Proposal for a new Bassendean reference soil in Western Australia

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Abstract

Soils on the Lower Pleistocene Bassendean sands of the Swan Coastal Plain of Western Australia are among the most infertile in the world, but support plant communities of remarkable diversity. Following detailed studies of soil chronosequences in the Perth region, the current Bassendean reference soil near Yalgorup National Park appears to be on a Middle Pleistocene Spearwood dune, rather than a Lower Pleistocene Bassendean dune. This assessment is based on the bright yellow subsoil, rather than the bleached quartz sand that characterises soils on Bassendean sand. We therefore propose a new location for the Bassendean reference soil, on Lower Pleistocene dunes in the Yeal Nature Reserve north of Perth. The site forms part of the Guilderton soil chronosequence and the extensive Bassendean dunes in this region retain a distinct dune morphology. The proposed reference soil consists of many metres of medium and coarse-grained bleached quartz sand with extremely low total P concentrations (<3 g P m^{-2} in the upper metre). The profile provides an exemplary Bassendean soil suitable for the regional reference, and demonstrates the consequences of long-term pedogenesis on the Swan Coastal Plain.

Keywords: Bassendean, chronosequence, Entisol, Guilderton, Podzol, reference soil, Sand, Swan Coastal Plain

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INTRODUCTION

Southwestern Australia is known for its ancient landscapes, diverse plant communities, and infertile soils. Some of the most infertile soils are on the Swan Coastal Plain, associated with three major sand deposits formed by Quaternary interglacial sea-level high stands (McArthur 2004; Laliberté *et al*. 2012; Turner & Laliberté 2015; Turner *et al*. 2018). Soils on these deposits form a chronosequence, with Holocene soils on Quindalup dunes (Safety Bay Sand), Middle Pleistocene soils on Spearwood dunes (Tamala Limestone) and Lower Pleistocene soils on Bassendean dunes (Bassendean Sand, on the Ascot Formation; Laliberté *et al*. 2012; Turner *et al*. 2018). Long-term pedogenesis involves acidification and leaching of carbonate from Holocene soils, followed by leaching of iron oxides from Middle Pleistocene soils, leaving Lower Pleistocene soils consisting of bleached quartz sand profiles many metres deep (Turner & Laliberté 2015; Turner *et al*. 2018). These Bassendean soils are among the most infertile soils in the region, if not the world. They are of particular significance ecologically because they support some of the highest-diversity plant communities in Western Australia (Laliberté *et al*. 2014; Zemunik *et al*. 2015, 2016).

The soils of southwestern Australia were described in detail by McArthur and colleagues (McArthur & Bettenay 1974; McArthur & Russell 1978), including the identification of a series of reference soils (McArthur 2004). Their work provided the foundation for understanding soil development on the Swan Coastal Plain and guided us during our recent studies of soil chronosequences in the region (Laliberté *et al*. 2012; Hayes *et al*. 2014; Turner & Laliberté 2015; Zemunik *et al*. 2016; Turner *et al*. 2018). These studies include soils of the coastal sandplains from Jurien Bay in the north to D'Entecasteaux National Park in the south (on the Scott Coastal Plain). Our primary aim was to identify soil chronosequences that would allow us to examine relationships between soil development and biological communities during long-term ecosystem development (e.g. Laliberté *et al*. 2017; Turner *et al*. 2019).

During our research, we revisited several of McArthur's reference soil locations near Yalgorup National Park. However, we interpret the Bassendean reference soil (SCP 11 in McArthur 2004) as having been formed on a Middle Pleistocene Spearwood dune. The SCP 11 site was located in the Buller Nature Reserve, just south of Buller Road near the town of Waroona (32.86740°S, 115.82908°E). McArthur reported that the profile consisted of a 50 cm-thick, bleached grey A horizon over light yellowish brown (10YR 6/4) to yellowish brown (10YR 5/6 and 5/8) sand, with no spodic horizon in the upper 180 cm. However, the yellow is due to iron oxide coatings on sand grains and is characteristic of soils of the Spearwood dunes. The profile is similar to a Middle Pleistocene profile nearby on a Spearwood dune, termed the old Spearwood profile in Turner *et al*. (2018). In contrast, the much older Bassendean soils have lost iron oxides from the entire profile, yielding bleached grey/white sand many metres deep.

We are confident that we examined the same soil described by McArthur (McArthur 2004) and our observations by auger match the original description of the SCP 11 reference soil. The site is close to an extensive area of Bassendean soils to the east on flat terrain, although this is now almost all converted to agricultural land and little natural vegetation remains, perhaps explaining why McArthur positioned the reference soil at this location. We identified an area of Bassendean soil under native vegetation nearby in the Buller Nature Reserve (about 1.7 km to the SSE, 32.88197°S, 115.83583°E), which we included in the Yalgorup chronosequence (Turner *et al*. 2018). However, this site was probably influenced to some extent by nearby farmland, reflected in a slightly greater total P concentration than typical of Bassendean profiles elsewhere.

Given that the location of the current Bassendean reference soil appears to be on a Spearwood dune, we propose an alternative site for the Bassendean reference soil (Fig. 1). There is an appropriate profile in the Yeal Nature Reserve south-west of Guilderton, approximately 70 km north of Perth, which contains an extensive area of Bassendean soil (Fig. 2). This profile was previously included in a publication describing a series of 2 million-year chronosequences, where it was assigned to stage six of the chronosequence (Turner *et al*. 2018). Here we describe the profile in detail and provide comprehensive information on its physical and chemical properties. The profile represents an exemplary Bassendean soil that is suitable as a new reference for the region.

METHODS

Location and sampling

The proposed Bassendean reference soil is adjacent to the Gnangara–Moore River State Forest on the Swan Coastal Plain north of Perth, Western Australia at 31.39909°S, 115.76005°E (Fig. 1), and is 71 m above sea level. On 16 August 2013, during winter, we excavated a profile pit to approximately 2 m on the upper backslope of the dune. The profile (Fig. 2a) was described by genetic horizon and samples taken for physical and chemical analysis. Deeper samples were obtained using a sand auger by

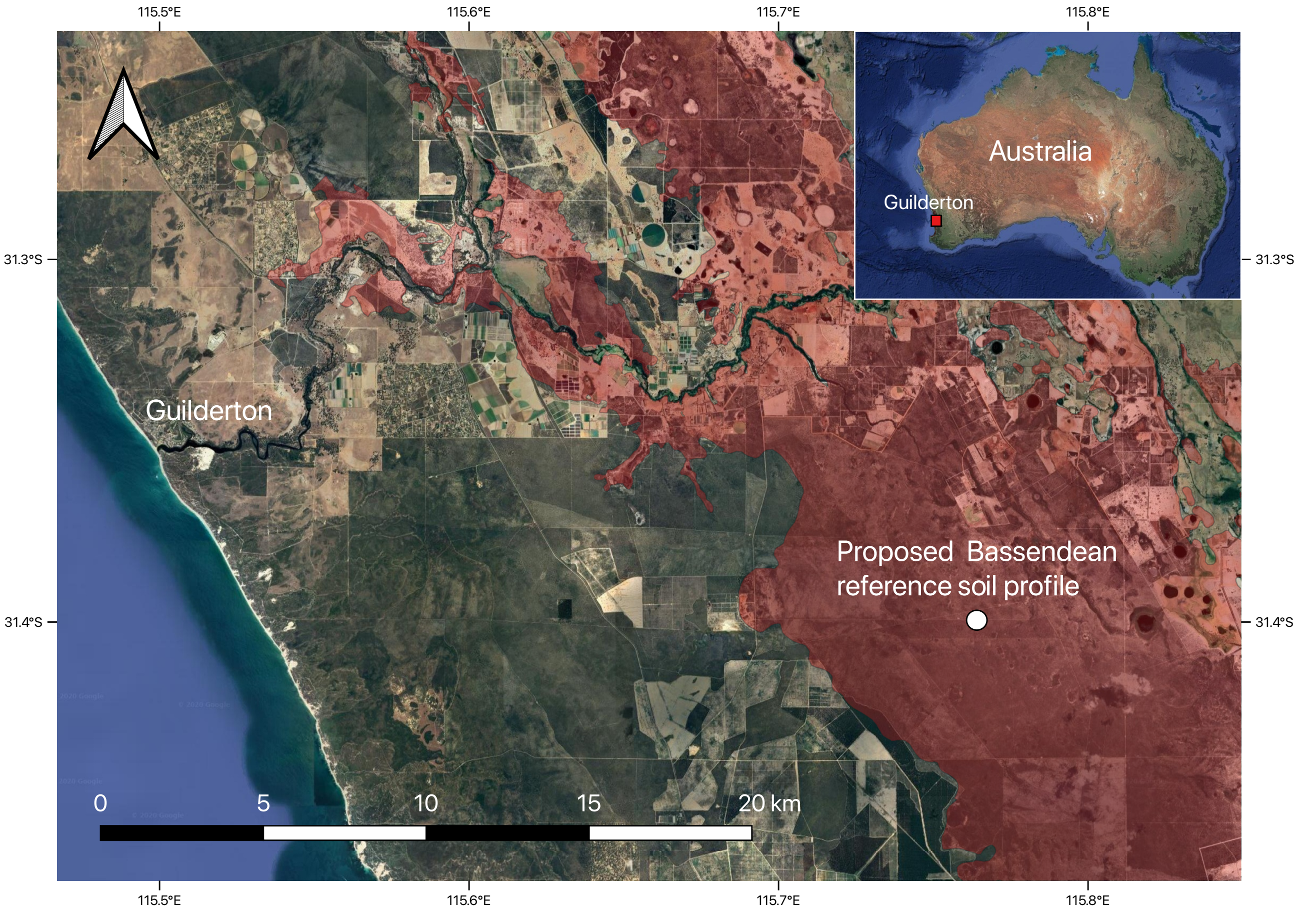

Figure 1. Location of the described profile for the proposed Bassendean reference soil for Western Australia (white circle). The boundary of the Bassendean Soil System is in red (Soil Landscape Mapping – Systems DPIRD-064 dataset, Western Australian Department of Primary Industries and Regional Development; https://catalogue.data.wa.gov.au/dataset/soil-landscape-mapping-systems). Arrow points toward the north. Projected spatial reference system: EPSG:3857. Basemap: Google Inc.

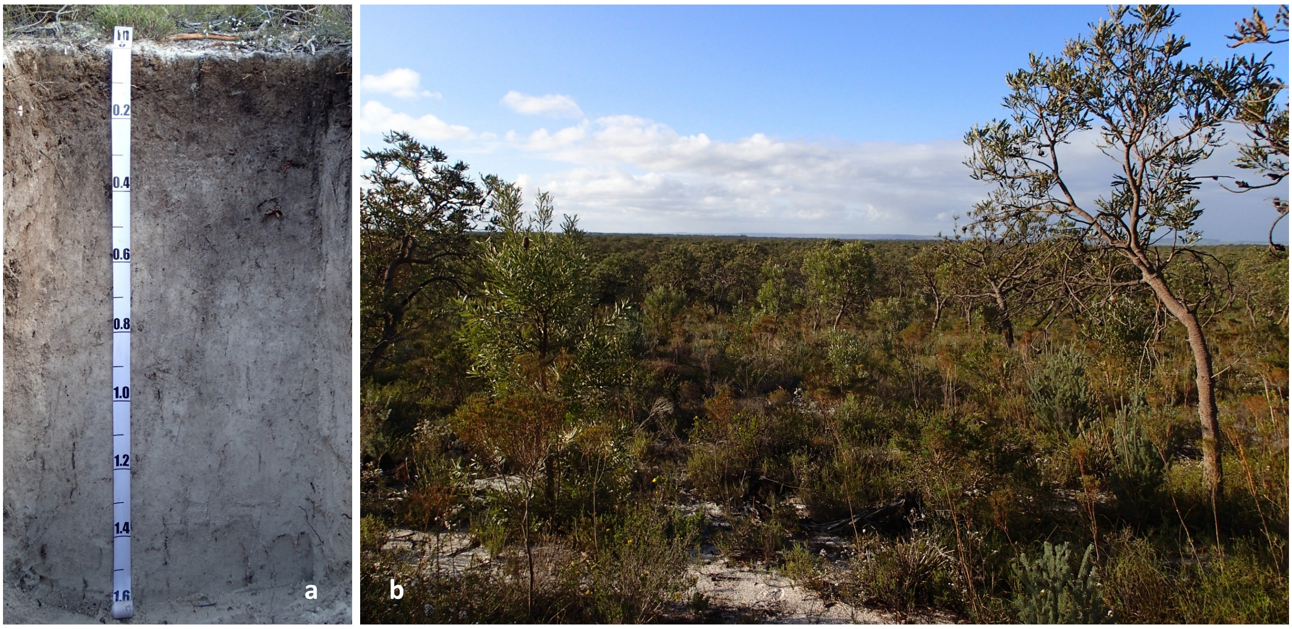

Figure 2. a) The proposed Bassendean reference soil for Western Australia, and b) its landscape position and vegetation.

augering through the base of the profile pit. However, we could not retrieve samples deeper than 5 m due to the incoherent nature of the sand, despite adding water to the auger hole. The soil was classified according to Soil Taxonomy (Soil Survey Staff 1999) and the Australian Soil Classification (Isbell 2002). We do not have soil temperature data for the chronosequences, but estimate the soil temperature regime from air temperatures at Guilderton Aerodrome (data from 1996–2015). The control section for the profile (Soil Taxonomy) is between 30 and 90 cm below the soil surface.

Laboratory Analysis

Following the analytical methodology previously described by Turner & Laliberté (2015) and Turner *et al*. (2018), soil pH was determined in both deionised water and 10 mM $CaCl_2$ in a 1:2 soil to solution ratio using a glass electrode. The concentrations of sand (53 μm to 2 mm), silt (2–53 μm), and clay (<2 μm) sized particles were determined by the pipette method following pretreatment to remove soluble salts and organic matter (Gee & Or 2002), with further separation of sand fractions by manual dry sieving. Total carbon (C) and nitrogen (N) were determined by automated combustion and gas chromatography with thermal conductivity detection using a Thermo Flash 1112 elemental analyser (CE Elantech, Lakewood, NJ, USA). Total phosphorus (P) was determined by ignition (550°C, 1 hr) and extraction in 1 M H_2SO_4 (16 hr, 1:50 soil to solution ratio). Exchangeable cations were determined by extraction in 0.1 M $BaCl_2$ (2 hr, 1:30 soil to solution ratio), with detection by inductively-coupled plasma optical-emission spectrometry (ICP–OES) on an Optima 7300 DV (Perkin-Elmer Ltd, Shelton, CT, USA; Hendershot *et al*. 2008). Total exchangeable bases (TEB) was calculated as the sum of charge equivalents of calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na); effective cation exchange capacity (ECEC) was calculated as the sum of the charge equivalents of aluminium (Al), Ca, iron (Fe), K, Mg, manganese (Mn), and Na; base saturation was calculated by (TEB ÷ ECEC) × 100. Bulk density was determined by taking three replicate cores of known volume in each horizon using a 7.5 cm diameter stainless steel ring and determining the soil mass after drying at 105°C. Total mineral elements were determined by digestion in concentrated (70%) HNO_3 under pressure at 180°C in PTFE vessels (PDS-6 Pressure Digestion System, Loftfields Analytical Solutions, Neu Eichenberg, Germany), with detection by ICP–OES. This also provided a second measurement of total P.

RESULTS

Soil forming factors

The five soil-forming factors are climate, parent material, topography, organisms, and time (Jenny 1941). Mean annual temperature at the site is 18.4°C. The monthly mean minimum temperature is 12.3°C in July and the monthly mean maximum temperature is 25.2°C in January. Mean annual precipitation (mm) 653.4 mm, of which 15% falls in the dry season from November to April inclusive (defined as months with <30 mm rainfall). Potential annual evapotranspiration is 1403 mm, with an annual water balance of –750 mm (Turner *et al*. 2018). The soil moisture regime is therefore xeric and the soil temperature regime is thermic. The parent material is Bassendean Sand, which we assume is approximately 2 million years old based on the age of the underlying Ascot Formation (Kendrick *et al*. 1991). The profile was located on the shoulder of a broad, low dune ridge, facing northeast (5% slope; Fig. 2b). The vegetation is undisturbed Mediterranean shrubland known locally as kwongan (Lamont *et al*. 1984; Lambers 2014), with scattered *Banksia attenuata* and *B. menziesii* up to 3 m tall, a sparse shrubby understory (~50% cover), and a thin layer of dry leaf litter with approximately 25% bare ground. Roots were present throughout the profile to at least 300 cm.

Profile description

A1—0 to 1 cm; light grey (10YR 7/1) sand; loose, single grain; medium and coarse clean quartz sand grains; abrupt smooth boundary.

A2—1 to 18 cm; very dark brown (10YR 2/2) loamy sand; weak very coarse blocky structure held by very fine sand-binding roots, breaking under moderate force to single grain; moist; medium and coarse clean quartz grains; common coarse, medium, and fine, and many very fine roots; many cluster roots; clear smooth boundary.

A3—18 to 30 cm; very dark greyish brown (10YR 3/2) sand; very weak coarse structure, held by very fine sand-binding roots; moist; medium and coarse clean quartz grains; common coarse, medium, and fine, and many very fine roots; clear smooth boundary.

EA—30 to 62 cm; light brownish grey (10YR 6/2) sand; very weak coarse structure held by very fine sand-binding roots; otherwise loose, single grain; moist; slightly cohesive; medium and coarse clean quartz grains; common coarse, medium, and fine, and many very fine roots; gradual smooth boundary.

E1—62 to 103 cm; light grey (10YR 7/1) sand; loose, single grain; subrounded, medium and coarse clean quartz grains; common coarse, and few medium, fine, and very fine roots; not cohesive, collapsing into pit from side walls and face; gradual smooth boundary.

E2—103 to 500+ cm; white (10YR 8/1) sand; loose, single grain; subrounded, medium and coarse clean quartz grains; very few medium, fine, and very fine roots to at least 300 cm.

Soil classification

Diagnostic horizons and features (Soil Taxonomy) are (*i*) xeric moisture regime, *(ii)* ochric epipedon from 0 to 30 cm, (*iii*) albic horizon from 30 to 500+ cm, (*iv*) >90% quartz sand in the particle-size control section, (*v*) <5% silt and clay in the particle size control section. The soil is an Entisol because it lacks diagnostic horizons in the upper 200 cm of the profile. The sandy particle size class places it in the Psamment suborder, and the dominance of quartz qualifies it as a Quartzipsamment at the Great Group level. The xeric moisture regime and lack of other diagnostic features qualifies the profile as a Xeric Quartzipsamment. In the absence of a spodic horizon (at least within the upper 5 m) the profile qualifies as an Arenic Grey-Orthic-Tenesol in the Australian Soil Classification System.

Physical and chemical properties

The soil consists of >97% sand with a bulk density between 1.3 and 1.5 g cm^{-3} (Appendix Table 1). The profile is therefore extremely well-drained, although the surface soil becomes water-repellent when dry. The sand is primarily medium and coarse grained (0.25 to 1.00 mm), although there is a greater proportion of fine sand below 340 cm (Appendix Table 2). The soil is moderately acid (measured in water). Total C and total N concentrations decline with depth, with wide C:N ratios (approximately 50–60; Table 3). The profile contains no carbonate, so total C is equivalent to organic C. Total P concentrations are extremely low throughout (<5 mg P kg^{-1}, and <3 g P m^{-2} in the upper metre of the profile), and corresponding C:P ratios exceed 6000 in the A horizon (Appendix Table 3). Exchangeable cations are low, particularly in the subsoil, and base saturation is 100% throughout (extractable Al, Fe, and Mn are undetectable; Appendix Table 4). Total mineral elements are very low, with undetectable concentrations of some micronutrients (i.e. B, Cu, Zn; Appendix Table 5).

DISCUSSION

That the soil is classified as a young undeveloped soil (i.e. an Entisol) despite its great age is an artifact of the US Soil Taxonomy system, which does not recognise old, coarse textured and strongly weathered soils such as the Bassendean, where diagnostic horizons are >200 cm deep. We did not encounter a spodic horizon in this profile, but if there was one at >5 m depth then the soil would qualify as a Giant Humosesquic Aeric Podosol in the Australian Soil Classification. Quartz-rich soils often contain insufficient metals to yield a spodic horizon and therefore develop into Quartzipsamments (Fanning & Fanning 1989). However, there are spodic horizons at depth in old Spearwood (Middle Pleistocene) and Bassendean dunes elsewhere on the Swan and Scott coastal plains. In addition, Giant Podosols are a feature of coastal dune chronosequences elsewhere in Australia, such as the Cooloola soil chronosequence in Queensland (Thompson 1981, 1992), albeit on younger (Middle Pleistocene) dunes than those studied here. Whether a spodic horizon lies at depth in the proposed Bassendean reference soil perhaps depends on water table depth, which has been linked to the presence of a spodic horizon elsewhere in the Swan Coastal Plain (McArthur & Russell 1978).

The Bassendean reference soil is extremely infertile, representing one of the most infertile soils worldwide. In particular, it contains an extremely small amount of total P, most of which is in organic form (Turner *et al*. 2018). Base cation concentrations are also extremely low, with cation exchange capacity almost entirely associated with soil organic matter. In these respects, the Bassendean reference soil is characteristic of Bassendean soils throughout the Swan coastal plain, with similar soils on the Scott Coastal Plain (e.g. near Warren Beach; Turner *et al*. 2018).

The sandy nature of the Bassendean soil means that it is extremely well-drained, although the surface soil can exhibit a high degree of water repellency when dry (Salama et al. 2005). This hydrophobicity is caused by coatings of waxy organic matter around sand grains (Roberts & Carbon 1972; Harper & Gilkes 1994) and is common in Western Australia (Roberts & Carbon 1971). Although the water-repellent surface soil can reduce infiltration, it appears to conserve soil moisture during the dry season by reducing evaporation (Rye

& Smettem 2017). Water-repellency can also be caused by fire (DeBano 1981), with subsequent surface runoff across the surface accelerating ecosystem retrogression by transferring ash and associated nutrients from dune crests to swales (Turner & Laliberté 2015).

The Bassendean soil is of considerable ecological and conservation importance in the region, because it supports a remarkable diversity of plant species, both taxonomically and functionally. Within the Swan Coastal Plain, both alpha and beta diversity reach their maximum values on the Bassendean dunes (Laliberté *et al*. 2014, Zemunik *et al*. 2016). Similarly, the diversity of plant nutrient-acquisition strategies is greatest on the Bassendean soil (Zemunik *et al*. 2015). Given that most of the extremely small concentrations of plant nutrients are associated with the surface soil, and that there are no subsoil nutrient reserves, the Bassendean soil is particularly sensitive to disturbance. It should have high conservation priority, especially considering that *Banksia* woodlands on Spearwood and Bassendean dunes around Perth are highly fragmented and threatened by urbanization (Ramalho *et al*. 2014; Department of the Environment and Energy 2016).

CONCLUSION

We present an alternative Bassendean reference soil for Western Australia. The new profile is located in an extensive area of Bassendean sand with undisturbed vegetation and a distinct dune morphology. The soil is extremely infertile and forms the end-point of the Guilderton soil chronosequence. These soils are extensive throughout the Swan Coastal Plain, with comparable soils under greater rainfall on the Scott Coastal Plain. The Bassendean soil has high conservation priority given its association with a threatened ecological community.

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APPENDIX.

Table 1

Bulk density and particle-sizes in genetic horizons of the proposed Bassendean reference soil. nd, not determined.

Depth cm	Designation	Bulk density (fine earth) g cm-3	Coarse fragments (>2 mm) % vol	Sand %	Silt %	Clay %	Textural class
0–1	A1	nd	0	99.3	0.1	0.7	Sand
1–18	A2	1.31	0	97.2	1.5	1.3	Sand
18–30	A3	1.46	0	98.6	0.7	0.6	Sand
30–62	EA	1.39	0	98.9	0.4	0.7	Sand
62–103	E1	1.36	0	98.9	0.4	0.6	Sand
103–340	E2 (1)	1.46	0	98.9	0.4	0.7	Sand
340–500+	E2 (2)	nd	0	99.3	0.1	0.7	Sand

Table 2

Sand size fractionation in genetic horizons of the proposed Bassendean reference soil.

Depth cm	Very fine sand (0.05–0.10 mm)	Fine sand (0.10–0.25 mm)	Medium sand (0.25–0.5 mm)	Coarse sand (0.50–1.0 mm)	Very coarse sand (1.0–2.0 mm)
	% total sand				
0–1	0.2	3.3	51.9	44.6	0.0
1–18	0.0	1.9	42.8	55.0	0.2
18–30	0.1	3.3	45.7	50.8	0.1
30–62	0.0	1.4	43.6	54.7	0.3
62–103	0.2	3.8	48.6	47.4	0.0
103–340	0.0	3.8	52.7	43.0	0.5
340–500+	1.1	28.1	52.3	18.4	0.0

Table 3

Soil pH and total carbon (C), nitrogen (N), and phosphorus (P) concentrations in genetic horizons of the proposed Bassendean reference soil.

Depth	Soil pH			Total C	Total N	Total P[a]	C:N	C:P
cm	Water	$CaCl_2$	$BaCl_2$	g kg^{-1}	mg kg^{-1}	mg P kg^{-1}		
0–1	6.31	4.37	4.79	4.19	89.0	2.7	47.1	1534
1–18	5.94	3.80	3.63	28.98	594.5	4.6	48.7	6369
18–30	5.65	3.65	3.69	8.41	158.6	2.3	53.0	3613
30–62	5.55	3.64	4.08	2.78	45.2	1.7	61.4	1642
62–103	5.48	4.02	4.46	1.17	18.9	0.8	62.1	1447
103–340	5.61	4.42	4.84	0.34	3.6	1.0	94.5	358
340–500+	5.61	5.09	5.14	0.20	0.5	1.4	375.5	146

[a] Total P determined by ignition and acid digestion.

Table 4

Exchangeable cations by $BaCl_2$ extraction in genetic horizons of the proposed Bassendean reference soil. TEB, total exchangeable bases; ECEC, effective cation exchange capacity; BS, base saturation.

Depth cm	Al	Ca	Fe	K	Mg	Mn	Na	TEB	ECEC	BS %
	cmol$_c$ kg^{-1}									
0–1	<0.01	0.40	<0.01	0.03	0.12	<0.01	0.02	0.58	0.58	100
1–18	<0.01	2.09	<0.01	0.03	0.54	<0.01	0.09	2.75	2.75	100
18–30	<0.01	0.79	<0.01	0.02	0.27	<0.01	0.03	1.11	1.11	100
30–62	<0.01	0.12	<0.01	0.02	0.05	<0.01	0.01	0.20	0.20	100
62–103	<0.01	<0.01	<0.01	0.02	0.01	<0.01	<0.01	0.04	0.04	100
103–340	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.01	0.01	100
340–500+	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	0.01	0.04	0.04	100

Table 5

Total mineral elements determined by HNO_3 digestion in genetic horizons of the proposed Bassendean reference soil.

Depth cm	Al	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	Zn
	mg kg^{-1}										
0–1	122	33	141	<1	43	17	28	<5	111	<5	<5
1–18	93	<5	549	<1	74	14	88	<5	25	<5	<5
18–30	24	<5	160	<1	33	<10	34	<5	17	<5	<5
30–62	13	<5	70	<1	58	<10	13	<5	9	<5	<5
62–103	13	<5	13	<1	93	<10	<10	<5	28	<5	<5
103–340	26	8	10	<1	123	<10	<10	5	17	<5	<5
340–500+	24	6	21	<1	226	14	<10	6	51	<5	<5