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Research Article

Health and Characteristics of Australian Apple Growing Soils

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Despite being the highest value fruit crop in Australia, little is known about the types and condition or "health" of Australia's apple growing soils. This study is unique in being the first to report the condition and characteristics of Australia's apple growing soils; it provides essential baseline data for future monitoring of soil health in apple production systems, as well as soil physical and chemical data required for the development of perennial soil-tree-climate models. Soil chemical and physical properties were measured at 34 orchards, across five states. Soils were assessed for water retention, hydraulic conductivity, bulk density, macroporosity, organic carbon, CEC, ESP, pH, and EC. Despite high to very high levels of organic carbon, most topsoils were moderately to poorly structured. Around one-third to half of all sites showed evidence of poor aeration or impeded drainage, whilst 10 of the 34 sites were prone to nutrient leaching. Plant available soil water (PAWC) varied greatly between sites from 31 mm to 170 mm from 0 to 60 cm depth and between sites within the same soil order. Whilst topsoils had high to very high levels of organic carbon (average: 2.46%), they were otherwise poorly structured, with higher than expected bulk density (average: 1.32 g/cm^3) and lower than expected air capacity (average: 9.97%) and macroporosity (average: 1.75%). Subsoils were also found to have little soil water availability (average: 15.39 mm/100 mm), low air capacity (average: 5.28%), and low CEC (average: 8.12 cmol (+) kg^{-1}). Notably, 10 of the 34 sites had less than 6 cmol (+) kg^{-1} CEC throughout the entire soil profile, indicating potential risk of nutrient leaching. This study indicates that apple growing soils require careful management to improve topsoil structure, and to maintain or increase soil carbon, as well as use of soil moisture sensors to schedule irrigation. In addition, some sites also require improved subsoil drainage and care to ensure fertigation and irrigation do not result in leaching of nutrients beneath the root zone.

1. Introduction

Apple production in Australia is valued at nearly $620 million making it one of the highest value fruit industries in Australia [2]. Despite the economic importance of the Australian apple industry, little is known about the condition and characteristics of Australia's apple growing soils. Mapping and characterisation of Australia's apple growing soils are scarce. The limited mapping which exists was mostly conducted at the 1 : 10000 to 1 : 1000000 scale which is not sufficient for farm management or reporting soil condition [3]. Intensive soil mapping and characterisation have only been conducted in two apple growing regions, the Huon Valley in Tasmania [4] and the Shepparton Irrigation District in Victoria [5–12].

Knowledge of Australia's apple growing soils and their condition is needed for the Australian apple industry to report on soil health, as a baseline to enable changes in soil condition to be monitored over time, and to provide data required for the development of perennial tree crop-soil-climate models. The "health" or "quality" of Australian apple growing soils has not previously been reported, nor the soil types or properties of soils in each of Australia's apple growing regions. Assessing soil health or soil quality is not straightforward, as there are no universally agreed parameters, protocols, or values for quantitatively determining soil health [13–15], much less agreed values for orchard soils. Difficulty reaching agreement is in part due to the complexity of soil systems, abundance of potential soil indicators [16], and lack of data to support linking specific soil indicators and thresholds to different soil types, and the purpose to which the soil is used [15, 17, 18]. For example, Gatica-Saavedra et al. [16] identified 342 potential indicators of forest soil health, which they coalesced into 62 chemical, 28 biological, and 32 physical indicators. A number of approaches have been developed to quantify the health of cropped soils, for which threshold values for different soil indicators have been defined [22–27]. However, similar approaches have not been developed for orchard soils. Whilst DuPont et al. [28] described orchard soil health as the capacity of soil to support productive trees without negatively affecting the surrounding environment, specific indicators of orchard soil health or threshold values of what constitutes "good" and "bad" orchard soil health have not been identified.

Over the last two decades, biophysical models have been developed to support strategic and tactical decision making in most agricultural industries [29–32], for example, APSIM [33], CERES [34], SWAP [35], and DSSAT [36]. Development of the SPASMO (Soil Plant Atmosphere System Model) perennial tree crop model and its user interface SINATA [37] has been hampered by the lack of soil data from Australian apple growing regions. Unlike most soil water models which have relatively simple tipping bucket soil-water modules, the SPASMO model requires knowledge of the soil water retention curve described by the van Genuchten model and saturated hydraulic conductivity for each soil layer [38–40], which is not available in any Australian soil databases.

Consequently, this study was commissioned to (i) characterise the physical and chemical properties of key apple growing soils in each of the major apple growing regions of Australia, (ii) provide a "snapshot" of current soil condition or soil health, (iii) establish a baseline for future monitoring of soil health, and (iv) provide chemical and physical data required to further advance development of the perennial orchard model SPASMO and its user interface SINATA.

2. Materials and Methods

2.1. Site Location and Sampling. Representative apple growing soils were identified in each of 10 major apple growing regions in Australia. In Victoria, four sites were located in the Yarra Valley, two in Gippsland, and two at Harcourt. In South Australia, nine sites were located in the Adelaide Hills. In New South Wales, four sites were located in both Orange and Batlow, and one in Bilpin. In Tasmania, four sites were located in the Huon Valley, and one site in the Derwent Valley. In Western Australia, one site was located in each of Manjimup, Pemberton, and Kirup (Table 1).

Given the absence of detailed soil mapping in most regions, orchard selection, and sampling sites were selected on the basis of expert opinion, and on-site recognisance by experiences soil scientists, assisted by local industry advisors. This ensured that representative soils, orchards, and sites within orchards, were selected for investigation. At each site, a single soil profile was excavated to around 70 cm depth, within the centre of the tree mound, using a mechanical auger "Dingo" with a 600 mm diameter auger. The soil profile was described according to NCST [41] and classified according to Isbell [42]. Sampling for chemical and physical properties was conducted on a soil horizon rather than depth basis. For each soil horizon, three 250 cm^3 intact cores were extracted from beneath the tree row for analysis of the soil water retention function at each site. In addition, a 300 g composite sample of disturbed soil was obtained from each horizon from beneath the tree row for analysis of soil chemical properties at each site.

2.2. Soil Water Retention. The soil water retention function was determined using the KuPF apparatus (UGT, Germany; ICT International, Australia) between saturation and −80 kPa, supplemented with "dry end" retention data determined in triplicate by either WP4C dewpoint potentiometry (METER Group, Inc. USA) or pressure chamber data at −1500 kPa. The soil water retention data were fitted for the van Genuchten equation [43] using Excel Solver software according to

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m}, \quad (1)$$

in which h is matric potential (cm), n and m are the van Genuchten empirical shape parameters, θ_s ($cm \cdot cm^{-1}$) is the saturated water content, θ_r($cm \cdot cm^{-1}$) is the residual water content, and α (1/cm) is the van Genuchten soil structure parameter.

Saturated water content or total porosity was determined following at least 5 days of saturation for topsoils and 14 days for subsoils. The plant available water content (PAWC) was calculated as the water filled pore space between field capacity (FC) at −10 kPa and the permanent wilting point (PWP) at −1500 kPa [44, 45]. The readily available water content (RAW) was determined as the soil moisture held between field capacity at −10 kPa and the refill point at −50 kPa. PAWC and RAW were calculated to 60 cm depth rather than 100 cm depth, due to the use of dwarf root stock in apple orchards.

Air capacity is the volume of air filled pores or pores greater than 30 μm diameter following drainage at −10 kPa, to approximate field capacity [1, 46–48]. An air capacity of 10% is recommended to maintain root function and avoid yield loss [1, 49–51].

Macroporosity is related to the soil's ability to quickly drain excess water and facilitate root proliferation. Macroporosity was measured as the proportion of pores larger than 300 μm calculated as the difference in soil moisture between saturation (0 kPa) and −1.0 kPa [1, 48, 52]. Macroporosity values over 5% are considered optimal, whilst values less than 4% have been associated with compaction [1].

The soil retention S value is a measure of soil structure derived from the shape of the inflection point in the soil water retention curve, measured as the slope of the

Table 1: Site location and soil type.

State	Site	Location	Longitude	Latitude	Soil classification	Texture A1 and A12	Texture B21 and B22
NSW	N1	Orange	149.119375	−33.216402	Red Ferrosol	Clay loam	Medium clay
NSW	N2	Orange	149.007012	−33.303826	Red Ferrosol	Clay loam	Medium clay
NSW	N3	Orange	149.043010	−33.314524	Red Ferrosol	Clay loam	Medium clay
NSW	N4	Orange	149.014139	−33.32719	Red Ferrosol	Medium clay	Medium clay
NSW	N5	Bilpin	150.540179	−33.501313	Brown Ferrosol	Clay loam	Medium clay
NSW	N6	Batlow	148.101244	−35.536548	Red Ferrosol	Light clay	Medium clay
NSW	N7	Batlow	148.114584	−35.479089	Red Ferrosol	Clay loam	Medium clay
NSW	N8	Batlow	148.151081	−35.477269	Red Dermosol	Clay loam	Light clay
NSW	N9	Batlow	148.150059	−35.482863	Red Dermosol	Clay loam	Medium clay
SA	S1	Lenswood	138.832653	−34.914525	Brown Chromosol	Loam	Heavy clay
SA	S2	Lenswood	138.836878	−34.905747	Brown Dermosol	Silty clay loam	Medium clay
SA	S3	Forest Road	138.828069	−34.903756	Brown Dermosol	Clay loam	Medium clay
SA	S4	Lenswood	138.830122	−34.906408	Black Dermosol	Medium clay	Heavy clay
SA	S5	Lenswood	138.823497	−34.906675	Brown Chromosol	Loam	Silty loam
SA	S6	Uraidla	138.756308	−34.953353	Brown Chromosol	Loam	Medium clay
SA	S7	Nairne	138.893061	−35.018794	Brown Sodosol	Sandy loam	Heavy clay
SA	S8	Birdwood	138.942547	−34.836692	Brown Chromosol	Sandy loam	Medium clay
SA	S9	Forest range	138.800019	−34.933144	Brown Dermosol	Clay loam	Medium clay
TAS	T1	Mountain River	147.097814	−42.950808	Grey Kurosol	Sandy loam	Medium clay
TAS	T2	Lucaston	147.058067	−42.993603	Grey Kurosol	Sandy loam	Light clay
TAS	T3	Huon Valley	147.065392	−43.014179	Grey Kurosol	Clay loam	Light clay
TAS	T4	Lucaston	147.060470	−42.99806	Brown Kurosol	Loam	Clay loam
TAS	T5	Plenty	146.972117	−42.736902	Red Dermosol	Clay loam	Light clay
VIC	V1	Three Bridges	145.681530	−37.842995	Red Ferrosol	Clay loam	Light clay
VIC	V2	Launching Place	145.580200	−37.783253	Yellow Dermosol	Clay loam	Light clay
VIC	V3	Gruyere	145.450880	−37.717293	Grey Hydrosol	Clay loam	Clay loam
VIC	V4	Gruyere	145.449430	−37.714127	Grey Dermosol	Clay loam	Light clay
VIC	V5	Warragul	145.963070	−38.18291	Yellow Dermosol	Clay loam	Light clay
VIC	V6	Officer	145.411940	−38.04555	Red Kurosol	Clay loam	Silty clay loam
VIC	V7	Harcourt North	144.272580	−37.00624	Yellow Chromosol	Sand clay loam	Medium clay
VIC	V8	Harcourt	144.287980	−36.965813	Yellow Chromosol	Sand clay loam	Sandy clay
WA	W1	Kirup	151.937765	−33.710283	Red Kandosol	Sand	Sandy loam
WA	W2	Manjimup	152.075781	−34.292778	Brown Chromosol	Loamy sand	Clay loam
WA	W3	Pemberton	152.081644	−34.409849	Red Kandosol	Loamy sandy	Sand

gravimetric water content, θ_g (kg kg^{-1}), versus the natural logarithm of the pore water tension head, calculated as

$$S = \left| -n\left(\theta_{gs} - \theta_{gr}\right)\left[1 + \frac{1}{m}\right]^{-(m+1)} \right|, \tag{2}$$

where n and m are the van Genuchten empirical shape parameters, θ_{gs} (cm cm^{-3}) is the gravimetric saturated water content, θ_{gr} (cm cm^{-3}) is the gravimetric residual water content, and α (hPa^{-1}) is the van Genuchten soil structure parameter. Reynolds et al. [1] suggest that S values ≥ 0.050 represent very good, $0.035 \leq S < 0.050$ represent good, $0.020 \leq S < 0.035$ represent poor, and $S < 0.020$ represent very poor soil structure or physical quality.

2.3. Infiltration and Hydraulic Conductivity. Infiltration and saturated hydraulic conductivity were determined at the soil surface in triplicate using the SATURO Dual Head Infiltrometer (Meter Group, Inc. USA) operated for approximately 120 minutes. The Dual Head Infiltrometer applies water at two pressure heads, repeated over three cycles, such that the effect of sorptivity and lateral flow can be excluded from the calculation of saturated hydraulic conductivity. Failure of the Dual Head Infiltrometers at several sites (especially the Victorian sites) resulted in measurement of surface soil infiltration and hydraulic conductivity by 200 mm diameter, single-ring constant head infiltration in which the calculation of saturated hydraulic conductivity was solved according to Reynolds and Elrick [53] assuming an alpha value of 0.12 cm^{-1}.

Subsoil infiltration and hydraulic conductivity were determined by Guelph permeameter [54] and a purpose built thin tube constant head well permeameter, in which saturated hydraulic conductivity was solved by the single head method assuming an alpha value of 0.12 cm^{-1}. Measurements were conducted in triplicate at approximately 600 mm depth (B2 horizon) in which a 100–150 mm head was maintained in a 30 mm radius borehole for at least 20 minutes. Saturated hydraulic conductivity was solved using the Guelph permeameter software based on Elrick et al. [55] and Reynolds and Elrick [56, 57].

2.4. Chemical Analysis. Bulk soil samples from each soil horizon from Tasmania, Victoria, and Western Australia were sent to CSBP laboratories for analysis, whilst samples from NSW and South Australia were sent to DPI lab in Lismore, QLD. Electrical conductivity (EC) and pH were measured using a soil to solution ratio of 1 : 5. Acidity was measured in both water and $CaCl_2$ solution (Rayment and Lyons [58] methods 4A1, 4B3, 3A1). Exchangeable cations were determined following leaching with both an alcohol and glycerol solution (prewash) to remove soluble salts from the soil prior to extraction using 1M ammonium chloride. Exchangeable cation concentrations were determined using inductively couple plasma (ICP) spectroscopy (Rayment and Lyons [58] method 15A2). Exchangeable aluminium was measured for three sites in Tasmania and all sites in South Australia and New South Wales following 1M potassium chloride extraction (Rayment and Lyons [58] method 15G1). Soil organic carbon (SOC) was determined by wet oxidation [59] (Rayment and Lyons [58] method 6A1). CEC was calculated as the sum of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) excluding Al^{3+} due to missing data from Victoria.

2.5. Selection of Soil Health Indicators. As soil health indicators have not previously been identified for orchard soils, the soil health indicators adopted in this study are based on the desirable attributes of apple growing soils. Whilst apples grow in a wide variety of soil types and soil conditions, ideal soils for apple production are genrally considered to be, well drained, well aerated or porous, with good water holding capacity, and slightly acid to neutralpH [28, 60]. Consequently, for the purpose of this study, soil health indicators focused on measures of soil water availability (PAWC, RAW), macroporosity (Macropore %, S value), drainage status (Ksat, AC, BD), and general chemical soil health indicators (pH, CEC, OC), as well as potential barriers to production (ESP, pH, exchangeable Al^{+3}). Threshold values for what constitutes "good" as opposed to "poor" indicator values (Table 2) were largely based on existing thresholds.

3. Results

3.1. Soil Water Availability. The average PAWC to 60 cm depth was 117 mm (SD ± 28) (Figure 1(a), Table 4). Threshold values for PAWC and RAW for apple growing soils have not been defined. Based on McIntyre [68], Hazelton and Murphy [51] suggest that a PAWC of less than 10% or 60 mm to 60 cm depth is considered low (Table 2). One site, a Western Australian Red Kandosol, had low PAWC, 16 sites had moderate PAWC, and 17 sites had high levels of PAWC. The average PAWC to 60 cm depth of the A1, A2, and B2 horizons was 23.52 mm/100 mm (SD ± 7.37), 18.44 mm/100 (SD ± 16.73), and 15.39 mm/100 mm (SD ± 4.80), respectively (Figure 1(a)). Notably, the proportion of unavailable soil water in the B2 horizons was high at 25.43 mm/100 mm (SD ± 6.72) (Figure 1(d)). The average RAW to 60 cm depth in the A1, A2, and B2 horizons was 9.44 mm/100 mm (SD ± 2.55), 8.04 mm/100 (SD ± 4.13), and 5.13 mm/100 mm (SD ± 1.55), respectively. According to Hazelton and Murphy [51], the PAWC to 60 cm depth was high in 35 of 48 A1 horizons (A1, A11, and A12 horizons), 6 of 18 A2 horizons (A2, A21, and A22 horizons), and 5 of 54 B2 horizons (B2, B21, and B22 horizons) (Figure 1(d)) and low in 0 of 48 A1 horizons (Figure 1(b)), 2 of 18 A2 horizons (Figure 1(c)), and 6 of 54 B2 horizons (Figure 1(d), Table 4).

3.2. Soil Structure and Macroporosity. Bulk density in the A1 horizons averaged 1.32 g/cm^3 (SD ± 0.16) in which values for individual sites ranged from 0.88 g/cm^3 for a clay loam Red Ferrosol to 1.67 g/cm^3 in a sandy Red Kandosol (Figure 2(a)). Of the 48 A1 horizons, 29 horizons had moderate to high levels of bulk density [51] (Figure 2(a)). Air capacity in the A1 horizons averaged 9.97% (SD ± 5.76), in which 26 of 48 horizons had values below the 10% threshold required for proper aeration and root function [51, 69] (Figure 2(b)). In addition, 43 of the 48 A1 horizons had macroporosity (>300 μm) values which were less than the 5% threshold for good soil structure (Figure 2(d)). In contrast to these data which suggest the A1 horizons were poorly structured, the soil water retention S value indicated that 39 of the 48 A1 horizons had good or very good structure (Figure 2(e)), whilst the average saturated hydraulic conductivity of the A1 horizon was 250 mm/hr (SD ± 328) which is considered as being very high (Figure 2(c)) [51, 70].

The A2 horizons had higher average bulk density, lower hydraulic conductivity, and lower macroporosity than the A1 horizons. The average bulk density for the A2 horizons was 1.43 g/cm^3 (SD ± 0.21) (Figure 2(f)). The average air capacity of the A2 horizons was 8.02% (Figure 2(g)), which was similar to the A1 horizon. None of the A2 horizons had more than 5% macroporosity (>300 μm) (Figure 2(i)), whilst the average S value was 0.04 in which 7 of 15 A2 horizons were classed as having poor to very poor structure (Figure 2(j)). The average hydraulic conductivity of the A2 horizons was classed as moderate at 55 mm hr^{-1} (SD ± 160) (Figure 2(h)) [51].

The average bulk density for the B2 horizons was 1.44 g/cm^3 (SD ± 0.18) (Figure 2(k)) which was similar to the A2 horizon (Figure 2(f)). The average air capacity and hydraulic conductivity of the B2 horizons were 5.28% (SD ± 3.81) and 17.03 mm/hr (SD ± 82.46), respectively (Figures 2(i) and (m)). Notably, 28 of 48 the B2 horizons were considered to have moderate density, and 9 horizons were considered to have high to extreme density. Only 7 of the 48 the B2 horizons had air capacity values above the 10% threshold required for adequate root function (Figure 2(l)). The average macroporosity in the B2 horizons was only 1.11% (Figure 2(n)), in which none of the 55 horizons exceeded the optimum macroporosity threshold of 5%. The average retention curve S value in the B2 horizons was 0.03 in which 10 horizons were classed as having good to very good structure (Figure 2(o)), mostly Ferrosols and Dermosols, whilst six horizons were classed as having very poor structure. Hydraulic conductivity in the B2 horizons varied enormously in which only 3 of 35 horizons had hydraulic conductivity values greater than 10 mm/hr, whilst 15 of the 35 horizons had average hydraulic conductivity values less than 1 mm/hr (Figure 2 (m)).

Table 2: Indicators and classification of soil "health."

	Indicators	Classification					Reference
		Very high	High (good)	Medium	Low (poor)	Very low	
Chemical	pH_{h20}			6.5–5.5			Jonkers and Hoestra [61]
	$EC_{1:5}$	>4.0–1.15	2.0–0.58	0.29–1.0	0.5–0.15	0–0.25	Hardie and Doyle [62]
	CEC cmol (+) kg^{-1}	>40	40–25	25–12	12–6	<6	Hazelton and Murphy [51]; Metson [63]
	ESP %		>15	6–14		<6	Northcote and Skene [64]
	OC %	>3	3–1.8	1.8–1	1–0.6	<0.6	Emerson [65]; Charman and Roper [66]; Hazelton and Murphy [51]
	Exe. Al^{+3}%		>0.4		>0.4		Voiculescu et al. [67]
Physical	PAWC mm (0–60 cm)		>120	60–120	<60		Hazelton and Murphy [51]; McIntyre [68]
	PAWC %		>20	20–10	<10		Hazelton and Murphy [51]; McIntyre [68]
	AC %		>10		<10		Hazelton and Murphy [51]; Cass [69]
	K_{sat} mm/hr	<120	120–60	60–20	20–10	<10	Hazelton and Murphy [51]; Geeves et al. [70]
	BD g/cm^3	>1.9	1.9–1.6	1.6–1.3	1.3–1.0	<1	Hazelton and Murphy [51]
	Macro %		5		4		Reynolds et al. [1]
	S value	>0.05	0.05–0.035		0.035–0.02	<0.02	Reynolds et al. [1]

pH_{h20}: acidity-alkalinity, $EC_{1:5}$: electrical conductivity measured as a 1 : 5 solution, CEC: cation exchange capacity, ESP: exchangeable sodium percent, OC: organic carbon, $EXE.AL^{+3}$: exchangeable aluminium, PAWC: plant available water content, AC: air capacity, K_{sat}: saturated hydraulic conductivity, BD: bulk density, Macro: macroporosity >300 μm, and *S* value: soil structure parameter.

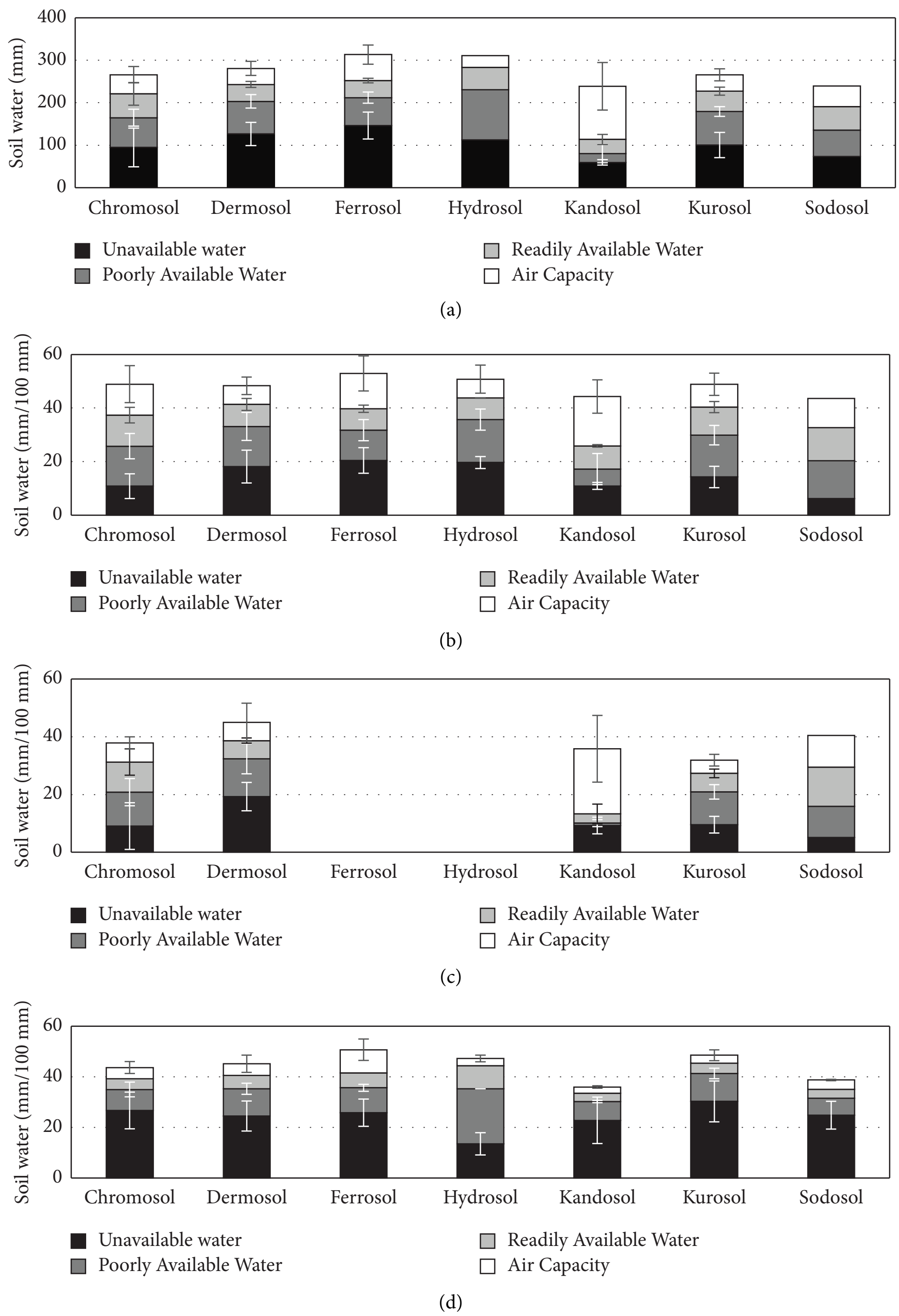

Figure 1: Comparison of the average air capacity (white), readily available water −10 to −50 kPa (light grey), poorly available water −50 to −1500 kPa (dark grey), and unavailable soil water <−1500 kPa (black) between soil orders, measured as, (a) soil water to 60 cm depth (mm), and (b, c, d) the proportion of soil water per 100 mm soil depth (mm/100 mm), for (b) A1, A11, and A12 horizons, (c) A2 horizons, and (d) B2, B21, and B22 horizons. Error bars represent ±1 standard deviation. Corresponding van Genuchten parameter values are presented in Table 3.

3.3. Soil Chemical Attributes. The average organic carbon content of the A1 horizons was high at 2.48% (SD 1.12%), in which individual horizon values ranged from 0.95% in the A12 horizon of at the Yellow Chromosol site to 6.80% in a Brown Ferrosol in Bilpin, NSW (Figure 3(a)). Of the 46 A1 horizons, soil carbon was classed as very high for 12 horizons, high for 20 horizons, moderate for 13 horizons, and low in only one horizon [51]. By comparison, the average organic carbon content of the A2 horizons was 0.75% (SD ± 0.55) in which 6 of the 16 of the A2 horizons had lower organic carbon levels than the upper B2 horizons (Figure 3(a), Table 5). The average organic carbon content of

Table 3: van Genuchten–Mualem values.

Horizon	Soil order/state	n	θ_s (cm/cm)		θ_r (cm/cm)		α (cm^{-1})		η		Ksat (mm/hr)	
			$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
A1, A11, A12	Chromosol	10	0.489	0.078	0.017	0.023	0.039	0.046	1.360	0.212	248	313
	Dermosol	14	0.483	0.037	0.044	0.093	0.025	0.024	1.236	0.048	203	166
	Ferrosol	9	0.529	0.076	0.084	0.099	0.061	0.052	1.255	0.111	172	202
	Hydrosol	2	0.508	0.035	0.000	0.000	0.026	0.029	1.184	0.057	249	
	Kandosol	2	0.443	0.021	0.068	0.071	0.039	0.017	1.641	0.561	1065	926
	Kurosol	10	0.488	0.069	0.020	0.035	0.020	0.018	1.281	0.115	200	219
	Sodosol	1	0.435		0.000		0.017		1.355		38.1	
A2	Chromosol	6	0.378	0.114	0.037	0.078	0.015	0.012	1.441	0.280	7.69	11.70
	Dermosol	2	0.450	0.072	0.055	0.077	0.029	0.036	1.224	0.017	45.5	
	Kandosol	2	0.359	0.040	0.092	0.029	0.030	0.002	3.482	2.194	284	391
	Kurosol	5	0.319	0.021	0.001	0.002	0.012	0.005	1.250	0.059	2.64	3.74
	Sodosol	1	0.405		0.023		0.015		1.541		0.316	
B2, B21, B22	Chromosol	10	0.396	0.160	0.122	0.103	0.030	0.029	1.233	0.135	100	220
	Dermosol	19	0.451	0.051	0.058	0.093	0.023	0.029	1.184	0.111	1.33	1.28
	Ferrosol	13	0.507	0.044	0.052	0.087	0.054	0.029	1.177	0.164	2.85	3.00
	Hydrosol	2	0.473	0.058	0.011	0.016	0.004	0.002	1.343	0.119	0.09	0.08
	Kandosol	2	0.360	0.054	0.066	0.094	0.020	0.013	1.122	0.013	36.5	50.2
	Kurosol	6	0.486	0.072	0.104	0.112	0.018	0.017	1.144	0.031	0.71	0.65
	Sodosol	2	0.388	0.063	0.041	0.030	0.031	0.005	1.091	0.031	0.04	
A1, A11, A12	NSW	9	0.503	0.081	0.084	0.099	0.064	0.049	1.254	0.112	159	195
	SA	13	0.501	0.051	0.057	0.093	0.041	0.042	1.330	0.192	152	130
	TAS	8	0.501	0.071	0.025	0.038	0.024	0.019	1.286	0.128	183	205
	VIC	15	0.472	0.051	0.000	0.000	0.013	0.012	1.246	0.059	357	285
	WA	3	0.501	0.102	0.057	0.053	0.047	0.018	1.485	0.480	727	879
A2	SA	6	0.395	0.101	0.027	0.042	0.017	0.018	1.466	0.287	1.95	2.50
	TAS	4	0.314	0.020	0.001	0.003	0.015	0.001	1.244	0.066	2.64	3.74
	VIC	3	0.342	0.056	0.000	0.000	0.015	0.020	1.260	0.020	22.9	32.0
	WA	3	0.413	0.098	0.126	0.062	0.025	0.008	2.767	1.985	197	314
B2, B21, B22	NSW	16	0.509	0.039	0.043	0.080	0.059	0.029	1.161	0.150	2.63	2.88
	SA	16	0.454	0.058	0.105	0.108	0.019	0.013	1.209	0.131	1.62	1.39
	TAS	8	0.470	0.070	0.090	0.098	0.019	0.016	1.154	0.035	0.46	0.37
	VIC	11	0.379	0.142	0.036	0.064	0.013	0.024	1.199	0.095	0.70	0.79
	WA	3	0.379	0.050	0.125	0.122	0.037	0.030	1.252	0.225	189	266

Table 4: Soil water limits.

Horizon	Soil order/state	n	Field capacity (%)		Air capacity (%)		Readily available water (%)		Plant available water capacity (%)		Bulk density (g/cm^3)	
			$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
A1, A11, A12	Chromosol	10	37.32	5.93	11.56	6.90	11.58	2.92	26.49	5.78	1.33	0.19
	Dermosol	14	41.35	3.18	6.97	3.29	8.22	2.22	23.20	7.01	1.34	0.09
	Ferrosol	9	39.74	5.39	13.21	6.55	8.02	1.38	19.34	4.87	1.23	0.19
	Hydrosol	2	43.74	1.67	7.03	5.22	8.04	0.04	24.06	3.90	1.28	0.07
	Kandosol	2	25.87	4.08	18.45	6.21	8.66	0.46	14.97	5.38	1.56	0.15
	Kurosol	10	40.35	4.92	8.50	4.17	10.46	2.09	26.09	4.73	1.33	0.18
	Sodosol	1	32.69		10.85		12.36		26.52		1.48	
A2	Chromosol	6	31.26	10.87	6.59	2.11	10.44	4.55	22.14	6.94	1.60	0.28
	Dermosol	2	38.67	0.60	6.38	6.56	6.28	0.91	19.39	4.31	1.45	0.16
	Kandosol	2	13.29	7.55	22.59	11.57	3.16	3.43	4.02	4.62	1.72	0.04
	Kurosol	5	27.37	3.41	4.54	2.03	6.46	1.49	17.80	2.28	1.80	0.04
	Sodosol	1	29.51		11.01		13.60		24.35		1.55	

Table 4: Continued.

Horizon	Soil order/state	n	Field capacity (%)		Air capacity (%)		Readily available water (%)		Plant available water capacity (%)		Bulk density (g/cm^3)	
			$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
B2, B21, B22	Chromosol	10	39.30	9.69	4.39	2.37	4.28	1.17	12.62	4.52	1.55	0.20
	Dermosol	19	40.60	4.28	4.55	3.41	5.30	1.28	16.05	3.09	1.46	0.14
	Ferrosol	13	41.62	4.44	9.09	4.24	5.90	1.03	15.80	2.96	1.30	0.11
	Hydrosol	2	44.47	4.48	2.81	1.29	9.16	0.65	30.90	0.14	1.39	0.20
	Kandosol	2	32.69	4.62	2.42	0.51	3.39	1.22	10.80	3.28	1.72	0.13
	Kurosol	6	45.46	7.29	3.10	2.19	4.07	0.86	15.14	4.04	1.35	0.18
	Sodosol	2	35.06	5.96	3.72	0.29	3.47	0.04	10.17	0.46	1.66	0.15
A1, A11, A12	NSW	9	37.29	2.61	13.03	6.63	7.75	1.32	18.29	3.71	1.30	0.20
	SA	13	39.29	5.36	10.86	5.88	10.34	3.74	23.97	8.35	1.30	0.13
	TAS	8	40.31	5.03	9.75	3.73	10.76	2.19	25.83	4.81	1.30	0.19
	VIC	15	41.27	5.18	5.96	3.21	9.08	1.61	26.18	3.40	1.36	0.14
	WA	3	32.45	11.74	17.69	4.59	8.98	0.63	17.90	6.35	1.39	0.31
A2	SA	6	32.08	8.33	7.41	3.12	11.29	4.55	23.27	6.38	1.56	0.25
	TAS	4	26.07	2.04	5.36	1.02	6.89	1.33	17.16	2.07	1.80	0.05
	VIC	3	30.11	9.60	4.08	4.46	5.61	0.84	19.01	4.25	1.74	0.16
	WA	3	23.57	18.59	17.69	11.78	5.12	4.16	9.23	9.61	1.59	0.24
B2, B21, B22	NSW	16	41.68	4.40	9.18	3.84	5.85	0.95	15.68	2.60	1.29	0.10
	SA	16	41.33	6.22	4.12	2.52	4.96	1.29	14.30	4.14	1.48	0.15
	TAS	8	43.29	7.38	3.71	2.47	4.65	1.30	15.80	3.65	1.40	0.18
	VIC	11	39.03	7.62	2.67	1.64	5.17	2.31	17.93	7.32	1.55	0.18
	WA	3	32.94	3.29	4.34	3.35	3.23	0.90	9.26	3.54	1.70	0.10

Field capacity = −10 kPa, air capacity = 0 to −10 kPa, readily available water = −10 to −50 kPa, and plant available water content = −10 kPa to −1500 kPa.

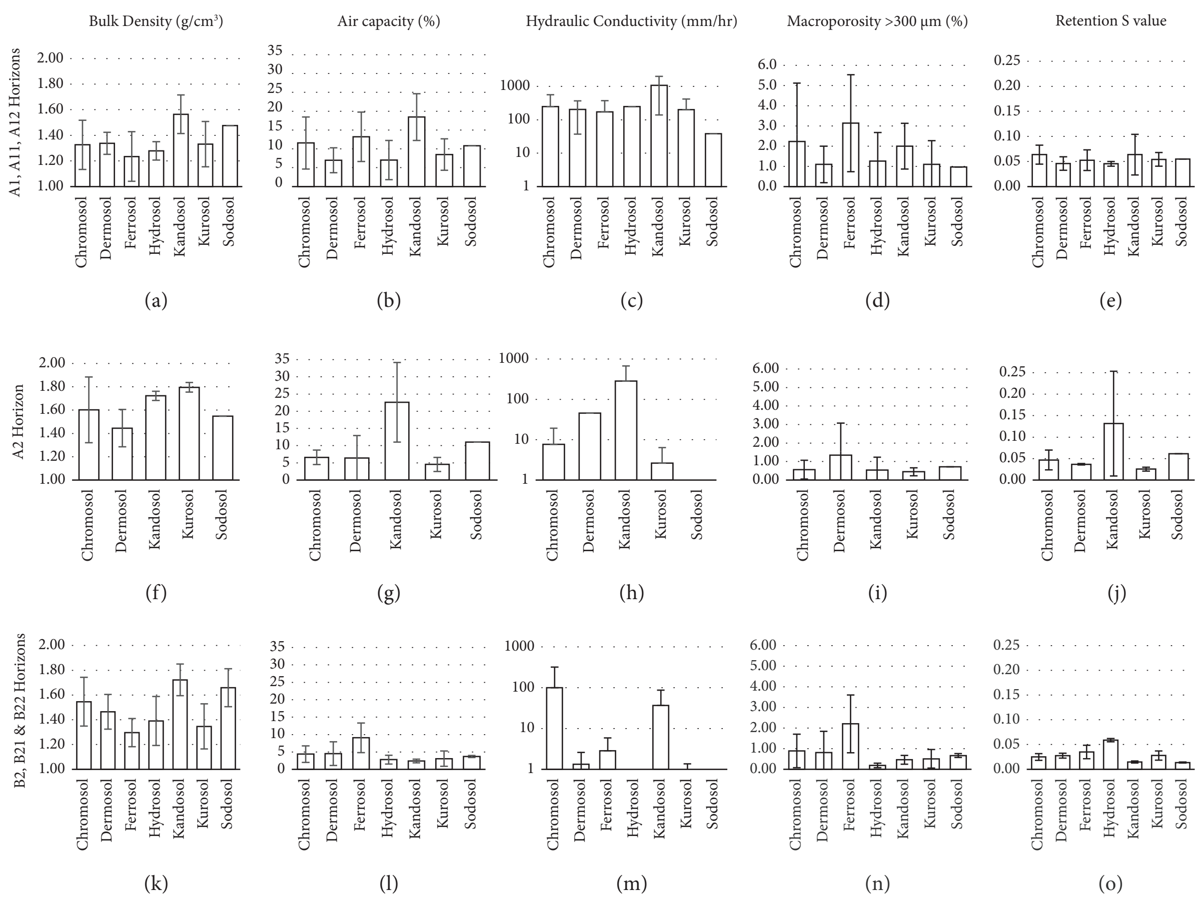

Figure 2: Values of the physical measures of soil health (columns), by soil horizon (rows) and soil order (bars), in which (a), (f), and (k) represent bulk density (g/cm^3), (b), (g), and (l) represent air capacity (%), (c), (h), and (m) represent saturated hydraulic conductivity (mm/hr), (d), (i), and (n) represent macroporosity <300 μm (%), and (e), (j), and (o) represent the retention S value. (a, b, c, d, e) A1, A11, and A12 horizons, (f, g, h, i, j) A2 horizons, and (k, l, m, n, o) B2, B21, and B22 horizons.

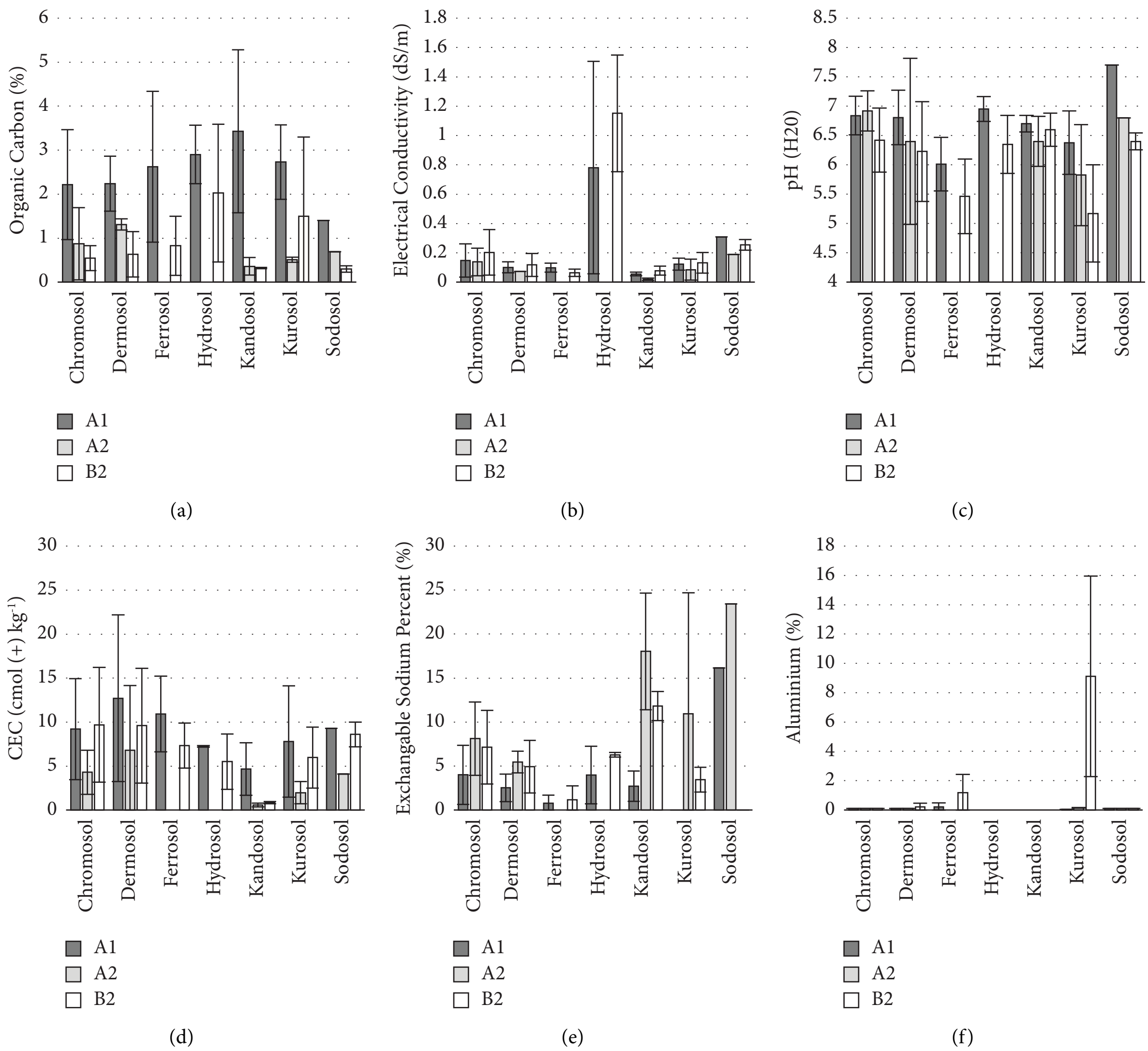

Figure 3: Differences in soil chemical attributes between soil horizons and soil orders: (a) organic carbon, (b) EC salinity, (c) pH_{H20} 1 : 5 extract, (d) CEC (cation exchange capacity), (e) ESP (exchangeable sodium percent), and (f) exchangeable aluminium.

the B2 horizons was low at 0.80% (SD ± 0.87%), in which only 5 of 55 horizons were classified as having high to very high levels of organic carbon.

Overall, CEC was substantially lower than expected, given the high organic carbon and clay contents at most sites (Figure 3(d)). The CEC averaged 10.10 cmol (+) kg^{-1} (SD: 7.01) in the A1 horizons, 2.83 cmol (+) kg^{-1} (SD: 2.19) in the A2 horizons, and 8.12 cmol (+) kg^{-1} (SD: 5.47) in the B2 horizons (Figure 3(d)). Of the 117 soil horizons, 50 were classified as having low (6 to 12 cmol (+) kg^{-1}) to very low (<6 cmol (+) kg^{-1}) CEC, and this included 16 of 47 A1 horizons, 13 of 15 A2 horizons, and 21 of 55 B2 horizons (Figure 3(d)). Only 3 of the 118 soil horizons were classified as having high to very high CEC (>25 cmol (+) kg^{-1}), all at the South Australian Black Dermosol site (Figure 3(d), Table 5).

Apples trees are considered to be moderately sensitive or slightly tolerant to salinity [71, 72] in which 50% yield reduction is predicted at a soil salinity of 5 EC_e dS/m. Analysis indicated that only 7 horizons had EC values greater than 0.3 dS/m, and only 2 horizons, both at the Hydrosol site, had EC values greater than 1.0 dS/m (Figure 3(b), Table 5). Given a texture multiplier of 9 for a clay loam [62], apple yield is predicted to be severely affected at the Hydrosol site in Victoria, with the possibility of a slight yield reduction at the Brown Sodosol and three Brown Chromosol sites in South Australia. No other sites appear to be affected by salinity.

Sodicity occurred in at least one soil horizon at 17 of the 34 sites (Figure 3(e)). Of the 118 soil horizons, 26 were classed as moderately sodic (ESP: 6–14) [64], plus 7 horizons were classified as being highly sodic (ESP > 14). Sodicity was highest in the Sodosols, Kandosols, and one of the Brown Chromosols (Figure 3(e)). Only 5 of the 47 A1 horizons were classed as sodic, whilst 10 of the 14 A2 horizons were sodic, and 18 of the 57 subsoil B2 horizons were sodic or strongly sodic (Figure 3(e)). Notably, all but one of the 22 Ferrosol soil horizons was nonsodic.

Table 5: Key soil chemical properties.

Horizon	Soil order/state	n	Organic carbon (%)		Electrical conductivity (EC) (dS/m)		pH_{H2O}		Cation exchange capacity (CEC) (cmol (+) kg^{-1})		Exchangeable sodium percent (ESP) (%)	
			$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	σ
A1, A11, A12	Chromosol	10	2.22	1.25	0.15	0.11	6.84	0.33	9.20	5.76	3.99	3.35
	Dermosol	14	2.24	0.62	0.10	0.04	6.81	0.46	12.71	9.63	2.51	1.55
	Ferrosol	9	2.62	1.71	0.10	0.03	6.01	0.46	10.93	4.11	0.76	0.92
	Hydrosol	2	2.90	0.66	0.78	0.72	6.95	0.21	7.26	0.09	3.98	3.26
	Kandosol	2	3.43	1.85	0.06	0.01	6.70	0.14	4.67	3.00	2.70	1.73
	Kurosol	9	2.73	0.85	0.12	0.04	6.38	0.54	6.38	6.33	7.81	6.33
	Sodosol	1	1.40		0.31		7.70		7.70		9.31	
A2	Chromosol	5	0.87	0.82	0.14	0.09	6.92	0.34	4.31	2.50	8.12	4.17
	Dermosol	2	1.31	0.13	0.07	0.00	6.40	1.41	6.79	7.16	5.46	1.23
	Kandosol	2	0.36	0.20	0.02	0.01	6.40	0.42	0.60	0.22	18.03	6.64
	Kurosol	4	0.51	0.06	0.09	0.07	5.83	0.86	1.98	0.66	10.94	13.77
	Sodosol	1	0.69		0.19		6.80		4.10		23.41	
B2, B21, B22	Chromosol	10	0.55	0.28	0.20	0.16	6.42	0.55	9.69	6.49	7.13	4.18
	Dermosol	19	0.63	0.51	0.12	0.08	6.23	0.85	9.61	6.47	4.92	3.00
	Ferrosol	13	0.83	0.67	0.06	0.03	5.46	0.63	7.34	3.24	1.14	1.59
	Hydrosol	2	2.03	1.56	1.15	0.40	6.35	0.49	5.52	3.15	6.27	0.27
	Kandosol	2	0.32	0.01	0.08	0.03	6.60	0.28	0.86	0.12	11.81	1.66
	Kurosol	7	1.50	1.80	0.13	0.07	5.17	0.83	5.98	3.24	3.44	1.41
	Sodosol	2	0.30	0.07	0.26	0.04	6.40	0.14	8.60	1.41	19.60	1.71
A1, A11, A12	NSW	9	2.29	1.76	0.08	0.03	5.43	0.41	12.58	1.85	0.43	0.26
	SA	13	2.16	0.88	0.16	0.11	6.22	0.36	15.42	8.78	5.06	4.42
	TAS	7	2.81	0.82	0.12	0.04	5.79	0.45	10.26	6.47	1.51	0.98
	VIC	15	2.38	0.68	0.20	0.31	5.75	0.74	4.48	1.44	2.86	1.24
	WA	3	3.89	1.53	0.08	0.05	5.67	0.15	5.97	3.10	2.19	1.51
A2	SA	5	0.76	0.46	0.13	0.06	5.96	0.40	6.20	3.55	11.47	7.34
	TAS	3	0.53	0.06	0.09	0.09	5.00	0.90	2.22	0.58	13.57	15.58
	VIC	3	0.69	0.46	0.06	0.02	5.13	0.93	1.92	1.09	6.38	3.22
	WA	3	0.99	1.10	0.10	0.14	5.53	0.60	2.13	2.66	12.66	10.42
B2, B21, B22	NSW	16	0.73	0.64	0.06	0.02	4.84	0.73	7.05	3.02	1.36	1.07
	SA	16	0.61	0.56	0.21	0.12	5.80	0.47	12.40	5.73	9.75	4.94
	TAS	8	1.43	1.67	0.11	0.08	4.83	1.09	8.16	6.12	2.83	1.39
	VIC	12	0.79	0.77	0.30	0.42	5.14	0.80	3.97	2.08	4.80	1.32
	WA	3	0.59	0.46	0.09	0.03	6.07	0.23	1.40	0.95	9.21	4.66

Acidity ($pH_{1:5}$) in the A1 horizons averaged 6.60 (SD ± 0.55) in H_20 and 5.82 (SD ± 0.57) in $CaCl_2$ (Figure 3(c)). The acceptable pH_{H20} range for apples is generally between 5.5 and 6.5 [61]. Only two soil horizons had a pH_{H20} less than 5.5, whilst 52 of 119 horizons had a pH_{H20} above 6.5, yet only one had a pH_{H20} above 7.5 (Figure 3(c)). The average pH_{H20} in the A2 horizon was 6.45 (SD ± 0.76) in which 2 of the 14 A2 horizons had a pH $_{H20}$ below 5.5 (Figure 3(c)). Subsoil pH tended to vary with soil order, and the average pH_{H20} in the B21 horizons was 6.08 (SD ± 0.81) and 5.87 (SD ± 0.88) in the B22 horizons, in which 17 of the 57 subsoil horizons had low pH_{H20} below 5.5 which included 4 Kurosol, 5 Dermosol, and 8 Ferrosol horizons (Figure 3(c), Table 5).

Exchangeable aluminium is considered to be toxic for apple production at levels above 0.4% [67]. Exchangeable aluminium was absent (<0.1%) from all but one of the A1 horizons (Figure 3(f)). Only 12 of the 71 tested soil horizons had exchangeable aluminium levels above 0.4%, 6 of which were B21 horizons, and 5 of which were B22 horizons. This included 2 Red Ferrosols, 1 Brown Ferrosol, 1 Red Dermosol, and 1 Grey Kurosol, all of which had a pH_{H20} between 4.5 and 5.4 (Figure 3(f), Table 5).

4. Discussion

Plant available water content is a key soil attribute for apple production [28]. PAWC and RAW varied greatly within the same soil order, which has implications for irrigation management. Comparing the two South Australian Brown Chromosols, site SA6 had 40 mm RAW, whilst site SA8 had 109 mm RAW to the same depth. Assuming a crop factor of 1.2 [73] and an average peak summer reference evapotranspiration (ET_0) of 45 mm per week [74], site SA6 would need to be irrigated every 5 days in summer, whereas site SA8 would need to be irrigated every 14 days in summer. Furthermore, variance between sites within the same soil order means that irrigation scheduling should be guided by soil moisture probes/sensors rather than relying on generic district-based irrigation guidelines or soil type-based irrigation guidelines.

Drainage appeared to be a key soil limitation to production in many apple growing regions including Tasmania, Victoria, and parts of South Australia. Apple production requires good soil drainage [28], yet at least half to two-thirds of all sites showed some evidence of poor subsurface drainage, and almost one-third of sites showed some evidence of impaired drainage in the A1 horizons. Evidence for poor drainage was supported by pedological observations (reported elsewhere) which revealed that 23 of the 34 sites had colour mottling due to temporary waterlogging in at least one soil horizon. Notably, six sites had mottling in the A1 or A2 horizons which indicated drainage and aeration in both topsoil and subsoil horizons.

As most apple orchards utilise dwarfing rootstock, the A1 horizon is the most important soil layer for production and management, in which good drainage, including having low soil density and high hydraulic conductivity, is required [28]. Being perennial, and thus infrequently cultivated or disturbed, it was expected that the A1 horizons would be very well structured with high carbon contents, high water retention, and high levels of macroporosity. This was not the case; whilst the A1 horizons generally had high to very high levels of organic carbon (average: 2.46%, SD ± 1.12), many of the A1 horizons were poorly structured. Values for bulk density were higher than expected (average: 1.32 g/cm^3, SD ± 0.16); in which 19 of 34 sites had insufficient air capacity to facilitate proper root function, whilst only 4 of the 34 sites had high levels of macroporosity. However, the high Ksat values indicate the macropores that were present must have been highly connected and relatively efficient at transporting water and air within the A1 horizons as evidenced by the generally high values for saturated hydraulic conductivity and *S* value.

All but one of the A2 horizons (site W3, Red Kandosol) was poorly structured, with high average bulk density (1.66 g/cm^3, SD ± 0.21), low air capacity (8.19%, SD ± 6.96), low RAW (7.97 mm/100 mm, SD ± 4.13), and very little macroporosity (average 0.50%). The A2 horizons also had poor chemical attributes for plant growth and function including very low levels of organic carbon (0.75%, SD ± 0.55), very low CEC (3.35 cmol (+) kg^{-1}, SD 11.05), and moderate levels of sodicity (ESP 11.05%, SD ± 8.94). Overall, the presence of an A2 horizon within a soil profile indicated the likelihood that root growth would be restricted.

The "health" and function of the B2 horizons appeared to be largely related to inherent soil properties rather than management practices. The majority of B2 horizons appeared to be somewhat hostile to root growth and function, due to their low air capacity (average: 5.27%, SD ± 3.81), high bulk density (average: 1.44 g/cm^3, SD ± 0.19), high proportion of unavailable soil water to 60 cm depth (average: 37.73 mm/100 mm, SD ± 33.22), suboptimal macroporosity of 1.19%, and at some sites (notably the Ferrosols), low pH and high exchangeable aluminium. Notably, subsoil pH was less than 5.5 at 13 of the 34 sites in which 7 sites also had exchangeable aluminium levels above the 0.4% threshold for toxicity. Many subsoil horizons also had surprisingly low CEC (average: 8.12 cmol (+) kg^{-1}, SD ± 5.32). In fact, 10 of the 34 sites had low to very low CEC (<6 cmol (+) kg^{-1}) throughout the whole soil profile. These sites were not associated with any particular soil order; they included a Hydrosol, a Ferrosol, three Kurosols, a Chromosol, and a Dermosol. Soils with low CEC are more likely to develop deficiencies in potassium (K^+) and magnesium (Mg^2+) and are at risk of nutrient leaching beneath the root zone [75], which is both inefficient for production, and potential cause of environmental harm [76]. Sites with low CEC (<6 cmol (+) kg^{-1}) require frequent, small amounts of fertigation to prevent nutrient leaching below the tree root zone.

Recommendations for soil management are limited by the highly variable nature of the data for the different soil health indicators; however, despite the high to very high levels of organic carbon in the A1 horizons, soil structure was poorer and more dense, with lower air capacity, RAW, PAWC, and macroporosity than would otherwise be expected given the lack of cultivation and soil disturbance in perennial orchards. Of particular note was the relatively poor status of many of the Ferrosols and Dermosols which were expected to have better soil structure and water retention than the Chromosols and Kurosols.

For growers seeking improved soil structure or soil carbon levels, normal orchard floor management practices including application of composts, mulches, "living mulches," or throwing cuttings from the inter-row onto the tree row [77–79] have been shown to increase soil carbon and improve under tree soil characteristics, especially on degraded or sandy soils. However, in soils with A1 horizons that already have moderate to high levels of soil carbon, further increasing soil carbon may prove frustratingly slow as soil carbon levels are likely to approach equilibrium or saturation over time [80]. Consequently, application of further organic material is unlikely to greatly increase soil carbon, although small changes in soil structure may still be achievable. Importantly, living mulches and organic residues may confer improvements in soil structure and macroporosity associated with root growth, reduced raindrop impact, and increased soil fauna burrowing [81, 82].

5. Conclusions

This study has provided valuable insight into the types and properties of soils used for apple production in Australia. Apple production was reported from a diverse range of soil types including Ferrosols, Chromosols, Kandosols, Hydrosols, Sodosols, Kurosols, and Dermosols. The data presented in this paper serve as a baseline for future soil condition monitoring for the Australian apple industry, as well as soil data required for use and development of the SPASMO and SINATA perennial tree crop models.

Chemical and physical soil properties were noted to vary greatly both within and between soil orders. There is no one soil type which is ideal for apple growing, in which most sites and all soil orders were prone to some form of either physical or chemical soil limitation to production. Whilst topsoils generally had high to very high levels of organic carbon, evidence suggested that the A1 horizons at most sites were moderately to highly compact, poorly aerated, and lacking large macropores. Yet the pores that were present were highly connected and efficient at transporting water and air within the topsoil. Almost all sites had restricted drainage and potential for poor aeration in the subsoil. A small number of sites also demonstrated potential issues with aeration in the A1 horizon as evidenced by poor air capacity and mottling.

Only one site was found to be saline; however, almost one-third of all soil horizons were found to be sodic (ESP > 5), and 10 of the 34 sites had CEC values less than 6 cmol (+) kg^{-1} throughout the entire soil profile, indicating potential for leaching of nutrients from the root zone and potential for aluminium toxicity because low pH was inferred at 6 of the 34 sites.

Soil water availability (RAW and PAWC) varied enormously between sites, even within the same soil order or region such that irrigation scheduling needs to be guided by infield soil moisture probes/sensors, rather than relying on generic district or soil type-based irrigation guidelines.

Management recommendations include use of soil moisture sensors/probes for scheduling irrigation, improved subsoil drainage and mounding of the tree row at planting, and use of living mulches and organic residues to improve soil structure and maintain or improve soil carbon. Recommendations for future study include extending the analysis to all major apple growing regions in Australia, and that analysis be repeated 10 years after the initial study to determine trends in soil condition over time, and further studies to identify improved indicators and threshold values for perennial orchard soils.

Nomenclature

CEC:	Cation exchange capacity
ESP:	Exchangeable sodium percent
pH:	Acidity-alkalinity
EC:	Electrical conductivity measured as a 1 : 5 solution
ECe:	Equivalent electrical conductivity
RAW:	Readily available soil water
PAWC:	Plant available water content
KuPF:	Hydraulic conductivity-matric potential device
WP4C:	Soil water potential dew point hygrometer
AC:	Air capacity
FC:	Field capacity
PWP:	Permanent wilting point
Θ_{gs}:	van Genuchten gravimetric saturated water content
Θ_{gr}:	van Genuchten gravimetric residual water content
α:	van Genuchten soil structure parameter
S value:	Reynolds et al. [1] soil structure parameter.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

MH, GO, WC, BW, and RL were responsible for field work. GO and MH were responsible for laboratory analysis. MH was responsible for statistical analysis and paper preparation. WC and NS were responsible for comments and edits.

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References

[1] W. D. Reynolds, C. F. Drury, C. S. Tan, C. A. Fox, and X. M. Yang, "Use of indicators and pore volume-function characteristics to quantify soil physical quality," *Geoderma*, vol. 152, no. 3-4, pp. 252–263, 2009.

[2] H. Innovation, "Australian Horticulture Statistics Handbook 2020/21: the nation's most comprehensive source of Australian horticulture data," *Hort Innovation*, vol. 12, 2022.

[3] ASRIS, "Asris- Australian soil resource information system," 2011, http://www.asris.csiro.au.

[4] J. K. Taylor and C. G. Stephens, "The apple growing soils of Tasmania Part 2. A soil survey of part of the huonville district," in *Bulletin 92*, CSIRO, Canberra, Australia, 1935.

[5] B. E. Butler, J. G. Bladwin, F. Penman, and R. G. Downes, *Soil Survey of Part of County Moira, Victoria*, CSIRO, Canberra, Australia, 1942.

[6] E. J. Johnston, "The soils of the western part of the murray valley irrigation area and their classification for irrigation," in *Soils and Land Use Series No. 4*, Division of Soils, CSIRO, Canberra, Australia, 1952.

[7] J. K. M. Skene and T. J. Poutsma, "Soils and land use in part of the goulburn valley, Victoria," in *Technical Bulletin No. 14*, Department of Agriculture, Victoria, Australia, 1962.

[8] J. K. M. Skene, "Soils and land use in the deakin irrigation area Victoria," in *Technical Bulletin No. 16*, Department of Agriculture, Victoria, Australia, 1963.

[9] J. K. M. Skene and L. B. Harford, "Soils and land use in the rochester and echuca districts, Victoria," in *Technical Bulletin No. 17*, Department of Agriculture, Victoria, Australia, 1964.

[10] J. K. M. Skene and J. R. Freedman, "Soil survey of part of Shepparton irrigation district, Victoria," in *Technical Bulletin No. 3*, Department of Agriculture, Victoria, Australia, 1944.

[11] R. Maxwell, *Soil Surveys of the Shepparton Irrigation Region*, Department of Natural Resources and Environment, Victoria, Australia, 2000.

[12] B. Mehta and Q. J. Wang, *Irrigation in a Variable Landscape: Matching Irrigation Systems and Enterprises to Soil Hydraulic Characteristics*, Department of Primary Industries, Tatura, Victoria, 2004.

[13] P. C. Baveye, "Bypass and hyperbole in soil research: worrisome practices critically reviewed through examples," *European Journal of Soil Science*, vol. 72, no. 1, pp. 1–20, 2021.

[14] M. M. Wander, L. J. Cihacek, M. Coyne et al., "Developments in agricultural soil quality and health: reflections by the research committee on soil organic matter management," *Frontiers in Environmental Science*, vol. 7, 2019.

[15] O. Rinot, G. J. Levy, Y. Steinberger, T. Svoray, and G. Eshel, "Soil health assessment: a critical review of current methodologies and a proposed new approach," *Science of the Total Environment*, vol. 648, pp. 1484–1491, 2019.

[16] P. Gatica-Saavedra, F. Aburto, P. Rojas, and C. Echeverría, "Soil health indicators for monitoring forest ecological restoration: a critical review," *Restoration Ecology*, vol. 31, no. 5, 2023.

[17] J. Letey, R. E. Sojka, D. R. Upchurch et al., "Deficiencies in the soil quality concept and its application," *Journal of Soil and Water Conservation*, vol. 58, no. 4, pp. 180–187, 2003.

[18] E. K. Bünemann, G. Bongiorno, Z. Bai et al., "Soil quality – a critical review," *Soil Biology and Biochemistry*, vol. 120, pp. 105–125, 2018.

[19] J. Lehmann, D. A. Bossio, I. Kögel-Knabner, and M. C. Rillig, "The concept and future prospects of soil health," *Nature Reviews Earth & Environment*, vol. 1, no. 10, pp. 544–553, 2020.

[20] D. E. Stott, "Recommended soil health indicators and associated laboratory procedures," *Soil Health Technical Note*, vol. 25, 2019.

[21] H. M. Hughes, S. Koolen, M. Kuhnert et al., "Towards a farmer-feasible soil health assessment that is globally applicable," *Journal of Environmental Management*, vol. 345, Article ID 118582, 2023.

[22] B. N. Moebius-Clune, D. J. Moebius-Clune, B. K. Gugino et al., *Comprehensive Assessment of Soil Health: The Cornell Framework Manual*, NY Cornell University, Geneva, Switzerland, 2016.

[23] J. E. Herrick, M. M. Wander, M. T. Walter, T. M. Nissen, and M. Corbeels, *The Rapid Assessment of Soil Health Using Available Carbon and Infiltration Capacity*, USDA-ARS National Soil Tilth Laboratory, Ames IA, USA, 2008.

[24] L. Lilburne, G. Sparling, and L. Schipper, "Soil quality monitoring in New Zealand: development of an interpretative framework," *Agriculture, Ecosystems & Environment*, vol. 104, no. 3, pp. 535–544, 2004.

[25] S. S. Andrews, D. L. Karlen, and C. A. Cambardella, "The soil management assessment framework: a quantitative soil quality evaluation method," *Soil Science Society of America Journal*, vol. 68, no. 6, pp. 1945–1962, 2004.

[26] S. Huber, B. Syed, A. Freudenschuss, V. Ernstsen, and L. Peter, *Proposal for a European Soil Monitoring and Assessment Framework*, EEA, Bulgaria, Balkans, 2001.

[27] M. M. Leinfelder, *Orchard Soil Health Protocols: Evaluation and Economic Impacts*, Cornell University, Ithaca, NY, USA, 2010.

[28] T. DuPont, D. Granatstein, and B. Sallato, *Soil Health in Orchards*, Washington State University, Pullman, WA, USA, 2020.

[29] D. Pasquel, S. Roux, J. Richetti, D. Cammarano, B. Tisseyre, and J. A. Taylor, "A review of methods to evaluate crop model performance at multiple and changing spatial scales," *Precision Agriculture*, vol. 23, no. 4, pp. 1489–1513, 2022.

[30] J. Sihag and D. Prakash, "A review: importance of various modeling techniques in agriculture/crop production," *Advances in Intelligent Systems and Computing*, vol. 52, 2019.

[31] S. Kaur and M. Singh, "Modeling the crop growth- a review," *Mausam*, vol. 71, no. 1, pp. 103–114, 2020.

[32] K. O Rauff and R. Bello, "A review of crop growth simulation models as tools for agricultural meteorology," *Agricultural Sciences*, vol. 6, no. 9, pp. 1098–1105, 2015.

[33] B. A. Keating and R. L. McCown, "Advances in farming systems analysis and intervention," *Agricultural Systems*, vol. 70, no. 2-3, pp. 555–579, 2001.

[34] C. A. Jones and J. R. Kiniry, *CERES-Maize: A Simulation Model of maize Growth and Development*, Texas A&M University Press, College Station, TX, USA, 1986.

[35] J. G. Kroes, J. C. van Dam, R. P. Bartholomeus et al., "SWAP version 4; Theory description and user manual," in *Wageningen, Wageningen Environmental Research*, LEI Wageningen UR, Wageningen, Netherlands, 2017.

[36] G. Hoogenboom, C. H. Porter, K. J. Boote et al., "The DSSAT crop modeling ecosystem," *Advances in Crop Modeling for a Sustainable Agriculture*, vol. 23, 2019.

[37] N. D. Swarts, M. Hardie, S. Green, and D. C. Close, *Strategic Irrigation and Nitrogen Assessment Tool for Apples (SINATA)*, University Of Tasmania, Tasmania, Australia, 2017.

[38] S. Green and B. E. Clothier, "SPASMO modelling of precision fertigation: appendix 3 final report," in *PIPS Precision Fertigation for Improved Apple Orchard Productivity: Milestone 8 Final Report*, Tasmanian Institute of Agriculture, University of Tasmania, and Plant and Food Research, New Zealand, Oceania, 2016.

[39] S. R. Green, M. Deurer, and B. E. Clothier, "A Consumptive water footprint analysis for apple fruit production," *Acta Horticulturae*, vol. 951, pp. 197–204, 2012.

[40] S. R. Green, I. Vogeler, B. E. Clothier, T. M. Mills, and C. V. D. Dijssel, "Modelling water uptake by a mature apple tree," *Soil Research*, vol. 41, no. 3, pp. 365–380, 2003.

[41] Ncst, *Australian Soil and Land Survey Field Handbook*, CSIRO Publishing, National Comitee on Soil and Terrain, Collingwood, Melbourne, 3rd edition, 2009.

[42] R. F. Isbell, "The Australian soil classification," *Australian Soil and Land Survey Series*, CSIRO Publishing, Clayton, Australia, 2002.

[43] M. T. van Genuchten, "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils," *Soil Science Society of America Journal*, vol. 44, no. 5, pp. 892–898, 1980.

[44] L. G. James, *Principles of Farm Irrigation System Design*, Wiley, New York, NY, USA, 1988.

[45] N. C. Brady and R. Weil, *Elements of the Nature and Properties of Soils*, Prentice Hall, New Jersey, NY, USA, 3rd edition, 2010.

[46] E. Rabot, M. Wiesmeier, S. Schlüter, and H. J. Vogel, "Soil structure as an indicator of soil functions: a review," *Geoderma*, vol. 314, pp. 122–137, 2018.

[47] M. Pulido Moncada, L. Helwig Penning, L. C. Timm, D. Gabriels, and W. M. Cornelis, "Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses," *Soil and Tillage Research*, vol. 140, pp. 20–28, 2014.

[48] W. D. Reynolds, C. F. Drury, X. M. Yang, and C. S. Tan, "Optimal soil physical quality inferred through structural regression and parameter interactions," *Geoderma*, vol. 146, no. 3-4, pp. 466–474, 2008.

[49] R. E. White, *Principles and Practice of Soil Science*, Blackwell Publishing, Oxford, UK, 4th edition, 2006.

[50] C. Zou, C. Penfold, R. Sands, R. K. Misra, and I. Hudson, "Effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine seedlings," *Plant and Soil*, vol. 236, no. 1, pp. 105–115, 2001.

[51] P. Hazelton and B. Murphy, *Interpreting Soil Test Results: What Do All the Numbers Mean?* CSIRO Publishing, Clayton, Australia, 2007.

[52] A. R. Dexter and E. A. Czyż, "Applications of S-theory in the study of soil physical degradation and its consequences," *Land Degradation & Development*, vol. 18, no. 4, pp. 369–381, 2007.

[53] W. D. Reynolds and D. E. Elrick, "Ponded infiltration from a single ring: I. Analysis of steady flow," *Soil Science Society of America Journal*, vol. 54, no. 5, pp. 1233–1241, 1990.

[54] Eijkelkamp, *2800 Guelph Permeameter Opperating Instructions*, Soilmoisture Equipment Corporation Santa Barbara, Calif, Goleta, California, 2011.

[55] D. E. Elrick, W. D. Reynolds, and K. A. Tan, "Hydraulic conductivity measurements in the unsaturated zone using improved well analyses," *Groundwater Monitoring & Remediation*, vol. 9, no. 3, pp. 184–193, 1989.

[56] W. D. Reynolds and D. E. Elrick, "IN situ measurement of field-saturated hydraulic conductivity, sorptivity, and the α-PARAMETER using the guelph permeameter," *Soil Science*, vol. 140, no. 4, pp. 292–302, 1985.

[57] W. D. Reynolds and D. E. Elrick, "A method for simultaneous in situ measurement in the vadose zone of field-saturated hydraulic conductivity, sorptivity and the conductivity-pressure head relationship," *Groundwater Monitoring & Remediation*, vol. 6, no. 1, pp. 84–95, 1986.

[58] G. E. Rayment and D. Lyons, *Soil Chemical Methods– Australasia*, CSIRO Publishing, Clayton, Australia, 2011.

[59] A. Walkley and I. A. Black, "An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method," *Soil Science*, vol. 37, no. 1, pp. 29–38, 1934.

[60] A. Jenkins, "Soil management in orchards," in *NSW Department of Primary Industries*, NSW Department of Primary Industries, Orange, Australia, 2004.

[61] H. Jonkers and H. Hoestra, "Soil pH in fruit trees in relation to specific replant disorder of apple. I. Introduction and review of literature," *Scientia Horticulturae*, vol. 8, no. 2, pp. 113–118, 1978.

[62] M. Hardie and R. Doyle, "Measuring soil salinity," in *Plant Salt Tolerance: Methods and Protocols*, Humana Press, Totowa, NJ, USA, 2012.

[63] A. J. Metson, "Methods of chemical analysis for soil survey samples," Soil Bureau Bulletin No. 12: Government Printer, Wellington, New Zealand, 1961.

[64] K. H. Northcote and J. K. M. Skene, "Australian soils with saline and sodic properties," in *CSIRO Divison of Soils*, Soil Publication, Bhopal, Madhya, 1972.

[65] W. W. Emerson, "Structural decline of soils, assessment and prevention," *Soil Research*, vol. 29, no. 6, pp. 905–921, 1991.

[66] P. E. V. Charman and M. M. Roper, "Soil organic matter," in *Soils – Their Properties and Management*, P. E. V. Charman and B. W. Murphy, Eds., Oxford University Press, Melbourne, Australia, 2007.

[67] V. Voiculescu, S. Stefanescu, G. Craioveanu, and V. Iacob, *Exchangeable Aluminium Toxicity of Acid Soils to Apple Tree and Pear Tree Growth*, Paper presented at the Lucrarile Conferintei Nationale pentru Stiinta Solului-Pitesti 29-31 august 1988 (Romania), Romania, Europe, 1989.

[68] D. S. McIntyre, "Water retention and moisture characteristics," in *Methods for Analysis of Irrigated Soils*, J. Loveday, Ed., Commonwealth Agriculture Bureau, England, UK, 1974.

[69] A. Cass, "Interpretation of some soil physical indicators for assessing soil physical fertility," in *Soil Analysis: An Interpretation Manual*, K. I. Peverill, L. A. Sparrow, and D. J. Reuter, Eds., CSIRO Publishing, Clayton, Australia, 1999.

[70] G. W. Geeves, B. Craze, and G. J. Hamilton, "Soil physical properties," in *Soils – Their Properties and Management*, P. E. V. Charman and B. W. Murphy, Eds., Oxford University Press, Oxford, UK, 2007.

[71] C. Rosen, B. Peter, and R. Eliason, "Soil test interpretations and fertilizer management for lawns, turf, gardens, and landscape plants," University of Minnesota Extension Service, St. Paul, MN, USA, 2022.

[72] A. Galvani, "The challenge of the food sufficiency through salt tolerant crops," *Reviews in Environmental Science and Biotechnology*, vol. 6, no. 1-3, pp. 3–16, 2007.

[73] FAO, *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*, Food and Agricultural Organisation, Rome, Italy, 1998.

[74] S. J. Jeffrey, J. O. Carter, K. B. Moodie, and A. R. Beswick, "Using spatial interpolation to construct a comprehensive

archive of Australian climate data," *Environmental Modelling & Software*, vol. 16, no. 4, pp. 309–330, 2001.
[75] P. Rengasamy and G. J. Churchman, "Cation exchange capacity, exchangable cations and sodicity," in *Soil Analysis, an Interpretation Manual*, K. I. Peverill, L. A. Sparrow, and R. J. Reuter, Eds., CSIRO Publishing, Clayton, Australia, 2001.
[76] M. A. Hardie, G. Oliver, B. E. Clothier, S. A. Bound, S. A. Green, and D. C. Close, "Effect of biochar on nutrient leaching in a young apple orchard," *Journal of Environmental Quality*, vol. 44, no. 4, pp. 1273–1282, 2015.
[77] C. M. Culumber, J. R. Reeve, B. L. Black, C. V. Ransom, and D. G. Alston, "Organic orchard floor management impact on soil quality indicators: nutrient fluxes, microbial biomass and activity," *Nutrient Cycling in Agroecosystems*, vol. 115, no. 1, pp. 101–115, 2019.
[78] P. Losciale, L. Gaeta, L. Manfrini, L. Tarricone, and P. Campi, "Orchard floor management affects tree functionality, productivity and water consumption of a late ripening peach orchard under semi-arid conditions," *Applied Sciences*, vol. 10, no. 22, p. 8135, 2020.
[79] S. Hussain, M. K. Sharma, A. R. War, and B. Hussain, "Weed management in apple cv. Royal delicious by using different orchard floor management practices," *International Journal of Fruit Science*, vol. 20, no. 4, pp. 891–921, 2020.
[80] C. E. Stewart, K. Paustian, R. T. Conant, A. F. Plante, and J. Six, "Soil carbon saturation: concept, evidence and evaluation," *Biogeochemistry*, vol. 86, no. 1, pp. 19–31, 2007.
[81] W. Tang, H. Yang, W. Wang et al., "Effects of living grass mulch on soil properties and assessment of soil quality in Chinese apple orchards: a meta-analysis," *Agronomy*, vol. 12, no. 8, p. 1974, 2022.
[82] W. R. Żelazny and M. Licznar-Małańczuk, "Soil quality and tree status in a twelve-year-old apple orchard under three mulch-based floor management systems," *Soil and Tillage Research*, vol. 180, pp. 250–258, 2018.