242± 0.022	0.252± 0.022	0.248± 0.010
	θ_{1500}	(cm^3 cm^{-3})	0.218± 0.028	0.171± 0.012	0.148± 0.021	0.158± 0.015	0.128± 0.004
	Ks1	(cm h^{-1})	18.23± 19.26	69.77± 12.48	26.21± 5.84	10.98± 10.98	14.27± 10.83
	Ks5	(cm h^{-1})	19.09± 18.28	67.52± 12.27	26.02± 7.22	13.09± 7.56	14.90± 9.60
20 - 40 cm	Sand	(%)	49.53± 6.12	46.24± 3.43	36.10± 2.21	42.96± 2.51	37.84± 2.13
	Silt	(%)	28.47± 4.18	27.18± 2.59	33.58± 1.27	31.56± 0.80	36.00± 1.04
	Clay	(%)	22.00± 2.04	26.57± 2.14	30.32± 2.96	25.48± 2.45	26.15± 1.26
	Pd	(Mg m^{-3})	2.75± 0.11	2.65± 0.13	2.79± 0.18	2.76± 0.28	2.72± 0.13
	SOM	(%)	2.63± 0.48	3.73± 0.56	2.43± 0.50	3.37± 0.15	3.25± 0.43
	R	(-)	1.55± 0.44	2.40± 1.10	1.50± 0.11	3.37± 0.72	3.10± 1.51
	cyBd	(cm^3 cm^{-3})	1.63± 0.07	1.47± 0.10	1.43± 0.04	1.51± 0.10	1.45± 0.09
	clBd	(cm^3 cm^{-3})	1.88± 0.05	1.83± 0.06	1.77± 0.10	1.74± 0.08	1.80± 0.14
	DR	(%)	53.79± 6.90	49.75± 13.68	56.54± 9.88	44.05± 12.20	59.37± 4.76
	MDV	(mm)	8.05± 1.79	3.66± 1.12	4.71± 0.69	5.53± 2.78	5.57± 0.96
	LL	(%)	25.32± 1.72	26.03± 1.45	23.30± 0.65	25.34± 1.06	25.22± 0.96
	LP	(%)	18.55± 2.11	17.82± 1.51	15.34± 3.29	17.81± 1.05	18.99± 0.39
	PR	(N cm^{-2})	527.79±52.44	284.04± 24.79	248.56± 78.95	270.10± 48.79	152.05± 38.52
	θ_{33}	(cm^3 cm^{-3})	0.274± 0.022	0.230± 0.022	0.229± 0.023	0.245± 0.014	0.256± 0.014
	θ_{1500}	(cm^3 cm^{-3})	0.185± 0.012	0.156± 0.005	0.155± 0.014	0.157± 0.009	0.150± 0.005
	Ks1	(cm h^{-1})	8.57± 7.91	22.63± 13.76	3.83± 1.97	6.95± 6.95	2.80± 1.37
	Ks5	(cm h^{-1})	14.82± 15.39	20.82± 11.14	5.45± 4.46	7.60± 5.46	3.73± 0.54
40 - 60 cm	Sand	(%)	61.05± 5.88	54.72± 7.04	34.44± 2.24	48.18± 3.62	41.04± 1.88
	Silt	(%)	21.22± 4.70	23.70± 7.16	33.96± 1.68	29.10± 4.88	32.96± 2.16
	Clay	(%)	17.73± 1.22	21.58± 3.72	31.60± 2.43	22.72± 2.17	26.00± 0.85
	Pd	(Mg m^{-3})	2.69± 0.09	2.73± 0.12	2.70± 0.22	2.85± 0.06	2.70± 0.27
	SOM	(%)	2.17± 0.46	2.74± 0.34	2.51± 0.08	2.99± 0.64	2.51± 0.25
	R	(-)	1.45± 0.81	1.61± 0.61	1.80± 0.50	2.07± 0.77	1.45± 0.81
	cyBd	(Mg m^{-3})	1.64± 0.10	1.48± 0.14	1.51± 0.10	1.50± 0.09	1.48± 0.03
	clBd	(Mg m^{-3})	1.81± 0.07	1.81± 0.09	1.83± 0.09	1.77± 0.04	1.83± 0.17
	DR	(%)	66.20± 4.16	52.20± 12.80	62.39± 3.98	57.73± 16.77	60.77± 6.02
	MDV	(mm)	7.03± 1.05	3.87± 2.40	5.69± 2.34	7.64± 1.65	6.91± 1.05
	LL	(%)	21.10± 1.44	22.47± 1.83	22.23± 0.56	22.62± 1.42	22.82± 0.41
	LP	(%)	17.85± 1.44	15.06± 0.82	15.90± 0.82	17.65± 1.40	16.50± 1.75
	PR	(N cm^{-2})	612.29± 23.21	282.47± 28.35	381.02± 139.33	370.54± 71.39	226.50± 74.53
	θ_{33}	(cm^3 cm^{-3})	0.258± 0.038	0.199± 0.045	0.258± 0.009	0.216± 0.015	0.243± 0.016
	θ_{1500}	(cm^3 cm^{-3})	0.158± 0.019	0.123± 0.016	0.156± 0.029	0.137± 0.002	0.133± 0.007
	Ks1	(cm h^{-1})	2.36± 1.16	12.87± 1.86	4.43± 1.99	4.68± 4.68	2.30± 0.89
	Ks5	(cm h^{-1})	2.27± 1.46	11.10± 1.47	4.08± 0.83	5.34±1.89	2.51± 0.89

Pd, particle density; SOM, soil organic matter content; R, water repellency index; clBd, bulk density determined from clods; cyBd, bulk density determined from cylinders; DR, dispersion ratio; MDV, mean diameter variation; LL, liquid limit; PL, plastic limit; PR, penetration resistance; θ_{33} and θ_{1500}, volumetric water content at 33 kPa and 1,500 kPa, respectively; and Ks1 and Ks5, hydraulic conductivities at 1 h and 5 h, respectively.

Supplemental Material 3.

The correlation matrix. Assessed and estimated soil properties in the studied field (n=60) in central Chile.

	sand	silt	clay	Pd	cyBd	clBd	DR	MDV	SOM	W_{33}	W_{1500}	Ks1	Ks5	R	PR	PL	LL	StI	S	SP	TP	e	RFC	AC	AWP	FDP	SDP	UWP
Pd	**0.09**	0.07	0.09	1																								
cyBd	0.44^{+}	**0.39**$^{+}$	**0.38**$^{+}$	**0.19**	1																							
clBd	0.30	**0.39**$^{+}$	**0.10**	**0.04**	0.54^{+}	1																						
DR	0.02	**0.00**	**0.03**	**0.15**	0.19	**0.04**	1																					
MDV	0.18	**0.09**	**0.24**	**0.05**	0.61^{+}	0.31*	0.24	1																				
SOM	**0.09**	0.19	**0.05**	0.04	**0.50**$^{+}$	**0.37**$^{+}$	**0.33**$^{+}$	**0.55**$^{+}$	1																			
W_{33}	**0.22**	0.30*	0.06	**0.06**	0.32*	0.05	0.07	0.24	**0.01**	1																		
W_{1500}	**0.05**	0.09	**0.02**	**0.08**	0.38^{+}	0.19	**0.18**	0.04	0.26*	0.67^{+}	1																	
Ks1	0.07	**0.06**	**0.05**	**0.16**	**0.40**$^{+}$	**0.08**$^{+}$	**0.34**	**0.57**$^{+}$	0.59^{+}	0.16	0.19	1																
Ks5	0.05	**0.05**	**0.04**	**0.15**	**0.40**$^{+}$	**0.09**$^{+}$	**0.36**	**0.52**$^{+}$	0.57^{+}	**0.12**	0.20	0.96^{+}	1															
R	**0.14**	0.24	**0.02**	**0.01**	**0.53**$^{+}$	**0.40**$^{+}$	**0.24**	**0.51**$^{+}$	0.73^{+}	**0.11**	0.06	0.58^{+}	0.56^{+}	1														
PR	0.57^{+}	**0.55**$^{+}$	**0.42**$^{+}$	**0.03**	0.72^{+}	0.45^{+}	0.11	0.54^{+}	**0.51**$^{+}$	0.09	0.15	**0.28***	**0.26***	**0.43**$^{+}$	1													
PL	**0.20**	0.27*	0.05	0.01	**0.44**$^{+}$	**0.28***	**0.39**$^{+}$	**0.54**$^{+}$	0.87^{+}	0.12	0.41^{+}	0.67^{+}	0.68^{+}	0.75^{+}	**0.47**$^{+}$	1												
LL	**0.00**	0.18	**0.22**	**0.12**	**0.26***	**0.38**$^{+}$	**0.17**	**0.39**$^{+}$	0.69^{+}	0.07	0.29*	0.59^{+}	0.55^{+}	0.71^{+}	**0.27***	0.77^{+}	1											
StI	0.28	**0.16**	**0.35**$^{+}$	0.01	**0.32***	**0.22**	**0.31***	**0.47**$^{+}$	0.92^{+}	**0.12**	0.22	0.61^{+}	0.58	0.64^{+}	**0.28***	0.76^{+}	0.65^{+}	1										
S	**0.39**$^{+}$	0.34^{+}	0.34^{+}	0.60^{+}	**0.90**$^{+}$	**0.45**$^{+}$	**0.23**	**0.52**$^{+}$	0.42^{+}	**0.30**	**0.34**$^{+}$	0.26*	0.26^{+}	0.42^{+}	**0.59**$^{+}$	0.36^{+}	0.16	0.27*	1									
SP	**0.20**	0.05	0.33^{+}	0.14	**0.60**$^{+}$	0.34^{+}	**0.28***	**0.41**$^{+}$	0.22	**0.32***	**0.22**	0.38^{+}	0.37^{+}	0.22	**0.36**$^{+}$	0.23	**0.05**	0.16	0.56^{+}	1								
TP	**0.17**	0.28*	**0.03**	0.43^{+}	**0.21**	**0.84**$^{+}$	0.09	**0.06**	0.17	0.07	**0.09**	**0.17**	**0.16**	0.17	**0.18**	0.09	0.21	0.07	0.36^{+}	**0.57**$^{+}$	1							
E	**0.38**$^{+}$	0.34^{+}	0.32*	0.60^{+}	**0.89**$^{+}$	**0.49**$^{+}$	**0.19**	**0.50**$^{+}$	0.42^{+}	**0.26***	**0.33***	0.25	0.26*	0.43^{+}	**0.59**$^{+}$	0.36^{+}	0.17	0.26*	0.99^{+}	0.52^{+}	0.40^{+}	1						
RFC	0.14	**0.04**	**0.22**	**0.13**	0.65^{+}	0.28*	0.07	0.42^{+}	**0.16**	0.81^{+}	0.69^{+}	**0.14**	**0.12**	**0.24**	0.39^{+}	**0.02**	0.01	**0.13**	**0.59**$^{+}$	**0.46**$^{+}$	**0.06**	**0.55**$^{+}$	1					
AC	**0.30**	0.26*	0.26*	0.15	**0.66**$^{+}$	**0.41**$^{+}$	**0.08**	**0.34**$^{+}$	0.13	**0.32**	**0.61**$^{+}$	0.00	0.00	0.23	**0.40**$^{+}$	0.01	**0.01**	0.02	0.60^{+}	0.35^{+}	0.20	0.59^{+}	**0.74**$^{+}$	1				
AWP	**0.24**	0.32*	0.07	0.00	**0.01**	**0.17**	0.25	0.26*	**0.28***	0.53^{+}	**0.27***	**0.40**$^{+}$	**0.37**$^{+}$	**0.16**	**0.06**	**0.29***	**0.20**	**0.38**$^{+}$	**0.00**	**0.18**	0.20	0.03	0.26*	0.29*	1			
FDP	**0.22**	0.17	0.22	0.26*	**0.81**$^{+}$	**0.38**$^{+}$	**0.15**	**0.53**$^{+}$	0.38^{+}	**0.56**$^{+}$	**0.50**$^{+}$	0.28*	0.26*	0.39^{+}	**0.53**$^{+}$	0.28*	0.16	0.30*	0.77^{+}	0.54^{+}	0.16	0.76^{+}	**0.87**$^{+}$	0.72^{+}	**0.16**	1		
SDP	**0.36**	0.27*	0.35^{+}	**0.08**	**0.20**	**0.22**	0.05	**0.04**	**0.11**	**0.11**	**0.31***	**0.27***	**0.25**	**0.03**	**0.14**	**0.20**	**0.12**	**0.23**	0.13	0.05	0.08	0.11	**0.43**$^{+}$	0.65^{+}	0.24	0.17	1	
UWP	**0.05**	0.09	**0.01**	**0.08**	0.38^{+}	0.19	**0.18**	0.04	0.26*	0.67^{+}	1.00^{+}	0.19	0.20	0.06	0.15	0.41^{+}	0.29*	0.22	**0.34**$^{+}$	**0.22**	**0.09**	**0.33***	0.69^{+}	**0.61**$^{+}$	**0.27***	**0.50**$^{+}$	**0.31***	1

Values in bold indicate negative Pearson's correlation coefficients (r<1). * and $^{+}$ represent the $p<0.05$ and $p<0.01$ significance values, respectively. AC, air capacity; AWP, available water pores; clBd, bulk density determined from clods; cyBd, bulk density determined from cylinders; DR, dispersion ratio; FDP, fast-drainage pores; R, hydro-repellency index; LL, liquid limit; MDV, mean diameter variation; MDS, minimum data set; Wo, optimal range of gravimetric water content for agricultural use; Pd, particle density; PR, penetration resistance; PI, plastic index; PL plastic limit; RFC, relative field capacity to water saturation; SDP, slow drainage pores; SOM, soil organic matter; Ks1 and Ks5, hydraulic conductivities at 1 h and 5 h, respectively; SP, structural porosity; TP, textural porosity; TDS, total data set; S, total porosity; UWP, unavailable water pores; e, void ratio; W_{33}, gravimetric water content at 33 kPa; and W_{1500}, gravimetric water content at 1,500 kPa.