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Cork and Compost as Mitigators of Soil Compaction from Trampling in Urban Green Areas: Effects on Plant Growth and Soil Functionality

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Abstract: Compacted soils in urban areas suffer from reduced porosity, impairing plant growth, water infiltration, and gas exchange, thus exacerbating other potential environmental issues. Amending soil with organic matter can reduce bulk density and increase permeability, thereby enhancing soil fertility and functionality. This study evaluated the effects of two organic soil amendments (i.e., chipped cork and municipal waste compost) on soil functionality and the physiology of *Quercus ilex* trees, following a soil compaction treatment. Five soil treatments were compared: control (no compaction and amendments), soil compaction without amendments, and compaction with amendments including cork, compost, or a combination of both. Soil and plant physiological responses were analyzed during the summer months, focusing on soil gas exchange, temperature, moisture, microbial respiration, enzymatic activity, leaf gas exchange, leaf chlorophyll fluorescence, chlorophyll content, and maximum daily trunk shrinkage. The results showed that amended soils exhibited increased soil gas exchanges, lower temperatures, and higher microbial activity than non-amended compacted soils, thereby reducing the detrimental effects of soil compaction on plant physiology. These findings suggested that incorporating organic amendments into urban soils, especially those subjected to frequent trampling, could make them more resistant/resilient to compaction, supporting healthier green spaces and more sustainable urban ecosystems.

Keywords: maximum daily trunk shrinkage; photosynthesis; plant physiology; soil enzymatic activity; soil health; soil respiration

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1. Introduction

Global threats to soils are among the greatest concerns of the 21st century. With the urban population expected to grow by 2.5 billion between 2018 and 2050 [1], there is an increasing need for proper management of urban environments. Soil plays a crucial role in ecosystem functioning, acting as a fundamental component for various ecosystem services

(ESs) that contribute to human well-being and environmental sustainability [2,3]. The widespread expansion of cities highlights the critical role of urban soils in maintaining ESs, including their ability to support vigorous plant growth and mitigate urban heat islands [4,5].

Good urban soil conditions are vital for plant growth, which in turn contributes to various ESs such as air pollutant abatement, temperature regulation, carbon sequestration, and the creation of enhanced green spaces that promote mental and physical health [6–8]. However, urban soils frequently undergo compaction due to the continuous passage of pedestrians and vehicles [9,10]. Indeed, in the urban context, soil compaction is the primary cause of impaired soil functioning and urban environmental degradation because of decreased porosity [11]. When soil is extremely compacted, its physicochemical characteristics are similar to those of sealed soils, i.e., unable to allow soil–atmosphere exchanges of gases or liquids [10,12]. As a result, surface runoff and flood risk increase, while reduced evapotranspiration limits the soil ability to mitigate temperature peaks and, therefore, the urban heat island effect [5,10,13]. Negative impacts of soil compaction on soil quality and the growth and health status of plants are widely reported in forests, both for seedlings and adult trees [14–17], while less documented are the effects in urban environments [18–20]. In particular, soil compaction can hinder normal root development and, consequently, water uptake, which may further expose plants to environmental stressors, especially during the summer season when soil moisture is lower and temperatures are higher, potentially impacting the provision of ESs by green areas [21–24].

Organic matter amendment can make soil more able to contrast compaction, thus conserving its fertility and functionality. In this regard, Paradelo and Barral [25] investigated the mechanical behavior of a constructed soil adding increasing rates of compost (approximately 3%, 7%, and 14% dry weight), observing progressively flatter compaction curves and reduced maximum bulk density. Somerville et al. [26] tested the effectiveness of municipal green waste compost and biochar as amendments for compacted urban soils and evaluated the responses of planted trees. They found that these amendments improved soil physical and biological properties and, ultimately, tree growth, with any significant differences being observed between the various types of organic matter used.

Using organic urban waste as a soil amendment is also a viable solution for waste management. A United Nations project estimated that 1.3 billion tons of edible food waste are generated globally every year [27]. Effective urban management of organic waste would reduce total global GHG emissions and decrease social costs [28]. Thus, repurposing organic urban waste as a soil amendment improves soil health and contributes to the goal of the 2030 Agenda for Sustainable Development [29].

Against this backdrop, unlike previous studies that predominantly explored the effects of compaction on agricultural or forest soils, this research addressed the impact of compaction on urban soil. It examined the possible ameliorative effects of organic amendments. Indeed, the main purpose of this study was to assess the effects of three organic soil amendments (chipped cork, municipal waste compost, and their combination) on the properties of an urban soil subjected to compaction and on the plant physiology of a tree species, *Quercus ilex*, growing there. The study aimed to (i) evaluate changes in gas exchange, temperature, and enzymatic activity of soil following the application of these amendments and soil compaction and (ii) investigate the physiological responses of trees to these conditions during a critical period, the Mediterranean summer. By integrating soil biochemical and physical properties with plant physiological responses, this research provides a framework for understanding and mitigating the adverse effects of compaction in urban green spaces. In fact, we hypothesized that these organic amendments mitigated the negative effects of soil compaction on both soil and plant health. The findings contribute novel insights into urban soil management and support the development of sustainable practices to enhance the resilience of urban ecosystems, particularly under increasing urbanization and climate change.

2. Materials and Methods

2.1. Plant Material and Experimental Design

The experiment was conducted in an eight-year-old experimental stand of holm oak (*Quercus ilex* L.) planted at the Department of Agricultural, Food, Environmental and Forestry Sciences (DAGRI) of the University of Florence (43°47′40.0″ N, 11°10′38.9″ E). We focused on the holm oak due to its large use in Mediterranean urban environments. The soil on which the stand is growing on is a Eutric Cambisol (Loamic, Prototechnic), according to WRB 4th edition. Planting was carried out according to a hexagonal pattern at a distance of 1.80 m in the winter of 2018–2019 using 2-year-old containerized seedlings from seeds collected in autumn of 2016. At the time of this study, the plants were, on average, 330 cm tall, with a DBH of 6 cm and a crown radius of 110 cm. Fifteen holm oaks, scattered throughout the stand, were selected to be considered in the study.

A randomized block experimental design was employed, based on 5 treatments and 3 replicates per treatment: B, the "control" (no added amendment and no compaction performed); C (no amendment; yes compaction); CRK (soil amended by mixing with 10% *w*/*w* cork; compaction); CRK + CMP (soil amended by mixing with 5% *w*/*w* cork and 10% *w*/*w* compost; compaction); and CMP (soil amended by mixing with 10% *w*/*w* compost; compaction). The basic characteristics of these substrates are reported in Table S1. The experiment was set up in April, when a circular portion of soil with a radius of 1.5 m around each trunk, except in the control (treatment B), was tilled up to a depth of 10 cm, and then compost and cork were added to the soil and accurately mixed. The soil was then compacted three times, in April and in May, using a vibrating plate (Batmatic—FPH1650, Batmatic S.r.l., Bianconese, Italy), for 5 min in each area. The dimensions of the plate were 500 × 560 mm, the frequency of vibration was 90 Hz, the power was 4.0 kW, and the weight of the machine was 88 kg.

The compost was supplied by the Faltona composting plant (https://www.aerspa.it/Compostaggio_a_Faltona.pdf, accessed on 20 December 2024), which processed organic and green waste collected through door-to-door collection. The characterization of the compost was made by the factory and is reported in the Supplementary Material (Table S2). The chipped cork, ranging in particle size from 4 to 14 mm, was provided by STEACOM S.r.l. (Brendola, Italy), an Italian company specialized in solutions and technologies for the construction industry (https://www.steacom.it/, accessed on 12 December 2024).

Soil and plant analyses were conducted in July and August (the driest and hottest months in Italy, respectively). Soil sampling for determining soil physico-chemical and biochemical properties was carried out using a steel cylinder (8 cm inner diameter and 5 cm height).

2.2. Soil Measurements

2.2.1. Soil Gas Exchange, Temperature, and Humidity

CO_2 and H_2O emissions from the soil were measured using the static chamber methodology [23] and a photoacoustic multi-gas analyzer (Photoacoustic Gas Monitor INNOVA 1512, Lumasense—Ballerup, Denmark). The chamber consisted of two parts: an anchor and a lid for the chamber. The anchors were made of PVC cylinders of 20 cm diameter that were inserted between 2 and 4 cm into the soil and left in position for the entire duration of the experiment. The anchor served as a support for the lid of the chamber. The chamber lids were PVC cylinders 20 cm in diameter and 20 cm high. The top of each lid was a PVC stopper that was sealed using silicon glue and covered by a reflective mylar tape to reduce the effect of solar radiation and to avoid temperature increase inside the chamber. On top of the lid, a hole of approximately 1 cm was drilled, and a quick-release coupling was placed as a sampling port.

Since the chambers were covered by reflective mylar tape, the temperature inside them was not higher than the air outside. Thus, the air volume inside the chambers was considered in standard condition (22.4 L at 15 °C and 1 bar).

Measurements (n = 3) were carried out at mid-morning between 9.00 a.m. and 11.00 a.m.—since in this timespan temperatures were close to the average daily temperature [30]—with a random sequence determined by a computer program.

Along with the soil gas exchange measurements, the soil temperature and moisture were recorded (n = 3), point by point. For this purpose, we used the PT100 temperature probe (TR Turoni s.r.l., Forlì, Italy) and the ML3 ThetaProbe Soil Moisture Sensor (Delta-T Devices, Cambridge, UK).

2.2.2. Soil Microbial Respiration and Enzymatic Activities

Soil sampling for the analyses was carried out in July, at approximately 70 cm from the trunk in the southeast direction. Basal respiration was determined on 20 g of fresh soil (at field moisture) placed in a sealed glass jar along with a vial containing 4 mL of 1 M NaOH and incubated for 72 h at 25 °C in the dark. After incubation, 0.75 N $BaCl_2$ and 3 drops of phenolphthalein indicator were added to NaOH, and the mixture was titrated using 0.1 N HCl to quantify the captured CO_2, according to Anderson and Domsch [31].

The activity of soil enzymes linked to the biogeochemical cycles of some major nutrients was determined. For the N cycle we determined urease activity following the protocol proposed by [32]. The ammonium (NH_4^+) produced by urease activity was determined by a colorimetric method with Nessler's reagent, and absorbance was measured at 420 nm using a calibration curve derived from ammonium standards. Protease activity was determined using casein as a substrate [33]. Tyrosine released by protease activity was measured using the Folin–Ciocalteau reagent, with quantification performed by a spectrophotometer (lambda 2, Perkin Elmer, Waltham, MA, USA) at 700 nm. Considering the P cycle, the activities of acid and alkaline phosphomonoesterase were determined according to Tabatabai and Bremner [34]. β-glucosidase activity was measured according to Tabatabai [35], as major soil glycosyl hydrolases. The determinations of acid and alkaline phosphomonoesterase, β-glucosidase, and arylsulfatase activities were quantified based on a p-NP calibration curve at 400 nm.

2.3. Leaf Gas Exchange, Chlorophyll Content, and Fluorescence Measurements

Leaf gas exchange analyses (n = 6; 2 leaves per plant) were conducted, using an infrared gas analyzer (Li-cor 6400 XT; Li-cor, Lincoln, NE, USA), between 11:00 and 13:00 on randomly selected fully expanded leaves on a south-facing branch with a light intensity of 1600 µmol m^{-2} s^{-1}. A constant CO_2 concentration of 400 µmol mol^{-1} inside the leaf chamber was maintained, and the flow rate was set at 500 µmol s^{-1}. Once a steady state was attained, various parameters, including the net CO_2 assimilation rate (P_n), stomatal conductance (g_s), and intercellular CO_2 concentration (C_i), were measured.

The chlorophyll content and fluorescence analyses (n = 18; 6 leaves per plant) were conducted in parallel to gas exchange analyses. The chlorophyll content was measured through the transmittance of red (650 nm) and infrared (940 nm) radiation by using the SPAD 502 Plus (Spectrum Technologies, Aurora, IL, USA). On each leaf, away from the main leaf vein, the Chlorophyll-a fluorescence was measured by a portable fluorimeter (Handy-PEA; Hansatech Instruments, Ltd., King's Lynn, UK). Leaves were dark-adapted with leaf clips (4 mm diameter) for 20 min; then samples were lightened for 1 s with a saturating (up to 3500 µmol photons m^{-2} s^{-1}) red light pulse, and fluorescence emission was recorded for one second. Then, the effects of the treatments were assessed by the maximum quantum yield of photosystem II (PSII) photochemistry (F_v/F_m).

2.4. Dendrometer Measurements

Three trees per treatment were monitored with dendrometers installed halfway up the stem. Automatic point dendrometers were used to measure the stem radius variations [36] by collecting data every 15 min. The dendrometer measured the linear displacement of a sensing rod pressed against the bark (DENDROLOG Rossi Strumenti SRLS—Scandicci, Italy) by recording stem radial variation from 0 to 12 mm with an average sensitivity of 0.3 mm. The stem expansion and contraction transmitted a signal to a transducer (0–10 V; FL SENS 3.3V—Rossi Strumenti SRLS—Scandicci, Italy), and the variable potential was digitized by an analogue-to-digital converter (datalogger, FL SENS—Rossi Strumenti SRLS—Scandicci, Italy) connected to a PC-based data recording system. The maximum daily shrinkage (MDS, mm) in July and August was measured. The MDS corresponded to stem diurnal variation calculated as the difference between the maximum point of shrinkage (the daily decrease in the stem radius defined by the transpiration process) and the onset of this event [37].

2.5. Statistical Analyses

The normality of the data was assessed using the Shapiro–Wilk test, and homoscedasticity was examined using the Bartlett test. All data collected from analyses were subjected to one-way ANOVA, using treatments as the source of variation. All the means were separated by Fisher's least significant difference (LSD) post hoc test ($p < 0.05$). The software used for the statistical analyses was GraphPad (GraphPad, La Jolla, CA, USA).

3. Results

3.1. Soil Gas Exchanges, Temperature, and Humidity

In July, treatments B and CRK showed the highest CO_2 emission values, with mean values of 88.75 kg-C ha^{-1} h^{-1} and 91.02 kg-C ha^{-1} h^{-1}, respectively (Figure 1a). The lowest CO_2 emission was in treatment C, 41.40 kg-C ha^{-1} h^{-1}, which was 53% less than treatment B (Figure 1a). No statistical differences were observed in terms of H_2O emissions in July between treatments (Figure 1b). In August, treatment C showed lower emissions of CO_2 (mean value 29.08 kg-C ha^{-1} h^{-1}) and H_2O (46.7 kg ha^{-1} h^{-1}) from the soil compared with those in treatment B (Figure 1a). No differences in soil temperature were observed in July, while in August, treatment C exhibited the highest temperature value of ~28 °C, marking a 21% increase compared with treatment B (Figure 2a). No significant differences emerged among treatments in terms of soil humidity in both July and August (Figure 2b).

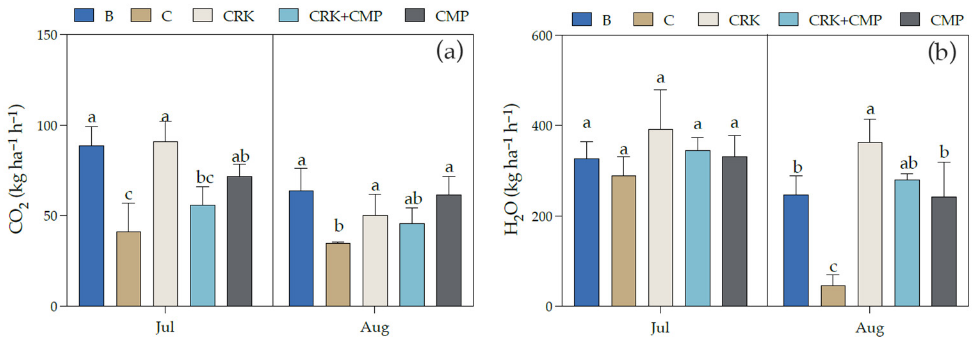

Figure 1. CO_2 (**a**) and H_2O emission fluxes (**b**) in uncompacted (B) and compacted urban soil (C) and compacted urban soil previously amended with cork (CRK), cork + compost (CRK + CMP), and only compost (CMP). Means were subjected to one-way ANOVA with the treatment as the source of variation. Means with different letters are significantly different for $p < 0.05$ after Fisher's least significant difference post hoc test.

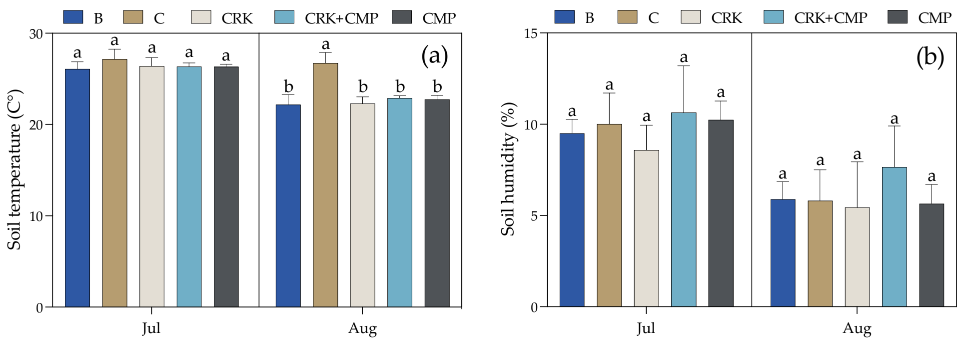

Figure 2. Soil temperature (C°; (**a**)) and soil humidity (%; (**b**)) in uncompacted (B) and compacted urban soil (C) and compacted urban soil previously amended with cork (CRK), cork + compost (CRK + CMP), and only compost (CMP). Means were subjected to one-way ANOVA with the treatment as the source of variation. Means with different letters are significantly different for $p < 0.05$ after Fisher's least significant difference post hoc test.

3.2. Soil Microbial Respiration and Soil Enzymatic Activities

Soil microbial respiration and soil enzymatic activity data are reported in Table 1. Soil microbial respiration was lowest in C (2.44 mg C-CO_2 kg^{-1} soil day^{-1}) and highest in CRK + CMP (6.04 mg C-CO_2 kg^{-1} soil day^{-1}), whereas no differences were observed between the amended soils (CKR, CRK + CMP, and CMP) and B.

Concerning enzymatic activities, no differences between treatments were found for alkaline phosphatase and β-glucosidase. For acid phosphatase, lower values were found in the C and CRK treatments than in B (about −43%). The highest values of arylsulfatase activity were observed in CRK + CMP and the lowest in C and CRK. Regarding urease activity, the C treatment showed the lowest value (−38% compared with the B treatment) and CRK + CMP the highest (+28% compared with the B treatment). Protease activity was lowest in the C and CRK treatments and highest in CRK + CMP but in both cases did not differ significantly from the B treatment.

Table 1. Soil basal respiration and enzymatic activities measured in July in uncompacted (B) and compacted urban soil (C) and compacted urban soil previously amended with cork (CRK), cork + compost (CRK + CMP), and only compost (CMP). Means were subjected to one-way ANOVA with the treatment as the source of variation. Means with different letters are significantly different for $p < 0.05$ after Fisher's least significant difference post hoc test.

	Soil Basal Respiration	Alkaline Phosphatase	Acid Phosphatase	Arylsulfatase	β-Glucosidase	Urease	Protease
	mg C-CO_2 kg^{-1} soil day$-^{1}$	g pNP g^{-1} soil				mg pNP g^{-1} soil	mg N-NH_4^+ g^{-1} soil
B	3.21 ± 0.63 ab	31.41 ± 2.21 a	9.18 ± 2.99 ab	7.05 ± 1.92 ab	14.30 ± 3.90 a	23.66 ± 4.55 b	0.23 ± 0.08 ab
C	2.44 ± 0.70 b	22.74 ± 4.19 a	5.10 ± 0.92 c	5.17 ± 0.66 b	10.29 ± 1.62 a	14.58 ± 0.96 c	0.19 ± 0.05 b
CRK	3.20 ± 2.01 ab	23.19 ± 7.69 a	5.24 ± 1.72 c	4.83 ± 1.37 b	11.65 ± 2.18 a	17.92 ± 4.77 bc	0.19 ± 0.06 b
CRK + CMP	6.04 ± 0.61 a	27.71 ± 4.79 a	11.36 ± 1.25 a	7.74 ± 1.42 a	15.57 ± 2.03 a	34.02 ± 6.93 a	0.29 ± 0.05 a
CMP	5.97 ± 3.40 a	28.40 ± 5.88 a	7.77 ± 1.96 bc	5.21 ± 1.35 ab	13.52 ± 4.03 a	20.82 ± 2.67 bc	0.25 ± 0.01 ab

3.3. Leaf Gas Exchange, Chlorophyll Content, and Fluorescence

In July, there was a distinctive reduction in net CO_2 assimilation, specifically observed in trees of treatment C, accounting for a 24% lower value in comparison with trees in treatment B (Figure 3a). In August, all treatments displayed significantly lower net photosynthesis (P_n) values relative to those recorded in July (Fisher's test, $p < 0.05$). Trees in C exhibited the lowest P_n, while those in CRK were the highest (−30 and +22% for C and CRK trees compared with B trees, respectively; Figure 3a).

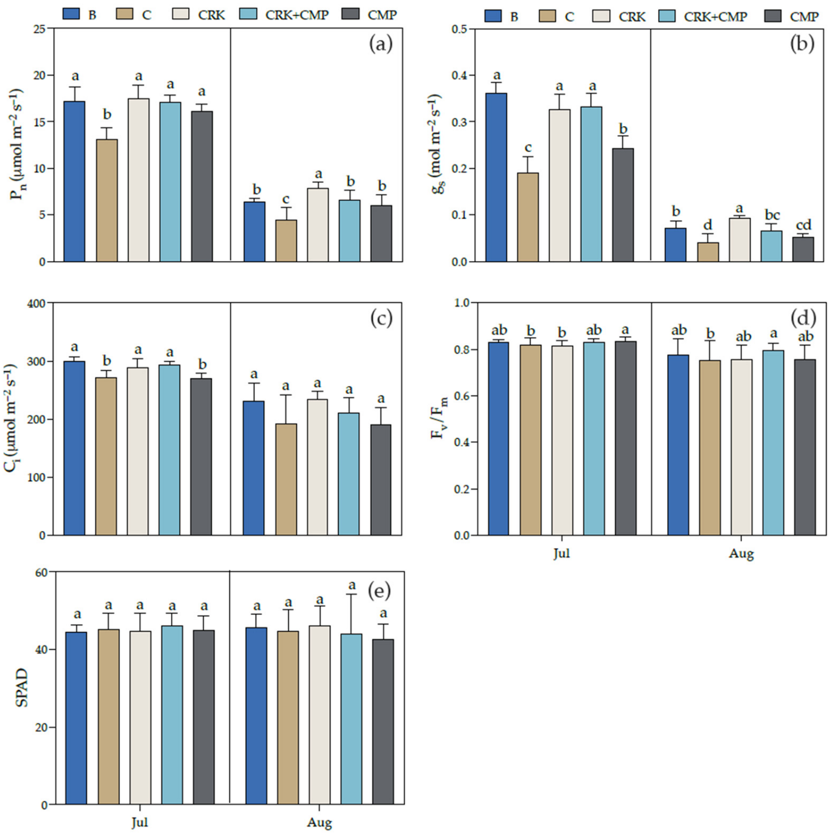

Figure 3. Net photosynthesis (P_n; (**a**)), stomatal conductance (g_s; (**b**)), intercellular CO_2 concentration (C_i; (**c**)), PSII maximum quantum yield (F_v/F_m; (**d**)), and SPAD values (**e**) of *Quercus ilex* trees grown in uncompacted (B) and compacted urban soil (C) and compacted urban soil previously amended with cork (CRK), cork + compost (CRK + CMP), and only compost (CMP). Means were subjected to one-way ANOVA with the treatment as the source of variation. Means with different letters are significantly different for $p < 0.05$ after Fisher's least significant difference post hoc test.

Stomatal conductance in July reached the lowest values in C trees, followed by CMP trees, displaying reductions of 47% and 33%, respectively, compared with B trees (Figure 3b). In August, stomatal conductance (g_s) declined in all treatments compared with the data obtained in July (values compared by Fisher's test, $p < 0.05$; Figure 3b). Again, C trees exhibited the lowest g_s values, whereas CRK displayed the highest (−43 and +28%) for C and CRK trees compared with B trees, respectively (Figure 3b).

In July, intercellular CO_2 concentration decreased only in C and CMP trees (~10%) for both C and CMP trees compared with B trees (Figure 3c). No significant differences were observed for C_i values in August.

Concerning chlorophyll, treatments C and CRK exhibited lower F_v/F_m compared with CMP in July, while in August, treatment C showed lower F_v/F_m values than CRK + CMP (Figure 3d). In both July and August, there was no significant difference in chlorophyll content as expressed by SPAD values across the five treatments (Figure 3e).

3.4. Dendrometer Data

MDS showed the highest values in the control (B) trees in July and August, whereas lower values were in CRK in July and in the control and CRK + CMP in August in comparison with the other treatments (Figure 4). In July, no differences in MDS were found between the control, CRK + CMP, and CMP and in August between the control and CRK + CMP and between the control, CRK, and CMP (Figure 4).

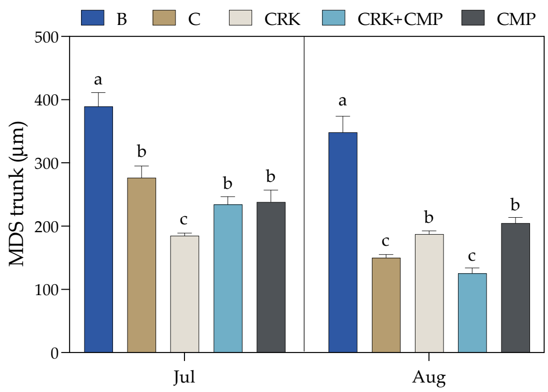

Figure 4. Maximum daily shrinkage (MDS, µm) of *Quercus ilex* trees grown in untreated (B) and compacted urban soil (C) and compacted urban soil previously amended with cork (CRK), cork + compost (CRK + CMP), and only compost (CMP) in July and August. Means were subjected to one-way ANOVA with the treatment as source of variation. Means with different letters are significantly different for $p < 0.05$ after Fisher's least significant difference post hoc test.

4. Discussion

As urbanization intensifies, the need for sustainable soil management becomes increasingly critical, particularly in mitigating the adverse effects of soil compaction on urban green spaces. Soil compaction, exacerbated by urban activities such as pedestrian and vehicular traffic, severely limits the ability of soils to support plant growth by reducing porosity and impairing water and gas exchanges [38–40]. In this respect, the addition of organic material can enhance soil functionality [41], as also demonstrated by our results of soil microbial respiration and enzyme activities. In particular, there was lower soil microbial activity in compacted unamended soil (C) than in compacted soil amended with compost and cork (CRK + CMP), confirming the detrimental effect of soil compaction on SOM mineralization due to adverse conditions for soil microbial community activity [42,43]. Indeed, compaction affects the supply of water, air, and nutrient content in soil, compromising soil microbial activity and organic matter decomposition [40]. In contrast, we observed that the amendment with both compost and cork (CRK + CMP) enhanced soil properties such as available P and SOM content (Table S1) and, consequently, the activity of microbial communities. The higher value of acid phosphomonosterase activity in CRK + CMP compared with all other treatments can be related to the increase in the available P (Table S1), indicating that the amendment with compost and the potential increase in the porosity induced by cork application stimulated microbial community activity [44]. Moreover, the higher enzymes activities of protease and urease, which were crucial for C and N biogeochemical cycles, in CRK + CMP soil compared with C soil, confirmed that a higher SOM content enhanced soil functionality, as found by Siczek and Fraç [44]. The higher arylsulfatase activity in soil amended with both cork and compost compared with compacted and unamended soil (C) indicated an improvement in soil health as this enzyme was particularly sensitive to soil conditions [45,46].

The application of only cork (CRK) did not stimulate microbial activity or improve soil properties, as indicated by similar soil enzymatic activities and available P content compared with the unamended and compacted soil (C). This result was most probably due to the cork's resistance to degradation [47], which can have negative implications on nutrient availability (e.g., phosphorus and sulfur) [48,49]. Conversely, our study suggested that the combination of cork and compost (CRK + CMP treatment) was effective in mitigating the negative effects of soil compaction from trampling on the soil microbial community. Indeed, this treatment promoted a strong enzymatic response compared with the C treatment and the control (B), particularly in terms of urease activity. Cork is actually a porous material that provides an ideal environment for microbial community development [50]. On the other hand, the propensity of compost to degrade quickly could offset the challenges associated with cork degradation, providing more efficient support to the microbial community.

Compaction can influence soil temperature and moisture regimes, in particular the rates of soil warming and cooling [5,51]. In fact, in treatment C, there was a substantial decrease in water vapor (H_2O) exchange with the atmosphere compared with treatment B. This could explain why the compacted soil without amendments (C) showed higher temperatures in August compared with the other treatments. It is reasonable to assume that the limited movement of air and water in soil of treatment C reduced the soil capacity to dissipate heat and temperature compared with the other treatments. Moreover, the soil gas exchange analyses conducted in the field highlighted a strong compaction-induced reduction in total CO_2 emission from soil in the C treatment in both months, as well as H_2O emissions in August, compared with B. Such a reduction in soil CO_2 emission could be also due to reduced root functionality as plant roots contributed more than 40% to the total soil respiration [52,53]. Indeed, the worse condition of compacted soils could depress plant growth, negatively affecting plant physiological responses [38,54].

Photosynthesis, a crucial process for plant growth and CO_2 sequestration, is highly dependent on the availability of water and nutrients, which may be compromised in compacted soils [14,55]. Compared with non-compacted conditions (B), restrictions of net photosynthetic rates, mainly due to stomatal limitations, were only observed in treatment C. In compacted soils, plants may limit stomatal opening and its duration [55]. Indeed, the observed reduction in terms of g_s, especially in treatment C, might be attributed to the limitation of both water and nutrient absorption [38]. In a recent meta-analysis study, Mariotti et al. [14] observed that water availability is a primary cause of the decrease in plant photosynthetic rate in compacted soils. This may be due to the limiting effects of soil compaction on root growth and hydraulic conductivity [56,57]. However, despite these limitations, no significant alteration in the maximum efficiency of PSII was observed, suggesting no significant impacts on the photosynthetic efficiency. This was further supported by the unchanged leaf chlorophyll contents (i.e., no significant changes in SPAD values) among treatments, indicating that these parameters may not have been sensitive indicators of stress under the specific conditions of this experiment.

Overall, our results indicated that the soil amendment with cork and compost and their combination mitigated some of the negative effects of compaction on plant physiological performances in both July and August. In particular, among treatments, CRK (cork alone) showed the best physiological responses under soil compaction conditions in August (i.e., the highest P_n and g_s values). Cork porous structure likely improved soil aeration, which was critical for root respiration, thereby supporting better physiological performance of plants. Compared with compost alone (CMP), the combination of cork and compost (CRK + CMP) provided a better improvement (i.e., no differences in g_s values were observed in August compared with B treatment), suggesting that such mixed amendments might be more effective in mitigating the adverse effects of soil compaction than using compost alone. Actually, previous research emphasizes the importance of soil aeration in maintaining healthy root systems under compacted conditions [10,58].

Interestingly, when considering the maximum daily shrinkage (MDS), there were notable reductions in all compaction treatments compared with B in both months. MDS values were lower in CRK in July but remained constant in August, while values observed in all the other treatments dropped, possibly due to reduced soil humidity (Figures S1 and S2). The lower MDS values in treatment CRK during both July and August may suggest a reduced water demand. This observation aligned with the hypothesis that cork may have mitigated some of the adverse effects of compaction on water availability, even though physiological traits did not show significant alterations. The lack of information from previous studies about the complex interaction between soil compaction and trunk maximum daily shrinkage indicator makes future research on the topic necessary.

5. Conclusions

Our study underscores the need for sustainable soil management practices in urban environments, particularly in mitigating the adverse effects of soil compaction in urban green spaces. The compacted soil without amendments exhibited reduced enzymatic activity, diminished gas exchanges, higher soil temperatures, and impaired plant physiological performances. On the contrary, cork and compost as amendments have emerged as effective tools for mitigating the adverse effects of soil compaction. They improved soil enzymatic activity when mixed, as well as supporting better plant performances than in non-amended compacted soil during the summer period. Hence, using as amendment a combination of cork and municipal waste compost appears to be a viable approach for maintaining or improving soil biochemical properties and supporting plant physiological performances under soil compaction conditions.

The results obtained in this research should benefit a wide range of stakeholders, including municipal authorities, urban planners, landscape architects, and professionals in urban arboriculture. By providing insights into effective soil management strategies to mitigate compaction, such findings can guide the development of more sustainable urban green spaces and improve soil and vegetation health in existing ones. Future research should further explore the complex interactions between soil compaction and plant–soil–water dynamics to refine and optimize soil management practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/urbansci9010005/s1: Table S1: Basic characterization of the soil in the various treatments. The pH was measured in a 1:2.5 soil:deionised water suspension (ISO 10390:2021) using a XS pH-meter model PC8. Available phosphorus by the Olsen method (ISO 11263:1994). Organic carbon was extrapolated from the loss-on-ignition determined according to

Nelson and Sommers (Soil Organic Matter–SOM) and multiplied by the Van Bemmelen factor, i.e., 0.58. Total nitrogen was determined by an elemental analyser (Model Leco CN828 Carbon Nitrogen Determinator, St. Joseph, MO, USA) after pulverizing the sample. Particle-size analysis was carried out using the methodology proposed by Pansu and Gautheyrou; Table S2: Characterisation of the compost used in the study, as provided by the composting company. Heavy metals were determined after concentrated hydrochloric acid attack, so they can be assumed as total concentrations; Figure S1: Maximum daily shrinkage (MDS, µm) of *Quercus ilex* trees growing in uncompacted (B) and compacted urban soil (C), and compacted urban soil previously amended with cork (CRK), cork + compost (CRK+CMP) and only compost (CMP) in July and August. Means were subjected to two-way ANOVA with the treatment and time as source of variation. Means with different letters are significantly different after for $p < 0.05$ after Fisher's least significant difference post-hoc test; Figure S2: Soil humidity (%) in uncompacted (B) and compacted urban soil (C), and compacted urban soil previously amended with cork (CRK), cork + compost (CRK+CMP) and only compost (CMP). Means $\pm$ SD of July *vs* August values were compared by Student's *t*-test, **: $p < 0.01$. References [59–61] are cited in the supplementary materials

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