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The Effect of Long-Term Different Land-Use Types on Aggregate-Associated Organic Carbon

Uzun Süreli Farklı Arazi Kullanım Türlerinin Agregatla İlişkili Organik Karbon Üzerine Etkisi

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Abstract: Land use can strongly influence aggregate stability, a key factor in conserving soil organic carbon over extended periods. Therefore, the long-term effects of three different land-use types on aggregate stability (AS) and aggregate-associated organic carbon (AAOC) were assessed in this study. The study was conducted on the campus of Çukurova University, Adana, Türkiye. The land-use types were; arable land (AL, continuously used as cropland since 1974), olive orchard (OO, cultivated as olive trees since 1974), and eucalyptus plantation (EP, established in 1997). In June 2025, soil samples were collected from the surface horizon of each land-use type. The results showed that AS and AAOC differed significantly among the long-term different land-use types. In each land-use type, OO and EP significantly affected AAOC. The highest AS was obtained in OO and EP compared to AL, which is conventionally tilled. The land-use type EP had the highest OC (1.48%), which was 32.1% higher than OO (1.12%) and 80.5% higher than AL (0.82%), followed by OO and AL. The highest AAOC was determined in the 4–2 mm aggregate, followed by the 1–2 mm and 0.5–1 mm aggregates, respectively. The results indicated that orchard and plantation promoted improved aggregation and enhanced SOC retention within surface horizon, whereas conventional tillage showed reduced aggregate stability and carbon retention.

Keywords: Aggregate, Land use, Organic carbon, Mediterranean

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Öz: Arazi kullanımı, uzun süreler boyunca toprak organik karbonunun korunmasında önemli bir faktör olan agregat stabilitesini güçlü bir şekilde etkileyebilir. Bu nedenle, bu çalışmada üç farklı arazi kullanım türünün agregat stabilitesi (AS) ve agregatla ilişkili organik karbon (AAOC) üzerindeki uzun dönemli etkileri değerlendirilmiştir. Çalışma, Türkiye'nin Adana ilinde, Çukurova Üniversitesi yerleşkesinde yürütülmüştür. Arazi kullanım türleri; tarım arazisi (AL, 1974'ten beri sürekli olarak tarımda kullanılmaktadır), zeytinlik (OO, 1974'ten beri zeytin yetiştiriciliği yapılmaktadır) ve okaliptüs plantasyonu (EP, 1997 yılında tesis edilmiştir) olarak belirlenmiştir. Haziran 2025'te her arazi kullanım türünün yüzey horizonundan toprak örnekleri alınmıştır. Sonuçlar, AS ve AAOC'nin uzun vadeli farklı arazi kullanım türleri arasında anlamlı farklılıklar gösterdiğini ortaya koymuştur. Her bir arazi kullanımında OO ve EP, AAOC üzerinde önemli etkiler göstermiştir. En yüksek AS, geleneksel olarak işlenen AL'ye kıyasla OO ve EP'de elde edilmiştir. EP kullanım türü, %1.48 ile en yüksek organik karbon (OC) değerine sahip olmuş; bu değer OO'dan (%1.12) %32.1 ve AL'den (%0.82) %80.5 daha yüksek bulunmuştur. En yüksek AAOC, 4–2 mm agregat fraksiyonunda, bunu sırasıyla 1–2 mm ve 0.5–1 mm agregatlar izlemiştir. Elde edilen bulgular, zeytinlik ve plantasyon arazilerinde yüzey horizonunda daha iyi bir agregasyon ve gelişmiş SOC tutulumunu desteklediğini, buna karşın geleneksel toprak işlemenin daha düşük agregat stabilitesi ve karbon tutulumu ile ilişkili olduğunu göstermektedir.

Anahtar Kelimeler: Agregat, Arazi kullanımı, Organik karbon, Akdeniz

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Plagiarism/Ethic: Bu makale, en az iki hakem tarafından incelenmiş ve intihal içermediği, araştırma ve yayın etiğine uyulduğu teyit edilmiştir. / This article has been reviewed by at least two referees and it has been confirmed that it is plagiarism-free and complies with research and publication ethics. https://dergipark.org.tr/tr/pub/ijaws

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INTRODUCTION

Agricultural soils constitute the largest carbon reservoir within terrestrial ecosystems (Mohamed et al., 2025). However, when these soils are inadequately protected or subjected to inappropriate management practices without consideration of their carbon sequestration potential, soil organic carbon (SOC) stabilized within soil aggregates can be released into the atmosphere, thus influencing climate change (Kan et al., 2022). Thus, conservation of AAOC plays a vital role in sustaining agricultural productivity over time.

SOC has an essential role in enhancing soil structure (Zhou et al., 2020), and regulating climate change through carbon sequestration (Lal, 2010). A substantial proportion of SOC is stabilized within soil aggregates (Kan et al., 2022), which provide a protective environment that reduces microbial degradation (Six et al., 2002) and thus contribute to the long-term storage of carbon in terrestrial ecosystems. In this context, soil aggregates and organic carbon interact synergistically (Mohamed et al., 2025). SOC dynamics within aggregates are influenced by land use and management practices (Guo et al., 2020; Mohamed et al., 2025), as these factors determine the inputs of organic matter, the intensity of soil disturbance, and the biological activity within the soil matrix. The interaction between soil aggregates and OC strongly influences agricultural sustainability.

Different land use systems, such as arable land, orchard, and forest plantation, have contrasting effects on aggregate formation and stability and SOC. Arable lands, particularly those under conventional tillage, show a decline in AS and SOC content due to mechanical disturbance and reduced organic matter inputs (Gencer et al., 2024; Topa et al., 2021). However, perennial systems such as olive orchards (*Olea europaea* L.) and eucalyptus plantations (*Eucalyptus spp.*) typically promote higher aggregate stability and SOC accumulation due to continuous litterfall, minimal soil disturbance, and root turnover (Fahad et al., 2022). Olive orchards represent a long-standing traditional Mediterranean agroecosystem (Marchi et al., 2018) and thus have significant potential for carbon storage (Lopez-Bellido et al., 2016). Eucalyptus plantations, widely established for timber and pulp production, contribute to SOC dynamics through rapid biomass production and litter decomposition (Oliveira et al., 2021).

Despite the recognized importance of AAOC (Acar et al., 2018; Mohamed et al., 2025; Qiu et al., 2015; Wei et al., 2013; Yu et al., 2023), limited research has been examined how long-term and contrasting land-use histories - such as the persistence of olive orchards, the continuous cultivation of arable lands, and the relatively recent establishment of *Eucalyptus* plantations – affect AAOC and AS under Mediterranean conditions. This knowledge gap restricts our understanding of how land-use continuity influence soil carbon dynamics and, consequently ecosystem sustainability. Understanding how land use systems affect AAOC is critical for developing sustainable land management strategies. Therefore, the impacts of contrasting land uses—arable land, olive orchard, and eucalyptus forest—on AAOC and AS were assessed in the study. Our hypothesis was that perennial systems, such as olive orchards and *Eucalyptus* plantations, exhibit greater aggregate stability and higher AAOC compared to conventionally tilled arable land.

MATERIAL AND METHOD

This study was conducted on Kızıltapır soil series in the campus of Çukurova University, Adana, Türkiye (Figure 1). The region has a typical Mediterranean climate, with hot and dry summers and mild and rainy winters. According to 95 years of climatic data for Adana province, the annual average temperature is 19.3 °C, and the annual precipitation is 667.5 mm (Anonymous, 2025).

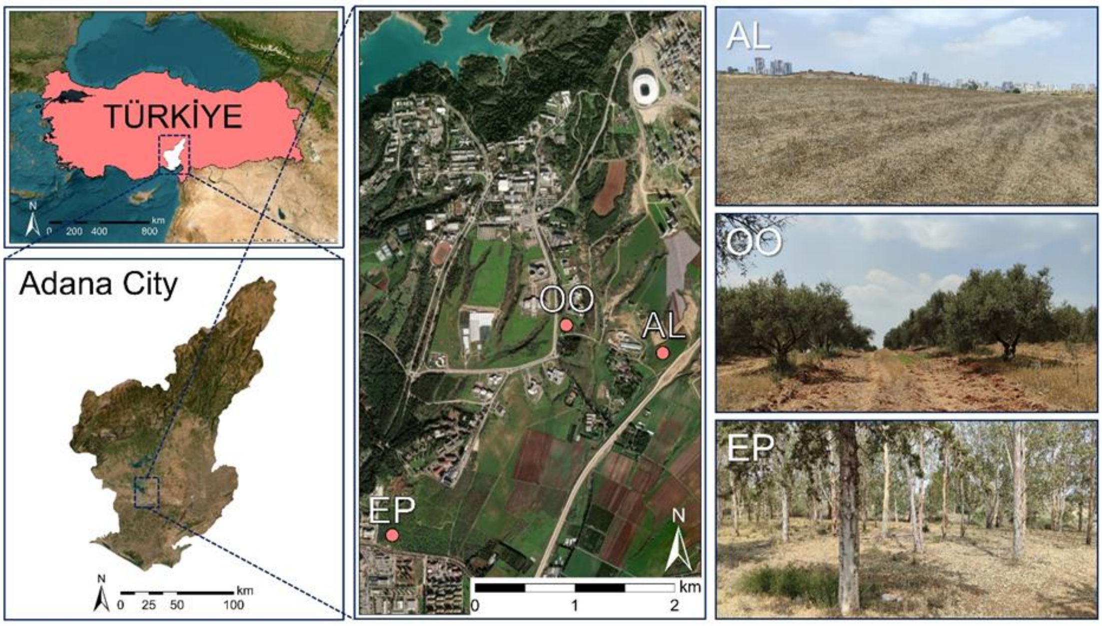

Figure 1. Study area (AL, arable land; OO, olive orchard; EP, eucalyptus plantation).
Şekil 1. Çalışma alanı (AL, ekilebilir arazi; OO, zeytinlik; EP, ökaliptüs plantasyonu).

Kızıltapır soil series was classified as Calcic Rhodoxeralfs according to Soil Taxonomy (2022). Kızıltapır soil series has developed over conglomerate parent material, with an A-Bt-C-R horizon sequence. These soils have a shallow to medium solum thickness (approximately 50 cm), a dark red surface soil color (2.5 YR) when dry, and have formed under a Xeric moisture regime (Özbek et al., 1974). Long-term different land-use types are found on this soil series. In this study, soils under arable land (AL), olive orchard (OO), and *Eucalyptus* plantation (EP) were examined. The texture class of the soils in AL (sand 44.7%, silt 23.9%, and clay 31.4%), OO (sand 44.8%, silt 21.6%, and clay 33.6%), and EP (sand 44.6%, silt 23.7%, and clay 31.7%) is clay loam.

The land use of the study area over the years is presented in Figure 2. According to the soil maps prepared by Özbek et al. (1974) and the interpretation of aerial photographs archived by the Department of Soil Science and Plant Nutrition at Çukurova University, together with recent satellite images (Google Earth, Airbus), AL has been used as arable land and OO as an olive orchard continuously since 1974. EP, on the other hand, was used as arable land between 1974 and 1993, after which it was converted into a *Eucalyptus* plantation through afforestation efforts and has remained so until the present.

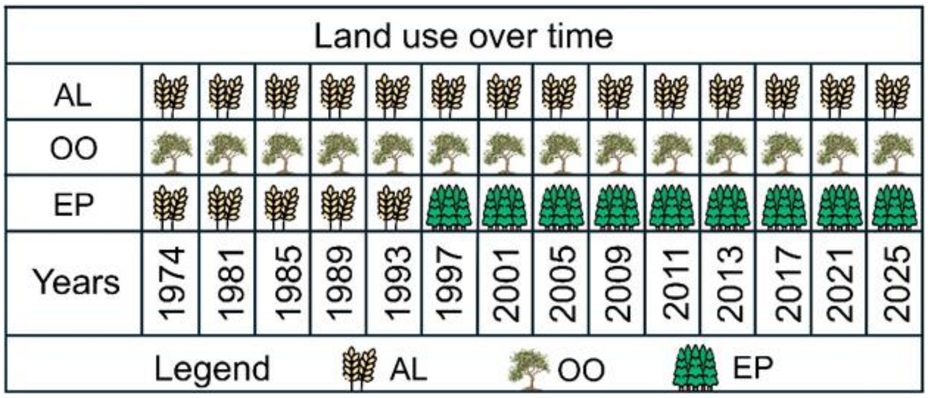

Figure 2. Land-use types of the sampled areas during 1974–2025 (AL, arable land; OO, olive orchard; EP, eucalyptus plantation).
Şekil 2. 1974–2025 yılları arasında örneklenen alanların arazi kullanımı (AL, ekilebilir arazi; OO, zeytinlik; EP, ökaliptüs plantasyonu).

Soil Sampling

To determine the effects of long-term different land-use types on AS and AAOC in the Kızıltapır soil series, cartographic materials (aerial photographs, satellite images) belonging to Çukurova University campus and satellite images were examined. Based on these examinations, coordinates under AL, OO, and EP vegetation were identified, and soil sampling was conducted. Soil sampling was carried out on 18.07.2025 at three randomly selected points representing each land use (each point corresponding to a composite sample obtanied by mixing subsamples collected from the corner points of a 2 m^2 area). Disturbed soil samples were taken from the surface horizon (0–10 cm soil depth) using a shovel, homogenized in a plastic container, transferred into bags, and brought to the laboratory. Subsequently, the soils were air-dried at room temperature until reaching an air-dry moisture level to prepare them for analysis.

Laboratory Analyses

Water-stable aggregates were obtained by wet sieving through 2-, 1-, 0.5-mm sieves according to the procedures described by Cambardella and Elliott (1993). A 100 g soil aggregate sample was slowly immersed into and withdrawn from a container filled with distilled water for 10 minutes. The material remaining on each sieve was transferred to a glass container and dried at 50 ^oC for 72 h.

Soil samples obtained from water-stable aggregates were air-dried and passed through a 2-mm sieve. The amount of oxidizable organic carbon in these samples was determined using the Walkley–Black wet oxidation method as described by Nelson and Sommers (1996).

Aggregate stability was carried out by wet sieving method using a set of sieves (4, 2, 1 and 0.5 mm diameters) according to Kemper and Rosenau (1986).

Statistical Analyses

The results were reported as mean ± standard error. The distribution of the data was tested for normality using the Kolmogorov-Smirnov test, and the homogeneity of variances was assessed using Levene’s test. Variations across land-use types were statistically analyzed using one-way ANOVA, and pairwise differences were identified with Tukey’s HSD test. 95% confidence interval was adopted for the statistical analyses. OriginPro 2024 software (OriginLab Inc., Northampton, MA, USA) was used for statistical analyses and graph generation. ArcGIS (version 10.8) was used to prepare the location map.

RESULTS AND DISCUSSION

Aggregate Stability and Aggregate-Associated Organic Carbon

Long-term land-use types had statistically important effects on AS (Figure 3). The highest aggregate stability was obtained in OO (83.9%), followed by EP (71.9%) and arable land (25.5%). Conventional tillage with a mouldboard plow is a management practice that reduces AS (Acar et al., 2018; Çelik et al., 2019). AS in arable land markedly showed the adverse effects of conventional tillage in the study. In contrast to arable land, aggregate stability was found to be 229% and 182% higher in EP and OO, respectively, where tillage was absent or only applied occasionally when necessary. Consistent with the findings of this study, Zhong et al. (2019) reported that aggregate stability improved when the disruptive effect of tillage on soil aggregates was discontinued and the land was revegetated with forest and shrub species over a 42-year period. A possible explanation is that tree residues in EP and OO provided more substantial biomass contributions than the limited inputs characteristic of conventional tillage, thereby enhancing the formation of binding agents and promoting AS (Ayoubi et al., 2012).

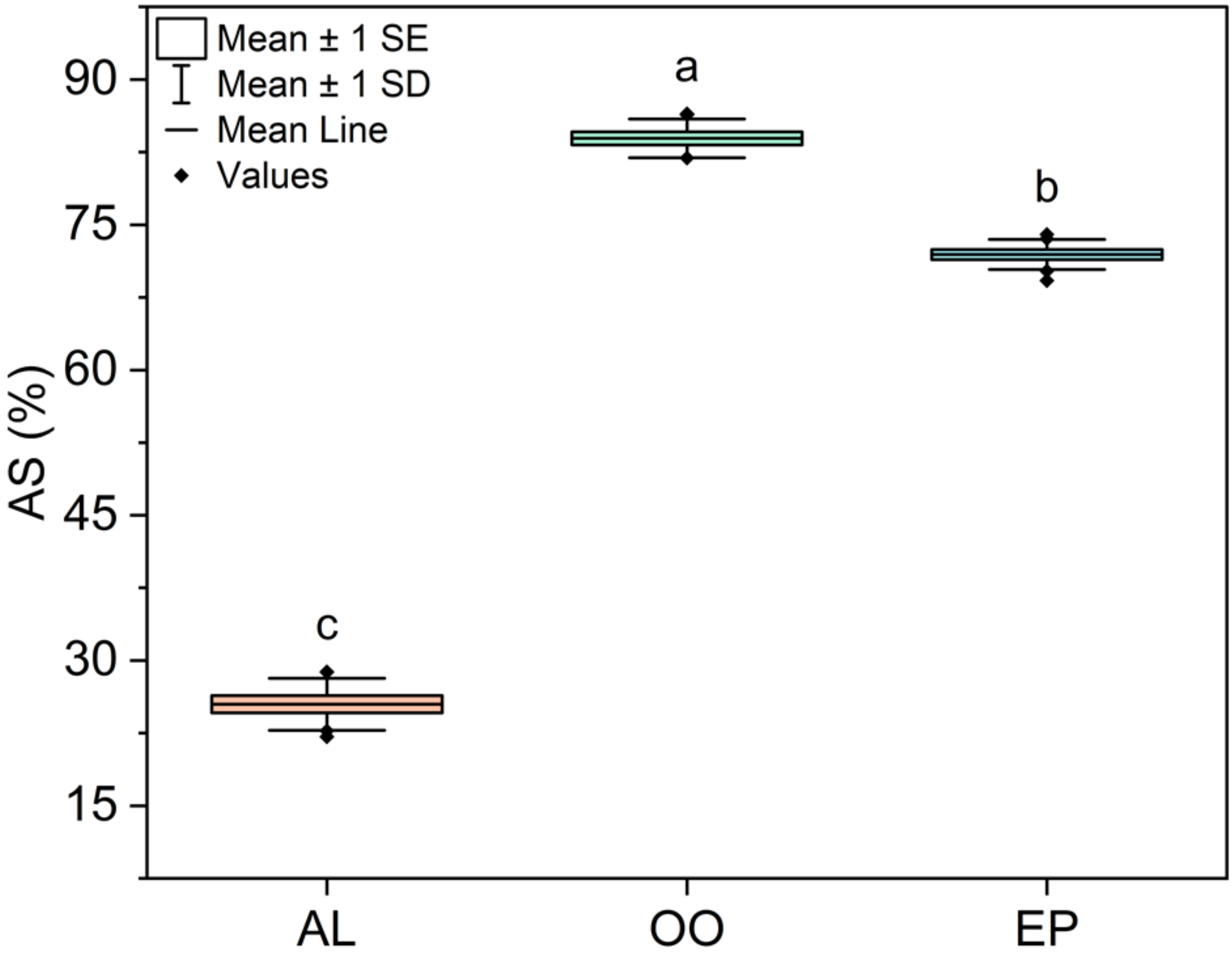

Figure 3. Aggregate stability under different land-use types (AL, arable land; OO, olive orchard; EP, eucalyptus plantation).
Şekil 3. Uzun süreli farklı arazi kullanım türünün agregat stabilitesi (AS) üzerine etkisi (AL, ekilebilir arazi; OO, zeytinlik; EP, ökaliptüs plantasyonu).

The improvement in AS under perennial systems likely enhanced the physical protection of organic carbon within soil aggregates. Stable aggregates create micro-environments with restricted oxygen diffusion and limited microbial access, thereby slowing decomposition and promoting long-term carbon storage (Six et al., 2000). Moreover, root exudates and microbial mucilages act as biological binding agents that cement soil particles into aggregates and provide substrates for microbial activity, leading to organo-mineral complex formation (Lei et al., 2023). Organo-mineral complexes, including associations with iron and aluminum oxides or humic substances, contribute to the long-term stabilization of organic carbon in macroaggregates (Six et al., 2002)

Long-term different land-use types had statistically significant effects on AAOC (Figure 4). The highest AAOC content was obtained in EP (1.48%), followed by OO (1.12%) and arable land (0.82%), which belonged to different statistical groups. While the variation in organic carbon among different aggregate size fractions was not statistically significant in Arable land, significant differences were observed in OO and EP. In both OO and EP, the highest organic carbon contents were determined in the 4–2 mm fraction. Organic carbon decreased as aggregate size declined. However, the lowest organic carbon values in OO and EP were still higher than those in Arable land.

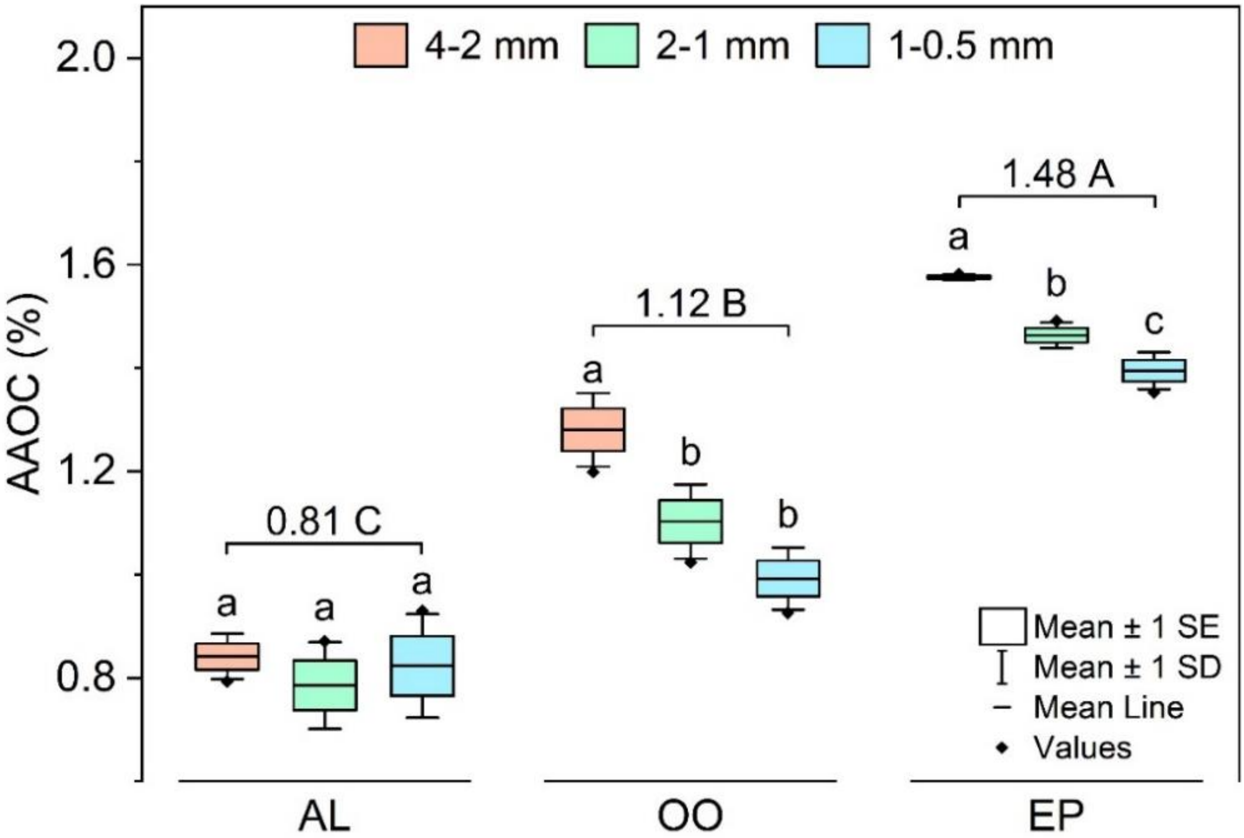

Figure 4. Aggregate-associated organic carbon under different land-use types (AL, arable land; OO, olive orchard; EP, eucalyptus plantation).

Şekil 4. Uzun süreli farklı arazi kullanım türünün agregatla ilişkili organik karbon (AAOC) üzerine etkisi (AL, ekilebilir arazi; OO, zeytinlik; EP, ökaliptüs plantasyonu).

Tillage is an agricultural practice that induces significant changes in stability of aggregate and organic carbon (Liu et al., 2021). In soils conventionally tilled with a mouldboard plow, the disruption of aggregates and the consequent oxidation of organic matter protected within them lead to a decline in organic carbon (Acar et al., 2018; Gencer et al., 2024). In the arable land of the Kızıltapır series, which has been cultivated conventionally for many years, the effect of tillage is pronounced. Previous studies support the finding that land use under conventional tillage results in a decrease in OC (Çelik et al., 2019; Kumari et al., 2011; Zhang et al., 2024). Compared to arable land, tillage in OO is carried out only occasionally when needed, whereas no tillage is applied in EP. In these soils, the quantity of surface plant residues is greater than in arable land. The long-term presence of plant residues on the soil surface, combined with reduced or absent tillage, has increased OC, particularly in the A horizon, possibly as a consequence of organic matter inputs from litter, root secretions, and decayed roots. (Six et al., 2000).

Considering aggregate size, higher organic carbon contents were observed in the 4–2 mm fraction, particularly in OO and EP, and organic carbon decreased with decreasing aggregate size. Macroaggregates protect internal organic carbon from microbial decomposition more effectively than microaggregates due to reduced surface area exposure and stronger binding with mineral surfaces (Tisdall and Oades, 1982). These findings are consistent with previous studies. In a study conducted in Northern Ethiopia, Gelaw et al. (2015) reported that macroaggregates contained more organic carbon compared to microaggregates. Similarly, Das et al. (2022), observed that aggregate-associated total SOC declined with decreasing aggregate size, and that, especially in the surface soil, macroaggregates under natural forest contained more organic carbon compared to those under tilled agricultural land. Another study reported that in land uses such as broadleaf forest, mixed conifer, natural grassland and orchard, aggregate-associated organic carbon decreased as aggregate size declined from >2.0 mm to 0.053 mm (Dorji et al., 2020). The higher organic carbon content in large aggregates of OO and EP soils can be attributed to greater organic matter contributions, reduced decomposition due to minimal soil disturbance, and the development of organo-mineral complexes. As a result, the differences in AS among land-use types are reflected in their AAOC contents, with perennial systems showing higher AAOC due to enhanced biological and physical protection and continuous organic matter inputs.

CONCLUSION

In this study, the effects of contrasting land uses on AAOC and AS were investigated under Mediterranean conditions. The results indicated that different land use statistically affected AAOC and AS. OO and EP land uses indicated substantially higher AS and AAOC compared to AL, with AS and in OO and EP being approximately 229% and 182% higher, respectively, and AAOC approximately 38% and 83% higher, respectively. In arable land under conventional tillage, aggregate disruption reduces stability, and thereby the oxidation of organic matter previously protected within aggregates results in a decline in soil organic carbon. Therefore, our results suggest that sustainability in agricultural production should be promoted by moving away from conventional tillage practices, particularly in arable land systems under Mediterranean conditions. However, the study was limited by sampling at a single depth and short temporal coverage. Future research should focus on long-term monitoring and microbial mechanisms affecting aggregate formation and carbon stabilization to better understand soil structural and biochemical dynamics under different land-use systems.

CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article

DECLARATION OF AUTHOR CONTRIBUTION

The authors' contributions to the article are equal.

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