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Mineralogical and micromorphological characteristics of red pine and oak root zone soils in southern Turkey

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Abstract: Plant species exert differential effects on soil mineralogical and micromorphological characteristics. The effect of red pine and oak tree roots on the mineralogical and micromorphological characteristics of rhizosphere soils in two sampling sites in the Göksu catchment was studied. The climate, topography, and bedrock conditions were kept consistent, whereas the plant factor was kept as the only variable in each site. Rhizosphere soils under the canopies of 100 years old and naturally occurring trees were compared via macromorphology, submicroscopy, mineralogy, and physical and chemical properties. The soils of red pine (RP_1 and RP_2 profiles) were determined to have higher porosity when compared to the soils of the oak tree profiles (Ok_1, Ok_2). However, the higher amounts of welded/cemented aggregates in the Ok_1 and Ok_2 profiles were probable indicators of maturity and probable stability of the aggregates/MSUs. The dominant clay mineral in sampling site 1 was kaolinite, whereas it was smectite in sampling site 2.

Key words: Göksu catchment, soil, rhizosphere, red pine, oak

1. Introduction

The physiological processes of long-enduring trees in forest ecosystems depend on the support of their root systems, which also induce the soil physical, chemical, and biological activities and thus soil formation (Estrada-Medina et al., 2013; Guendehou et al., 2014; Gartzia-Bengoetxea et al., 2016; Meier et al., 2016; Shuangmiao et al., 2016; Kooch et al., 2017). Broad-leaved and coniferous forest trees are especially widespread in the Göksu catchment, which is a productive highland-wetland topographic basin sequence for agriculture in the south of Turkey (Demirel et al., 2010; Özdoğan, 2011). The red pine/Turkish pine (*Pinus brutia* Ten.) and oak (*Quercus coccifera*) are the most dominant species in the forests of this ecoregion (Zohary, 1973; Kaya and Raynal, 2001). Earlier studies have highlighted significant outcomes concerning one of the factors that influence the structure of porosity in the soil, the presence of tree roots, and land use (Pagliai et al., 2000; Kodešová et al., 2006). Forest trees with high amounts of litter and deep root systems in comparison to other cover types increase the soil organic matter content, porosity, and soil formation processes (Kelly et al., 1998; Pawlik et al., 2016) coupled with clay minerals and their aggregates that vary under pine and oak tree canopies (Birkeland, 1969; Tice et al., 1996; Gillot et al., 1999; Tolpeshta et al., 2010; Mareschal et al., 2013; Viennet et al., 2015). There are also numerous studies on thin-section descriptions regarding soil micromorphometry, soil porosity, and structure in forest soils (Bullock et al., 1985; FitzPatrick, 1993; Stoops, 2003). In addition, scanning electron microscopy (SEM) has been shown to be a useful tool in describing the spatial relationships between the various components of the rhizosphere and direct information about the root–soil interface (Foster et al., 1983).

Little is known on the mineralogical, micromophological, and morphological characteristics; the pore size distribution; and shape as indicators of the physical characterization of the soil under pine and oak canopies. The present study aimed to reveal the influence of the red pine (*P. brutia*) and the oak (*Quercus coccifera*) tree canopies on rhizosphere soil development under similar climatic and parent material conditions and topographies in the forest soils of the Göksu catchment via mineralogical and micromorphological properties.

2. Materials and methods

2.1. Study area

The study area was located in the Göksu catchment, which is located in the Mediterranean region of southern Turkey extending from 36°14′20″–37°13′21″N latitudes

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to 32°06′29″–34°04′39″W longitudes (Figure 1). The rhizosphere soil sampling areas were selected from two sites 100 km apart from one another in the Göksu catchment. The sample collection sites were selected to best represent the Cambisol rhizosphere horizons, dominant tree populations, canopy vegetation, parent materials, slopes, and aspects.

2.2. Soil sampling and analysis

2.2.1. Soil sampling and submicroscopy

Natural red pine (100 years old) and oak (100 years old) rhizosphere soils were sampled. The samplings were conducted in June 2013. Soils, of profiles RP_1 and Ok_1 (first sampling site) and RP_2 and Ok_2 (second sampling site), were sampled from the horizons of the rhizospheres of Calcaric Cambisols (IUSS 2015). In addition, the aggregates clinging to the roots were collected from the horizons for submicroscopy (SEM analysis). Moreover, undisturbed samples of Bw horizons were impregnated by epoxy resin and processed for making thin sections (FitzPatrick, 1993) for porosity determination (see 2.2.3.).

2.2.2. Physical and chemical analyses

The soils were air dried and sieved through a 2-mm sieve. The particle size distribution, pH (1:2.5 soil: water), and CEC were determined according to Bauyoucos (1954), McLean (1982), and Black et al. (1965), respectively. Soil organic carbon (SOC) was determined by a modified Walkley–Black wet oxidation method (Jackson, 2005). The physical and chemical properties of the horizons under red pine and oak canopies of the study area are shown in Table 1.

2.2.3. Porosity

For image analysis, 12 thin sections prepared according to Murphy (1986) in three replicates from 4 undisturbed samples were collected from the Bw horizons of each profile. The total porosity was determined according to the image analysis techniques of Pagliai et al. (1984) with Micro Publisher 3.3. RTV, using the software Image Pro-Plus (Media Cybernetics, Silver Spring, MD, USA). Pore distributions were measured according to their shape and sizes according to Bouma et al.'s (1977) classification. Here the shape factor [perimeter^2/(4π area)] was divided into three classes as regular (1–2), irregular (2–5), or elongated (>5). In addition, according to Pagliai et al. (1984), the pores of each shape group were subdivided into size classes according to either their equivalent diameter (regular and irregular pores) or their width (elongated pores). The pores ranging from 50 to 500 μm (transmission pores) are more useful for plant growth in comparison to pores >500 and <50 μm (Greenland and Pereira, 1977). Thus, in the present study, the pore sizes of 50 to 500 μm were analyzed in the macrophotographs of vertically oriented thin sections (frame length was 32 mm × 24 mm and 1 pixel = 15.8 μm) of the Bw horizons suitable for statistical analysis and comparison due to their presence in all profiles.

2.2.4. Clay mineralogy

Clay size fractions were separated (after removal of carbonates, organic matter, and iron oxides) and saturated

Figure 1. The location of the study area and the sampling sites in the Göksu catchment, Turkey.

Table 1. The physical and chemical properties of the horizons under red pine and oak canopies.

Profile	Horizons	Depth	pH	CEC	OC	Sand	Silt	Clay	Texture
		(cm)		(cmol kg^{-1})	(%)	______%_____			
RP_1	Ah	5–10	7.9	93.7	6.72	53.5	39	7.7	Loam
	A_2	10–19	7.4	38.3	3.42	37.9	44	18	Loam
	Bw	19–28	7.3	28.2	1.62	40.5	39	20	Loam
	Bk/C	28–45	7.4	22.8	1.25	41.2	40	20	Loam
RP_2	Ah	8–16	7.1	157	6.99	43	33	24	Clay loam
	Bw	16–30	7.5	45	2.48	18	49	33	Clay loam
Ok_1	Ah	3–6	7.4	49.7	4.33	48	36	16	Loam
	Bw	6–15	7.4	34.3	2.22	27	38	35	Clay loam
	Bk/C	15–32	7.4	27	1.51	29.9	38	32	Clay loam
Ok_2	A_1	0–7	7.4	52.4	2.52	18	25	57	Clay
	A_2	7–13	7.3	51.8	2.2	22	24	54	Clay
	Bw	13–27	7.2	40.7	1.55	18	20	62	Clay

RP_1 and RP_2 = Soil samples collected from the rhizospheres under red pine canopies.
Ok_1 and Ok_2 = Soil samples collected from the rhizospheres under oak canopies.

with Mg^{++} and K^+. Mg^{++}-saturated slides were solvated with glycerol. All slides were scanned from 3 to 30 2θ at room temperature (Jackson, 1979). The K^+ slide was also scanned from 3 to 30 2θ after being heated to 550 °C for 1 h (Jackson, 1979). The semiquantitative amounts of the clay minerals were determined by peak intensities. The random oriented clay slides were run on an XRD Shimadzu model 6000 with a copper tube, at a voltage of 40 kW and 30 mA intensity from 3 to 30 2θ.

2.2.5. Scanning electron microscopy (SEM)

SEM images were interpreted according to FitzPatrick (1993) for morphology, mineral contents and weathering, soil organic matter, and faunal activity in the aggregates clinging to the roots.

2.2.6. Statistical analyses

The statistical analyses were conducted on all pore shapes and size in the soils of the horizons of profiles. The analysis of variance of the data was carried out using MSTATC and SPSS and one-way ANOVA, followed by Duncan's multiple range test, which was used to determine the mean comparability.

3. Results and discussion

3.1. Porosity

The porosity determined in the Bw horizons of RP_1, RP_2 Ok_1, and Ok_2 profiles revealed that all pore shapes, sizes, and the interaction of pore shapes × size classes were significantly different from one another ($P \leq 0.001$). In the Bw horizon of profiles RP_1 and RP_2 the highest porosity (1.65% and 1.32%) was observed in elongated pores with 100–200 µm (Table 2). However, the porosity percentage in elongated pores with 300–400 µm the porosity percentage also was higher in the Bw horizons of profiles RP_1 and RP_2. According to Pagliai and Vignozzi (2002) there is a close relation between elongated pores and hydraulic conductivity. The interplay of the elongated pores in plant growth is significant in easing root penetration, water drainage, and air exchange (Greenland and Pereira, 1977). The lowest porosity percentages of the soils of the Bw horizon of RP_1 were determined for the regular pores of all size classes and also in the irregular pores varying from 50 to 500 µm size and elongated pores >1000 µm size (Table 2). In RP_2 a similar trend of lower porosity was observed in the regular pores and the elongated pores >400 µm size (Table 2). Small regular pores were less effective in water transmission than irregular and elongated pores. Therefore, infiltrability of water depends not only on total porosity but also on distribution of pore shapes and sizes (Valentin, 1991). In addition, in the Bw horizon of RP_2 the pores >1000 µm size were lower than the other sizes of pores in all 3 shapes of the soils of this study (Table 2). In the Bw horizons of the Ok_1 and Ok_2 soils the highest porosities were 1.99% and 0.83% in the elongated pores (100–200 µm), respectively (Table 2). Zucca et al. (2013) reported higher percentages of elongated pores under pasture in the 2–4-cm layer of the soils of the Mediterranean region. The regular pores especially with the sizes >1000 µm were significantly the lowest (0.04%) in the Bw horizon of the profile Ok_1 (Table 2). The maximum pore size class of the

Table 2. Pore size and shape distribution in the Bw horizons of profiles RP_1, RP_2, Ok_1, and Ok_2.

RP_1	Porosity (%)						
Size (μm)	50–100	100–200	200–300	300–400	400–500	500–1000	>1000
Shape							
Regular	0.23 de[≠]	0.4 cd	0.21 de	0.18 de	0.12 de	0.26 de	0.12 e
Irregular	0.11 de	0.27 de	0.33 cd	0.37 cd	0.32 cd	1.04 b	0.99 b
Elongated	0.4 cd	1.65 a	1.22 b	1.60 a	0.35 cd	0.58 c	0 de
RP_2							
Shape							
Regular	0.39 d	0.7 c	0.27 d	0.13 ef	0.08 ef	0.12 ef	0 g
Irregular	0.13 ef	0.39 d	0.67 c	0.5 d	0.38 d	0.68 c	0.19 e
Elongated	0.67 c	1.32 a	0.72 c	1.13 b	0 g	0 g	0 g
Ok_1							
Shape							
Regular	0.21 fgh	0.32 ef	0.17 fghi	0.1 ghi	0.06 ghi	0.1 ghi	0.04 hi
Irregular	0.1 ghi	0.24 fg	0.34 ef	0.3 ef	0.21 fgh	0.65 d	1.04 c
Elongated	0.44 e	1.99 a	1.17 bc	1.3 b	0.19 fgh	0 i	0 i
Ok_2							
Shape							
Regular	0.39 ef	0.57 bc	0.24 gh	0.1 ijk	0.04 jk	0.06 jk	0.56 bcd
Irregular	0.15 hij	0.42 def	0.49 bcde	0.4 ef	0.31 fg	0.52 bcde	0.61 b
Elongated	0.33 fg	0.83 a	0.45 cdef	0.43 cdef	0.22 ghi	0.52 bcde	0 k

RP_1 and RP_2 = Soil samples collected from the rhizospheres under red pine canopies.
Ok_1 and Ok_2 = Soil samples collected from the rhizospheres under oak canopies.
[≠] Means separated in each column followed by same letter is not significantly different at P ≤ 0.01, using Duncan's multiple range test (DMRT).

soils of Bw horizons of profiles RP_1, RP_2, Ok_1, and Ok_2 for elongated pores were <1000 μm, <400 μm, <500 μm, and <1000 μm, respectively (Table 2). Beside the elongated pores (>1000 μm), the lowest porosity percentages for the Bw horizon of profile RP_2 were determined for the regular pores with 400–500 μm (0.04%) and 500–1000 μm (0.06%) sizes without a significant difference between them (Table 2).

The statistical analysis based on ANOVA and multiple range tests showed that the four soil profiles were possibly based on the similarities and differences among the 2D porosities and the shapes of the pores. The statistical analysis of the pore characteristics determined in the Bw horizons of all profiles of the study revealed that all the pore shapes of the profiles and the interaction of pore shapes × profiles were significantly different from one another (P ≤ 0.001). Irregular pores were quite evenly distributed among the three pore shapes in Ok_1, Ok_2, and RP_2. However, the highest percentages of irregular pores (3.44%) and elongated pores (9.85%) were observed in profile RP_1 (Figure 2). The pore spaces in a soil vary in abundance, according to the type of the soil and its management. Soils under natural vegetation generally exhibit high porosity because of high biological activity and lack of interference by humans (Shaxson and Barber, 2016). Generally, profiles RP_1 and RP_2 had the highest percentages of porosity compared to profiles Ok_1 and Ok_2, most likely indicating higher biological activity compared to the root zone soils under the oak (Figure 2).

3.2. Clay minerals

The dominant clay minerals were kaolinite, illite, and smectite in the loamy soils of RP_1 and Ok_1, whereas smectite, illite, and kaolinite were dominant in the more clayey and higher CEC soils of RP_2 and Ok_2 (Tables 1 and 3). Kaolinite of site 1 soils may also be inherited from the parent rock. In this respect, it would be rather difficult to interpret the

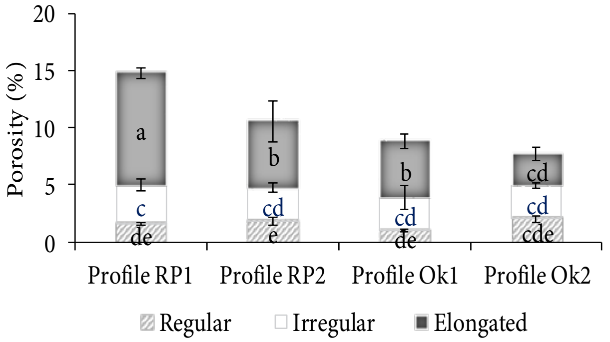

Figure 2. Pore size distribution, according to the equivalent pore diameter for regular and irregular pores, or the width for elongated pores, in the Bw horizons of the profiles.

precise effect of the canopy on the clay mineral contents. Similarly, Alexander et al. (1993), Watanabe et al. (2004), Mareschal (2008), Graham and O'Geen (2010), and Baker (2010) did not comment on the variations in mineral contents versus canopy types. They only mentioned that in the soils under pine and oak canopies the clay mineral contents were kaolinite, smectite, and illite.

3.3. Submicroscopy (SEM)

3.3.1. submicroscopy of the Ah, A2, Bw, and Bk/C horizons of profile RP_1

The Ah horizon of profile RP_1 consisted of well-preserved root remnants/residues in the aggregates/MSUs coated by biofilms (Figure 3a). The root remnants/residues in this horizon surrounding the aggregates/MSUs form the individual grains and smaller microaggregates together by interwoven and curled masses of roots (Figure 3b). The frequent cemented aggregates determined in the Ah, A_2, and Bw horizons (Figures 3a, 3c, and 3d) reflect the effect of the exudate-root system. There are abundant very fine clay aggregates in the absence of biofilms within rare root remnants in the Bk/C horizon (Figure 3e).

3.3.2. The submicroscopy of the Ah and Bw horizons of profile RP_2

Rare to occasional pollen fragments of red pine were observed in aggregates/MSUs abundant in root remnants in horizon Ah (Figure 3f). Fine root taps and roots were also observed to protrude through the biofilm-welded matrix of the MSUs in the same horizon (Figure 3g), reflecting pore development by root action. Figure 3h reveals a dominant network of fine to very fine roots, clay mineral aggregates, and biofilms formed by exudates. This was also indicative of the vigorous biological activity most likely increasing the resistance of the aggregates against physical and chemical changes (in size and composition) and especially erosion. There were similar networks of clay minerals and fine clay mineral aggregates cemented/welded by hyphea-roots and/or organic filaments and biofilms in the horizon Bw (Figure 3i), indicating vigorous biological activity. Occasional very fine fresh roots and others coated by clay mineral grains likely reflected the on-going vigorous contemporary root activity. Primary

Table 3. Clay mineral contents (XRD) of the soils of profiles RP_1, RP_2, Ok_1 and Ok_2

Profile	Horizons	Depth	Clay minerals		
		(cm)	Smectite	Illite	Kaolinite
RP_1	Ah	5–10	×	××	×××
	A2	10–19	×	××	×××
	Bw	19–28	×	××	×××
	Bk/C	28–45	×	××	×××
RP_2	Ah	8–16	×××	××	××
	Bw	16–30	×××	××	××
Ok_1	Ah	3–6	×	××	×××
	Bw	6–15	×	××	×××
	Bk/C	15–32	×	××	×××
Ok_2	A1	0–7	×××	××	×
	A2	7–13	×××	××	×
	Bw	13–27	×××	××	×

(×××, ××, and × show abundant, moderate, and rare contents of clay minerals in the horizons, respectively.)

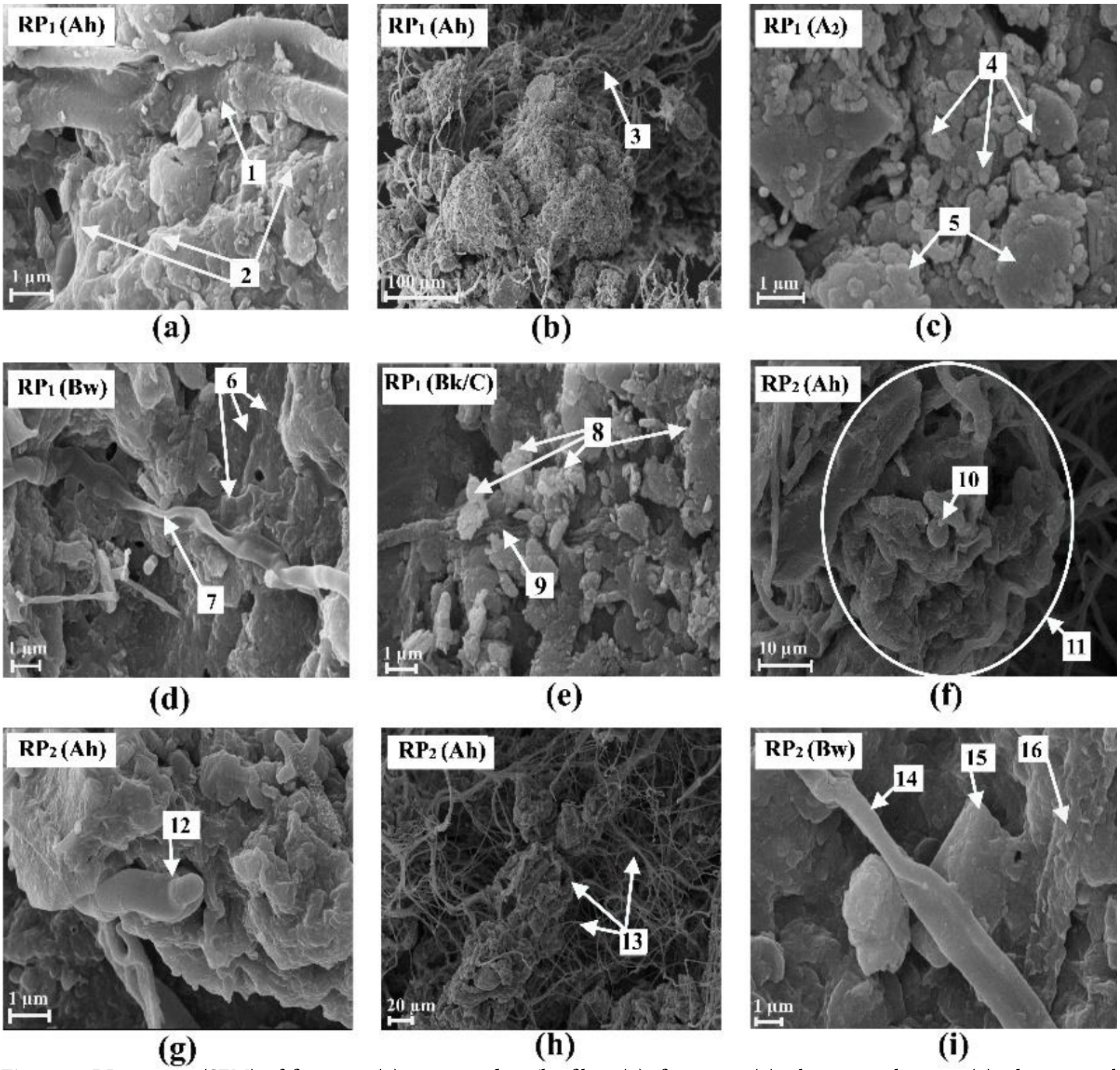

Figure 3. RP_1 images (SEM) of fine root (1), root exudates/biofilms (2), fine roots (3), clay mineral grains (4), clay mineral aggregates (5), root exudates/biofilms (6), organic filament (7), fine clay aggregates (8), fine root (9), and RP_2 images (SEM) of aggregates with abundant root remnants (10), pollen (11), root tap protruding through clay aggregate coated by exudates (12), dominant network of fine roots (13), and organic filament, primary mineral, clay minerals coating organic filament (14, 15, 16).

minerals in the matrix with fresh weathering surfaces in close contact with roots may also show a probable on-going vigorous biological pedo-environment (Figure 3i). The frequent microaggregates of clay minerals in this horizon were composed of common cementing organic-filaments/hyphea manifesting similar vigorous root activity in the soils of RP_2.

3.3.3. The submicroscopy of the Ah, Bw, and Bk/C horizons of profile Ok_1

Abundant bacterial filaments, fine roots, and/or root taps and mycorrhizal spores were determined in horizon Ah (Figure 4a). The frequent irregular to angular aggregates/MSUs cemented by the exudates and clay mineral grains together with the root remnants coated by clay minerals indicated an advanced stage of maturity for horizon Bw compared to the ones above it (Figure 4b). Root sections completely decomposed and partly integrated to the matrix contain abundant cemented/welded very fine aggregates/MSUs and the section wall completely coated with clay minerals or aggregates (Figure 4c). There is frequent development of lace-like organic filament deformation with exudation (development of organic films) and presence of mycorrhizal spores in the matrix. All indicate advanced mycorrhizal and microbial activity

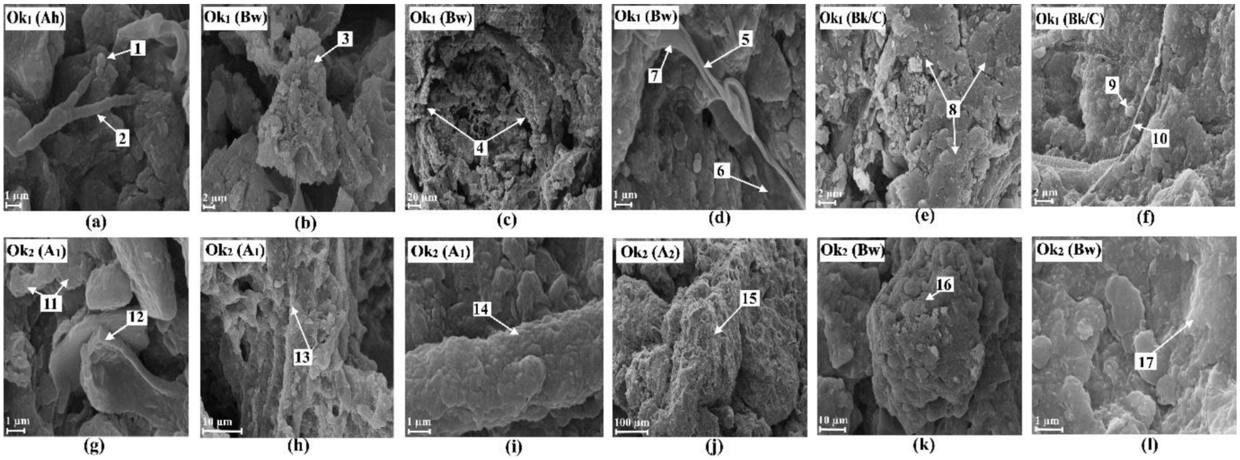

Figure 4. Ok_1 images (SEM) of mycorrhizal spores (1), bacterial filaments (2), clay mineral grains cemented by exudates (3), root section (4), lace-like organic filament (5), root capsule (6), biofilm (7), aggregates of overlapped sheets of clay minerals (8), mycorrhizal spores (9), hyphae and/or root (10) and Ok_2 images (SEM) of clay mineral aggregates (11), root tap (12), clay minerals were aligned along root walls (13), clay mineral coated very fine root/hyphea (14), highly welded aggregates (15), well-developed subangular blocky to irregular welded micro-aggregates (16) and welded sheets of clay minerals (17).

under the oak canopy (Figure 4d). The overlapping sheets of clay minerals in the Bk/C likely reveal the tendency to aggregate around decomposing roots (Figures 4e and 4f).

3.3.4. The submicroscopy of the Ah, Bw, and Bk/C horizons of profile Ok_2

There were frequent old and completely matrix-integrated root remnants and root taps (Figure 4g) in horizon A_1. Clay minerals were aligned along root walls. Some clay mineral sheets seem to be completely coated by biofilms of root exudates (Figure 4h). Figure 4i revealed the occurrence of a completely clay mineral-coated very fine root/hyphae. The abundant, highly welded MSUs reflect the higher amounts of clay size particles (Table 1; Figure 4j) and the presence of well-developed subangular blocky to irregular welded microaggregates (Figure 4k), especially in horizon Bw. Welded sheets of clay minerals (smectite/illite) (Figure 4l) indicated the high activity/exudation (high biofilm formation) of the roots to cement/weld the fine clay particles in this horizon.

4. Conclusions

The highest soil porosity was observed in the elongated pores (9.85%) of RP_1 in this study. Generally, profiles RP_1 and RP_2 had the highest percentages of porosity compared to profiles Ok_1 and Ok_2. The higher regular pores (most probably formed by earthworm activity) of the Ok_1 and Ok_2 profiles compared to the RP_1 and RP_2 profiles support the higher stability of the aggregates/welded MSUs (SEM images). Similarly, Graham et al. (1995) also reported higher stable aggregates under scrub oak than under Coulter pine canopy. The dominant clay mineral in sampling site 1 is kaolinite, whereas it is smectite in sampling site 2. Despite the expected effect of the tree canopies on the clay mineral contents of the soils, the higher kaolinite contents of site 1 most probably do not indicate higher weathering than the soils of site 2. This may rather indicate inherited kaolinite from the parent rock. Our results revealed significant differences via canopies in soil porosity (image analysis) and aggregate (microstructure-SEM) development. The clay mineral results did not provide outcomes supporting any major effect on the soils of the red pine and oak root-zones, except the probable contribution of higher smectite contents to the formation of the welded aggregates under oak canopies. Results documented that, independent from depth and slope, under red pine and oak covers the soil organic carbon levels of the study site are two- to three-fold higher in carbon content than the agricultural soils of the region (about 1.5%). Thus, at 100–700 m elevations of the limestone areas of the Mediterranean region of Turkey, maintaining red pine and oak vegetation is an efficient tool for combating and mitigating climate change by the former (via sequestrating higher organic carbon) and protecting soil against erosion by the latter (by inducing formation of the welded aggregates).

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