



Use of compost to improve Technosol properties and spontaneous plant-soil relationships of Mediterranean species potentially suitable for urban greening

Ermenegilda Vitale¹ · Pasquale Napoletano² · Claudio Colombo² · Carmen Arena^{1,3,4} · Anna De Marco^{4,5}

Accepted: 24 April 2024 / Published online: 21 May 2024
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Abstract

Organic-based amendments are promising, eco-friendly solutions among soil requalification strategies. In this context, the current study explored the application of compost to Technosols (2 kg m⁻²) to improve soil quality, making the substrate suitable for plant growth. Changes in soil quality have been assessed before compost addition (time zero, T0) and plant transplanting and at 2, 4 and 11 months (T2, T4, and T11) after plant establishment. To test the soil suitability for plant growth, we monitored (at T2, T4, and T11) structural and functional ecological traits in the herbaceous spontaneous species *Malva sylvestris* L. and in transplanted Mediterranean sclerophyllous *Phillyrea angustifolia* L., and *Quercus ilex* L., often used in the urban greening, also considering plant and soil relationships. Our study demonstrated that compost increased soil nutrients availability over time, favoring *M. sylvestris* physiological performance in long-lasting, compared to sclerophyllous, since the beginning of the application. *M. sylvestris* exhibited high photosynthetic efficiency and carbon investment in photosynthetic tissues (higher leaf area and lower leaf mass per area) on compost-enriched soil. On the other hand, *P. angustifolia* and *Q. ilex*, even if they did not benefit from compost addition for photosynthetic efficiency, after 11 months, maintained higher leaf water content despite limited soil water availability. These results encourage the use of compost in ameliorating the quality of Technosols for urban greening, also evidencing that the species' choice is pivotal in obtaining benefits from plants and a period longer than one year is needed for sclerophyllous to see beneficial effects.

Keywords Compost · Plant functional traits · Soil quality · Soil restoration · Technosols · Urban ecology

Introduction

The increasing pollution in the most populated cities, together with the disappearance of green spaces and the benefits for citizens deriving from urban greening, has enhanced the attention on the need to improve the deterioration of soils of urban areas for the restoration of the public green aimed to population well-being by providing space for rest, relaxation and exercise.

The restoration policies include the requalification of abandoned lands or planning new green areas supplying cities and society with important ecosystem services such as recreational and aesthetic benefits, pollutant and dust removal, balancing of atmospheric carbon emissions, urban microclimate regulation and preservation of plant biodiversity (Deeb et al. 2020; O'Riordan et al. 2021). The sustainable use of soil represents a key action of a correct restoration policy. The improvement of the soil quality may be obtained with the addition of biomasses of organic origin.

Ermenegilda Vitale and Pasquale Napoletano contributed equally to this work.

✉ Carmen Arena
carena@unina.it

- ¹ Department of Biology, University of Naples Federico II, Naples 80126, Italy
- ² Department of Agricultural, Environmental and Food Sciences, University of Molise, Campobasso 86100, Italy
- ³ NBFC-National Biodiversity Future Center, Palermo 90133, Italy
- ⁴ BAT Center—Interuniversity Center for Studies on Bioinspired Agro-Environmental Technology, University of Naples Federico II, Portici 80055, Italy
- ⁵ Department of Pharmacy, University of Naples Federico II, Naples 80131, Italy

Among them, compost may represent an eco-friendly valid tool to improve soil nutrients and physical characteristics, acting as fertilizer and amendment at the same time (Wang et al. 2022). The over-exploited urban soils such as Technosols, characterized by the $\geq 20\%$ quantity of human artefacts in the upper 100 cm (Schad 2018), poor structure, extreme pH values, low organic matter, nutrients, and biological activity enhanced using compost (Napoletano et al. 2021; Rodríguez-Espinosa et al. 2021; Di Iorio et al. 2022). Recovering degraded Technosols through the use of organic fertilizers would guarantee plant growth in the urban environment over time, exerting positive effects on primary production. However, it may be considered that the success of the urban greening practice depends on the relationships between soil quality and properly selected plants. Generally, the use of autochthonous plants, such as species of the Mediterranean maquis, according to their specific adaptation capability and local biodiversity preservation, is a common practice in the restoration plans of the Mediterranean area (Pavao-Zuckerman 2008; Sullivan et al. 2009).

Increasing soil quality following compost addition may induce the increase of soil organic compounds, essential nutrients, water holding capacity and favourable conditions for the edaphic community (Termorshuizen et al. 2004; Memoli et al. 2017). These soil properties significantly affect plant physiological performance increasing primary production (Da Matta et al. 2002). More specifically, higher nutrient availability and water holding capacity of soil following the compost addition may improve gas exchanges and biomass accumulation in many species (Maisto et al. 2010). The leaf functional traits are considered good predictors of plant response to soil quality over time, as they may change according to the soil nutrient status (Wright et al. 2005).

In particular, leaf traits such as specific leaf area (SLA) and leaf dry matter content (LDMC), indicator of tissue density, are related to the plant's ability to utilize nutrients (Reich et al. 1997) and thus are good proxies of plant nutritional status, being involved in the trade-off between the quick production of biomass and the efficient conservation of nutrients (Poorter and Garnier 2007).

The main goal of this research was to establish suitable edaphic conditions for greening degraded lands or overexploited Technosols by adding green compost. We assumed that changes in the soil quality of selected Technosols, following the compost addition during one year, may promote plants' growth and healthy status, contributing, in turn, to enriching the soil of nutrients.

To assess the impact of compost on Technosols, we analyzed over time the soil quality by means of pH, soil water content, total and soluble carbon, and nitrogen, and the functional attributes of different plant species: the herbaceous *Malva sylvestris* L., able to rapid soil colonization and Mediterranean sclerophyllous *Phillyrea angustifolia* L.

and *Quercus ilex* L., often utilized for urban greening. In our study, experimental mesocosms were set up in which *M. sylvestris* was left to grow spontaneously while sclerophyllous species were transplanted. Our open questions were:

1. How may compost addition improve Technosols properties linked explicitly to plant growth?
2. How do different species respond to compost addition regarding functional and structural attributes?
3. How may the relationships between plant-soil be affected by both compost and plant species?

Methods

Experimental design and mesocosm set-up

In order to evaluate the effect of compost addition on Technosol properties and highlight the responses of different species commonly present in the Mediterranean area, we conceived a mesocosm experiment. The experimental site is located in Naples (Campania region, Southern Italy) at the Campus of Monte Sant'Angelo, University of Naples Federico II (40° 50' 12.63" N, 14° 10' 58.03" E, 122 a.s.l.) and included an area which comprises eight mesocosms (Fig. 1a–b). In detail, the studied mesocosms were constructed in concrete with rectangular shape (area: 16 m², depth: 2 m each) filled with mixed natural and antropogenic materials and classified as Isolatic Ekranic Technosols (IUSS Working Group WRB 2015; Napoletano et al. 2021). In particular the Technosols were characterized by more than 20% of artefacts deriving from cracked building rubble mixed with autoctonus pyroclastic substrate dating back to construction of the Campus in 2006 (Fig. 1b). From 2006 to 2010, the mesocosms were colonized by spontaneous vegetation, mainly represented by *Gramineae*, *Leguminosae* and *Malvaceae* families (Fig. 1c) (Di Iorio et al. 2022). In December 2010, the spontaneous vegetation was manually removed and the soil substrate was uniformly mixed with a compost quantity of 2 kg m⁻² (the minimum amount used by farmers for agriculture purposes) (Ventorino et al. 2012). The spreading of compost was performed with a shovel, taking care not to exceed the depth of 30 cm, and then the soil surface was levelled again. The compost was produced and provided by Gesenu S.p.A. (Perugia, Italy) and consisted of green refuse resulting from tree pruning, grass cuttings, and vegetable wastes derived from the processing of agricultural products. The compost had the following characteristics: salinity = 53.2 meq 100 g⁻¹ d.w.; pH = 7.9; water content = 35.0% d.w.; organic carbon = 28.0% d.w.; N = 2.1% d.w.; C/N = 13.3; P = 0.8% P₂O₅ d.w.; K = 1.8% K₂O d.w.; total Cu = 67.2 mg kg⁻¹ d.w.; total Zn = 146 mg kg⁻¹ d.w. (Panico et al. 2019).

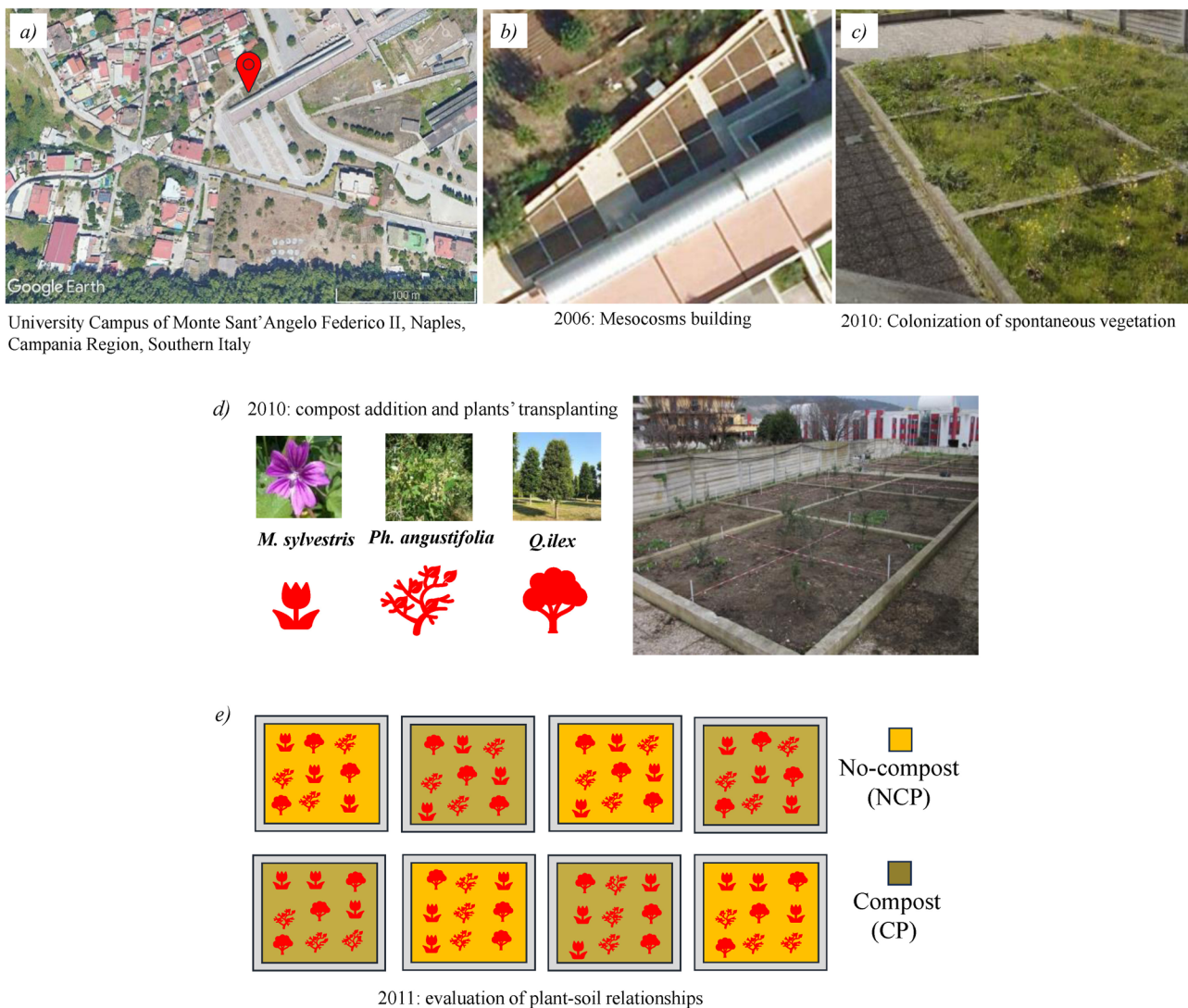


Fig. 1 **a** The experimental site in Naples (Campania region, Southern Italy), at the Campus of Monte Sant'Angelo University of Naples Federico II; **b** mesocosms filled with Technosol in 2006 ("Map data ©2006 Google"); **c** mesocosms with spontaneous vegetation in 2010; **d-e** four NCP mesocosms without compost served as control, four CP

mesocosms were enriched with compost quantity 2 kg m^{-2} (CP). In each mesocosm, three individuals of *Quercus ilex* L. and *Phyllirea angustifolia* L. were transplanted while *Malva sylvestris* L. was spontaneously present (2010). Plant-soil relationships were evaluated at 2, 4 and 11 months from compost addition (T2, T4, T11), in 2011

Compost was added randomly to four mesocosms (CP), while the remaining four were not treated (NCP). To simulate a possible greening intervention in the Mediterranean region, after seven days from compost addition, specimens of *Quercus ilex* L. (Qi) and *Phillyrea angustifolia* L. (Pa), often naturally in association in the Mediterranean maquis (Vitale et al. 2007), were transplanted. We randomly planted six plants in each mesocosm: three individuals representative of each sclerophyll, twelve individuals per Qi, and twelve per Pa per experimental condition (NCP and CP). Conversely, the herbaceous *Malva sylvestris* L. (Ms) grew spontaneously in each mesocosm (Fig. 1f).

It must be considered that herbaceous *M. sylvestris* is a fast-growing species compared to sclerophyllous *Ph. angustifolia* and *Q. ilex*; thus, the timing of observation of 2, 4, and 11 months (T2, T4, and T11) from plant establishment (T0) takes into account the different growth rates of plant species and the evaluation of both short- and long-term responses of the different plants and Technosol to compost addition.

We assumed that the amount of compost (2 kg m^{-2}) provided through a single application was sufficient to affect Technosol properties and plant growth positively. In our experiment, we used the observations made at 2 and 4 months after compost addition to assess short-term effects

and those after 11 months to evaluate long-term effects on plants, especially sclerophyllous species, and Technosol physical and chemical characteristics.

Our experiment was concluded one year after adding compost (from December 2010 to December 2011), which is a sufficient time to understand if a single application of amendment (2 kg m^{-2}) may be enough or should be followed by consecutive annual applications.

During the experimental period, the mesocosms were irrigated twice a week over two months, with an average amount of water of approximately 17 L m^{-2} per mesocosm, and then left undisturbed and subjected to the natural conditions typical of the Mediterranean area. Specifically, the climate was warm temperate, characterized by annual rainfall of 929 mm and mean monthly temperatures ranging from 11°C in January to 26°C in August (Napoletano et al. 2021).

Soil analyses were carried out before compost addition and plant establishment (time zero, T0) and after 2, 4 and 11 months (T2, T4 and T11) from compost addition and plant transplant. From each mesocosm, composite samples (five sub-samples) were collected at the depths of 0–10 and 10–20 cm. The soil samples were passed through a 2-mm stainless steel sieve (No. 10, USDA standard sieve) and subjected to physical and chemical analysis according to the Italian Official Methods of Soil Chemical Analysis (Colombo and Miano 2015).

As a proxy of plant health status and growth, plants of three species grown on NCP and CP substrates were analyzed for photochemical activity and functional leaf characteristics at T2, T4 and T11. Measurements were carried out on twelve individuals per treatment, considering two leaves per plant.

Furthermore, to assess the effects of compost on plant growth, the sclerophyllous species were compared for stem diameter, plant height and leaf length at the end of observation period (T11). Growth measurements were conducted on five individuals per treatment, considering one leaf per plant.

Soil analyses

The following soil parameters were evaluated: pH, soil water content (SWC), total carbon (Cs), nitrogen (Ns) and their ratio (C/Ns), soluble carbon (Sol Cs), nitrogen (Sol Ns) and their ratio (Sol C/Ns). Briefly, pH was evaluated in soil:distilled water (1:2.5 = w:v) suspension by potentiometric method; SWC was determined after drying at 105°C in a ventilated oven until constant weight; C and N were evaluated in oven-dried (105°C) and grounded samples by CNS analyser (Thermo Finnigan, EA 112 series). Soluble C and N were determined on oven-dried (105°C) samples soaked in 200 mL of distilled water, stirred for 24 h (Universal Table-Shaker 709, 130 rpm) with two sonications, lyophilized and measured by gas-chromatography (De Marco et al. 2013). From total Cs and Ns, and Sol Cs and Sol Ns, their respective ratios (C/Ns, Sol C/Ns) were calculated.

All the soil parameters were measured in triplicate.

Plant photochemical activity and functional leaf characteristics

Chlorophyll *a* fluorescence measurements

Fluorescence measurements were performed in vivo on fully expanded leaves developed after the compost addition and the transplanting, using the pulse amplitude modulated fluorometer (MiniPAM, Walz) equipped with a leaf-clip holder (Leaf Clip Holder 2030-B, Walz), under natural conditions of temperature. The background fluorescence signal (F_0) was induced by a weak measuring light of $0.5 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ at 0.6 kHz frequency, on 30 min dark-adapted leaves, following the procedure reported by Vitale et al. (2012). The maximal fluorescence in the dark-adapted state (F_m) was obtained by applying a 1 s saturating light pulse ($10,000 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$) at 20 kHz frequency. F_0 and F_m values were used to calculate the maximal PSII photochemical efficiency (F_v/F_m) as: $(F_m - F_0)/F_m$.

Carbon and nitrogen leaf content and functional leaf traits

Carbon (C), nitrogen (N) and (C/N) ratio in leaves were estimated on oven-dried (75°C) and grounded samples by CNS analyser.

The leaf functional traits, namely leaf area (LA), specific leaf area (SLA), leaf mass per area (LMA), leaf dry matter content (LDMC), leaf water content (LWC) and relative water content (RWC), were estimated according to Cornelissen et al. (2003). LA (cm^2) was calculated using the Image J software (National Institute of Health, MD, USA). SLA ($\text{cm}^2 \text{ g}^{-1}$) was obtained as the ratio between leaf area and leaf dry mass, while LMA (g cm^{-2}) corresponded to the ratio between leaf dry mass and leaf area. LDMC (g g^{-1}) was determined as leaf dry mass to saturated fresh mass. LWC (%) was calculated as (leaf fresh mass – leaf dry mass)/(leaf fresh mass) while RWC (%) was obtained as (leaf fresh mass – leaf dry mass)/(leaf saturated fresh mass – leaf dry mass). The saturated fresh mass was obtained by submerging the leaf petiole in distilled water for 48 h in the dark at 4°C , whereas the dry mass was achieved after oven-drying leaves at 75°C for 48 h.

Plant growth measurements

Plant growth measurements were acquired determining stem diameter, plant height and leaf length. The stem diameter is one of the most common measurements performed to assess the growth of woody vegetation (Paul et al. 2017). Stem diameter measurements in *Q. ilex* and *P. angustifolia* were carried out with a digital Vernier caliper (Caliper digital 1000 mm,

Limit, Sandbergsvägen, Sweden). Considering that our plants were young trees, we cannot take measurements at breast height, as is usually for a trunk, but at 15 cm above the soil. The diameter was measured at plant's transplanting and the end of the experimental period. The plant height was evaluated considering the elongation of the main stem, whereas the leaf length was assessed through the leaf lamina elongation. All growth parameters were expressed in cm.

Statistical analysis

The statistical analysis and graphs were performed by Sigma-Plot_12.2 software (Systat Software Inc., San Francisco, CA, USA) for the investigated Technosols and plants. The normality of the data distribution was assessed by the Shapiro–Wilk test. Comparisons among T0, NCP and CP treatments (at T2, T4 and T11) for soil and plant parameters were tested by One-Way ANOVA in each treatment. The effect of the compost addition was evaluated within each species by applying the *t*-test between plants grown on NCP and CP substrate.

To assess the effect of soil quality without or after compost addition on plants (Ms, Pa and Qi), multiple linear regressions (MLRs) were computed. The plant characteristics (C, N, C/N, LA, SLA, LDMC, LMA, LWC, RWC, F_v/F_m) were established as dependent variables, whereas soil characteristics at the depths of 0–10 and 10–20 cm (pH, SWC, Cs, Ns, Sol Cs and Sol Ns) were established as independent variables. Differences and regressions were considered statistically significant for at least $p \leq 0.05$.

Table 1 Physical and chemical soil characteristics for T0 (before compost), with (CP) and without the compost addition (NCP) at two, four and eleven months (T2, T4 and T11), at different depths (0–10 and 10–20 cm): pH, SWC (Soil water content), Cs (Carbon), Ns (Nitrogen), C/Ns, Sol Cs (Soluble C), Sol Ns (Soluble N), Sol C/Ns.

	Depth (cm)	T0	T2		T4		T11	
			CP	NCP	CP	NCP	CP	NCP
pH	0–10	7.96 ± 0.05 ^a	7.68 ± 0.05 ^b	7.70 ± 0.08 ^{ab}	8.06 ± 0.10 ^a	7.97 ± 0.05 ^{ab}	7.67 ± 0.06 ^b	7.81 ± 0.07 ^{ab}
	10–20	8.30 ± 0.05	7.91 ± 0.07	7.95 ± 0.08	8.19 ± 0.05	8.18 ± 0.03	8.05 ± 0.12	8.00 ± 0.09
SWC (% d.w.)	0–10	27.7 ± 0.98 ^a	30.8 ± 1.29 ^a	29.7 ± 0.80 ^a	18.3 ± 0.90 ^b	16.41 ± 1.09 ^b	19.7 ± 0.13 ^b	18.2 ± 0.12 ^b
	10–20	21.9 ± 0.17 ^b	24.7 ± 0.54 ^a	24.7 ± 0.48 ^a	18.2 ± 0.37 ^d	18.01 ± 0.94 ^d	21.4 ± 0.21 ^b	20.3 ± 0.16 ^c
Cs (% d.w.)	0–10	1.57 ± 0.11 ^b	2.14 ± 0.33 ^{ab}	1.97 ± 0.18 ^{ab}	2.26 ± 0.11 ^a	1.76 ± 0.07 ^{ab}	2.22 ± 0.06 ^a	1.94 ± 0.09 ^{ab}
	10–20	1.16 ± 0.06	1.45 ± 0.23	1.31 ± 0.05	1.54 ± 0.10	1.41 ± 0.04	1.35 ± 0.03	1.20 ± 0.04
Ns (% d.w.)	0–10	0.18 ± 0.03	0.11 ± 0.01	0.10 ± 0.01	0.14 ± 0.01	0.13 ± 0.01	0.14 ± 0.001	0.13 ± 0.002
	10–20	0.13 ± 0.02 ^a	0.07 ± 0.01 ^{ab}	0.05 ± 0.01 ^b	0.10 ± 0.002 ^{ab}	0.08 ± 0.002 ^{ab}	0.12 ± 0.002 ^a	0.09 ± 0.001 ^{ab}
C/Ns	0–10	10.2 ± 0.58 ^b	19.8 ± 1.30 ^a	19.2 ± 1.24 ^a	16.3 ± 2.50 ^a	12.9 ± 0.84 ^{ab}	15.9 ± 0.30 ^a	14.7 ± 0.81 ^{ab}
	10–20	11.07 ± 0.72 ^d	22.14 ± 2.51 ^a	25.61 ± 2.73 ^a	17.66 ± 0.34 ^b	16.99 ± 0.58 ^b	11.37 ± 0.35 ^d	12.75 ± 0.27 ^c
Sol Cs (% d.w.)	0–10	0.13 ± 0.01 ^b	0.21 ± 0.01 ^{ab}	0.21 ± 0.01 ^{ab}	0.22 ± 0.004 ^{ab}	0.20 ± 0.01 ^{ab}	0.30 ± 0.004 ^a	0.21 ± 0.01 ^{ab}
	10–20	0.15 ± 0.01 ^d	0.35 ± 0.01 ^b	0.38 ± 0.01 ^a	0.38 ± 0.01 ^a	0.21 ± 0.01 ^c	0.14 ± 0.01 ^d	0.14 ± 0.002 ^d
Sol Ns (% d.w.)	0–10	0.02 ± 0.001 ^b	0.07 ± 0.002 ^a	0.06 ± 0.001 ^a	0.06 ± 0.001 ^a	0.01 ± 0.001 ^b	0.02 ± 0.001 ^b	0.02 ± 0.001 ^b
	10–20	0.03 ± 0.001 ^a	0.02 ± 0.002 ^b	0.02 ± 0.002 ^b	0.04 ± 0.002 ^a	0.03 ± 0.002 ^a	0.01 ± 0.001 ^a	0.02 ± 0.001 ^b
Sol C/Ns	0–10	6.86 ± 0.38 ^d	3.16 ± 0.14 ^f	3.50 ± 0.17 ^e	3.74 ± 0.14 ^c	19.1 ± 1.24 ^a	12.8 ± 0.64 ^b	10.0 ± 0.18 ^c
	10–20	5.01 ± 0.24 ^b	14.4 ± 0.60 ^a	14.5 ± 2.28 ^a	10.6 ± 0.58 ^{ab}	7.74 ± 0.64 ^{ab}	14.9 ± 1.56 ^a	7.41 ± 0.39 ^{ab}

In addition, the relationships among plant species subjected to NCP and CP treatments at T2, T4 and T11 were obtained through cluster analyses using linkage between groups and Euclidean distance as similarity measure and synthesized in dendrograms. The matrix used for cluster analysis included functional leaf traits, photochemical characteristics and soil characteristics. This analysis was graphed through a hierarchical clustering and performed by Syn-tax 2000 (Podani 1993).

Results

Technosols characteristics at different depths

The studied 8 mesocosms responded differently to compost and plant addition at 0–10 and 10–20 cm depths. In Table 1, physical and chemical soil characteristics before compost (T0) and at two, four and eleven months (T2, T4 and T11) after plant and compost addition were reported. Soil pH at 0–10 cm decreased in CP treatment at T2 and T11 compared to soil before compost addition. In the upper layer, SWC showed lower values at T4 regardless of the treatments, while it was more variable in the deeper layer (Table 1).

The content of Cs was usually higher in CP and NCP soils compared to T0, with the highest values at T4 in CP soils ($2.26 \pm 0.11\%$ d.w. at 0–10 cm depth and $1.54 \pm 0.10\%$ d.w. at 10–20 cm depth) (Table 1). After plant establishment and

The data represented the mean ± standard error ($n = 24$ per depth, T0; $n = 12$ per depth, all the other treatments). Different letters showed statistically significant differences among treatments and times, within each depth range, for at least $p \leq 0.05$ (One-Way ANOVA)

compost addition, soil Ns content decreased at both depths, mainly in NCP soils and at T2. In contrast, compared to T0, C/Ns showed higher values throughout the year regardless of the compost addition and depth.

On the other hand, soluble Cs was higher in NCP and CP soils than the initial values at 0–10 cm depth, while evident fluctuations were detected at 10–20 cm. Compared to T0, soluble Ns increased at T2 and T4 in the superficial layer, whereas it decreased at T2 in 10–20 cm depth. The complexity of soluble compounds affected C/Ns ratio, which showed different trends in soils at both depths. In the superficial layer, Sol C/Ns had the lowest values at T2; in deeper soil, Sol C/Ns had the lowest values at T0 (Table 1).

Effect of compost enrichment on plants

Leaf nutrients and functional traits

As shown for soils, plants grown in the 8 mesocosm responded differently to the compost addition over time.

Among species, *M. sylvestris* (Ms) showed higher values of leaf N than *P. angustifolia* (Pa) and *Q. ilex* (Qi), regardless of the compost addition, while the lowest values were found in Qi leaves (Fig. 2a). Nitrogen was higher in Ms plants grown on CP substrate than NCP (25, 26 and 20% at T2, T4 and T11, respectively) throughout the experiment. Conversely, the leaf N content in Pa and Qi plants on CP soil increased only at T2 (3 and 5.3%, respectively)(Fig. 2a).

Compost determined a significant increase in leaf C content in Compost-Ms plants compared to NCP (7, 10 and 5% at T2, T4 and T11, respectively). Conversely, no difference was found in Pa and Qi plants. The highest C content was measured in Pa leaves on both No-Compost and Compost soils, regardless of the time (Fig. 2b).

At T2, C/N ratio of Pa plants increased on Compost-soil, while it reduced in Ms plants at T2 and in the successive months (T4 and T11) compared to No-Compost soil. Qi plants showed higher C/N ratio than Pa at T2, while no difference was evidenced at T4 and T11. Conversely, Ms plants maintained lower C/N ratios than Qi and Pa plants, irrespective of compost addition and time (Fig. 2c).

The growth on different substrates did not affect LA in Pa plants. In Qi plants, LA was lower on Compost substrate at T2 but higher at T11 compared to No-Compost. On the other hand, Compost-Ms plants exhibited a significant increase in LA at T2 and T4 (23 and 44%, respectively) compared to those on No-Compost treatment. Among species, M plants showed the highest LA values on both substrates (Fig. 3a).

On CP substrate, SLA of Ms decreased at T2, while it increased at T11 in Ph (90%) and Q plants (23%). At T2 and T4, LMA was lower in Compost-Ms than in No-Compost plants. Ms showed the highest SLA and lowest LMA values

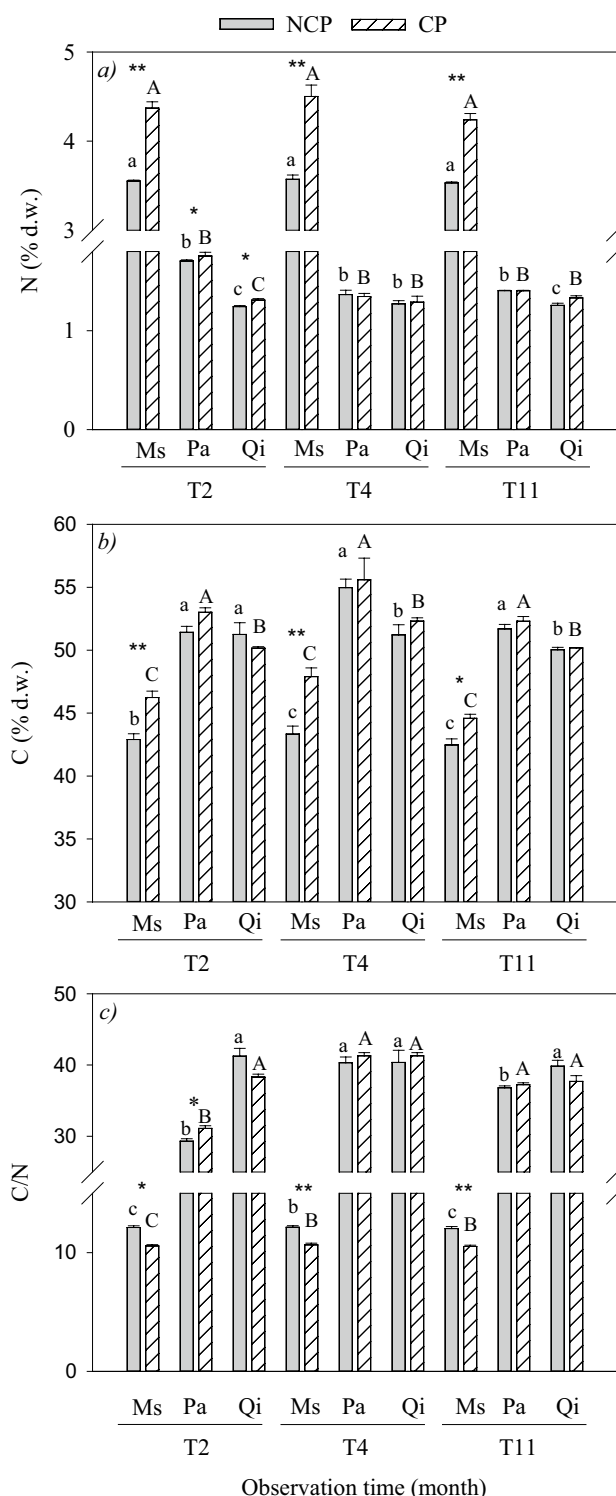


Fig. 2 Leaf contents of **a** N (% d.w.), **b** C (% d.w.) and **c** C/N ratio in *Malva sylvestris* L. (Ms), *Phillyrea angustifolia* L. (Pa) and *Quercus ilex* L. (Qi) grown on Technosols with (CP) and without compost (NCP) at two, four and eleven months from treatment and plant establishment (T2, T4 and T11). Different letters indicate statistically significant differences ($p < 0.05$) among the species grown on NCP or CP substrates. Asterisks represent statistically significant differences between NCP and CP plants within the same species (* $p \leq 0.05$, ** $p \leq 0.01$)

among species, irrespective of the time and growth substrate (Fig. 3b–d).

LDMC was higher in Compost-Pa than No-Compost Pa plants at T4 but the opposite trend was observed at T11. No difference was detected for the other species. Finally, according to SLA and LMA trends, LDMC decreased in Ms compared to Pa and Qi species (Fig. 3c).

The LWC increased in No-Compost-Pa and No-Compost-Qi plants compared to Compost ones at T2 and T4. Among species, Pa and Qi always showed comparable LWC values, lower than those measured in Ms plants (Fig. 3e).

The RWC was higher in Compost-Ms than No-Compost plants at T4. On Compost soil, at T2 and T4, Qi plants showed higher RWC than Ms and Pa plants, with significant differences only at T11 for Ms. Also on No-Compost soil, Pa and Qi showed higher RWC than Ms (Fig. 3f).

Plant growth

Compared to T0, Pa and Qi plants measured at T11 significantly increased ($p < 0.001$) stem diameter, height and leaf length. Compost-Pa and Compost-Qi plants exhibited a significant increase in stem diameter compared to No-Compost plants (24 and 22%, respectively) (Fig. 4a). For both species, on Compost substrate, plant height showed higher values than No-Compost (11% for Pa, 8% for Qi) (Fig. 4b). Also leaf length raised in Compost plants compared to No-Compost, displaying an increment of 16% for both species (Fig. 4c). The comparison between species evidenced since T0, higher values of height and leaf length in Qi plants than Pa, regardless of substrates (Fig. 4b–c). In contrast no difference in the stem diameter was evidenced (Fig. 4a).

Photosynthetic efficiency

Compost substrate significantly increased F_v/F_m in Ms and Pa plants compared to No-Compost, while no difference was evidenced concerning Qi plants (Fig. 5). In detail, F_v/F_m increased by 3, 6 and 1% in Compost plants compared to No-Compost at T2, T4 and T11, respectively. On the other hand, Compost-Pa plants showed an increment of 3 and 6% compared to No-Compost at T2 and T11, respectively. The comparison among species evidenced higher F_v/F_m values in Ms plants than Pa and Qi on both NCP and CP treatments. At T11, no difference was observed among species on the NCP soil. Conversely, concerning CP mesocosms, Ms showed higher F_v/F_m values than Pa and Qi plants (Fig. 5).

Relationships between soil and plants and focus on plant responses to treatments over time

The investigated plants responded differently to soil changes, depending on compost addition and depth. The results of

multiple linear regressions (MLRs) are reported in Table 2 and supplementary Table 1.

M. sylvestris was not affected by compost addition (CP), and statistically significant results ($p < 0.05$) were shown only for NCP treatment. In addition, plant responses were different for the depths of 0–10 and 10–20 cm. Indeed, the leaf traits SLA and LMA were statistically dependent on soil chemical characteristics, mainly SWC and pH. In detail, SLA was negatively correlated to SWC, and LMA was positively correlated to pH and SWC. Only leaf nutrients showed statistical correspondence with soil for the 10–20 cm depth. In detail, leaf N was positively correlated with soil pH, Sol Ns and negatively correlated with Sol C_s. Leaf C was positively correlated with pH and Sol C_s and negatively correlated with C_s and Sol Ns. Leaf C/N was positively correlated with soil pH and negatively correlated with Sol Ns.

Conversely, both Pa and Qi responded to the treatment with compost.

In *P. angustifolia* on No-Compost treatment, all the leaf traits reported $p \leq 0.05$, reflecting a good correspondence with soil parameters. For the 0–10 cm depth, soil pH influenced LDMC, LMA, LWC, RWC and negatively impacted SLA. Soil water content (SWC) was negatively correlated with LA and SLA, and positively correlated with LMA and LWC. The nitrogen soluble fraction (Sol Ns) was positively correlated with SLA and negatively correlated to LMA. For the depth of 10–20 cm, LA was negatively affected by Sol C_s. In Pa species on CP treatment, F_v/F_m showed a significant correlation to SWC and Sol C_s at 0–10 cm depth, while soil pH was related to LA (Table 2). In No-Compost, *Quercus ilex* L. leaf nutrients responded significantly to soil parameters only at 10–20 cm depth. In detail, leaf N was negatively influenced by soil pH and positively correlated with C_s and Sol Ns; leaf C was positively dependent on soil pH and negatively correlated with Sol Ns; leaf C/N was positively influenced by pH and negatively affected by SWC, C_s and Sol Ns. In addition, Qi species on Compost treatment at 0–10 cm was similar to Ph-CP at 0–10 cm response. Indeed, the photochemical efficiency F_v/F_m was positively correlated with SWC and Sol C_s (positive values).

The dissimilarity index reported in Fig. 6 summarized the overall plant responses to treatments. In this analysis, three principal clusters were represented by Ms (cluster I and II, on the right) and Pa and Qi together (cluster III, on the left), respectively. In clusters I and II, Ms appeared not particularly affected by treatments over time as shows a low dissimilarity index for Ms-NCP and Ms-CP. Conversely, in cluster III, Pa and Qi were affected by compost addition and showed similar responses. At T2, Pa and Qi were clustered per treatment. At T4 and T11 there is a separation per treatment, and only for NCP, Pa and Qi differed (Fig. 6).

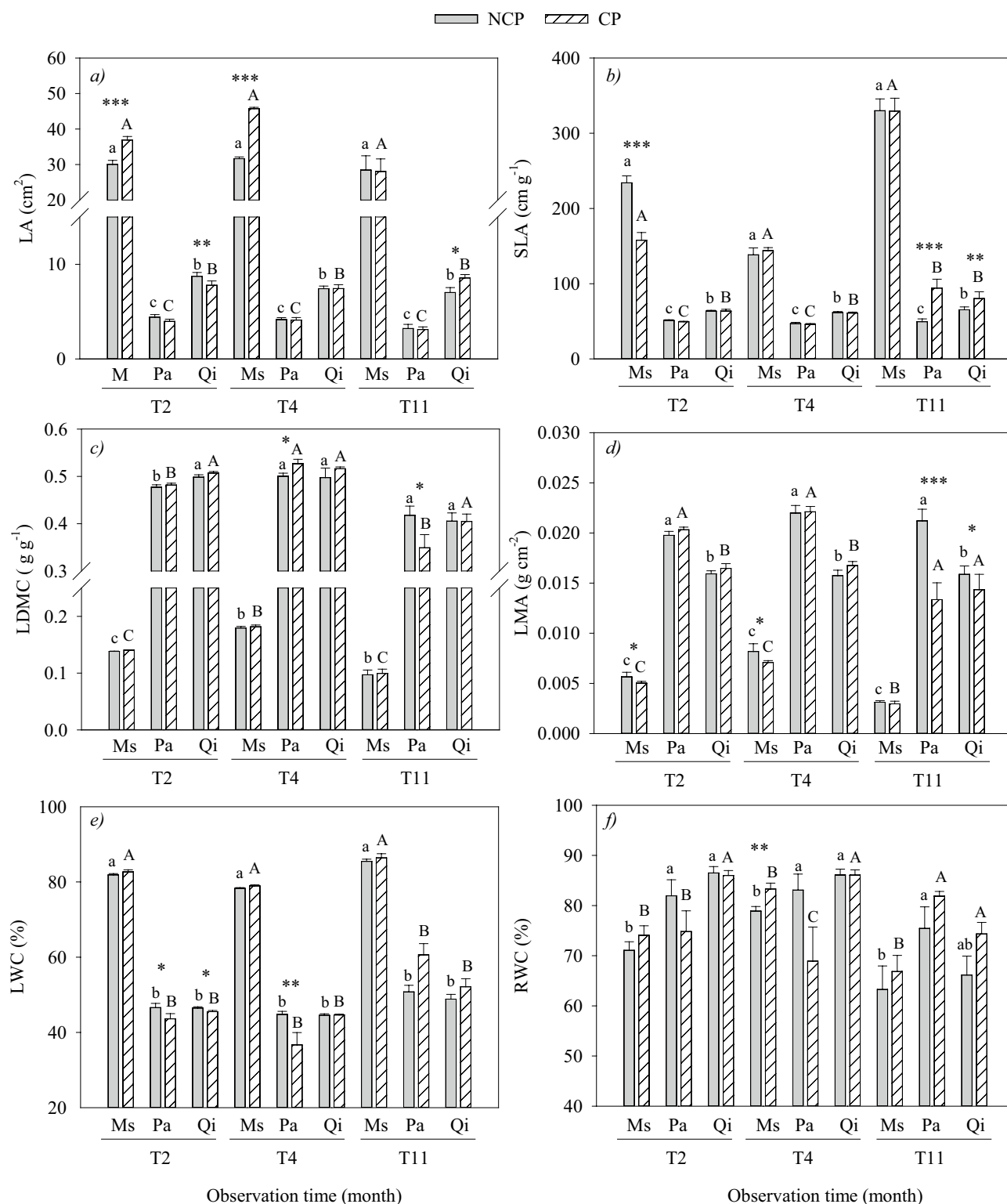


Fig. 3 Leaf functional traits: **a** leaf area (LA); **b** specific leaf area (SLA); **c** leaf dry matter content (LDMC); **d** leaf mass per area (LMA); **e** leaf water content (LWC); **f** relative water content (RWC) in *Malva sylvestris* L. (Ms), *Phillyrea angustifolia* L. (Pa) and *Quercus ilex* L. (Qi) grown on Technosols with (CP) and without compost (NCP) at two, four and eleven months from treatment and

plant establishment (T2, T4 and T11). Different letters indicate statistically significant differences ($p \leq 0.05$) among the species grown on NCP or CP substrates. Asterisks represent statistically significant differences between NCP and CP plants within the same species (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$)

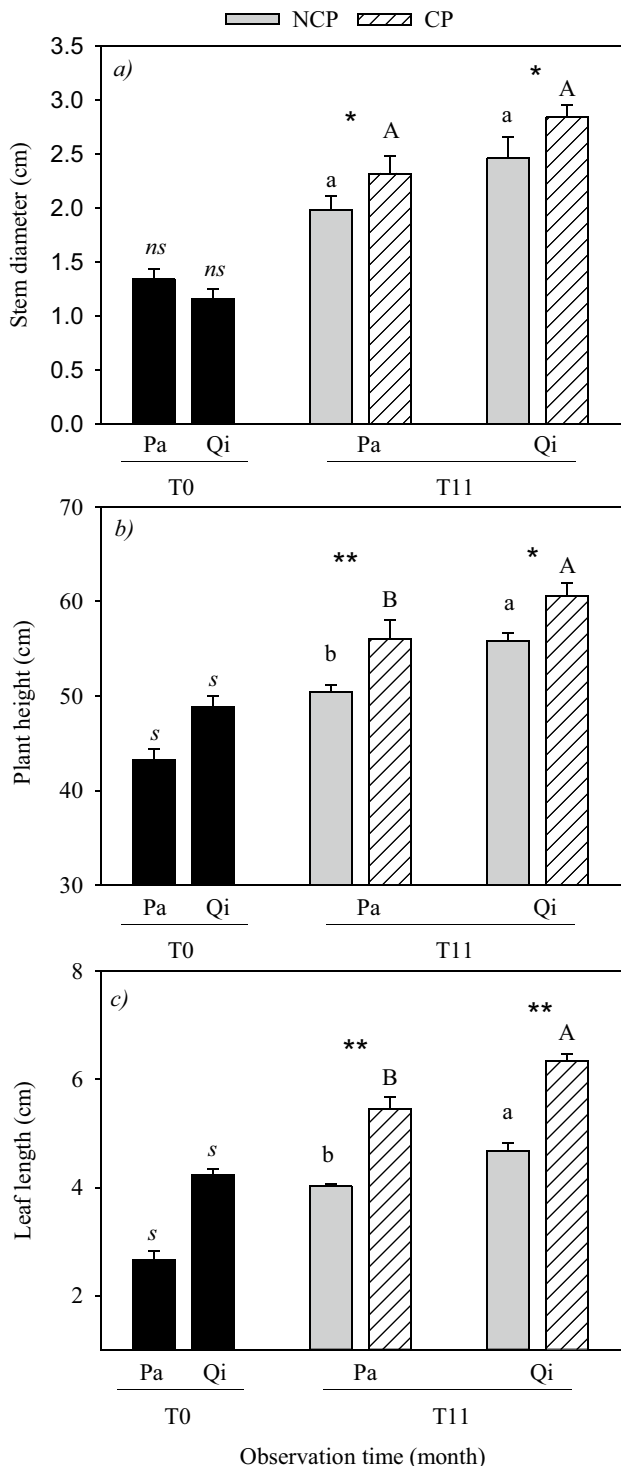


Fig. 4 Plant growth: **a** stem diameter; **b** plant height; **c** leaf length in *Phillyrea angustifolia* L. (Pa) and *Quercus ilex* L. (Qi) grown on Technosols with (CP) and without compost (NCP) at eleven months (T11) from treatment and plant establishment (time zero, T0). Different letters indicate statistically significant differences ($p < 0.05$) among the species grown on NCP or CP substrates. Asterisks represent statistically significant differences between NCP and CP plants within the same species (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$). To compare species at T0, the presence or absence of significant differences are indicated with s significant and ns no-significant

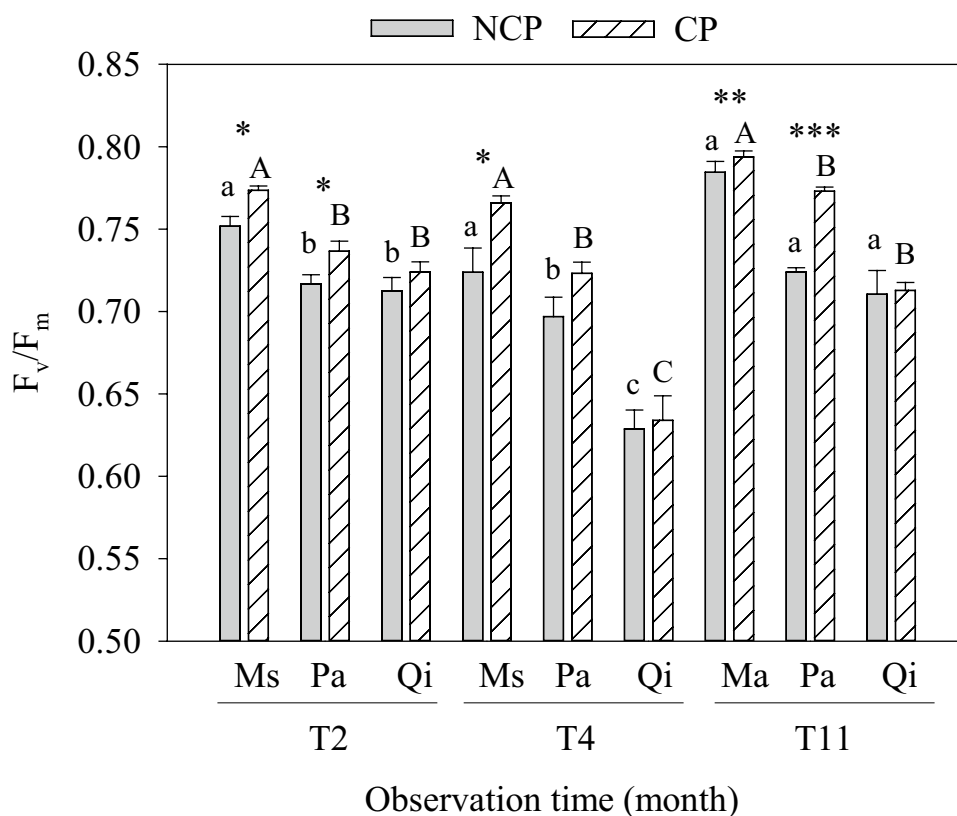
Discussion

This research highlights the relationships between technogenic derived soils treated with compost and Mediterranean plant responses that may occur during the application of urban greening practices. The choice of plant species is a key factor in the success of such a purpose because it must consider the relationships among the changes of soil properties due to compost addition and the plant responsiveness to them. Our results focused on the specific effects of compost-enriched Technosols on plant growth that primarily depend on different plant ecology. The overall results summarized by the dissimilarity index showed that *Malva sylvestris* L. is separated from *Phillyrea angustifolia* L. and *Quercus ilex* L.

M. sylvestris is a colonizer species in the first stages of ecological succession (Chang et al. 2014), with a broader capability of adaptation without the needs for peculiar soil conditions to grow (Godefroid et al. 2007). Conversely, *P. angustifolia* and *Q. ilex*, frequently co-occurring in Mediterranean forests, are metabolically more exigent regarding growth requirements as they appear during the last stages of the ecological succession (Erktan et al. 2018). As evidenced by the MLRs, following compost enrichment, in Pa and Qi plants, F_v/F_m is mainly influenced by surface soil characteristics (0–10 cm), particularly, soil water and soluble components availability. Our data are consistent with Ogaya et al. (2011), who reported a correspondence between the photochemical efficiency of these species and soil water content. Although in our case, SWC decreases over time, the increase of organic matter in Compost soil likely contributes to retain water for plants compared to No-Compost. Our results probably evidenced that the organic-based amendment may exert a global beneficial effect on photosynthesis, which depends on own species characteristics.

The ratio between the maximum fluorescence and variable fluorescence (F_v/F_m) is a suitable indicator of plant health status because it reflects the efficiency of light conversion in the photosynthetic process. The value of 0.8 of F_v/F_m ratio, close to the optimal threshold for unstressed plants (Maxwell & Johnson 2000; Modarelli et al. 2020), indicated in all species a positive photosynthetic response for investigated plants, with differences dependent on physiological intrinsic species characteristics. The F_v/F_m ratio increase in *P. angustifolia* and *M. sylvestris* on CP soil likely suggests a higher nitrogen investment in leaves towards chlorophyll synthesis, thereby favoring light harvesting and conversion to the reaction centers. In particular, in *M. sylvestris*, the leaf nitrogen content seems positively influenced by plant growth on Technosols enriched with compost, representing a prompt-available nitrogen source in the soil. The positive relationships between F_v/F_m and soil characteristics in the CP treatment (SWC and soluble components) highlight the significant effects of compost addition on plant growth.

Fig. 5 Maximal photochemical efficiency of PSII (F_v/F_m) in *Malva sylvestris* L. (Ms), *Phillyrea angustifolia* L. (Pa) and *Quercus ilex* L. (Qi) grown on Technosols with (CP) and without compost (NCP) at two, four and eleven months from treatment and plant establishment (T2, T4 and T11). Different letters indicate statistically significant differences ($p < 0.05$) among the species grown on NCP or CP substrates. Asterisks represent statistically significant differences between NCP and CP plants within the same species (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$)



Indeed, the foliar N, C content of *M. sylvestris* is significantly higher in mesocosms with compost, while the C/N ratio is lower. This result highlights that in compost-treated mesocosms, soil quality was improved. Conversely, leaf C and N in sclerophylls did not increase significantly with the addition of compost, even after almost one year. It may be supposed a different ecological growth strategy and use of energy resources than herbaceous plants, by which plants invest more carbon in woody structural tissue to overcome the environmental constraints, as evidenced by the higher values of LDMC.

The different ecological strategy adopted by sclerophylls *Q. ilex* and *P. angustifolia* and herbaceous *M. sylvestris* is evident not only in the leaf nitrogen and carbon content but also in leaf functional traits (De Marco et al. 2008; Ordoñez et al. 2009). In *Q. ilex* and *P. angustifolia*, the low values of SLA are associated with high LDMC and C/N ratio, while in the herbaceous *M. sylvestris*, an opposite response in leaf characteristics is found. The leaf functional traits generally display an expected decrease in relation to water and/or nutrient deficiency in the soil as well as a positive correlation with total soil N content (Ordoñez et al. 2009; Wright et al. 2017). According to previous researches, we attributed the differences in leaf traits found on Compost and No-Compost mesocosms among species to the diverse growth strategies of sclerophylls compared to herbaceous (Aerts 1999; Aerts and Chapin 2000). Also in our case, the low SLA measured in Pa

and Qi is associated with high leaf tissue density and reasonably indicated a greater resource allocation in biomass rather than in photosynthetic machinery components (pigments, proteins, sugars) (Parkhurst 1994; Terashima and Hikosaka 1995). In contrast, in CP mesocosms, Ms plants show significantly higher nitrogen content and lower C/N ratio than plants in NCP soil. The higher leaf nitrogen content and SLA suggested the occurrence of high photosynthetic metabolism in Ms plants, which invest more C and N in the constituents of the photosynthetic machinery, reducing defences against abiotic and biotic stresses (Reich et al. 1997). Monitoring plant status at the beginning of the compost addition up to 11 months allows to assess how long time is required to see some beneficial effects in the different species aimed at greening practices using amended Technosols.

Our study demonstrated that differently from *Q. ilex* and *P. angustifolia*, *M. sylvestris* quickly responded in Technosols treated with compost (CP mesocosms) exhibiting already at T2 and T4 a significant expansion of leaf lamina, accordingly to nitrogen and carbon allocation in protein production and tissue growth. The high leaf area in Ms likely supports an elevated light interception, favouring fast photosynthesis as confirmed by a high F_v/F_m ratio, close to the optimal value for healthy plants. Conversely, the sclerophyllous *Q. ilex* and *P. angustifolia* did not take immediate advantage from the compost addition as they exhibited smaller xeromorphic leaves providing benefit in hot and dry conditions of the Mediterranean basin, especially

Table 2 Equations, R^2 and p values for multiple linear regressions (MLRs) with plant characteristics established as dependent variables (C: Carbon; N: Nitrogen; C/N: LA: leaf area; SLA: specific leaf area; LDMC: leaf dry matter content; LMA: leaf mass per area; LWC: leaf water content; RWC: relative water content; F_v/F_m : maximal photochemical efficiency of PSII) and soil characteristics at the depths of

0–10 and 10–20 cm as independent variables (pH; SWC: soil water content; Cs: soil total carbon; Ns: soil total nitrogen; Sol Cs: soil soluble carbon; Soil Ns: soil soluble nitrogen). In the table, only statistically significant equations are shown and parameters with $p \leq 0.05$ within each equation are reported in bold

	R^2	p
<i>Malva sylvestris</i> L		
No-Compost treatment		
Soil 0–10 cm depth	0.438	0.050
SLA = 1463.93—(114.37 * pH)—(7.85 * SWC)—(12.78 * Cs)—(1147.50 * Ns)—(49.34 * SOL Cs)—(1523.04 * SOL Ns)		
LMA = -0.060 + (0.0064 * pH) + (0.00044 * SWC) + (0.0036 * Cs) + (0.0016 * Ns)—(0.00095 * SOL Cs) + (0.021 * SOL Ns)	0.625	0.005
Soil 10–20 cm depth		
N = 1,136 + (0.368 * pH) + (0.00141 * SWC)—(0.649 * Cs)—(0.281 * Ns) + (1.339 * SOL Cs) + (1.877 * SOL Ns)	0.808	<0.001
C = -14.33 + (8.76 * pH)—(0.0089 * SWC)—(10.75 * Cs) + (1.48 * Ns) + (20.28 * SOL Cs)—(138.23 * SOL Ns)	0.816	<0.001
C/N = 4.15 + (1.22 * pH)—(0.0074 * SWC)—(0.83 * Cs) + (1.37 * Ns) + (1.17 * SOL Cs)—(45.55 * SOL Ns)	0.678	0.005
<i>Phillyrea angustifolia</i> L		
No Compost treatment		
Soil 0–10 cm depth	0.279	0.030
LA = 9.069—(0.806 * pH)—(0.0854 * SWC) + (0.777 * Cs)—(5.571 * Ns) + (13.539 * SOL Cs)—(7.521 * SOL Ns)		
SLA = 251.49—(24.97 * pH)—(0.41 * SWC) + (3.07 * Cs)—(51.93 * Ns)—(9.08 * SOL Cs) + (131.90 * SOL Ns)	0.467	<0.001
LDMC = -0.106 + (0.079 * pH)—(0.00042 * SWC) + (0.000096 * Cs) + (0.10 * Ns)—(0.089 * SOL Cs) - (0.38 * SOL Ns)	0.387	0.002
LMA = -0.067 + (0.011 * pH) + (0.00021 * SWC) - (0.0017 * Cs) + (0.0297 * Ns) + (0.0072 * SOL Cs) - (0.049 * SOL Ns)	0.452	<0.001
LWC = -60.11 + (10.24 * pH) + (0.310 * SWC) + (3.97 * Cs) + (3.405 * Ns) + (55.40 * SOL Cs)—(8.916 * SOL Ns)	0.335	0.008
RWC = -350.94 + (47.46 * pH) + (0.664 * SWC) + (11.62 * Cs) + (41.02 * Ns) + (122.08 * SOL Cs) - (139.65 * SOL Ns)	0.425	<0.001
Soil 10–20 cm depth		
LA = -6.953 + (2.093 * pH) + (0.0234 * SWC)—(2.243 * Cs)—(3.084 * Ns)—(14.334 * SOL Cs)—(15.822 * SOL Ns)	0.299	0.007
Compost treatment		
Soil 0–10 cm depth		
F_v/F_m = 0.45 + (0.0019 * pH) + (0.0036 * SWC) + (0.0072 * Cs) + (0.041 * Ns) + (0.65 * SOL Cs) + (0.259 * SOL Ns)	0.457	0.006
LA = -4.497 + (1.457 * pH)—(0.047 * SWC) + (0.478 * Cs) + (15.86 * Ns)—(15.51 * SOL Cs)—(26.79 * SOL Ns)	0.243	0.016
<i>Quercus ilex</i> L		
No-Compost treatment		
Soil 10–20 cm depth	0.424	<0.001
N = 2.721—(0.232 * pH) + (0.00325 * SWC) + (0.213 * Cs)—(0.130 * Ns)—(0.328 * SOL Cs) + (6.223 * SOL Ns)		
C = 18.42 + (5.235 * pH)—(0.149 * SWC)—(3.203 * Cs) + (4.679 * Ns) + (7.821 * SOL Cs)—(202.11 * SOL Ns)	0.326	0.004
C/N = -30.83 + (11.378 * pH)—(0.218 * SWC)—(9.099 * Cs) + (7.668 * Ns) + (16.26 * SOL Cs)—(354.33 * SOL Ns)	0.467	<0.001
Compost treatment		
Soil 0–10 cm depth		
F_v/F_m = 0.415 + (0.0083 * pH) + (0.0033 * SWC) + (0.0132 * Cs) + (0.150 * Ns) + (0.469 * SOL Cs) - (0.072 * SOL Ns)	0.530	<0.001

in a conservation strategy aimed to save water (Niinemets et al. 2006; Ogaya et al. 2011; Tozer et al. 2015). The water resource is identified as one of the most limiting factors for the survival of *Q. ilex* species, especially for early germinated plants more sensitive to desiccation. Interestingly, at T2, *Q. ilex* plants grown on No-Compost soil showed higher values of LA and LWC compared to Compost-plants, while at T11, LA also increases in plants grown on Compost soil. Considering that LA promptly responds to water availability in the soil decreasing accordingly (Wang et al. 2019) and that at T4 and T11 soil water content declined compared to T0 and T2, it is reasonable to suppose that the amendment of Technosols with

compost may have improved the water retention within plant tissues, helping *Q. ilex* seedlings during the first year after the transplanting. The importance of soil water content (SWC) in influencing the leaf size is particularly significant in *P. angustifolia* grown on No-Compost Technosol. However, despite the SWC and soluble N decrease in all mesocosms at T11, also *P. angustifolia* seems to benefit from the compost addition showing lower LMA values. This result contrasts with the literature because a higher LMA is generally associated with plants with longer leaf longevity, growing on dry land and poor soil (Wright et al. 2005). In our context, the LMA reduction likely suggests an increase in soil fertility due to the compost addition.

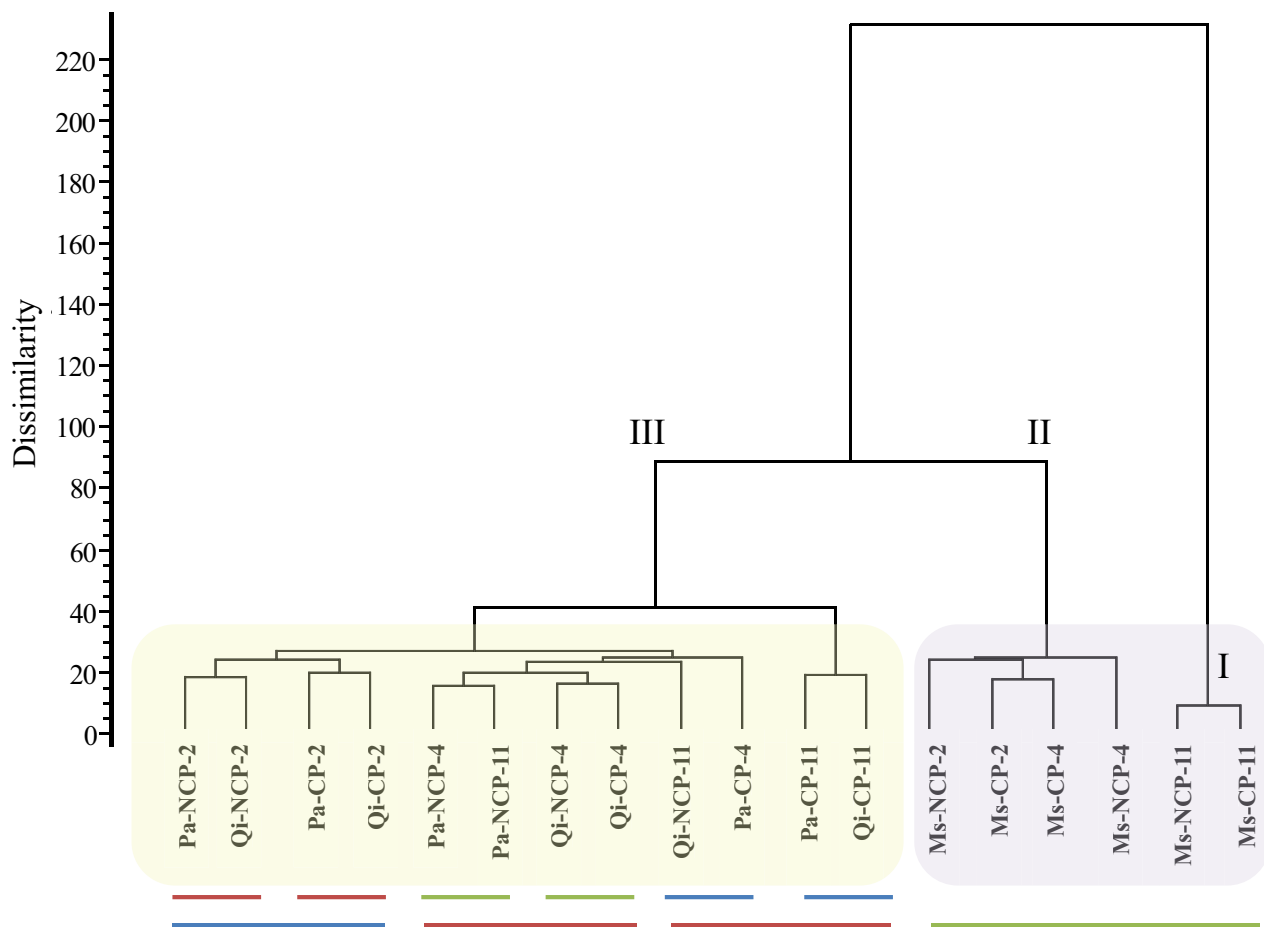


Fig. 6 Dissimilarity index displayed as dendrogram showing the relationships among leaf traits of *Malva sylvestris* L. (Ms), *Phillyrea angustifolia* L. (Pa) and *Quercus ilex* L. (Qi), and soil characteristics in CP and NCP treatments at two, four and eleven months from

compost addition and plant establishment (T2, T4, T11). Green lines group the same plant species; red lines group the same treatment, and blue lines group the same time (months) since the addition of compost and plants

Overall data demonstrated that the effect of compost on plant-soil relationships depends on time. Firstly, at T2, an effect due to tillage combined with compost addition and plant transplanting cannot be excluded. Such procedures may have favoured the soluble N coming from deeper layers making this fraction more exposed and detectable during measurements (Panico et al. 2019). Conversely, a more stable system can be assumed at T11. Moreover, comparing the NCP and CP treatments, specific pedoclimatic conditions and more complex relationships among the different factors may occur, making it tricky to highlight the main drivers of plant growth. However, the dissimilarity index proposes the ‘choice of the species’ as the principal discriminating factor, followed by the ‘employment of organic amendment’ and its relative effect during the experimental year. Within clusters I and II, composed of all treatments of *M. sylvestris*, we highlight that the subcluster-T11 incorporates both NCP and CP plants. Conversely, there is an evident clusterization of sclerophyllous species at T2 and T11 with a significant

impact of the compost addition, such as separating CP (Pa and Qi) from NCP plants.

Regarding the time, we can also observe that the organic amendment ameliorates the soil physico-chemical properties of Technosol, increasing soil nutrients over time. In the second instance, the photochemical efficiency promptly responds to compost addition, resulting in a good proxy of plant health status, while the leaf functional traits, requiring more time to respond to soil changes, are long-lasting indicators of plant adaptation to new environments. Comparing species, we found evidence that the herbaceous *M. sylvestris* takes more advantage of compost addition to Technosols, showing the highest photosynthetic efficiency and being more responsive at T2. However, sclerophyllous species, *Q. ilex* and *P. angustifolia* invest more photosynthates in structural carbon and require more time to show positive outcomes from compost addition visible predominantly at T11. Indeed, after eleven months (T11), *P. angustifolia* and *Q. ilex* took advantage from CP substrate, allocating more

biomass toward leaves and woody structures (increase of stem diameter and elongation).

Results of the study confirm the dependence of plant growth on the soil's chemical properties that change over time and are influenced by environmental conditions, plant transplanting and compost addition. A single application of compost to Technosols makes these substrates beneficial for plant growth, improving the soil–plant nutrient and water relationships.

The response of the three species to the CP treatment suggests that the recovery of soils containing residues of anthropogenic materials is really achievable. *M. sylvestris* may be employed to cover the revaluated sites spontaneously, regardless of the compost addition. At the same time, since the introduction of new green areas would require more water and soils resources for plant maintenance, *P. angustifolia* and *Q. ilex* may be specifically selected for their acclimatation capacity to high temperatures and other limiting factors of the Mediterranean area, such as nutrients and water availability, addressing the preservation of the local biodiversity (Arena et al. 2008; Rodriguez-Espinosa et al. 2021). Finally, the choice of these species may help furnish ecosystem services in the urban environment, as pollution biomonitors, carbon sequestration and pollution control from the atmosphere, and mitigation of the heat island phenomena (Gratani et al. 2000; Alfani et al. 2001; Fusaro et al. 2015; Marando et al. 2019; Perini et al. 2022).

In conclusion, the compost addition and plant establishment significantly affected the soil quality of Technosols. Indeed, Technosols result in more nutrients availability and a higher C/N ratio over time, whereas, among the investigated plants, the colonizing and fast-growing herbaceous *M. sylvestris* takes more advantage of compost addition to the soil at the beginning and after almost one year from fertilization. It is likely that sclerophyllous species, investing more photosynthates in structural carbon, need more time to show positive outcomes regarding growth and functional traits due to soil amendment with compost.

This study indicated the low soil moisture and nutrient availability, generally characterizing the Mediterranean area as the main parameters driving plant functional changes. Specifically, *M. sylvestris*, *P. angustifolia* and *Q. ilex* showed different abilities to adapt to changing water and nutrient availability and to compete for these resources.

The results showed that all species could grow on Technosols amended with compost and be employed for urban greening areas contributing to ecosystem services in urban contexts.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11252-024-01552-y>.

Acknowledgements The research was funded by the Department of Biology of the University of Naples Federico II. Thanks are due to all who took part in the experiment and Gesenu S.p.A. (Perugia, Italy) for providing the compost.

Author contributions CA and ADM conceived the research; CA, ADM, EV, PN and CC designed methodology; CA and ADM collected data; EV, PN and ADM analysed the data; EV and PN led the writing of the manuscript; CA, ADM and CC supervised the work. All authors reviewed and edited the final manuscript.

Funding Open access funding provided by Università degli Studi di Napoli Federico II within the CRUI-CARE Agreement. The research was funded by the Department of Biology of the University of Naples Federico II.

Data availability Data for this study are available on request from the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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