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RESEARCH

Incorporation of crushed asphalt as a circular economy strategy for de-sealed soil reclamation: case study in Prato, Italy

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Abstract
Sealing severely impairs soil ecosystem services. In addition to preventing further sealing and degradation, soil de-sealing is increasingly promoted as a compensatory strategy, especially in urban environments. However, its implementation is often limited by high costs and the need for imported topsoil. In this study, we evaluated the feasibility of reusing the crushed asphalt generated during de-sealing as a component of constructed urban soils as a circular economy strategy. A field experiment was conducted in Prato (Italy), in a newly de-sealed parking lot. After having verified that the in situ sealed soil was unsuitable for a prompt green recovery of the area, a transported urban soil amended with compost was mixed with increasing proportions of crushed asphalt (0, 10, 25, and 50% w/w). Over one year, we assessed soil physicochemical and biochemical properties, greenhouse gas fluxes, and vegetation establishment and diversity. Asphalt incorporation at the highest asphalt dose (50%) modified soil texture, increasing the sand fraction, reducing bulk density and lowering soil water availability. Soil chemical fertility showed limited and transient changes, with no persistent reductions in nutrient availability. Soil respiration, enzyme activities, and gas emissions were generally unaffected by asphalt addition. Finally, even the highest asphalt addition did not impair vegetation cover or biomass and species diversity, at least in the short-term monitoring period considered in this study. Although further research is needed to strengthen the evidence base on the effects of incorporating decommissioned asphalt into urban green spaces, these findings represent an encouraging step toward supporting the large-scale implementation of this practice, thereby promoting more widespread de-sealing practices in urban areas.

Keywords Soil un-sealing · Soil depaving · Soil desealing · Technosols · Urban soil restoration · Asphalt reuse

Introduction

The environmental issues stemming from urbanization and associated land consumption have led to increasing concerns among both the public and policymakers (Caselli et al. 2024). The practice of soil sealing, particularly with asphalt or concrete, is the most harmful form of land take, with detrimental effects on various ecosystem services (Cardelli et al. 2025; European Commission, 2012; Scalenghe and Ajmone Marsan 2009). Given this context, the European Commission (EC) has adopted a mitigation hierarchy aimed at limiting, then mitigating and ultimately compensating for the effects of soil sealing, while also emphasizing the importance of de-sealing (European Commission, 2012). The latter is to be understood as a form of compensatory intervention (Pannicke-Prochnow and Albrecht 2024) as it aims to reverse the negative impacts of soil sealing on soil functions.

In line with the EC's objective of achieving no net land take by 2050, soil de-sealing has been progressively integrated into European urban and territorial planning frameworks (European Commission, 2012). The "EU Soil

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Strategy for 2030" (COM/2021/699) further promotes locally driven initiatives for re-permeabilising artificial surfaces and restoring soil functionality. This framework has now been strengthened by Directive (EU) 2025/2360 on soil monitoring and resilience (Soil Monitoring Directive) (European Parliament and Council of the European Union 2025), which requires EU Member States to monitor soil health condition, address degradation (including sealing), and implement restoration measures. Consequently, soil de-sealing has gained increasing recognition and has become a widespread strategy for urban regreening and climate resilience, contributing to improve the quality of urban life and city aesthetics (Cardelli et al. 2025; Ceci et al. 2023; Garda 2022; Vieillard et al. 2024).

Despite this growing awareness, de-sealing initiatives have not yet become a standard practice, and de-sealing is still an underrepresented topic (Caselli et al. 2024). A comprehensive definition for terms like soil desealing/de-sealing, unsealing/un-sealing, or depaving/de-paving has yet to be established, although these terms have been used in scientific literature since the 1990s (Caselli et al. 2024; Vieillard et al. 2024). In urban contexts, de-sealing typically involves removing the impermeable cover, loosening or substituting the compacted layers beneath, and restructuring the soil profile (European Commission 2012; Maienza et al. 2021; Tobias et al. 2018; Vieillard et al. 2024). The goal is to restore soil functions to sustain vegetation and support greening initiatives.

De-sealing typically produces a lot of inert waste in the form of dismantled asphalt or, better said, bituminous conglomerate (Caselli et al. 2024; Mikajlo et al. 2025), which is typically a mixture of aggregates, bituminous binder, fillers, and supplementary additives (Azadgoleh et al. 2022). Restoring de-sealed areas also often involves using exogenous topsoil, either alone or mixed with improving organic or mineral materials (Maienza et al. 2021; Vieillard et al. 2024). This backfill topsoil is typically sourced from agricultural or other urban sites, implying considerable environmental and economic costs related to soil extraction and transportation (Maienza et al. 2021; Vieillard et al. 2024).

The implementation of soil de-sealing and regreening projects often entails substantial costs, which may be prohibitive for some public authorities or for private individuals. In France, for example, expenses can exceed 300 € per m² (Vieillard et al. 2024). Furthermore, obtaining natural topsoil is becoming less feasible due to tightening soil protection regulations, leading to the exploration of alternative solutions, such as using soil materials found on-site (Vieillard et al. 2024) or waste materials for soil construction (Araujo et al. 2025). In this context, the on-site interment of the removed asphalt pavement – the main by-product of de-sealing -— has been proposed as a promising strategy to enhance the economic and environmental sustainability of de-sealing (Mikajlo et al. 2025; Rompato et al. 2025). Incorporating this material can enhance soil drainage, thereby promoting efficient water infiltration, while posing negligible environmental risks from the potential release of PAH and heavy metals (Mikajlo et al. 2025; Rompato et al. 2025).

In this study, we aimed to test the feasibility of recovering a sealed urban soil also evaluating how the incorporation of increased amounts of the removed and crushed asphalt influenced soil physicochemical and biological properties, plant performance and diversity. We hypothesised that increasing doses of crushed asphalt incorporated into relocated soil derived from a de-sealing intervention, would not significantly impair the recovery of soil ecosystem services, at least up to moderate levels.

Materials and methods

Study site and de-sealing operations

The study was conducted at a former park-and-ride facility (5,235 m²) located on Pietro Nenni Avenue in Prato, Central Italy, (43°52′26.0″N, 11°04′55.8″E), implemented and paved in the late 1990s (Fig. 1). The site is within the *Csa* climate zone of the Köppen–Geiger classification, characterized by a temperate climate with hot, dry summers. Mean annual temperature is 15.5 °C and mean annual precipitation is around 900 mm. Over the past 15 years there has been a progressive shift to extreme precipitation regime characterized by prolonged drought periods alternating with highly intense rains. The city lies in the sedimentary basin of the Arno River, a flat area that has undergone substantial anthropogenic transformation in the last decades, driven mainly by industrialization and urbanization, which have significantly altered both landscape and natural environment as well as reduced the absorbent surface.

The municipality intended to de-seal part of the parking lot, removing the asphalt and backfilling the area with about 40 cm of relocated soil material sourced from other construction works carried out in the city, where the excavated soil had been scraped and preserved. Before the de-sealing, we selected a sub-area to be set-up, fenced, and monitored in terms of soil recovery and vegetation growth. The aim was to limit the environmental and economic cost of de-sealing testing the performance of a Technosols produced through in situ reusing of soil materials and part of the removed asphalt.

Assessing the quality of the available soil materials is essential to tailor de-sealing strategies to site-specific conditions and to foster more sustainable approaches in urban

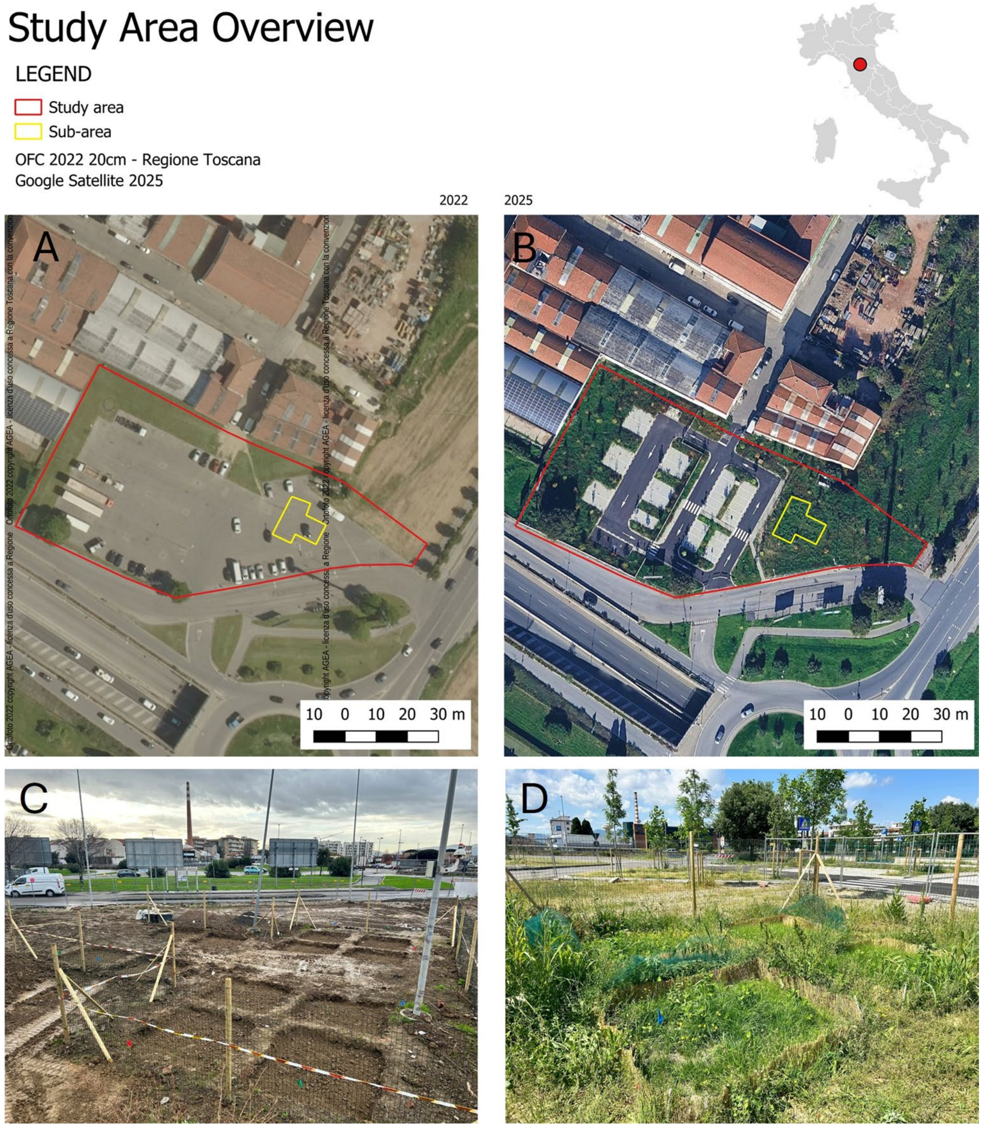

Fig. 1 Top: bird's-eye view of the study area before (**A**, left) and after (**B**, right) de-sealing. The red polygon delineates the entire de-sealed area, while the yellow polygon inside indicates the experimental area. Bottom: ground-level views of the experimental area showing plot preparation (**C**) and the site after several months (**D**), when vegetation had successfully covered the entire area

design. For this purpose, in December 2022 a soil trench was opened in the experimental area to a depth of ≈1 m. A soil profile was described and classified according to IUSS Working Group WRB (2022) (Supplementary Information SI 1). Soil samples were collected by genetic horizon, air-dried, and sieved at 2 mm for analysis.

Beneath the surface impervious layer of asphalt, there was a bed of coarse calcareous material and fragments of bricks, and further below a greyish, highly reduced, massive, and plastic C horizon that appeared poorly suited to support vegetation growth. For this reason, we applied the same excavated soil used in the rest of the former parking lot to our experimental area as well.

The experimental area (145 m^2) was divided into three blocks of 5 × 5 m. Every block was further subdivided into four plots (2 × 2 m, 40 cm deep). The plots were excavated and refilled with two layers: the lower 20 cm consisted of relocated soil material used to fill the rest of the parking lot, while the upper 20 cm comprised the same soil material amended with urban waste compost and crushed and sieved (< 2 cm) asphalt. Four treatments were established by incorporating increasing proportions of asphalt (0%, 10%, 25%, and 50% w/w). Compost was added to all treatments at a rate of 5% (w/w) to act as a soil amendment and stimulate microbial activity (Deeb et al. 2020). The compost, produced from the municipal organic waste collected in Prato, was supplied by the Faltona composting facility. It had a pH of 7.1, an organic carbon (OC) content of 34.7% and a total nitrogen (TN) content of 2.6%. Additional details are provided in the Supplementary Material of Rompato et al. (2025). The experimental plan comprised four treatments, T0 (control), T10, T25, and T50, representing increasing asphalt doses, each with three replicates.

To ensure homogeneity and proper integration of the asphalt and compost, all materials were carefully weighed and mechanically mixed prior to placement. After about three months, on 8th April 2024, a commercial seed mixture consisting of *Lolium perenne* L. (50% by weight), *Festuca rubra* L. (25%), and *Poa pratensis* L. (25%) was sown with a seeding rate of 25 g m^{-2}. Irrigation was applied manually only as an emergency measure during the summer.

For slightly more than a year, the experimental area was monitored for a range of physical, chemical, and biological soil properties, along with assessments of herbaceous plant growth and diversity.

Soil sampling

Soil sampling was carried out in March 2024 (M0) and after six months and one year (M6 and M12, respectively). On each date, in each plot, two disturbed soil samples were taken with a trowel, while, for measuring soil bulk density (BD), one undisturbed sample per plot was taken at M0 and M12 with a steel cylinder 5 cm high and 8.5 cm in diameter. In total, 36 soil samples were collected. Disturbed samples were sieved at 2 mm while still fresh. From each sample, an aliquot was obtained by quartering, and the aliquots from the same plot were combined to form a composite sample for biochemical analysis.

Gas exchange, soil temperature and moisture

Gases emissions (CO_2, CH_4, N_2O, NH_3, and SO_2) from soil were measured using 12 static chambers (one per plot) and a photoacoustic multi-gas analyzer (Photoacoustic Gas Monitor INNOVA 1512, Lumasense—Ballerup, Denmark). PVC cylinders (20 cm in diameter) were employed as anchors and inserted at 5 cm into the soil in a corner of the plot, where they remained in place throughout the experimental period. Each lid consisted of a PVC cylinder of identical diameter and 20 cm in height, sealed at the top with a PVC cap affixed using silicone adhesive. A central aperture (approximately 1 cm in diameter) was drilled in the upper section of each lid to accommodate a quick-release coupling, which functioned as a gas sampling port. The external surface of the lids was covered with reflective Mylar tape to minimize the influence of solar radiation and prevent temperature increases within the chambers. Thus, the air within each chamber was assumed to be under standard conditions (22.4 L at 15 °C and 1 bar). Measurements were conducted on 11 different dates between May 2024 and April 2025 during mid-morning hours (09:00–11:00 a.m.), when temperatures were representative of the daily mean (Parkin and Venterea 2010).

Complementary to the soil gas exchange measurements, soil temperature and moisture were recorded in triplicate at each plot, by using a PT100 probe (TR Turoni s.r.l.) and WET-2 Sensor (Delta-T Devices, UK), respectively.

Physicochemical and biochemical analysis of soil

Saturated soil hydraulic conductivity (K_{sat}) was measured in situ in October 2025 with a SATURO automated dual-head infiltrometer (Meter Group, Pullman, WA, USA) with a 14.4 cm (inner diameter) ring and a 5–10 cm insertion depth. The instrument automatically establishes and maintains two constant pressure heads and calculates K_{sat} using the simplified falling-head approach derived from Darcy's law, following the dual-head infiltrometer principle (Atalar et al. 2025).

After drying, all soil samples were passed through a 2 mm mesh, quartered and combined prior to laboratory physicochemical analyses. To determine soil bulk density (BD), the >2 mm fraction (the "skeleton") was weighed, and its volume measured by water displacement in a graduated cylinder. BD was then calculated as the ratio between the mass and volume of the total sample oven-dried to constant weight at 105 °C, both subtracted from the mass and volume of the skeleton, respectively. Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-distilled water suspension using an XS PC8 pH/EC meter. Soil texture was determined by the hydrometer method after dispersion with a 5% (w/v) sodium hexametaphosphate solution, and final quantification of the sand through sieving. Total carbonate ($CaCO_3$) was measured by the volumetric method after reaction with hydrochloric acid. Soil organic carbon and total nitrogen were quantified using the Walkley–Black wet oxidation method (Walkley and Black 1934) and the Kjeldahl digestion method (Bremner 1960), respectively. Available P was determined by the molybdenum blue spectrophotometric method (Olsen et al. 1954), cation exchange capacity (CEC) by the barium chloride and triethanolamine method (Hendershot and Duquette 1986), and exchangeable cations by ICP-OES.

Soil microbial activity was evaluated on fresh soil sampled at M0, M6, and M12 by measuring basal respiration through alkali absorption and titration. Fresh fine earth (20 g) was incubated in the dark for 72 h and a becker with 4 mL of 1 M NaOH was used to trap the evolved CO_2. After incubation, the residual NaOH was titrated with 0.1 N HCl to quantify the CO_2 released from the soil (Anderson and Domsch 1978). Enzyme activities related to main nutrient dynamics were determined at M0, M6, and M12 (Alef and Nannipieri 1995). Acid and alkaline phosphomonoesterase activities were measured following Tabatabai and Bremner (1969), and β-glucosidase activity was determined as in Alef and Nannipieri (1995). Hydrolase activities were quantified by measuring *p*-nitrophenol using a UV-Vis spectrophotometer (Lambda 2, Perki-nElmer). Urease activity was determined according to Nannipieri et al. (1974). Protease activity was determined by the hydrolysis of Na-caseinate and quantified spectrophotometrically using the Folin-Ciocalteu reagent (Ladd and Butler 1972).

Vegetation assessment

Ground cover was assessed as the percentage of soil surface covered by turfgrass within each plot by visual estimation on six different dates, from spring 2024 to autumn 2025. Assessments were conducted by the same trained operator at each sampling date under comparable light conditions, following the standard turfgrass evaluation procedures. Moreover, in the same dates, the aboveground biomass from a 0.5 m^2 surface was harvested using an electrical grass clipper, stored in sealable bags and then oven-dried at 80 °C in laboratory until constant weight to evaluate grass growth over time as reported in Argenti et al. (2021). After this confined harvest, the entire plot surface was cut using a brush cutter, leaving the shredded material on the ground.

Vascular plants composition and diversity in the plots was assessed by a survey performed at the time of maximum growth activity in spring 2025 (May 8th, M14). All taxa rooted within the plot were identified at species level and scored for percentage of ground cover. Plants projecting their crown over the plot surface, but rooted outside were not considered. After determining the frequency (%) and mean ground cover for each species, the main community α-diversity variables were calculated for each plot, namely species richness (SR), Shannon–Wiener diversity (H'), and evenness (J); the latter as H':lnS ratio, where S is the number of species in the plot.

Statistical analysis

The Shapiro–Wilk test was used to assess data normality, and Levene's test to determine the homogeneity of variance. Where these assumptions were not satisfied, the data underwent logarithmic transformation. Following these preliminary checks, a one-way analysis of variance (ANOVA) was applied to a broad set of variables, including soil physicochemical properties, enzymatic activities, and vegetation features to detect differences attributable to the asphalt addition. Significant differences between group means were further investigated using Tukey's post-hoc test ($P<0.05$). When data, even if transformed, did not pass normality and homogeneity of variance tests, they were analyzed using the non-parametric Kruskal–Wallis test. When significant effects were detected ($P<0.05$), Dunn's post-hoc test was applied for multiple pairwise comparisons with Bonferroni correction. These statistical analyses were performed using SPSS version 29 (IBM Corp., Armonk, NY, USA).

The soil gas fluxes dataset was checked for outliers using the standard interquartile range (IQR) method. The IQR was calculated as the difference between the third quartile (Q3) and the first quartile (Q1) for each measured gas. Data points falling outside the range defined by $Q1-1.5\times IQR$ and $Q3+1.5\times IQR$ were classified as outliers and subsequently removed from the dataset to minimize their undue influence on statistical analyses. For the specific analysis of soil gas fluxes, further data processing was conducted using R software. To ensure physical consistency, negative flux values for CO_2, N_2O, NH_3, and SO_2 were set to zero. Furthermore, the monitoring period was partitioned into three distinct phases M0-M4, M5-M9, and M10-M12. One-way ANOVA and Tukey's post-hoc tests were then performed within each period to assess the impact of asphalt addition over time. Time-series plots with standard error ribbons were generated using the *ggplot2* package to visualize the temporal dynamics of gas emissions.

Results

Physicochemical properties of soil

The physico-chemical properties of soil in the four treatments (T0, T10, T25 and T50) at month 0 (M0, March 2024) and after one year (M12) are presented in Tables 1 and 2.

The relocated soil material used to backfill the de-sealed parking lot had a silt loam texture, which was progressively shifted toward a sandy loam class with increasing asphalt additions mainly due to the increase in coarse and medium sand (>250 µm) (Table 1). At M0, higher total organic carbon (TOC) and total inorganic carbon (TIC) were measured with increasing asphalt incorporation, reaching values of 2.38% and 93.6 g kg-1, respectively, in T50. In contrast, total nitrogen (TN) did not differ significantly among treatments, and consequently, the C/N ratio tended to be higher at increasing asphalt content, up to 19.4 in T50. The differences in bulk density (BD) between treatments at M0 were not statistically significant.

Across sampling times, one year after the beginning of the experiment (M12), BD was significantly lower in T50 compared to control (T0) at M0 (Table 1). TIC values did not change significantly between M0 and M12, whereas TOC and TN in a few cases showed slight increases. The C/N ratio had decreased only in T50 compared to M0. Saturated hydraulic conductivity (K_{sat}) was significantly higher only in T25 compared with all other treatments.

Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and exchangeable K did not differ significantly either among treatments or between sampling times (Table 2). Exchangeable Ca, which was by far the

Table 1 Bulk density (BD), total organic and inorganic carbon (TOC and TIC, respectively), total nitrogen (TN), C/N ratio, soil texture (sand, silt, and clay proportions), and saturated soil hydraulic conductivity (K_{sat}) of the soil from the four treatments with increasing asphalt contents (T0, T10, T25, T50) at time 0 (March 2024) and one year later (M12). Saturated soil hydraulic conductivity (K_{sat}) was measured 19 months after the beginning of the experiment. Statistical analysis was performed on the entire dataset, including all sampling times, except for texture. Values are mean±standard deviation of three replicates. Different letters indicate significant differences between values in the same column, based on Tukey's or Dunn's test for $p \leq 0.05$

Time	Treatment	BD g cm^{-3}	TOC %	TIC g kg^{-1}	TN %	C/*N*	Sand %	Silt %	Clay %	K_{sat}* cm hr^{-1}
M0	T0	1.50±0.09^{a}	0.83±0.16^{a}	25.2±8.3^{a}	0.12±0.00^{a}	7.1^{a}	43	44	13	-
	T10	1.44±0.07^{ab}	1.29±0.16^{ab}	37.2±8.0^{a}	0.12±0.01^{ab}	10.4^{abc}	46	43	11	-
	T25	1.38±0.10^{ab}	1.60±0.36^{bc}	57.5±8.4^{abc}	0.12±0.01^{a}	13.5^{cd}	47	41	12	-
	T50	1.36±0.12^{ab}	2.38±0.16^{e}	93.6±27.0^{c}	0.12±0.01^{ab}	19.4^{e}	60	30	10	-
M12	T0	1.35±0.15^{ab}	1.16±0.17^{ab}	27.5±17.1^{a}	0.13±0.01^{ab}	8.6^{a}	41±2	53±3	6±2	6.8±0.2^{a}
	T10	1.35±0.08^{ab}	1.37±0.02^{bc}	30.7±3.0^{a}	0.14±0.01^{ab}	10.1^{ab}	42±7	52±6	6±1	9.0±1.1^{a}
	T25	1.21±0.18^{ab}	1.83±0.20^{cd}	45.9±9.8^{ab}	0.14±0.01^{b}	12.9^{bcd}	47±3	48±5	5±1	17.8±0.3^{b}
	T50	1.16±0.12^{b}	2.21±0.10^{de}	80.2±3.8^{bc}	0.15±0.01^{b}	15.2^{c}	50±4	44±6	6±1	6.7±2.5^{a}

*Saturated soil hydraulic conductivity (K_{sat}) was measured 19 months after the beginning of the experiment

Table 2 pH, conductivity, cation exchange capacity (CEC), exchangeable K, Ca, Mg, and Na and available P, of the soil from the four treatments with increasing asphalt contents (T0, T10, T25, T50) at time 0 (March 2024) and one year later (M12). Values are mean±standard deviation of three replicates. Statistical analysis was performed on the entire dataset, including all sampling times. Different letters indicate significant differences between values in the same column, based on Tukey's or Dunn's test for $p \leq 0.05$. Where no letters are reported, differences were not statistically significant

Time	Treatment	pH	Conductivity mS m^{-1}	CEC meq 100 g^{-1}	Exch. K mg kg.^{1}	Exch. Ca mg kg-^{1}	Exch. Mg mg kg^{-1}	Exch. Na mg kg^{-1}	Avail. *P* mg kg.$^{-1}$
M0	T0	8.2±0.1	309±21	8.8±0.6	70±2	1874±32^{a}	72±6^{ab}	50±8^{a}	59.2±6.8^{a}
	T10	8.3±0.1	264±33	8.4±0.2	78±2	1767±47^{ab}	72±14^{ab}	35±12^{ab}	97.7±55.7^{a}
	T25	8.3±0.2	305±15	8.4±0.3	70±7	1795±176^{ab}	81±6^{a}	39±14^{ab}	57.1±8.5^{a}
	T50	8.2±0.2	299±75	7.5±0.1	75±5	1570±73^{b}	56±2^{bc}	19±5^{b}	58.9±16.7^{a}
M12	T0	8.0±0.1	293±20	8.9±1.5	72±9	1988±79^{a}	41±7^{c}	18±2^{b}	108.6±16.0^{b}
	T10	8.0±0.0	285±10	9.8±1.0	86±9	1940±42^{a}	37±6^{c}	18±6^{b}	112.1±7.9^{b}
	T25	8.1±0.0	269±15	11.6±4.6	80±3	1859±72^{a}	36±8^{c}	19±3^{b}	96.4±19.4^{b}
	T50	8.1±0.1	299±2	8.5±0.9	92±28	1777±102^{ab}	43±6^{c}	18±1^{b}	117.8±22.5^{b}

dominant base cation, was lower in T50 compared to the control (T0) and showed a slight increase from M0 to M12. Exchangeable Mg and Na were lower at increasing asphalt content, while after one year they decreased across treatments, and the initial differences were no longer significant. Available P did not differ significantly among treatments at each either sampling date (Table 2). However, when considering the temporal trend across all treatments, mean concentration values at M12 were nearly double those at M0, indicating a substantial overall increase over time. Available P was also measured at M6, and values were not statistically different, both between treatments and sampling times (T0 = 123.5 ± 96.4 mg P kg–^{1} soil; T10 = 82.2 ± 88.5 mg P kg^{-1} soil; T25 = 78.0 ± 28.3 mg P kg^{-1} soil; T50 = 78.0 ± 47.6 mg P kg^{-1} soil).

Soil gas exchanges, temperature, and humidity

Soil temperature and moisture dynamics during the year of monitoring are inversely related (Fig. 2). In fact, the first is high and rises progressively in summer until September, while the second is low and tends to decline during the same period; the opposite occurs in winter until around March. Given the seasonality of soil temperature and moisture, which also influence soil gas exchanges, and considering that the plots were irrigated during the summer of 2024, soil gas flux, temperature and moisture data were grouped into three different periods (M0-M4; M6-M9; M10-M12) to highlight potential differences among the treatments. The resulting cumulative data were analysed using one-way ANOVA (Table 3).

Soil moisture was the only variable showing significant differences among the treatments, and only during the final measurement period (M10-M12) when T50 showed a markedly lower moisture content (10%) than the other treatments (18–22%).

The presence of asphalt, in any proportion, apparently did not affect soil gas emissions during any measurement period. The magnitude of CO_2 emissions varied across the study period in accordance with seasonal meteorological

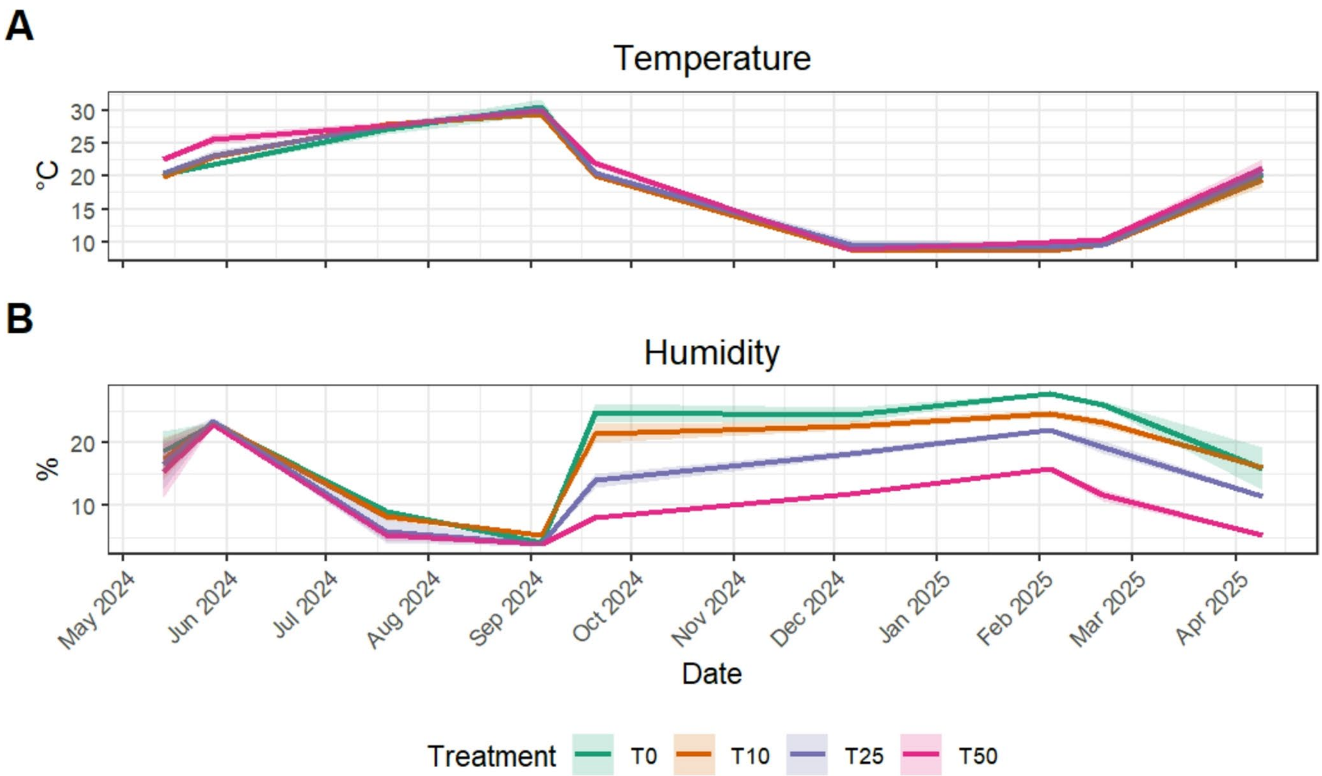

Fig. 2 Soil temperature (**A**, above) and moisture (**B**, below) dynamics in the four treatments (T0, T10, T25, T50) during a year of monitoring

Table 3 Cumulative values of soil moisture, temperature, and gas fluxes in plots with different asphalt contents (T0, T10, T25, T50) across three measurement periods (M0-M4, M5-M9, and M10-M12). Values are mean±standard deviation. Values reported as 0 are below the rounding threshold of the reported decimal precision. Statistical analysis was performed separately for each measurement period. Different letters indicate significant differences between values in the same column and measurement period, based on Tukey's test for $p \leq 0.05$. Where no letters are reported, differences were not statistically significant

Time	Treatment	Moisture % weight	Temperature °C	CO_2 kg ha^{-1} day^{-1}	CH_4 kg ha^{-1} day^{-1}	N_2O kg ha^{-1} day^{-1}	NH_3 kg ha^{-1} day^{-1}	SO_2 kg ha^{-1} day^{-1}
M0-M4	0	17.9±5.1	20.3±0.8	1375.8±611.5	-2.09±0.92	0.02±0.02	0.000±0.000	0.00±0.00
	10	20.3±2.9	21.9±1.4	354.7±150.2	-2.47±1.27	0.07±0.04	0.022±0.022	0.00±0.00
	25	20.4±3.2	22.6±1.2	316.4±165.1	-1.02±1.12	0.06±0.06	0.002±0.002	0.00±0.00
	50	17.3±3.6	22.8±0.4	1318.1±575.8	-2.16±0.65	0.03±0.02	0.000±0.000	0.06±0.06
M5-M9	0	14.6±6.0	24.8±2.6	101.5±97.9	-0.55±0.64	0.03±0.03	0.000±0.000	0.03±0.03
	10	12.7±4.2	24.8±2.7	18.0±18.0	-1.23±0.61	0.00±0.00	0.009±0.009	0.00±0.00
	25	7.9±2.4	26.3±2.4	129.3±52.6	-1.23±0.63	0.00±0.00	0.003±0.003	0.07±0.07
	50	6.2±1.2	25.8±2.4	18.0±10.6	-0.50±0.29	0.00±0.00	0.005±0.005	0.00±0.00
M10-M12	0	22.1±2.6[a]	13.9±2.3	1307.7±274.4	0.54±0.54	0.02±0.02	0.104±0.065	1.83±0.88
	10	21.4±1.2[a]	12.2±1.6	1170.5±157.1	-0.26±0.55	0.02±0.01	0.074±0.034	1.77±0.56
	25	18.5±1.3[a]	12.0±1.8	945.9±196.1	0.17±0.63	0.02±0.01	0.180±0.060	1.94±0.73
	50	10.6±1.1[b]	12.7±1.7	750.6±201.3	0.53±0.53	0.01±0.01	0.103±0.057	1.48±0.59

trends. The fluxes of N_2O, NH_3, and SO_2 from soil to the atmosphere were generally negligible and only weakly linked to the season, although a slight increase in NH_3 and SO_2 emissions was observed in all treatments during the final monitoring period (M10–M12, from January to April). A statistically significant increase in emissions was also observed for CH_4 during the last period (M10-M12).

Soil basal respiration and enzyme activities

Table 4 shows soil basal respiration and enzyme activities related to the C, N and P cycles at M0, M6 and M12.

Soil basal respiration, acid and alkaline phosphomonoesterase, and β-glucosidase activities did not significantly change over time. Soil respiration decreased from M0 to

Table 4 Soil basal respiration and enzyme activities in plots with different asphalt contents (T0, T10, T25, T50) at the beginning of the experiment and six and twelve months later (M0, M6, and M12). Values are mean±standard deviation. Statistical analysis was performed on the entire dataset, including all sampling times. Different letters indicate significant differences between values in the same column and measurement period, based on Tukey's or Dunn's test for $p \leq 0.05$. Where no letters are reported, differences were not statistically significant

Time	Treatment	Soil basal respiration	Acid phosphomonoesterase	Alkaline phosphomonoesterase	Beta-glucosidase	Urease	Protease
		mg C-CO_2 g soil^{-1}	mg *p*-NP g soil^{-1}	mg *p*-NP g soil^{-1}	mg *p*-NP g soil^{-1}	mg N-NH_4^+ g soil^{-1}	µg Tyr g soil^{-1}
M0	0	0.13 ± 0.09	1173,12 ± 324.22	1595.55 ± 646.09^a	738.719 ± 258.80^a	21.02 ± 11.73	77.74 ± 39.08
	10	0.14 ± 0.05	1195.31 ± 130.86	1592.44 ± 328.05^a	607.823 ± 399.27^a	20.40 ± 11.48	70.33 ± 24.30
	25	0.10 ± 0.04	1116.21 ± 146.97	1561.47 ± 422.92^a	430.81 ± 167.50^a	26.45 ± 5.82	58.57 ± 9.96
	50	0.09 ± 0.02	1167.05 ± 424.91	1425.31 ± 446.46^a	541.417 ± 422.52^a	6.08 ± 2.76	82.89 ± 13.03
M6	0	0.13 ± 0.05	1676.10 ± 554.28	2622.61 ± 275.78^a	1064.08 ± 739.35^a	29.86 ± 21.32	88.34 ± 6.64
	10	0.15 ± 0.02	2208.65 ± 258.51	2409.56 ± 600.87^a	1122.52 ± 483.24^a	21.22 ± 6.87	85.59 ± 19.65
	25	0.13 ± 0.05	1892.68 ± 561.40	1979.49 ± 264.52^a	731.624 ± 366.83^a	22.91 ± 5.44	89.88 ± 15.77
	50	0.08 ± 0.01	1914.59 ± 216.19	2860.42 ± 429.55^a	1283.08 ± 441.16^a	24.73 ± 9.16	106.87 ± 30.00
M12	0	0.08 ± 0.04	1492.51 ± 312.97	2194.14 ± 339.16^{ab}	971.10 ± 110.41^{ab}	41.65 ± 32.50	77.30 ± 40.00
	10	0.13 ± 0.07	1291.25 ± 167.87	2750.22 ± 109.60^a	1507.20 ± 549.16^a	53.75 ± 36.00	72.18 ± 25.91
	25	0.10 ± 0.07	1235.97 ± 75.19	1792.87 ± 98.52^b	654.804 ± 125.31^b	49.02 ± 15.90	56.48 ± 8.64
	50	0.07 ± 0.01	1369.61 ± 234.81	2661.56 ± 296.12^a	881.206 ± 175.04^{ab}	49.21 ± 29.43	80.62 ± 13.81

M12, whereas enzyme activities increased at M6. Protease activity did not change over time and in response to treatments. Treatment effects were observed only for alkaline phosphomonoesterase and β-glucosidase activities at M12. At M12, alkaline phosphomonoesterase activity was lower in T25 than in T10 and T50, whereas β-glucosidase activity was significantly lower in T25 compared with T10.

Vegetation assessment

The initial turfgrass establishment varied among treatments. At the first sampling date (M1), about one month after sowing, differences in ground cover among the treatments were highly significant, with markedly lower ground cover in T50 (Fig. 3). Later, during the first ten months of vegetation monitoring (up to M10), the differences among treatments - and particularly for T50 - remained significant although smaller. As vegetation developed over time, however, ground cover gradually converged, and no significant differences were detected from M14 until the end of the monitoring period (M18). Harvested biomass did not differ significantly among treatments, except at a single sampling date (M10), at the beginning of the second vegetative season (Fig. 3).

Overall, 43 species of vascular plants were recorded in the plots, including 15 monocots and 28 eudicot herbs, either annual or perennial (Supplementary Information SI 2). Synanthropic and ruderal graminoids (grasses and sedges) were the most abundant groups and shaped the vegetation physiognomy. Dicots were more diverse than monocots but contributed less to the vegetation cover. The most frequent and abundant species were grasses in the Poaceae

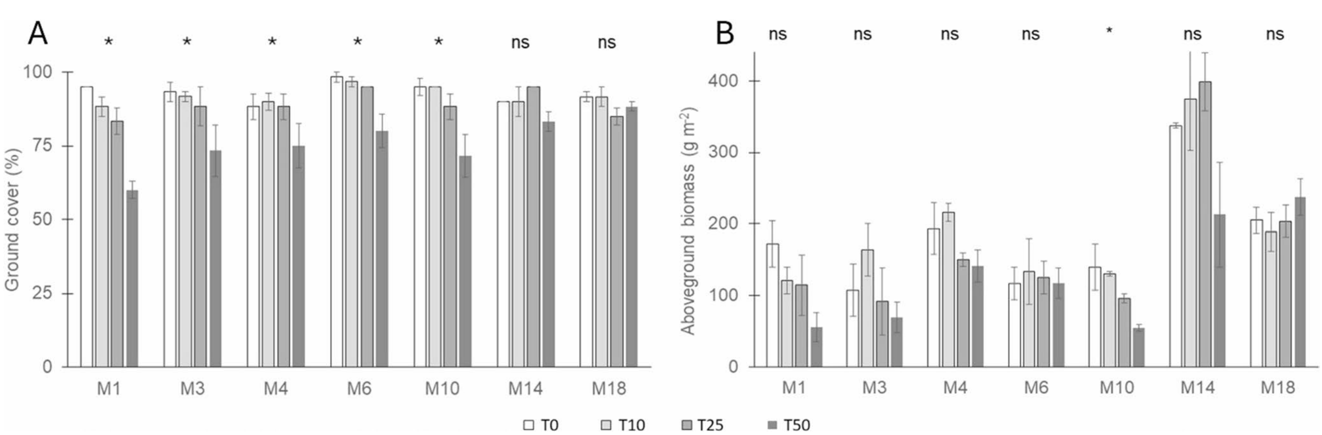

Fig. 3 Ground cover (left, **A**) and dry harvested biomass (right, **B**) in the four treatments (T0, T10, T25, T50) at different sampling date, i.e., 1, 3, 4, 6, 10, 14 and 18 months after sowing. Text above the bars indicates significant (*, $p \leq 0.05$), and non-significant (ns, $p > 0.05$) differences among the four treatments at each date

family (overall 30.2%): *Avena sterilis* (annual, frequency: 83.3%, mean ground cover: 18%) and *Agropyron repens* (perennial, frequency 66.7%, mean cover 15.2%). *Lolium multiflorum*, which was one of the species introduced by sowing, was present and abundant in all plots, with a mean ground cover close to 70%. Other well-represented grasses were *Bromus sterilis* and *Sorghum halepense*. The geophyte *Convolvulus arvensis* (Convolvulaceae) and the therophyte *Sonchus oleraceus* (Asteraceae) were the most frequent dicot herbs (83.3% frequency), though both contributed only marginally to ground cover in all plots. Notably, the deep-rooted umbellifer *Daucus carota* (wild carrot) showed a remarkably high frequency (75%), though with very low ground cover.

Species richness (SR) ranged from 13 to 16 across the treatments (species density range: 1.4-2 m^{-2}), with no significant difference detected (Table 5). Shannon diversity (H') ranged from 0.904 to 2.173, reflecting differences in both species richness and evenness, but did not differ significantly among treatments. Species evenness varied from 0.352 to 0.570, and likewise showed no significant differences.

Discussion

The sealed soil at our study site appeared poorly suited to support a sufficiently rapid recovery of soil ecosystem services and, consequently, its direct restoration was not investigated. Instead, the study focused on assessing the effects of the incorporation of increased amounts of crushed asphalt on various physicochemical and biochemical properties of a compost-amended relocated soil, as well as on plant growth and diversity.

Asphalt can potentially act as a source of contaminants due to its intrinsic composition and the accumulation of traffic-derived pollutants, such as polycyclic aromatic hydrocarbons (PAHs), oils, heavy metals, and residues from brakes and tires (Azadgoleh et al. 2022). However, a previous pot experiment carried out using the same substrates and concentrations applied in this study (Rompato et al. under review) showed that the heavy metals and PAHs concentrations in the leachate remained well below the legal thresholds established for urban green areas, at least in the short-term and under oxic conditions.

Table 5 Plant species richness (SR), Shannon diversity index (H') and species evenness (J) in the plots and treatments. Values are mean ± standard error. According to the Kruskal–Wallis test, no significant differences between treatments were detected ($p > 0.05$)

Treatment	SR	H'	J
T0	13.0 ± 3.0	1.23 ± 0.23	0.48 ± 0.04
T10	14.7 ± 2.9	1.24 ± 0.29	0.46 ± 0.10
T25	13.0 ± 0.0	1.23 ± 0.12	0.48 ± 0.04
T50	16.0 ± 2.0	1.68 ± 0.44	0.60 ± 0.14

Overall, we found that incorporating increasing amounts of crushed (< 2 cm) asphalt into the soil has had some influence on soil physicochemical and biochemical properties and on plant growth. The first evident effect was a shift to a coarser soil texture because part of the incorporated asphalt particles were < 2 mm in size and fell within the sand fraction (Table 1).

Asphalt addition also resulted in higher total carbon content in the soil. Indeed, asphalt comprises mineral grains, usually carbonates, which contributed to the higher TIC values, while bitumen - rich in highly condensed forms of organic carbon and poor in nitrogen - can explain the higher OC and C/N values observed at higher asphalt doses. The OC in bitumen is recalcitrant to microbial degradation (Xia et al. 2025), as highlighted by the biochemical data, which showed a limited effect of asphalt addition on soil basal respiration and enzymatic activities. From an analytical and functional perspective, asphalt addition to the soil can represent a sort of carbon "contamination", as it introduces a highly stable carbon fraction that is hardly released from the soil once it is incorporated and cannot be readily distinguished from the "active" C pool using standard analytical procedures (e.g., dry combustion or Walkley-Black). Under these conditions, the C/N ratio is no longer a reliable indicator of organic matter quality or decomposition dynamics.

Relatively high BD values were recorded at M0, likely as a consequence of the disruption of the pre-existing weak structure during soil mechanical mixing and reconstruction to carry out the experiment (Table 1). At M12, the T50 treatment exhibited a significantly lower BD compared to the control soil at M0. In general, both initial higher BD, due to soil settlement after backfilling, and final lower BD, driven by root activity and soil structuring, were expected outcomes. The latter effect evidently prevailed in the upper 5 cm of soil where root proliferation and organic inputs are greatest. In addition, most of the added asphalt consisted of small gravel-sized particles (2–20 mm), thereby behaving as coarse fragments that typically reduce the bulk density of the fine-earth fraction (Torri et al. 1994), as fine particles cannot pack as closely around larger particles as they do around particles of similar size (Robertson et al. 2021). Therefore, the presence of coarse asphalt fragments seems to influence soil structural dynamics, possibly accelerating the establishment of a more stable physical configuration in the reconstructed soil. Long-term stability and functional implications of this particle arrangement warrant further investigation.

Despite the lower BD with increasing asphalt content, which would be associated with higher soil (macro)porosity, saturated soil hydraulic conductivity (K_{sat}) did not exhibit any consistent trend across treatments; only T25 showed a statistically higher value compared to the other treatments. The presence of small rock fragments can exert complex, non-linear effects on saturated hydraulic conductivity, with the direction and magnitude of the response depending on soil texture, degree of contact between rocks and the surrounding soil matrix, and the amount, size and shape of the stones (Beckers et al. 2016; Sauer and Logsdon 2002). On the other hand, soil moisture in T50 was lower from M5 onward (Fig. 2), i.e., following the cessation of emergency irrigation. Considering the K_{sat} results, a major effect of macroporosity and preferential water flow paths in enhancing drainage and soil drying can be excluded. Consequently, this effect would be mainly due to the presence of non-porous asphalt coarse fragments that, by replacing fine particles that would otherwise store water, decrease the volume of the water-holding matrix (Beckers et al. 2016; Sauer and Logsdon 2002).

The altered water dynamics may have conditioned the lower alkaline phosphatase and β-glucosidase activities observed in T25 at M12, suggesting that enhanced soil drainage has constrained microbial and enzyme activity. Indeed, soil enzyme activities are known to be strongly influenced by soil moisture and water availability (Gomez et al. 2020; Reichart et al. 2025). In this context, as T25 did not exhibit lower soil moisture compared to the other treatments, the observed higher K_{sat} values likely reflects faster water percolation and reduced water residence time in the topsoil matrix, which may indirectly explain the lower β-glucosidase and alkaline phosphatase activities.

Emissions instead exhibited marked seasonality, with higher budgets during M0-M4 and M10-M12 than during M5-M9. This pattern was most evident for CO_2 and likely reflects more favourable temperature and moisture conditions that enhance microbial and root respiration (Karhu et al. 2014). Negative CH_4 fluxes indicated net methane uptake under predominantly aerobic conditions. However, detectable CH_4 emissions emerged during M10-M12, suggesting a temporary shifting toward anaerobic conditions favouring methanogenic processes. Notably, this pattern was not associated with increases in soil moisture or BD, which would typically indicate enhanced anaerobic conditions (Aishwath and Lal 2020), and therefore would warrant further investigation. The slight increase in NH_3 and SO_2 emissions observed during M10-M12 may be linked to progressive soil structuring and enhanced biogeochemical activity following reconstruction, stimulating nitrogen and sulfur transformations in soils (Nugent and Allison 2022; Renella 2020; Zhao et al. 2012). Supporting this interpretation, urease activity increased across the different treatments during M10-M12, providing further insight into the observed NH_3 emissions.

Vegetation establishment following soil de-sealing is pivotal to supporting numerous soil ecosystem services in urban environments (Peroni et al. 2022). Our data show that vegetation establishment is not impaired by the incorporation of some asphalt into the soil, even at high doses, at least in the short term. These results are consistent with Rompato et al. (2025), who reported similar findings under controlled conditions. The diversity of spontaneously colonizing species was also unaffected by asphalt addition during the monitored period. This is likely due to the autoecological and functional traits of the species driving site recolonization, most of which are typical hemerobic and ruderal weeds. These species take advantage of the frequent and intense disturbances to the soil-vegetation system that characterize urban environments, forming the early stages of the successional dynamics dominated by short-lived annuals and often including neophytes (Hill et al. 2002). Their high seed production and persistent soil seed banks facilitate rapid recolonization of urban substrates, thereby playing a key role in vegetation establishment (Albrecht et al. 2011). Notably, herbaceous legumes of the genera *Lotus*, *Medicago*, and *Trifolium* (Fabaceae), possibly originating from the soil seed bank, were observed and may have contributed to improving soil fertility through their symbiosis with nitrogen-fixing rhizobia (Janczarek et al. 2024; Lorite et al. 2018).

Indeed, beyond water availability, low fertility is usually a key constraint for vegetation establishment on urban soils (Heyman et al. 2019). The lower exchangeable Ca, Mg, and Na concentration at M0 in T50 may be related to a dilution effect due to the higher concentration of recalcitrant nutrient-poor asphalt-derived particles into the fine earth. However, no differences among the treatments were detected after one year in terms of CEC and major nutrients. As expected, compost addition contributed to improving fertility of these poor substrates, stimulating microbial activity and favouring the sown turf (Stacey et al. 2019). Moreover, available P increased at M12 in all treatments, likely reflecting improved soil functioning following de-sealing. Enhanced microbial activity may have promoted inorganic P solubilization (e.g., via organic acids) and organic P mineralization through phosphatase activity (Renella 2020; Richardson and Simpson 2011).

Conclusions

In this study we evaluated the effects of incorporating increasing amounts of crushed asphalt into a transported urban soil following a de-sealing intervention, monitoring soil physicochemical and biological properties as well as vegetation establishment and diversity. Asphalt incorporation at the highest dose (50%) modified some soil physical properties, particularly texture, bulk density and hydraulic behaviour. After one year, BD decreased more markedly at higher asphalt doses, suggesting stronger structural reorganization of the reconstructed soil under these conditions; this was accompanied by reduced water retention that, however, did not cause persistent adverse effects on soil chemical fertility, microbial activity, gas emissions, or plant performance and diversity. The highest asphalt dose, however, implied a transient significantly slower initial turfgrass establishment. These findings indicate that reusing asphalt generated during de-sealing operations represents a technically viable and environmentally sound strategy, even at relatively high incorporation rates (25%). Nonetheless, long-term monitoring is needed to assess the persistence of soil functions and ecosystem services over time. Overall, the in situ reuse of removed asphalt within constructed urban soils can reduce de-sealing costs and limit waste generation without hindering soil and vegetation recovery, thereby contributing to more sustainable urban land management. Further long-term investigations are required to evaluate the validity of this approach under varying conditions and to define site-specific safe and optimal asphalt incorporation thresholds. This and any other approach able to improve material circularity and enhance de-sealed soil functionality represent valuable steps toward more sustainable and widely applicable de-sealing practices.

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Declarations

Competing interests The authors declare no competing interests.

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