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Possible fertile island effect influenced by native plants that have differential controls on soil properties in the Atacama Desert

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The Yungay Oasis is a unique area within the hyper-arid Atacama Desert where native plants still thrive. This study aimed to evaluate how *Suaeda foliosa* and *Distichlis spicata* influence soil physicochemical and mineralogical properties and potentially induce the formation of “fertile islands”. Soil samples were collected along horizontal direction extending from 0 to 50 cm away from the plants at 10 cm intervals, and along vertical directions between 0 and 25 cm depth at 5 cm intervals. Unvegetated soils were also sampled for comparison. The results show that both plant species influenced soil physicochemical parameters by reducing soil alkalinity (from 7.8–8.5 to 6.9–7.2 and 6.6–7.6 in *S. foliosa* and *D. spicata*, respectively) and increasing phosphorus and different carbon fractions, primarily in *S. foliosa* soils, compared with unvegetated soils. In contrast to previous fertile island studies, nitrogen contents showed lower values, especially in *S. foliosa* soils, suggesting processes related to N losses driven by vegetation presence. These results were accompanied by mineral formation inside and outside *D. spicata* roots observed by SEM analysis, suggesting changes in physicochemical conditions driven by the roots in the soil, together with the formation of calcium carbonates such as vaterite. Additionally, weathering indices, including the Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), and Vogt’s Residual Index (V), indicated an increase in chemical weathering in soils under *D. spicata*. These findings indicate that *S. foliosa* and *D. spicata* potentially influence soil development, fostering a fertile island-like effect that enhances soil nutrient content and structure within the Yungay Oasis, making these species vital to ecosystem resilience in hyper-arid environments.

KEYWORDS

Atacama Desert, chemical weathering, hyper-arid soils, nutrient enrichment, plant-soil interaction

1 Introduction

In many environments, including desert ecosystems, vegetation generates soil spatial heterogeneity, which leads to the formation of fertile islands (1, 2). Fertile islands are known to enhance soil fertility (3–5), while their presence helps increase soil productivity and diversity through nutrient accumulation in soils (6–8). Soil moisture and pH have been identified as the principal parameters that drive the fertile island effect and the accumulation of nutrients (9). Additionally, plants may influence other parameters such as electrical conductivity and salinity of soils under their canopies (10). Plants are also capable of influencing and changing surrounding microbial communities, interacting and leading to a biological formation of soil processes (11–13). This interaction is relevant since microorganisms can optimize the use of resources, improve nutrient cycling, and accelerate soil development by altering soil minerals, leading to biological weathering (13).

The fertile island effect is variable and depends on many biotic and abiotic factors, including climate, seasonality, plant gender, and vegetation type among (1, 14–17). The effects of plants on soils have been widely studied in arid and semi-arid ecosystems (2, 6, 7). However, little is known about the fertile island effect and, specifically, how plants drive soil properties in hyper-arid ecosystems, where water availability, organic matter, and biological activity are scarce. Consequently, the influence of native plants on physicochemical and mineralogical soil properties in hyper-arid ecosystems remains poorly understood.

The Atacama Desert is one of the oldest and driest places on Earth (18–20). In its hyper-arid core, mean annual precipitation is less than 2 millimeters per year (21), resulting in very low organic matter contents. According to Fuentes et al. (22), the values of superficial total organic carbon (TOC) are between 160 and 310 μg TOC per gram of soil. Soil development is primarily controlled by atmospheric deposition (23), leading to salt accumulation (24); however, soil weathering has been reported as a slow process, and others, such as leaching and erosion rates, are almost negligible (25, 26). Due to these conditions, the hyper-arid core has been described as one of the most hostile and harsh environments for life on Earth and has been considered at the limit of microbial survival (27). Consequently, the hyper-arid core of the Atacama Desert has served as a model system for studying life in extreme environments (22, 27–29). Within the Atacama Desert lies the study site, referred to in this paper as the “Yungay Oasis”. In this oasis, it is possible to find a remarkable number of patches of salt grasses and shrubs that are fed by brackish groundwater (29–32). The presence of vegetation in this extreme environment provides an ideal natural laboratory to investigate influences on different soil properties under hyper-aridity and drought conditions. This knowledge is particularly important considering the imminent impacts of climate change on soils worldwide, including alterations in ecosystems, soil fertility, plant cover, richness, biomass, and plant productivity (33). Moreover, studying the effects of plants on hyper-arid soils may contribute to a broader understanding of the effects of fertile islands in extreme desert environments.

This study hypothesized that native plants could influence and modify soil physicochemical and mineralogical properties even under hyper-arid conditions. Therefore, the objective of this study

was to determine whether two native species that inhabit the Yungay Oasis are able to influence the physicochemical and mineralogical properties of hyper-arid soils and their potential to form fertile islands.

2 Methodology

2.1 Study site

This study was conducted in the Yungay Oasis area (24° 03'30"S, 69°49'37"W), located southeast of the city of Antofagasta, Chile, inside the Atacama Desert hyper-arid core (Figures 1A, B). This site is located at an elevation of approximately 950 m above sea level; the mean temperature ranges between 10 °C and 30 °C (34), and precipitation is scarce (21). In this oasis, it was possible to find remarkable vegetation cover (28, 32) (Figure 1C). Two plant species were selected, namely, *S. foliosa* and *D. spicata*, to sample their surrounding soil (Figures 1D, E). *S. foliosa* is a perennial plant that can grow in saline environments. The genus *Suaeda* has been reported to have several salt tolerance mechanisms (35). *D. Spicata* is commonly known as “saltgrass” and can tolerate high soil salinity and, therefore, can be found in diverse environments (36–39).

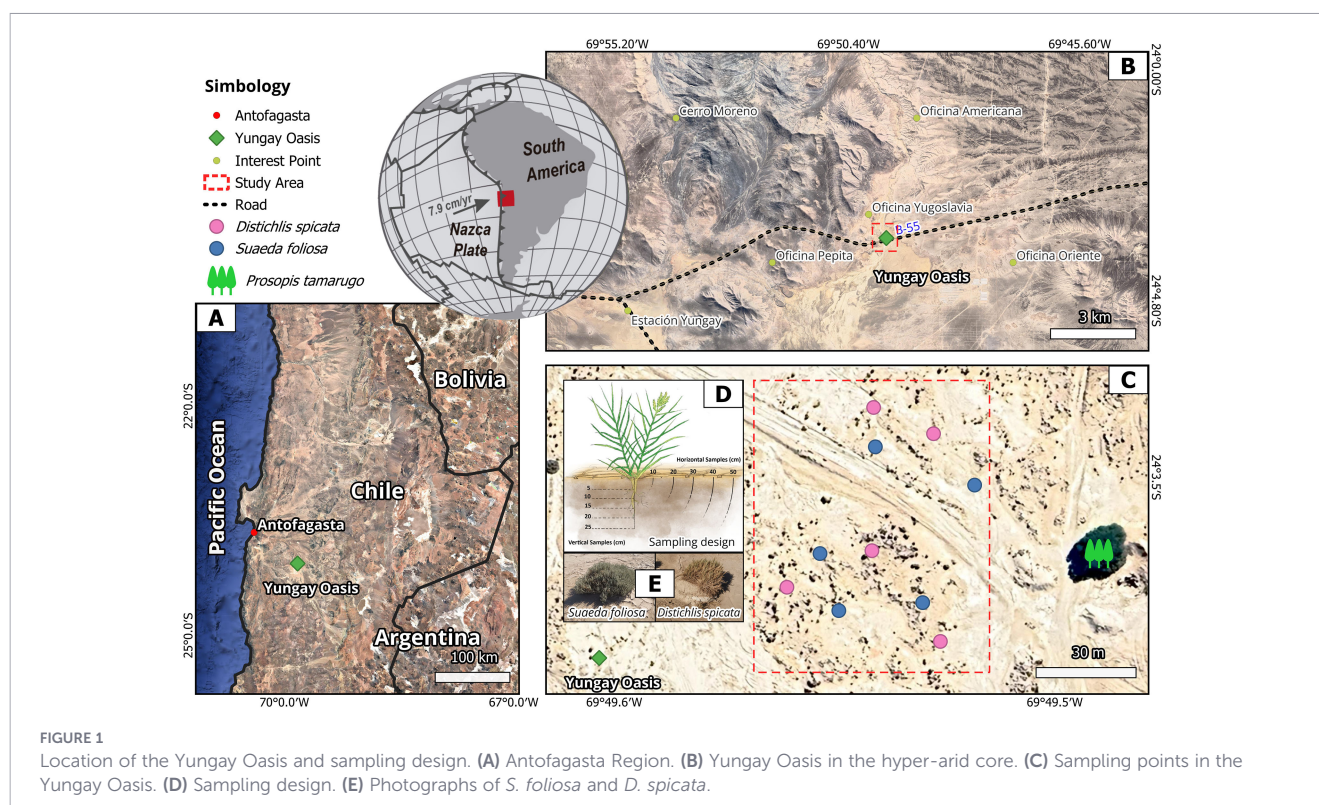
2.2 Soil sampling design

Samples were collected between May and June 2021, and five individuals per plant species were sampled. In the topsoil, horizontal samples were taken radially around the plant at 10 cm intervals from 0 to 50 cm, at a depth of 5 cm. Vertical samples were taken at 5 cm intervals from 0 to 25 cm depth (Figure 1D). Random bare soil samples were taken as control samples from the same area, approximately 50 m away from the plants. The control soil samples were taken vertically every 5 cm from 0 to 25 cm, and the first 5 cm were considered a single horizontal sample. Soil samples were collected manually and stored in plastic bags for subsequent physicochemical and mineralogical analyses.

2.3 Physicochemical characterization of the soil

Moisture content (MC) was measured following the methodology described in Sadzawka et al. (40). MC was measured immediately in the laboratory by drying each sample at 105 °C in an oven until constant mass; it was then calculated as the loss of weight after drying. The pH and electrical conductivity (EC) were measured using a soil:distilled water suspension in a 1:2.5 ratio. Total phosphorus (Pt), inorganic phosphorus (Pi), and organic phosphorus (Po) were determined using the extraction method reported by Saunders and Williams (41), and the concentrations were measured using the method proposed by Murphy and Riley (42). The total contents of nitrogen (TN) and carbon (TC) were determined using approximately 20 mg of soil sample by elemental analysis (Vario Micro Cube, Elementar, Hanau, Germany; ISO 10694, 1995).

Labile organic carbon (LOC), residual organic carbon (ROC), and total inorganic carbon (TIC) were determined using a Soli TOC



Cube (Elementar Analysensysteme, Hanau, Germany) instrument, following the methodology described by Mörchen et al. (43). LOC corresponds to the available fraction of total organic carbon, whereas ROC represents the fraction of organic carbon resistant to decomposition and not available for use. Therefore, the sum of LOC and ROC represents the total organic carbon (TOC).

2.4 Mineralogical characterization of the soil

To analyze the mineral composition, horizontal and vertical soil samples from one individual of *S. foliosa*, one of *D. spicata*, and a control soil were selected. These samples were subjected to X-ray diffraction (XRD) using a Siemens Model D5000 diffractometer (Cu K α 1). The same samples were analyzed by X-ray fluorescence (XRF; Siemens SRS-3000) to quantify total oxides.

To characterize soil morphology and elemental composition in the Yungay Oasis, samples were collected using a core barrel. Soil samples associated with *S. foliosa* and *D. spicata* were collected directly from the root zone. Additionally, a control soil core was sampled from unvegetated soil. In the laboratory, the soil cores were sectioned at 5 cm intervals from 0 to 25 cm depth. Finally, morphological characterization was performed through visual examination using high-resolution scanning electron microscopy (FE-SEM SU5000-MAINI[®] UCN 2018), while elemental composition was determined using energy dispersive spectroscopy (EDS) analysis.

2.5 Weathering index calculations

To quantify possible contributions of plants to soil weathering, seven different chemical weathering indices were calculated using

total oxides quantified by XRF, as described in Fuentes et al. (44). Seven different indices were calculated and expressed in moles: 1) weathering index 1 (WI1), 2) weathering index 2 (WI2), 3) chemical index of weathering (CIW), 4) chemical index of alteration (CIA), 5) weathering index of Parker (WIP), 6) Vogt's residual index (V), and 7) plagioclase index of alteration (PIA) (45–51).

2.6 Statistical analysis of soil physicochemical data

The data obtained were tested for normality of distribution using a Kolmogorov–Smirnov test ($n > 30$). The distribution was not normal; consequently, a non-parametric Mann–Whitney U test (intersample) was employed to determine significant differences ($p < 0.05$) between control soil and both species for moisture content (MC), pH, electrical conductivity (EC), total phosphorus (Pt), inorganic phosphorus (Pi), organic phosphorus (Po), total nitrogen (TN), total carbon (TC), labile organic carbon (LOC), residual oxidizable carbon (ROC), and total inorganic carbon (TIC).

Given the reduced number of individuals per species ($n = 5$), the statistical approach adopted in this study was primarily exploratory and comparative rather than inferential, aiming to identify dominant spatial trends and potential vegetation-associated signatures within a heterogeneous hyper-arid system.

To identify spatial patterns in soil physicochemical parameters, a multiscale exploratory statistical analysis was implemented considering both horizontal and vertical orientations (52, 53). Individual samples were first analyzed independently using descriptive statistics (mean, median, and standard deviation) to evaluate local heterogeneity and possible non-linear behaviors. Subsequently, samples corresponding to the same species were

integrated through global averages and dispersion measures represented as functions of distance and depth, allowing systematic comparisons between species and control soils without vegetation.

From a physical–statistical perspective, this approach allowed the evaluation of spatial variations potentially associated with transport, accumulation, and redistribution processes in hyper-arid soils. Unlike conventional geostatistical methodologies, which generally require substantially higher spatial sampling densities, the present approach focused on averaged spatial profiles and associated dispersion measures as a first exploratory stage prior to more advanced functional modeling (54, 55). Additional methodological details and extended statistical justifications are provided in the [Supplementary Material](#).

IBM SPSS Statistical software version 21 and OriginPro software were used for the statistical analyses. Principal component analysis (PCA) correlation plots were generated in R v4.3.1 (56) and RStudio v2023.09.0 + 463 (57) using the factoextra package (v1.0.7; 58), the ggplot2 package (v3.4.4; 59), and base R functions.

3 Results

3.1 Characterization of physical-chemical parameters of the soil

Moisture content (MC) increased with depth in both plant species, being more consistent beneath *D. spicata* than in *S. foliosa* (Figure 2A, B; [Supplementary Table 1](#)). In general, horizontal MC values were low across all soils (<2.7%), and both species exhibited

an initial decrease in MC with distance, followed by a subsequent increase ([Supplementary Figures 1A, B](#); [Figure 3](#); [Supplementary Table 1](#)). However, this behavior is accompanied by high data dispersion and pronounced spatial heterogeneity, reflected in low correlation coefficients and the absence of a dominant statistical signal ([Supplementary Figures 1A, B](#)).

Both plants modified the pH near the plant, tending to acidify alkaline hyper-arid soils from 7.77–8.50 in control soils to 6.86–7.09 in *S. foliosa* and 6.85–7.59 in *D. spicata*, with the greatest acidifications recorded at 20 cm depth ([Figures 2C, D](#); [Supplementary Figures 1C, D](#); [Supplementary Figure 2](#); [Supplementary Table 1](#)).

The horizontal electrical conductivity (EC) was greater in the control soil (131.5 mS·cm⁻¹), decreasing to 67 mS·cm⁻¹ in *S. foliosa* and 32.1 mS·cm⁻¹ in *D. spicata* ([Figure 3B](#); [Supplementary Figure 3](#); [Supplementary Table 1](#)). In general, EC tended to decrease with distance, highlighting the presence of a coincident inflection point in both species within the 30–40 cm range in the horizontal orientation, and reaching minimum values within the 15–20 cm interval in the vertical orientation ([Figures 2E, F](#); [Supplementary Figure 1](#)).

3.2 Nutrient characterization of the soil

Horizontally, total phosphorus (Pt) tended to be higher in *S. foliosa* soils, reaching 570 mgPt·kg⁻¹, while with depth, both plants showed higher values at 10–15 cm, reaching 610 and 624 mgPt·kg⁻¹ in *S. foliosa* and *D. spicata*, respectively ([Figure 4](#), [Supplementary Table 2](#)). Moreover, inorganic phosphorus (Pi) represented the major part of total phosphorus in all the samples, with maximum values of 580, 550, and 569 mgPi·kg⁻¹ for control, *S. foliosa*, and *D. spicata* soils ([Figure 4](#), [Supplementary Table 2](#)). Organic phosphorus

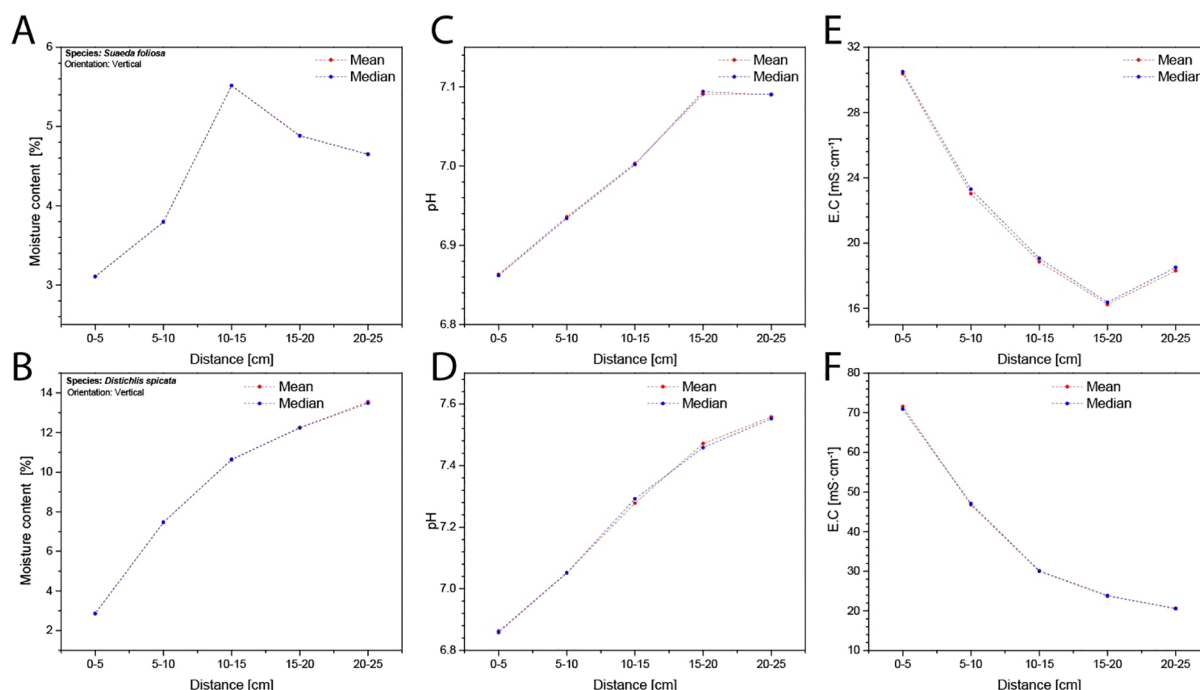
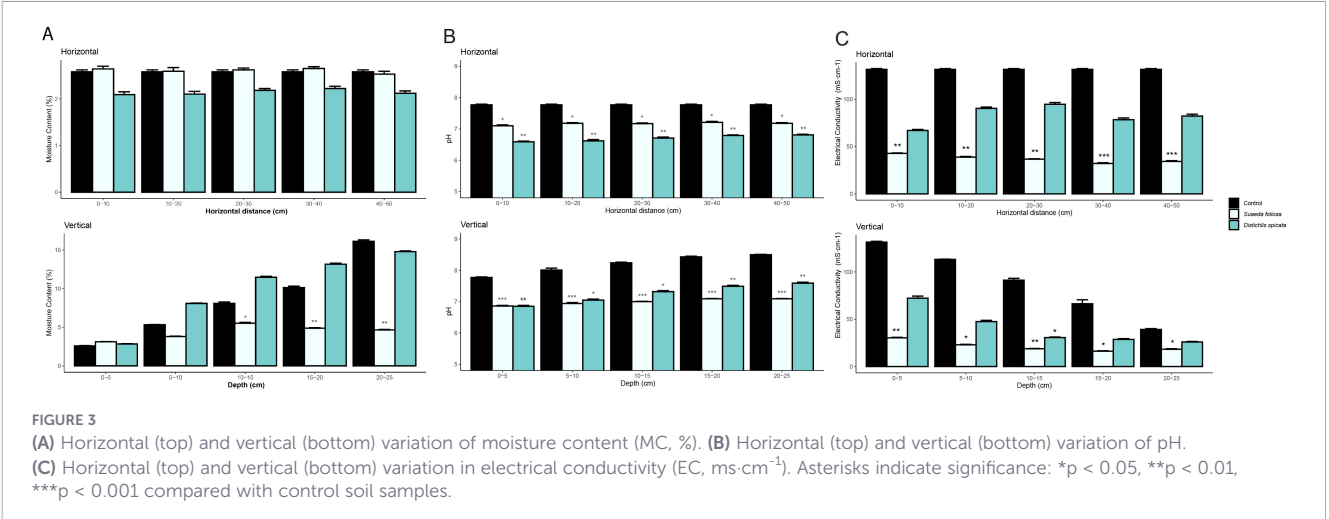


FIGURE 2

The average behavior of three soil physicochemical parameters is shown for both species, analyzed in vertical orientations. The first column displays soil moisture (A, B), the second column corresponds to pH (C, D), and the third column shows electrical conductivity (EC) (E, F). Regarding the row arrangement, the first row represents the behavior of these parameters for *S. foliosa* (A, C, E), and the second row corresponds to *D. spicata* (B, D, F).



(Po) was detectable in all the samples, with maximum values at depth, reaching 62 mgPo·kg⁻¹ at 10–15 cm in *S. foliosa* and at 15–20 cm in *D. spicata* (Figure 4, Supplementary Table 2).

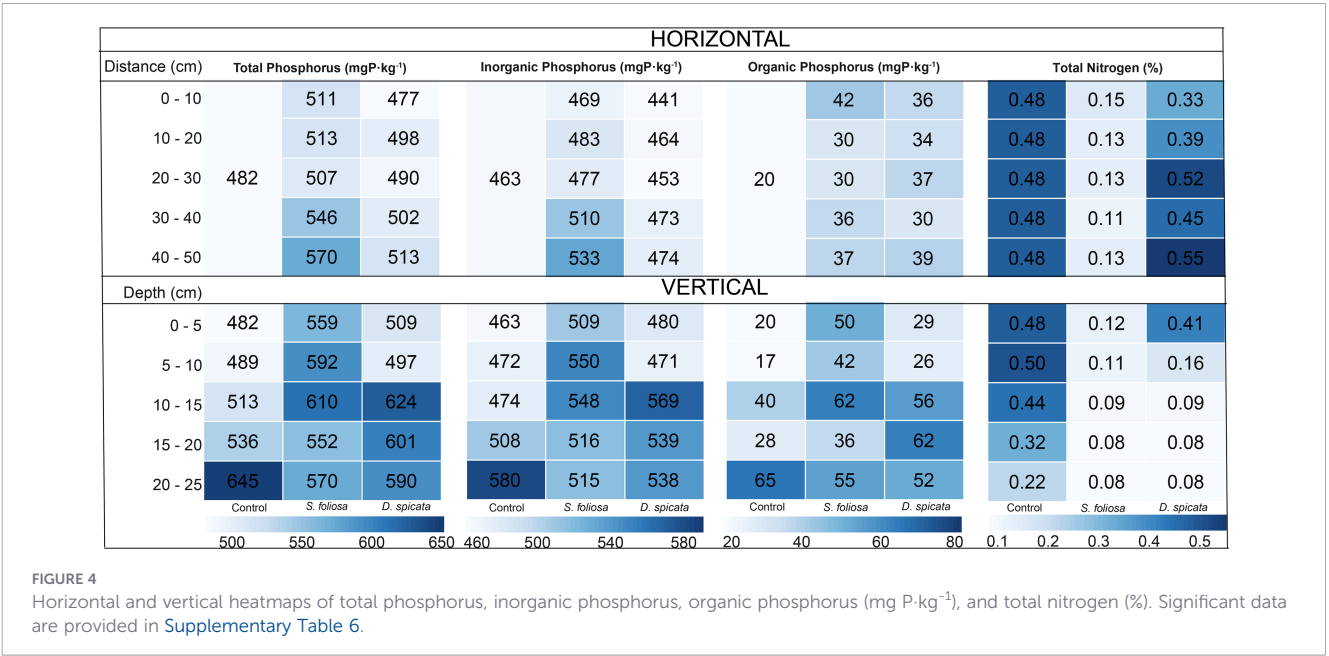
In general, total nitrogen (TN) was higher in soils without vegetation. Horizontally, *D. spicata* soils showed similar values to those of control soils (0.55% and 0.48%, respectively; Figure 4, Supplementary Table 2). Vertically, TN decreased with depth in all the samples, reaching minimum values of 0.08% at 15–20 cm and 20–25 cm depth in the soils of both plants (Figure 4, Supplementary Table 2).

Superficially, total carbon (TC) was greater in *S. foliosa* soils, with a higher value of 1.15% near the plant (Figure 5, Supplementary Table 2). Moreover, both species exhibited a decrease in TC with distance, followed by a progressive increase at 20–40 cm, being more pronounced in *D. spicata*, suggesting a higher gradient intensity and a clearer dominant signal compared to the other species studied (Supplementary Figures 4A, B). Vertically, no statistically significant

overall trend was evident; however, *S. foliosa* showed the highest TC values, ranging between 1.01% and 1.14% (Figure 5; Supplementary Figures 4E, F; Supplementary Table 2).

Labile organic carbon (LOC) was higher in *S. foliosa* soils at 0–10 cm, reaching 0.26% and 0.23% at 10–15 cm depth (Figure 5, Supplementary Table 3). Similarly, residual oxidizable carbon (ROC) was greater in *S. foliosa*, peaking at 0.25%, followed by 0.24% in control soil and 0.23% in *D. spicata* (Figure 5, Supplementary Table 3). Total inorganic carbon (TIC) represented the major fraction of carbon in soil samples and tended to be higher with depth, reaching values of 0.47% in *S. foliosa* (Figure 5; Supplementary Table 3).

In *S. foliosa* soils, the PCA analysis showed separation between horizontal and vertical soil samples, with Dim1 explaining 53.8% of the variance (Figure 6). The results suggest that TN, EC, and pH were higher in the horizontal samples, while parameters such as MC, TC, LOC, and P fractions were associated with vertical soil



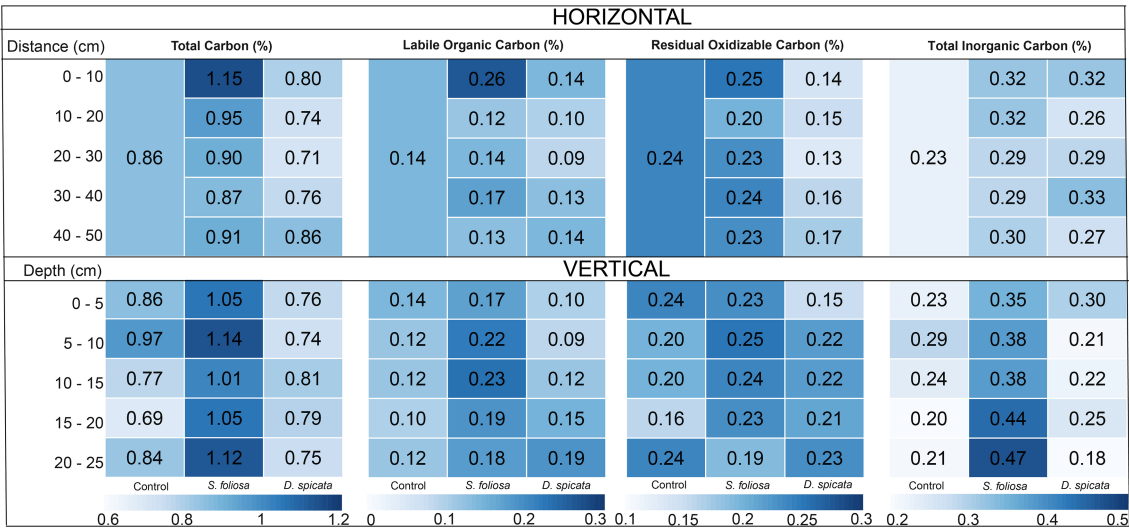


FIGURE 5
Horizontal and vertical heatmaps of total carbon, labile organic carbon, residual oxidizable carbon, and total inorganic carbon (%). Significant data are provided in [Supplementary Table 6](#).

samples (Figure 6). In *D. spicata* soils, horizontal samples overlapped with the superficial vertical samples (0–5 cm), indicating similarity across these samples (Figure 6). Nevertheless, separation between groups was still clear, with Dim1 explaining 71.58% of the variance (Figure 6). Here, it is also suggested that TN and EC were higher in the horizontal samples, while MC and P fractions were higher in the vertical samples. In contrast to *S. foliosa*, pH was associated with vertical samples (Figure 6).

3.3 Geological characterization of the soil

To evaluate the influence of *S. foliosa* and *D. spicata* on the mineralogy of Yungay Oasis soils, X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) analyses were performed.

3.3.1 Mineralogical characterization

Through XRD, typical primary silicates of the Atacama hyper-arid core were found in all three soil types, including quartz, albite, orthoclase, and muscovite (Table 1). Horizontally, clays were present as chlorite in variable percentages in *S. foliosa*, *D. spicata*, and control soil. Meanwhile, vertically, kaolinite was present in some samples from all three soil types, reaching 15.4% in *S. foliosa* and 14.7% in *D. spicata* (Table 1). In addition, feldspars such as orthoclase, microcline, and sanidine were observed. Superficially, salts were mainly present as gypsum across all soils. Likewise, halite was also present in all the soils, showing higher values in the horizontal control soils (17–41%). Interestingly, nitratine was identified only in superficial control soil samples, ranging between 19% and 31.2% (Table 1). Calcite was the most abundant carbonate,

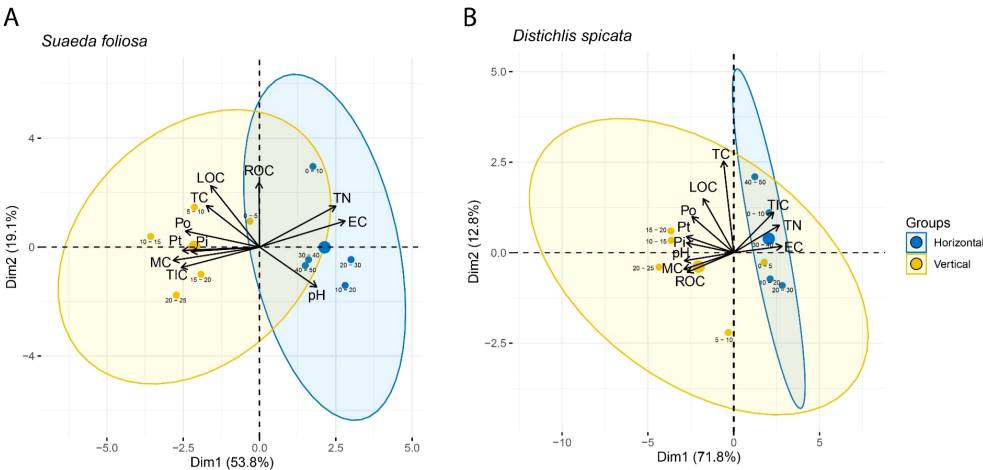


FIGURE 6
Principal component analysis (PCA) of soil physicochemical parameters. (A) PCA of *S. foliosa* soils. (B) PCA of *D. spicata* soils. Each point corresponds to the different horizontal (blue) and vertical (yellow) distances of soil samples grouped by ellipses. Arrows indicate the different physicochemical parameters measured. MC, moisture content; EC, electrical conductivity; Pt, total phosphorus; Pi, inorganic phosphorus; Po, organic phosphorus; TN, total nitrogen; TC, total carbon; LOC, labile organic carbon; ROC, residual oxidizable carbon; TIC, total inorganic carbon.

tending to show higher horizontal values in vegetated soils, reaching up to approximately 15%, and was the only carbonate present vertically (Table 1). Meanwhile, other carbonates such as vaterite, dolomite, and gaylussite were identified horizontally in some soil sample associated with both plant species (Table 1).

To examine mineral morphology and occurrence, with the aim of identifying the plant influence on soils, SEM analysis was performed (Figure 7). In control soils, prismatic and acicular mineral morphologies were found, with a Ca, S, Na, and Cl matrix at 20–25 cm depth (Figure 7B). In *S. foliosa* soils, calcium minerals were associated with Ca and S; additionally, Fe and Na-Cl formations were observed over a Si, Al, K, and Mg matrix (Figure 7C, Supplementary Figure 5). At 5–10 cm depth, calcium was found bound with P (Figure 7D, Supplementary Figure 6). Interestingly, mineral formations inside and outside *D. spicata* roots were observed, including calcium structures (Figures 7H, J; Supplementary Figure 5).

3.3.2 Major oxide composition

Major oxide composition showed a high variability in *D. spicata* soils, mainly in SiO₂ (17.3% to 52.9%), Al₂O₃ (4.6% to 14.8%), MnO (0.03% to 0.1%), MgO (1.6% to 4.5%), CaO (3.1% to 40.4%), and K₂O (0.7 to 3.2) (Supplementary Table 4A, B). In contrast, Fe₂O₃ showed similar concentrations across all samples (Supplementary Table 4A). Meanwhile, Na₂O reached 9.6%, 2.5%, and 6.1% at 30–40 cm in *S. foliosa*, *D. spicata*, and control soil, respectively (Supplementary Table 4B).

3.3.3 Weathering indices

Weathering indices were calculated using major oxide composition values. WI1, WI2, CIA, and PIA did not indicate chemical weathering in the analyzed soils. In contrast, CIW showed higher values with depth in *D. spicata* soils, reaching 61.3 at 15–20 cm depth (Supplementary Table 5). A similar behavior was observed for CIA, where a higher value of 53.5 was also calculated at 15–20 cm depth in *D. spicata* soils (Supplementary Table 5). Finally, the V index also tended to increase with depth in *D. spicata* soils, reaching values of 0.9 at 20–25 cm (Supplementary Table 5).

4 Discussion

A noticeable density of *Distichlis spicata* can be found in the Yungay Oasis. This saltgrass has been reported as a good plant indicator of groundwater and can be found in sites where subsurface water occurs at depths ranging from less than 2.5 to 4.3 m (37, 60–63). According to the national aquifer inventory (SDT N-403 2017, Chilean Ministry of Public Works), the Aguas Blancas aquifer is located in the Yungay Oasis area at a depth of approximately 6 m below the surface (32). Therefore, this aquifer could be serving as the principal water source that sustains life in this oasis and may explain the high moisture content measured with depth. Water availability in this distinct environment is crucial for life to be sustained (27, 64, 65), since the Atacama Desert presents extreme

conditions for life survival, such as scarce precipitation (21) and the highest amounts of ultraviolet irradiance ever measured (66). Moreover, according to Wang et al. (9), water is one of the key factors driving the fertile island effect in drylands, which agrees with observations from this study site. Unvegetated soil pH showed similar values to those previously reported in the Yungay area (22, 43, 67). pH has been described as an important parameter for evaluating plant influences on soils, since the pH value can affect multiple soil parameters, such as nutrient availability, organic matter decomposition, and enzymatic activities (9, 68, 69). Moreover, it is known that the exudation of organic acids can result in the acidification of surrounding rhizosphere soils (68). Fertile island studies have shown variable results, reporting decreases, increases, and no variation in pH between vegetated and unvegetated soils (1, 2, 9, 70). According to Wang et al. (9), a decrease in pH, as shown by the statistical trends in this work, could be related to an increase in the fertile island effect. This aligns with Busman et al. (71), who reported that the pH value has an important influence on nutrient availability.

Larger amounts of salt found in soils (i.e., halite and gypsum; see Table 1) may lead to higher EC values in soils. Thus, EC values were higher in *D. spicata* compared with *S. foliosa* soils, probably due to the salt removal process performed by the saltgrass via capillary action and evaporation (36, 39, 72), and the subsequent accumulation in the surrounding soil resulting from the wind-driven transport of salt from the leaves (32, 73). Wang et al. (9) found no correlation between soil salinity and the fertile island effect. Additionally, although *D. spicata* is a halophyte grass, no evidence of a salinity island effect was found, in contrast to the findings by Yu and Wang (74). Thus, the decrease in EC values observed in soils associated with vegetation in this work could indicate an enhancement of the fertile island effect under hyper-arid conditions and very low organic matter contents.

Higher horizontal Pt and Pi values in *S. foliosa* may be attributed to the decomposition of organic matter coming from its leaves. It is also proposed that plants could be acting as natural traps, since one of the inputs of P into dryland soils occurs through dust deposition (75, 76). Vertically, the increase in Pt and Pi (Figures 4, 6) is consistent with results reported by Fuentes et al. (22) near the area investigated in this work. Additionally, Pt, Pi, and Po values in *S. foliosa* and *D. spicata* may be influenced by vegetation, possibly indicating root-induced mechanisms used by the plants to obtain P (77), suggesting biological weathering of rocks. Moreover, microorganisms play an important role in P mobilization, enabling its release from soil minerals (78). This aspect is particularly interesting because SEM-EDS analysis detected P-Ca minerals (Supplementary Figure 6), which could confirm that rock is being used as a source of phosphorus. Po was detected in all samples and tended to be higher in the soils associated with plants. It is proposed that this Po originates from microbial phosphorus sources associated with the rhizosphere, organic acid compounds excreted by the roots, and interactions with animals that inhabit the oasis. It has been reported that plants roots have the capacity to acidify the rhizosphere, liberating protons and excreting carboxylates (e.g., citrate, malate, and oxalate) and enzymes (e.g., phosphatases and phytases) to facilitate phosphorus mobilization (77, 79, 80), which is

TABLE 1 X-ray diffraction (XRD) for control, *S. foliosa*, and *D. spicata*.

Orientation	Mineral	Control					<i>S. foliosa</i>					<i>D. spicata</i>				
Horizontal	Distance (cm)	0–10	10–20	20–30	30–40	40–50	0–10	10–20	20–30	30–40	40–50	0–10	10–20	20–30	30–40	40–50
	Quartz	14.7	16.5	12.9	19.2	15.1	16.5	20.5	15.7	20.6	16.4	35.7	16.3	27.2	39.4	45.6
	Albite	14.2	14.0	12.6	13.6	19.5	29.1	19.6	26.2	28.3	32.5	19.6	15.7	22.2	28.7	24
	Orthoclase	–	–	–	4.4	–	8.74	–	12.3	–	8.5	–	–	–	–	15.3
	Chlorite	4.3	2.5	–	2.0	–	11.1	–	21.0	15.2	15.3	17.6	–	20.4	–	–
	Gypsum	7.9	5.0	5.6	4.0	5.8	11.5	7.27	5.61	6.26	5.6	9.05	11.1	8.42	14.2	10.1
	Halite	26.3	17	41	19.9	20.1	11.1	14.1	5.06	3.02	6.6	1.11	–	–	3.55	–
	Microcline	–	–	–	–	–	–	22.2	–	9.62	–	4.17	19.3	10.7	7.72	–
	Muscovite-1M	–	8.2	4.0	8.2	7.1	–	–	–	–	–	–	–	–	–	–
	Kaolinite	1.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Calcite	3.6	1.7	2.4	5.2	2.2	12.1	12.6	13.7	8.9	15.1	12.3	15.2	5.09	2.83	5.1
	Gaylussite	–	–	–	–	–	–	–	–	8.04	–	–	13.9	6.03	3.58	–
	Vaterite	–	–	–	–	–	–	–	0.57	–	–	0.42	–	–	–	–
	Dolomite						–	–	–	–	–	–	0.11	–	–	–
	Anhydrite	0.2	–	–	–	1.1	–	–	–	–	–	–	1.2	–	–	–
	Laumontite	–	–	–	–	–	–	–	–	–	–	–	8.43	–	–	–
	Nitratine	19.0	31.2	19.2	23.5	25.7	–	–	–	–	–	–	–	–	–	–
	Probertita	–	–	–	–	1.4	–	–	–	–	–	–	–	–	–	–
	Bassanite	–	–	–	–	2.2	–	–	–	–	–	–	–	–	–	–
	Sanidine	4.4	3.9	2.4	–	–	–	–	–	–	–	–	–	–	–	–
	Brucite	–	–	–	–	–	–	3.73	–	–	–	–	–	–	–	–
	Muscovite-3T	4.5	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Vertical	Distance (cm)	0-5	5-10	10-15	15-20	20-25	0-5	5-10	10-15	15-20	20-25	0-5	5-10	10-15	15-20	20-25
	Quartz	35.9	33.9	33.3	24.3	23.4	26.5	34.8	29.4	38.9	50.8	29.9	7.6	35.7	24.2	19
	Albite	20.4	27.6	18.8	31.6	29.9	22.4	25.7	24.5	22.3	24.5	18.5	–	31.4	27	44
	Orthoclase	11.7	8.1	–	6.5	22.1	8.5	14.2	7.5	4.2	6.1	7.1	–	24.4	11.1	9.1
	Chlorite	–	8.8	–	–	–	–	–	–	–	–	4.1	–	–	14.7	–
	Gypsum	6.1	7.4	11.3	13.9	13.9	4.3	5.4	4.5	7.5	3.6	6.8	87.9	8.5	1.7	4.1
	Halite	9.1	1.7	–	–	–	7.5	–	–	–	–	1.9	–	–	–	–
	Muscovite-1M	–	–	15.3	15.7	–	–	–	–	–	–	–	–	–	21.3	–

(Continued)

TABLE 1 Continued

Orientation	Mineral	Control	<i>S. foliosa</i>					<i>D. spicata</i>				
	Muscovite-2M1	-	-	-	-	-	10.1	-	-	15.4	-	-
	Kaolinite	-	-	15.4	-	-	10.7	-	-	-	-	14.7
	Hematite	-	0.4	-	-	-	-	-	-	-	-	-
	Calcite	16.9	12.1	9.2	8	10.6	13.3	27	15	16.3	3.3	0.2
	Anhydrite	-	-	-	-	-	-	-	-	-	1.2	-

The Table shows the minerals present in soil samples from the control, *S. foliosa* and *D. spicata*, considering horizontal and vertical orientations for each sampled distance. Samples distances are indicated at the beginning of each orientation. The values are expressed as percentages (%), and the symbol “-” indicates that the mineral was not present in the sample.

important for determining community structure and other ecosystem processes (75, 76). Future functional microbiological approaches should therefore be used to confirm this result. Although Jones et al. (32) recently reported that microbial activity is limited in phosphorus, an increase in P in arid zones due to biological influence was previously reported by Navas Romero et al. (69), who attributed this increase to microfungi activity capable of releasing P, which could increase phosphorus availability for plants. In addition, this increase in P has been reported in other fertile island studies (2, 68, 81), indicating the occurrence of this effect in the Yungay Oasis, especially with depth.

Higher amounts of TN in the superficial control samples found in this study are consistent with Jones et al. (32), who reported greater nitrate amounts at the soil surface of the Yungay Oasis due to sodium nitrate accumulation. Since nitrate was detected only in horizontal control soils (Table 1), nitrate minerals were not found by either XRD or SEM in soils influenced by plants. Moreover, the decrease in TN with depth observed in this work was previously reported near the study site (22). On the other hand, as previously mentioned, the fertile island effect leads to the accumulation of nutrients, including N (2, 4, 68, 82). Nevertheless, the results show a tendency toward a decrease, especially with depth. The lower TN concentrations in *S. foliosa* suggest a higher uptake and greater N losses from the soil compared with *D. spicata* soils. Previously, Jones et al. (32) reported the accumulation of NaNO_3 under *D. spicata* soils due to wind action, which could explain the high surface concentration of TN compared with *S. foliosa*. Furthermore, labile carbon is key for the reduction of NO_3^- to NH_4^+ and its subsequent incorporation into organic compounds (83). Therefore, the presence of a higher concentration of LOC near *S. foliosa* could facilitate its assimilation. Likewise, the decrease in nitrogen under the presence of vegetation could be associated with denitrification processes and the release of NH_3 mediated by microorganisms present in Yungay Oasis soils during the processing of organic nitrogen (32). On the other hand, high temperatures at the study site could also contribute to ammonia volatilization (84), in agreement with the $\delta^{15}\text{N}$ values previously obtained in the oasis by Jones et al. (32).

Litter is considered an important biotic factor driving the formation of fertile islands (85). However, TC and LOC accumulation occurred primarily in *S. foliosa*, where a possible horizontal fertile island effect was restricted to the first 10 cm of soil. It is proposed that this is due to: a) the developmental stages of the sampled plants, since it has been reported that young plant individuals may have a lower fertile island effect than mature plants, and the litter coming from young plants may not be effectively trapped beneath them (86, 87); and b) the strong winds in the study area (18), which can drag the litter, resulting in ineffective litter trapping under the canopy. Yao et al. (7) suggested that the influence of vegetation on soils occurs in the first 10 cm of depth. Similar results were reported by Li et al. (87), who suggested that the fertile island effect is higher in the superficial samples due to the influence of the aerial parts of the plants. Vertically, LOC tended to be higher in *S. foliosa* than in *D. spicata* and control soils, indicating possible inputs coming from microbial activity and root exudates (88).

Through SEM analysis, acicular morphologies associated with sulfate minerals were observed, which are consistent with the presence

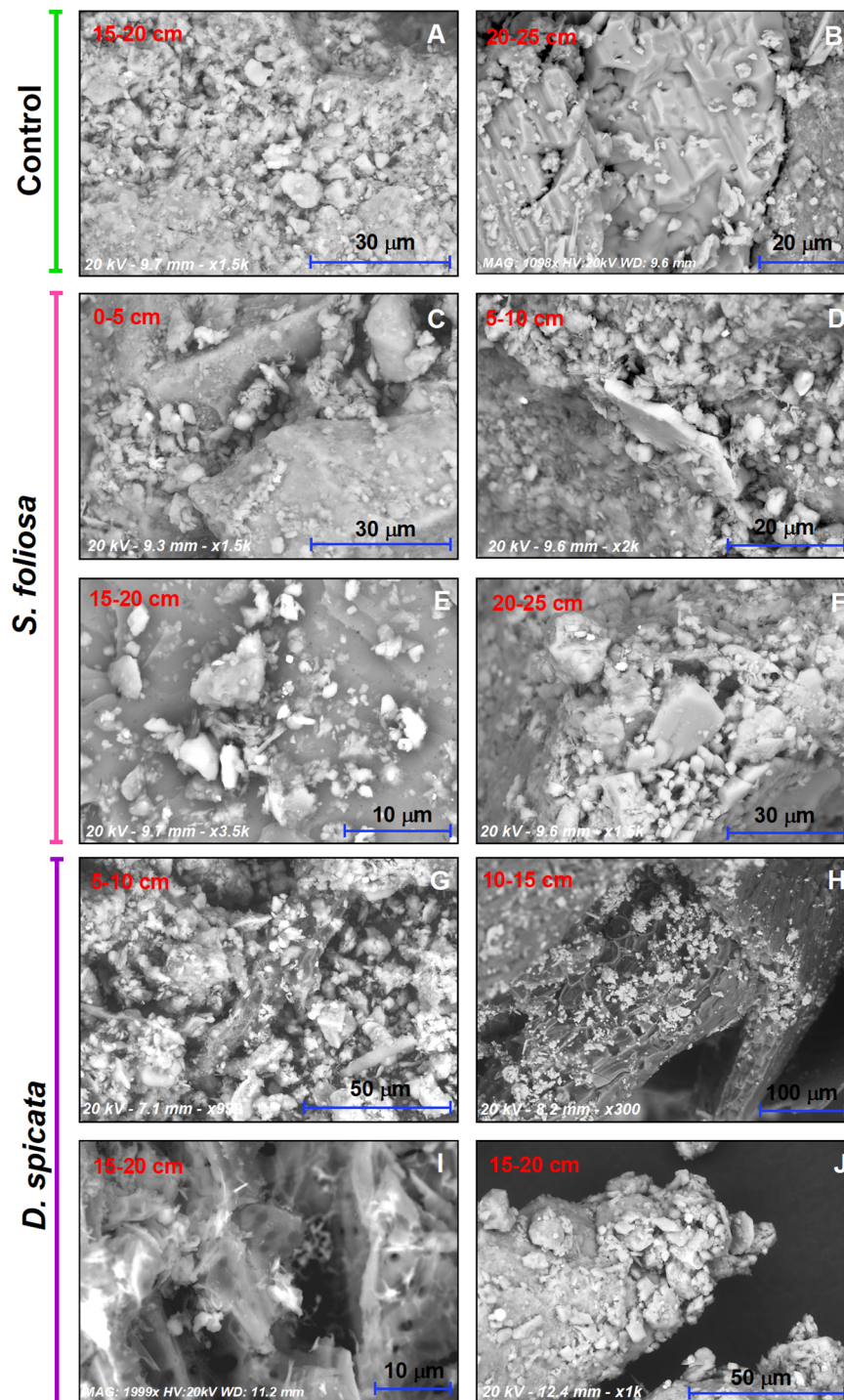


FIGURE 7
Scanning electron microscopy (SEM) images of control, *S. foliosa*, and *D. spicata* soils showing soil morphology. (A, B) Control soil. (C–F) *S. foliosa* soil. (G–J) *D. spicata* soil.

of gypsum identified through XRD analysis (Figure 7). Quartz was observed in high amounts in soil (Table 1). This is consistent with the result reported by Sutter et al. (89) in the hyper-arid Atacama Desert. Additionally, similar to our results, Ewing et al. (26) also found higher amounts of quartz, gypsum, anhydrite, chlorite, and kaolinite in soils near the Yungay Basin. Halite and albite were present in all the soil samples; these salts and feldspars were previously detected by Fuentes et al. (22) in a pit near the Yungay area.

Interestingly, vaterite, a highly unstable calcium carbonate (90), was identified in some horizontal samples associated with plants and, to our knowledge, has not been previously reported in the area. Its abiotic formation has been described through precipitation in cold environments and under alkaline conditions (90). Furthermore, its formation under CaCO_3 -supersaturated solutions and high sulfate concentrations has been demonstrated (91). Nevertheless, the biotic formation of this mineral has also been

reported, and it is proposed that its occurrence may have been mediated by plants and microorganisms. For example, some plant species are capable of producing carbonates; Wightman et al. (92) found evidence of vaterite in the leaves of *Saxifraga scardica*. Moreover, Liu et al. (93) reported that six bacteria, isolated from soils covered with litter in the Mu Us Desert, were able to precipitate carbonates, including vaterite and calcite, from atmospheric CO₂. These findings suggest that plants may generate the conditions necessary for the biological occurrence of mineral formation in the hyper-arid soils of the Yungay Oasis. Additionally, other carbonates, such as gaylussite and dolomite, were found only in soils associated with plants (Table 1). Finally, evidence of mineral formation was found both outside and inside the roots of *D. spicata*, possibly indicating root-soil interaction and favorable conditions for mineral formation. According to the results, these minerals contain elements such as Ca, Cl, K, Na, Mg, and Si (Supplementary Figure 5). This is especially important because, in addition to the plant-soil interaction, microorganisms present in the rhizosphere could also be contributing to mineral formation through the release of organic acids and chelating compounds that facilitate mineral dissolution, and through the production of reactive metabolites that mediate mineral precipitation and transform the material present in the soil (94).

It is known that weathering performed by plant roots and their interaction with microorganisms is important for nutrient acquisition by plants, and high soil humidity content may promote higher decomposition rates and greater soil weathering (95–97). To evaluate these processes, seven chemical weathering indices were calculated, the majority of which are based on the molar ratio between mobile and immobile major oxides (44). Among these, CIW, WIP, and V showed some degree of weathering in the soils samples associated with *D. spicata*. Feldspars are abundant and reactive minerals in the Earth's crust; therefore, their degradation and the formation of clay minerals correspond to dominant processes during chemical weathering (48). Consequently, both WIP and CIW reflect the alteration of feldspars into clay minerals, considering Na⁺ and Ca²⁺ as mobile cations in the case of CIW and Na⁺, Ca²⁺, K⁺, and Mg²⁺ in WIP. In addition, the V index is also based on the relationship between mobile cations, such as Mg²⁺, Ca²⁺, and Na⁺, and immobile cations; therefore, it also reflects chemical weathering processes in soils. In contrast, WI1 and WI2 are based on silica loss, considering aluminum and iron to be immobile during weathering, respectively (51). Nevertheless, these indices may not be appropriate for hyper-arid soils, as they were originally developed and tested in humid regions (46). Unlike CIW, CIA did not indicate chemical weathering, which may be because CIW does not consider the Al associated with feldspars, potentially leading to an overestimation of weathering in rocks rich in potassic feldspars (98). Finally, PIA is mainly used to analyze plagioclase weathering, such as that of albite. For this reason, CIW, WIP, and V may serve as indicators of the development of the fertile island effect in the Yungay Oasis.

Fertile island is a common effect associated with vegetation worldwide, with pH, moisture content, and nutrient accumulation being the principal soil parameters influenced by plants (2, 4, 9, 68, 82). Furthermore, under biotic influence in another arid ecosystem

in South America, Navas Romero et al. (69) reported behaviors more consistent with fertile island dynamics described worldwide. Nonetheless, distinct patterns were observed in the Yungay Oasis, primarily the decrease in N, which could represent an important fertile island effect in hyper-arid soils where nitrate accumulation plays an important role.

5 Conclusion

The native plants studied distinctly influenced the physico-chemical parameters of hyper-arid soils in the Atacama Desert. Nutrient accumulation is an expected characteristic in the formation of fertile islands. However, a reduction in nitrogen concentration was mainly evidenced in soils associated with *S. foliosa*, which may indicate greater nitrogen utilization and processes related to N losses in these soils. In addition, carbon accumulation was primarily restricted to soils located near *S. foliosa* and its roots. The influence of *D. spicata* on soils was mainly mineralogical, showing mineral formation associated with its roots and greater chemical weathering, indicating the occurrence of geochemical processes mediated by plant-soil interactions. The presence of vaterite exclusively in vegetated soils could indicate either a biological origin or the generation of favorable environmental conditions for its formation, potentially contributing to the formation of minerals. Furthermore, this study contributes to understanding how hyper-arid soils behave in the presence of plants, identifying their main influences and suggesting a possible fertile island effect. This is especially important considering the ongoing effects of desertification caused by climate change and poor soil management. Future research could include the taxonomic and functional characterization of microbial communities to identify processes mediated by plant-associated microorganisms. In addition, isotopic analyses of nutrients would be valuable for confirming the origin of carbonates and the processes that mediate changes in soil parameters. Finally, the use of multiscale exploratory analysis is useful for developing models that identify rates of change, scales, and relationships among variables, leading to a global statistical description of physicochemical dynamics in hyper-arid soils.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

AC-R: Writing – review & editing, Writing – original draft, Conceptualization, Methodology, Visualization, Investigation. BF: Formal analysis, Validation, Writing – review & editing, Supervision, Visualization, Software. RB: Validation, Writing –

review & editing, Visualization, Formal analysis. RM: Methodology, Writing – review & editing, Investigation, Supervision. WA: Data curation, Methodology, Formal analysis, Writing – review & editing. YG-L: Validation, Writing – review & editing, Methodology, Software, Formal analysis. JC-S: Visualization, Formal analysis, Validation, Writing – review & editing, Methodology. JF: Writing – review & editing, Formal analysis, Supervision, Investigation. RR: Writing – review & editing, Validation, Supervision, Formal analysis. CS: Formal analysis, Methodology, Supervision, Visualization, Writing – review & editing. FR: Visualization, Formal analysis, Writing – review & editing, Writing – original draft, Methodology, Software, Data curation, Investigation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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