Urban Forestry & Urban Greening 124 (2026) 129593

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Consequential life cycle assessment of nature-based solutions for land restoration in Turin (Italy) and its first-belt municipalities

Martina Della Casa [a,b], Benedetto Rugani [a,c,*], Gabriele Guidolotti [a,c], Chiara Baldacchini [a,d], Carlo Calfapietra [a,c]

[a] Research Institute on Terrestrial Ecosystems (IRET), National Research Council of Italy (CNR), Via G. Marconi 2, Porano, Terni 05010, Italy
[b] Department for Innovation in Biological, Agro-Food and Forest System, University of Tuscia, Via S. Camillo De Lellis snc, Viterbo 01100, Italy
[c] National Biodiversity Future Centre (NBFC), Piazza Marina 61, Palermo 90133, Italy
[d] Department of Ecological and Biological Sciences, University of Tuscia, Largo dell'Università, Viterbo 01100, Italy

ARTICLE INFO

Keywords:
Carbon uptake
Disability Adjusted Life Year (DALY)
Health impact assessment
Particulate Matter (PM)
Urban forestry
Soil rehabilitation

ABSTRACT

Urban and peri-urban soils are increasingly degraded by land consumption and surface sealing, with adverse consequences for ecosystem functioning, climate regulation, and human health. Nature-based Solutions (NbS) combining reconstructed soils with urban tree and shrub planting have emerged as promising strategies for land restoration, yet their system-wide environmental and health implications at metropolitan scale remains poorly understood. This study develops an ex-ante, time-dependent consequential life cycle assessment (CLCA) to evaluate a large scale technosol-based NbS programme in Turin (Italy) and its first-belt municipalities, covering ~200 ha of degraded land. The intervention was modelled through a 15-year phased roll-out followed by a 60-year operational lifetime, explicitly accounting for marginal material supply activation, capacity-constrained supplier switching, transport dynamics, and end-of-life activities. Environmental impacts on human health were balanced against the benefits associated with carbon sequestration and air pollution removal. Results show that NbS implementation entails substantial environmental burdens during the deployment phase, primarily driven by technosol production and material handling. These impacts peak within the first 15 years, after which a growing supply of ecosystem services generate net annual climate and air quality benefits. Carbon break-even is reached after approximately 45 years, while air pollution-related impacts become net negative after about 61 years. This study demonstrates the long-term benefits for human health and the material-related tradeoffs associated with large scale implementations of technosol-based NbS, advancing the methodological foundation for policy-relevant urban land restoration assessment.

Short synopsis statement

By developing an ex-ante, time-dependent consequential life cycle assessment that incorporates an ecosystem service accounting, we show that large scale technosol-based NbS (nature-based solutions) can deliver long-term net climate- and air pollution-related health benefits. However, these benefits are partially offset by non-climate damage pathways (primarily human toxicity) arising from upstream material production, transport, and processing.

1. Introduction

Urban expansion and artificial land appropriation are accelerating soil degradation and the decline of ecosystem services across European Union Member States, where sealed surfaces increased by around 3606 km^2 (by ~3.4%) between 2006 and 2018 (European Environment Agency, 2024). In Italy alone, nearly 84 km^2 of land were converted to artificial surfaces in 2024, reinforcing concerns about the loss of soil functions and related ecosystem services (ES) (Imbrenda et al., 2021; ICLEI Europe, 2021; SNPA, 2025).

All these processes of land take, soil sealing, and artificial surface expansion not only undermine ecological functionality and climate

* Corresponding author at: Research Institute on Terrestrial Ecosystems (IRET), National Research Council of Italy (CNR), Via G. Marconi 2, Porano, Terni 05010, Italy.
E-mail address: benedetto.rugani@cnr.it (B. Rugani).

https://doi.org/10.1016/j.ufug.2026.129593
Received 23 March 2026; Received in revised form 25 June 2026; Accepted 3 July 2026
Available online 4 July 2026

resilience but also generate measurable adverse consequences for human health. Impervious urban surfaces intensify urban heat island effects by several degrees Celsius, with temperature differences of 2–6°C reported between highly sealed and vegetated areas during heat wave events (Zawadzka et al., 2021). Epidemiological evidence indicates that each 1°C increase in daily temperature is associated with approximately 2–3% increases in heat-related mortality and emergency hospital admissions (Singh et al., 2024). In parallel, urban land conversion and reduced vegetation cover are associated with higher ambient concentrations of fine particulate matter ($PM_{2.5}$) (Della Casa et al., 2025). A 10 μg/m^3 increase in daily $PM_{2.5}$ has been linked to a 1–3% increase in all-cause mortality and cardiopulmonary hospital admissions (Ridlington et al., 2020; Southerland et al., 2022; Della Casa et al., 2025). Reduced ES provision, including diminished pollutant removal and microclimate regulation, thereby translates into quantifiable increases in respiratory and cardiovascular risk among exposed urban populations.

As a result, the restoration of degraded urban land has become a strategic priority within European climate adaptation, public health, and sustainable land use agendas (World Health Organization WHO, 2016; Montanarella and Panagos, 2021; Greening Cities Partnership, 2024). Within this context, Nature-based Solutions (NbS) have gained increasing attention as cost-effective and multifunctional approaches to address environmental degradation while delivering co-benefits for ecosystems and society (Xie et al., 2022; Greening Cities Partnership, 2024; Lozano et al., 2025). Among these, technosol-based NbS that combine regenerated soils (technosols) with urban tree and shrub planting have emerged as promising approaches to rehabilitate degraded lands and re-establish multifunctional ecosystem processes at metropolitan scale (Nicese et al., 2021; Rugani et al., 2024; Manzini et al., 2025; Antenucci et al., 2025). Overall, literature shows that such green areas can reduce urban land surfaces temperatures by 1–4°C, local PM concentrations by 7–24%, heat-related mortality by 2–3% and all-cause mortality and cardiovascular mortality by up to 8 and 16% respectively (Liu et al., 2022; Mueller et al., 2022; Nazish et al., 2024; Della Casa et al., 2025).

A recent case-study of successful implementation of a technosol-based NbS has been investigated in the municipality of Turin, Italy (Ascione et al., 2021; Rugani et al., 2024; Della Casa et al., 2025; Chialva et al., 2026). Previous studies related to this case-study demonstrated the technical feasibility of producing technosols from locally available excavation soils and municipal compost (Ascione et al., 2021), quantified the environmental performance of the intervention (Rugani et al., 2024), documented its capacity to support tree establishment and ecosystem functioning (Chialva et al., 2026), and estimated the associated air quality and human health benefits associated with PM removal (Della Casa et al., 2025). Turin was the city chosen to host such case study because it faces several challenges related to land rehabilitation in post-industrial landscapes both within the metropolitan area and its first-belt municipalities (Biasin et al., 2023; Dogan et al., 2023; Hosseini, 2025; Liao, 2025). Such areas often combine sealed surfaces, altered soil structure and legacy contamination, hence making conventional revegetation (and hence ES provision) difficult without substrate reconstruction. Accordingly, a specific type of technosol was produced through a circular-economy approach (Ascione et al., 2021), combining locally available excavation soil, compost derived from municipal bio-waste, and mineral amendments (e.g., zeolite or expanded clay), blended following predefined ratios to restore soil structure and functionality.

Despite NbS growing adoption in urban contexts, their system-wide environmental consequences remain insufficiently quantified and limited to relatively small-scale interventions (Nicese et al., 2021; Moinel et al., 2024; Rugani et al., 2024; Manzini et al., 2025). Only a limited number of studies have focused on the environmental impact assessment of NbS, mostly on urban afforestation alone (without soil substrate implementation) and adopting an attributional life cycle assessment (ALCA) approach (Lesage et al., 2007; McPherson and Kendall, 2014; Nicese et al., 2021; Moinel et al., 2024; Antenucci et al., 2025; Manzini et al., 2025; di Cristofaro et al., 2026; Van den Auwelant et al., 2026).

Through ALCA, one can transparently reproduce a profile of average environmental impacts for each NbS system, using consolidated inventory data about energy and raw materials, and enabling comparisons among NbS if system boundaries and functional units are consistently defined (Larrey-Lassalle et al., 2022). However, literature shows that the ALCA method is not suited to capture marginal market responses, displaced production, or avoided burdens (Schaubroeck et al., 2021; Ekvall and Weidema, 2004). In the case of technosol-based NbS, for example, ALCA might not allow to capture the partial diversion of excavated soil and/or organic waste from landfill disposal that can occur should technosols be produced and applied at large scale, or the additional supply required to compensate for such material diversion elsewhere in the system. In other words, to make a parallel with other territorial production systems from the literature (Rehl et al., 2012; Bernstad Saraiva et al., 2018; Brandão et al., 2014, 2024), the contribution of an isolated technosol-based NbS to the land use sustainability of an urban area remains uncertain when the LCA is limited to specific restoration sites and not integrated with the broader socioeconomic system of the city.

In contrast, consequential LCA (CLCA) is specifically designed to estimate the environmental consequences of decisions by modelling how supply chains, material flows, and waste management pathways change in response to an intervention (UNEP/SETAC Life Cycle Initiative, 2011; Sala et al., 2016; Ekvall, 2019; Finnveden et al., 2009; Schaubroeck et al., 2021; Brandão et al., 2024). When implemented at market or territorial scales, such interventions may reshape the demand of goods and services, activate marginal suppliers, change transport logistics, and modify end-of-life routes for waste and discarded materials (Ekvall, 2019; Finnveden et al., 2009; Schaubroeck et al., 2021). Neglecting these system-wide dynamics can lead to both under- and over-estimation of environmental trade-offs and of the potential human-health benefits associated with NbS in urban contexts.

Recent methodological advances in ex-ante and prospective CLCA attempt to incorporate future technological and market transitions when modelling the impact generated by large scale policy decisions and system changes (e.g., Maes et al., 2021; Maes et al., 2023). These approaches reflect a growing recognition that the evaluation of land restoration interventions as well require a long-term perspective to effectively inform sustainable urban planning and investment strategies, which also emerges from the environmental cost-benefit literature on NbS (Calfapietra et al., 2025; Celletti et al., 2025; United Nations Economic Commission for Europe UNECE, 2025).

However, despite their increased methodological sophistication, current prospective CLCA frameworks rarely represent the progressive, phased roll-out that characterizes the real-world (Pizzol et al., 2021; Nurdiwati et al., 2025). As a consequence, particularly in emerging applications such as land restoration where CLCA studies remain extremely limited (e.g., Lesage et al., 2007), NbS life cycle models should explicitly account for dynamic features including the gradual expansion of intervention areas, the associated evolution of supply chains, shifts in marginal production technologies, changing transport distances, and cumulative environmental effects.

On the other side, the environmental co-benefits provided by restored soils and urban vegetation, particularly carbon sequestration and the removal of airborne particulate matter (PM) through canopy deposition, have increasingly been explored in recent years, often through the combination of ecosystem service models and LCA (Alshehri et al., 2023; Antenucci et al., 2025; Babí Almenar et al., 2023; Favaretto et al., 2025; Schaubroeck et al., 2013; Taelman et al., 2024; Vander-Wilde and Newell, 2021; Yadav and Goyal, 2022). Nonetheless, these benefits are typically assessed outside the context of consequential LCA frameworks. Moreover, human health considerations are seldom integrated in a manner that enables ecosystem service–related benefits, particularly those derived from experimental data, to be consistently and methodologically aligned with health damage indicators (Hardaker et al., 2022).

In summary, despite the growing literature on urban NbS, several important knowledge gaps remain. First, most LCAs of urban greening interventions have adopted attributional approaches and therefore do not capture market-mediated consequences, material substitutions, avoided waste-management pathways, or changes in supply-chain behaviour induced by implementations at large scale. Second, existing studies rarely represent the phased deployment dynamics that characterize real world restoration programmes, where intervention areas expand progressively over time and interact with evolving supply-chains. Third, benefits gathered from ecosystem services, particularly carbon sequestration and air pollution removal, are generally assessed separately from consequential life cycle frameworks, limiting the evaluation of net environmental outcomes. Finally, human health implications are seldom quantified within a unified framework that consistently integrates environmental burdens and ecosystem service-related benefits using comparable health impact assessment indicators.

No previous study has assessed technosol-based NbS implementation scenarios at relatively large territorial scale using cradle-to-grave consequential LCA frameworks capable of simultaneously accounting for (i) phased restoration-oriented deployment, (ii) marginal supply activation and substitution pathways, (iii) end-of-life possible feedback and alternative routes, and (iv) ecosystem service-related benefits at urban and peri-urban scale. Therefore, addressing these dimensions within a unified framework would contribute substantially to overcoming the aforementioned knowledge gaps.

In the light of this, the present paper elaborates an ex-ante CLCA model of a large scale technosol application combined with tree and shrub planting on ~200 ha of degraded land across Turin (Italy) and its first-belt municipalities. The model builds upon the ALCA framework of Rugani et al. (2024). However, it goes beyond it by incorporating the annual expansion of rehabilitated areas and the associated temporal evolution of marginal material supply (i.e., the progressive activation of local, regional, and fallback sources of excavated soil, compost, and zeolite), material substitution pathways, transport dynamics, and system-level environmental outcomes. These are understood as the combined effects of changes in material sourcing, transport and waste management practices across the urban restoration areas of the city.

The key novelty of this work lies in the joint integration of technosol life cycle representation, phased large scale deployment, and human health assessment (from experimentally derived data of PM deposition) within a CLCA modelling framework. By accounting for ES in support of the human health impact quantification, this study contributes to the state of the art on urban and peri-urban NbS planning and design. To the best of the authors' knowledge, it provides the first cradle-to-grave CLCA of technosol-based land rehabilitation at metropolitan scale, grounded in territorially contextualized intervention areas and related market supply-chains. It also offers robust, policy-relevant insights to support sustainable land use planning, climate adaptation strategies, and evidence-based environmental governance data.

2. Materials and methods

2.1. Pilot site: "New Soil"

The present study builds upon the "New Soil" pilot site implemented within the metropolitan area of Turin, designed as a demonstrative NbS intervention for the restoration of degraded urban land through the application of technosol and tree planting. The pilot covers an area of approximately 1200 m^2 and is located along the banks of the Sangone River, within the "Parco del Sangone" area in the southern sector of the municipality of Turin (45.009102° N, 7.641204° E; Della Casa et al. 2025). The site consists of an urban forest plot created ex novo on a previously degraded and underutilised urban area.

The intervention was developed within the framework of the EU Horizon 2020 proGIreg project (Productive Green Infrastructure for post-industrial urban regeneration; Grant Agreement n° 776528; Baldacchini and Calfapietra, 2023). Site implementation and coordination were led by Environment Park, with contributions from several consortium partners and local stakeholders, including DUAL Srl (construction and site works), the University of Turin (environmental monitoring activities), ACEA (compost provision), CCS (biotic compound provision), and the City of Turin, Città Metropolitana di Torino, and ARPA Piemonte for administrative and regulatory support (Ascione et al., 2021).

The Technosol applied at the pilot site was produced following circular economy principles, using locally sourced excavation soil and organic amendments recovered within the same municipal context. Detailed descriptions of the pilot implementation, technosol composition, monitoring activities, and ALCA results are provided in Ascione et al., 2021; Rugani et al. (2024) and Della Casa et al. (2025).

2.2. NbS implementation areas

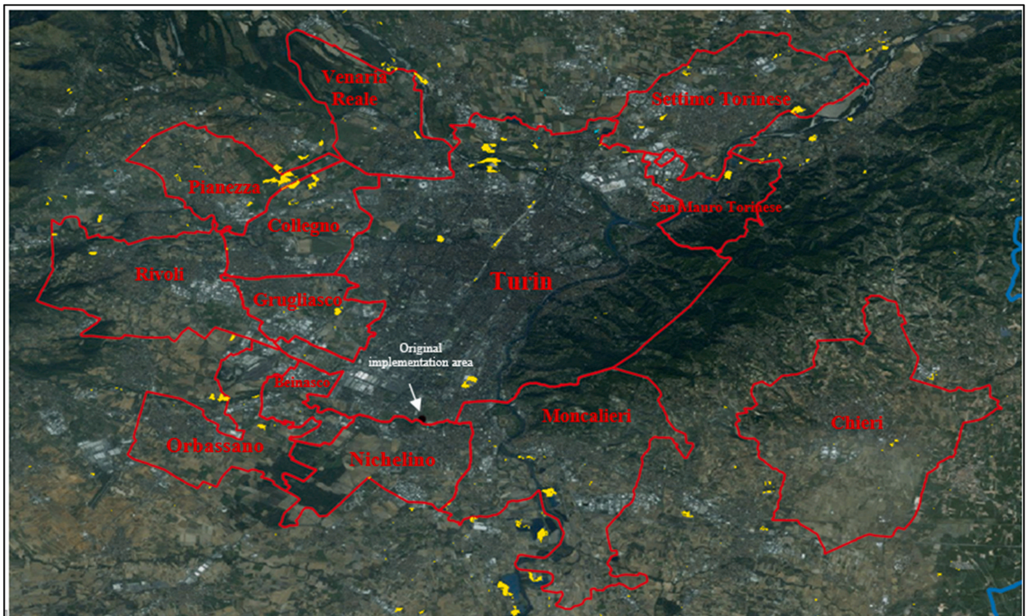
Building upon the real-scale implementation tested at the pilot site, this study develops a spatially explicit model of built forest areas established on technosol substrates across urban and peri-urban lands identified as suitable for rehabilitation within the metropolitan area of Turin.

Spatial analyses were performed using QGIS v3.28–3.34 (QGIS Development Team, 2023) and official ISPRA land consumption datasets (SC_2023_LAEA_v5; SC_2023_UTM32N1). All spatial processing was conducted in the ETRS89–LAEA coordinate reference system (EPSG:3035) to ensure metric consistency across the metropolitan area. The land consumption raster was first clipped to the administrative boundaries of Turin and its first-belt municipalities and subsequently polygonised to convert raster cells into vector features. Only land use classes DN12 (reversibly consumed soils), DN126 (other artificial covers), and DN202 (permeable infrastructural areas) were retained for further analysis.

The resulting polygons were spatially intersected with municipal boundaries to assign each feature to its corresponding municipality. A dissolve operation by municipality and land use class was then applied to merge contiguous polygons of the same class within each administrative unit. Surface areas were calculated in hectares for each resulting polygon and aggregated at the municipal level. This resulted in the selection of 200.38 ha of potentially recoverable, currently degraded and unsealed land across the metropolitan area of Turin and its first-belt municipalities (Fig. 1).

Then, to derive representative transport distances for consequential modelling between the technosol production area (cava di Collegno, 45.111788° N, 7.601594° E) and the identified implementation areas, municipal centroids were computed and used as proxies for the average spatial location of restoration activities within each municipality (as reported in the Supplementary Material 1, SM1, Section S1). Euclidean distances between municipal centroids and the reference excavation site (still Cava di Collegno) were calculated using the *Distance to Nearest Hub* tool (QGIS Development Team, 2023). This centroid-based approach was intentionally adopted to provide a spatially integrated and scale-consistent estimate of average transport distances, suitable for metropolitan-scale CLCA applications, where the objective is to characterize mean supply-chain behaviour rather than route-specific logistics.

The resulting spatial dataset, comprising total recoverable area per municipality and corresponding centroid-based transport distances, was subsequently used to scale the pilot-site results to the metropolitan level and to parameterize transport distances within the phased consequential LCA framework.



Land type	Label	Area (ha)
Reversible consumed land		197.64
Artificial covers not connected to agricultural activities, whose removal would restore the initial soil conditions		1.86
Permeable areas enclosed between road junctions and roundabouts, and service areas associated with road infrastructures		0.88

Fig. 1. Spatial distribution of degraded and potentially recoverable land suitable for technosol application and tree/shrub planting in Turin and its first metropolitan belt. Municipal boundaries are shown in red. Areas are classified into three main land consumption categories: (i) reversibly consumed soils (197.64 ha), (ii) artificial covers not connected to agricultural activities whose removal would restore original soil conditions (1.86 ha), and (iii) permeable roadside and infrastructural green spaces (0.88 ha).

2.3. *Ex-ante consequential LCA approach*

A CLCA framework was developed in Brightway v 2.4.7 (Mutel, 2017) using the ecoinvent 3.9.1 consequential database (Wernet et al., 2016). The system boundary, represented in Fig. 2, followed a cradle-to-grave perspective and included raw material provision (excavated soil, compost, zeolite, expanded clay, biostimulants), technosol mixing and field application, transport processes, nursery production of trees and shrubs, planting and establishment, and end-of-life (EoL) management of both technosol components and biomass.

2.3.1. *Counterfactual modelling and system expansion logic*

The CLCA framework was based on two counterfactual modelling scenarios (Fig. 2): a Business-as-Usual scenario (BaU, model reflecting the *status quo*, without any NbS intervention), and a Technosol-based NbS Scenario (TS, model including the NbS intervention projects). Under BaU conditions, the identified degraded areas were assumed to remain in their existing unmanaged state, with no restoration activities taking place. The inputs of raw materials and products normally required by the NbS system (following the recipe of life cycle inventory developed in Rugani et al., 2024) were therefore assumed to continue along their present, documented destination pathways within the socioeconomic system of the Turin metropolitan area and first-belt municipalities (SM1, Section S3). In TS, the same inputs were instead inventoried to model the technosol-based NbS implementation over the identified areas.

Consequential changes in environmental burdens were represented through “system expansion by substitution”, a modelling approach that explicitly accounts for the alternative fates of materials under BaU conditions (Heijungs et al., 2021; Ruini et al., 2025). For materials with a consolidated and documented local value chain, such as excavated soil, organic waste and zeolite, input flows in the BaU models were assigned a non-zero value based on current practice of consumption in Turin and its first belt. Specifically, under BaU conditions:

(i) excavated soil is predominantly recovered and used as inert material for backfilling and low-value construction applications (~70%), while the remaining fraction is disposed of in landfills (ISPRA, 2022; Cristóbal et al., 2024);
(ii) organic waste treated through composting is mainly valorised as a soil improver in agricultural systems, including peri-urban areas, and in urban green applications, while only a minor fraction is directed to low-value reuse or disposal; allocation shares (e.g., 60–30–10%) are parameterised based on literature-informed assumptions (Bruni et al., 2020; ISPRA, 2022);
(iii) zeolite is primarily used in water and air filtration applications (~50%), followed by landfilling (~20%) and construction-related uses (~30%), reflecting current market outlets in the Turin and first-belt context (Market Reports World, 2025).

In the project scenario (TS), the same amount of those material flows was diverted from their BaU destinations and only used for technosol production. Importantly, the underlying materials demand associated with BaU uses was assumed to persist.

An exception applied to the fraction of materials that, under BaU conditions, would have been disposed of in landfill. This fraction was directly diverted to technosol production in TS, leading to partial avoidance of landfill treatment burdens and reducing the amount of material that should be supplied from alternative sources. Subsequently, the net marginal demand in TS equalized the total material requirement

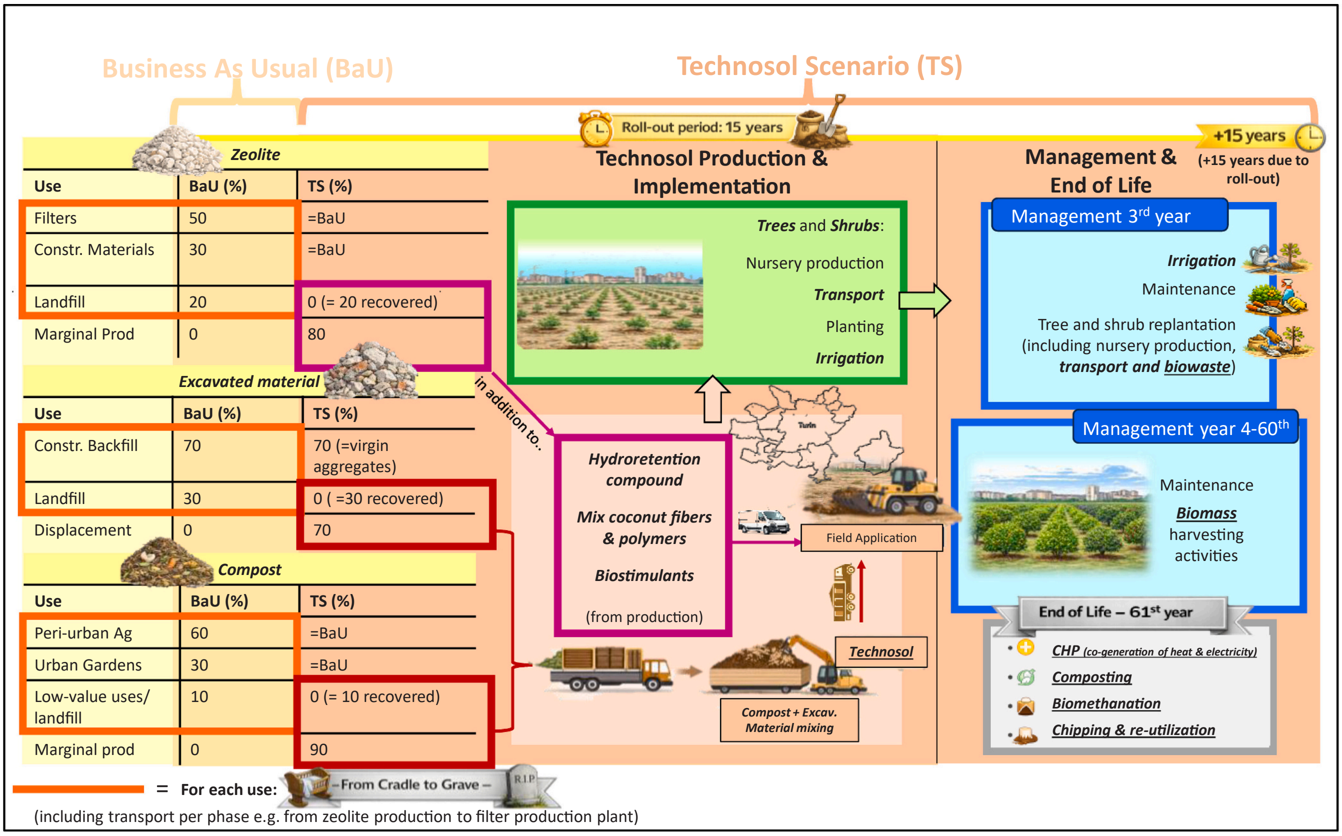


Fig. 2. System boundaries of the CLCA model; BaU = Business as Usual; TS = Project scenario of technosol production and application at large scale as substrate for planting in the NbS implementation. Processes and material flows are represented from cradle to grave. Elements shown in bold and italic indicate input flows to the system, whereas elements shown in bold, italic and underlined represent output flows generated by the system.

minus the fraction recovered from landfill diversion.

Large scale nursery production, plantation, and long-term management activities specifically associated with the restoration of degraded and unsealed soils were not documented as ongoing or marginally expanding practices in the assessed areas prior to project implementation. Consequently, under BaU conditions, no dedicated demand for these services was identified in relation to the targeted restoration areas. This also applied to mycorrhizal inocula, hydro-retention agents, and fibre or polymer-based soil conditioners, all niche inputs lacking a consolidated local market in the Turin area and whose BaU demand is also currently negligible. For these inputs, BaU flows were therefore set to approximately zero, and additional demand in TS was assumed to be met entirely by marginal production and capacity-constrained supplier switching, with associated revisions of transport distances. This assumption was considered appropriate given that, even under the phased large scale implementation, the projected demand remains small relative to the overall production capacity and market size of these inputs at the regional or European level and is therefore unlikely to induce structural market shifts or capacity expansion.

It is worth noting that an intermediate scenario could have been evaluated as a separate counterfactual scenario, i.e., tree planting without prior soil regeneration, as previously assessed (e.g., Nicese et al., 2021; Antenucci et al., 2025; Manzini et al., 2025). However, the approach followed in the present study was to model the combined soil–vegetation intervention as an integrated, decision-induced system change. This framing is consistent with CLCA principles, which require the modelling of structural modifications in material flows triggered by a decision (Ekvall & Weidema, 2004; Schaubroeck et al., 2021) and aligns with circular economy perspectives in which material recovery and ecosystem restoration are jointly considered.

2.3.2. *Modelling of marginal supply, capacity constraints and temporal dynamics*

The implementation of NbS-based restoration programme was modelled as a phased roll-out over 15 years, reflecting logistical, infrastructural, and administrative constraints in the metropolitan area of Turin. The roll-out followed a progressive increase in restored area (from 1 ha yr^{-1} in the initial pilot phase to a stable, capacity-constrained implementation rate of approximately 20 ha yr^{-1} during the core deployment period (years 8–14; SM1, Sections S3 and S6). This rate is consistent with the capacity of local composting facilities, and with transport distances remaining predominantly within 25–35 km during this phase. The final year corresponds to a completion phase, reaching the total restored area of 200.38 ha. This overall time frame was also aligned with typical municipal planning cycles, enhancing the policy realism of the scenario.

The phased roll-out was explicitly represented in the ex-ante CLCA. Annual intervention cohorts were simulated sequentially, such that each year contributed both to cumulative environmental impacts and to the annual activation of marginal suppliers. As demand increased over time, supplier switching occurred from local to regional and fallback sources according to predefined capacity limits and distance thresholds. The temporal boundary of the CLCA extended over 75 years, encompassing the full implementation phase (totalling 15 years) and the subsequent 60-year lifetime of the planted trees, during which ES and end-of-life processes were accounted for.

2.4. *Ecosystem service accounting procedure*

Benefits provided through ES supplied by the NbS were quantified in terms of carbon sequestration and $PM_{2.5}$ removal provided by the planted vegetation. The assessment was based on the tree species established within the New Soil pilot site (*Celtis australis*, *Quercus ilex*, *Malus* 'Evereste', *Tilia cordata* and *Gleditsia triacanthos*) and on the shrub species (*Elaeagnus* × *ebbingei*, *Ligustrum texanum*, *Physocarpus opulifolius* 'Diable d'Or', *Spiraea vanhouttei* and *Teucrium fruticans*). Species-specific leaf area development and biomass growth were derived from allometric relationships implemented in i-Tree Eco v6 (available at: https://www.itreetools.org/i-tree-tools-download; last access in June 2026), linking tree structural attributes (e.g., DBH, height and crown dimensions) to leaf area and biomass.

Annual carbon sequestration was estimated through simulated biomass accumulation and carbon stock dynamics generated by i-Tree Eco. $PM_{2.5}$ removal was quantified by combining experimentally derived deposition fluxes obtained from SEM/EDX leaf-surface analyses (Della Casa et al., 2025) with species-specific leaf area development. ES flows were quantified at the spatial scale of 1 ha and subsequently upscaled to the full restoration area according to the phased deployment schedule. The large scale deployment scenario assumed approximately 500 trees ha^{-1} and 500 shrubs ha^{-1} , corresponding to 100,190 trees and 100,190 shrubs across the 200.38 ha restoration programme. Further information regarding species-specific parameters, allometric equations, growth models, carbon sequestration estimates and $PM_{2.5}$ removal calculations is provided in the SM1 (Sections S4 and S6).

In addition to vegetation-driven services, soil-related climate services were explicitly represented for both counterfactual worlds (BaU and TS). In the BaU case, degraded and unmanaged soils were assumed to exhibit ongoing soil organic carbon (SOC) loss (and associated greenhouse gas - GHG releases), whereas under the technosol scenario soils were assumed to undergo SOC recovery and stabilization following restoration.

Because long-term, site-specific SOC trajectories for Turin's degraded soils were not empirically available at metropolitan scale, soil carbon stock-change rates (loss under BaU; recovery under TS) were parameterized using values from the literature and then applied consistently across the assessed time horizon. More specifically, data to model SOC loss and gain were retrieved from peer-reviewed literature on long-term soil carbon dynamics in degraded urban soils, and on SOC recovery following soil reconstruction or amendment interventions (e.g., technosol application) (Pouyat et al., 2006; Edmondson et al., 2012; Morel et al., 2015; Ugolini et al., 2020; further information are reported in the SM1, Section S5). These soil carbon dynamics were modelled as annual CO_2-equivalent fluxes and combined with vegetation sequestration to account for the net climate regulation service balance of the restoration programme over time.

2.5. Impact assessment framework

Environmental impacts in the Life Cycle Impact Assessment (LCIA) phase were characterized using the ReCiPe 2016 v1.03 method (Huijbregts et al., 2017). The Hierarchist (H) cultural perspective was adopted, representing the consensus-based modelling approach and the recommended default option. Two complementary LCIA levels were applied to both BaU and TS scenarios; these do not usually refer to different temporal phases of the life cycle, but to different positions along the cause–effect chain linking elementary flows to final damage:

(i) midpoint impact indicators were used to identify trade-offs across key stressor pathways relevant to urban restoration and associated impacts for humans; the selected midpoint categories included: climate change (GWP_{100}) and particulate matter formation (PMFP). GWP_{100} quantifies the radiative forcing impact of greenhouse gas emissions over a 100-year time horizon, expressed in kg CO_2-equivalents (only GWP hereafter, for simplicity). This indicator captures the contribution of life cycle processes to global warming and associated climate-related risks. On the other side PMFP, expressed in kg $PM_{2.5}$-equivalents, quantifies the potential formation of fine PM resulting from precursor emissions (e.g., NO_x, SO_2, NH_3). This category represents air quality-related pressures directly linked to respiratory and cardiovascular health effects. These indicators were prioritised as they are directly aligned with the core ES assessed in this study. Specifically, climate change captures carbon-related effects associated with soil and vegetation dynamics, while PM formation reflects air quality-related processes that are directly linked to vegetation-driven $PM_{2.5}$ removal. The selection therefore ensures conceptual consistency between the life cycle impact assessment and the ecosystem service-based health benefit quantification;

(ii) endpoint impact indicators for human health damage assessment were used expressing harmful effects for people in Disability Adjusted Life Years (DALYs). At this level, selected midpoint categories relevant for assessing the impact on human health ("_hh") were integrated along their cause–effect pathways and translated into the common DALYs' metric. Specifically, the endpoint results included the contributions from climate change (CC_hh), particulate matter formation (PMF_hh), human toxicity – cancer and non-cancer effects (HTPc_hh, HTPnc_hh), ionising radiation (IR_hh), ozone depletion (ODP_hh), photochemical oxidant formation (POF_hh), and water consumption (WU_hh).

In this study, the ReCiPe long-term (LT) variant was adopted to ensure internal consistency across categories where LT is the recommended harmonized set (Huijbregts et al., 2016), and to avoid mixing characterization sets that were not strictly comparable.

To ensure metric consistency between life cycle-related burdens and ES-related benefits, vegetation-driven $PM_{2.5}$ removal in the TS scenario was translated into avoided human health damage. The removed $PM_{2.5}$ mass was converted into DALYs using ReCiPe 2016 global damage factors under the same H endpoint perspective applied in the LCIA.

These avoided DALYs thus represented an additional health-benefit component expressed in the same damage metric (DALYs) as the endpoint human health burdens associated with the life cycle inventory of the technosol-based NbS system. In the TS scenario, total DALYs therefore included both (i) endpoint human health burdens from all life cycle foreground activities and (ii) avoided DALYs derived from ES-related $PM_{2.5}$ removal, as well as climate-related effects were mapped through endpoint categories (further methodological details are provided in the SM1, Section S6).

The net health balance of the restoration programme was calculated as the difference in total DALYs between BaU and TS over the full model time horizon (and BaU-related DALYs thus represented the counterfactual system without restoration and without ecosystem service gains).

2.6. Uncertainty and sensitivity analyses

Monte Carlo uncertainty propagation was performed in Brightway2 using MonteCarloLCA (N = 1000). The two BaU and TS systems were evaluated and compared for each relevant life cycle activity (i.e., compost and zeolite production systems, excavation process). To ensure paired sampling (common random numbers) and thus reduce Monte Carlo noise in the comparison, the same random seed (= 42) was set immediately before instantiating the BaU and the with-project MonteCarloLCA objects. The sole endpoint CC_hh-DALY indicator was used because considered most meaningful to characterize model uncertainty, as explained in Section 3.4.

Sensitivity was further assessed via a targeted One-at-a-Time (OAT) analysis on the most influential parameters (i.e., life cycle activities), including technosol production, transport and field-application logistics, and the excavated soil and compost production systems. Each parameter was perturbed by ±20% around its central estimate to quantify the elasticity of the climate-change-related human health endpoint across the health-relevant impact pathways. The selected perturbation range reflected realistic operational variability affecting site-specific foreground inventories, rather than probabilistic uncertainty. In this context, the ±20% variation was consistent with established LCA practice (Hamby, 1994; Heijungs and Huijbregts, 2004; European Commission, 2010; Maes et al., 2021; Reinhard et al., 2022).

Uncertainty arises primarily from implementation conditions such as applied quantities, process efficiencies, transport distances, logistical performance, and the allocation of avoided material flows. Accordingly, the OAT analysis provided an order-of-magnitude estimate of result sensitivity under feasible implementation variability, complementing the uncertainty propagation assessed through Monte Carlo simulation.

3. Results

3.1. Midpoint impact assessment

Figs. 3a and 3b illustrate, respectively, the absolute scores and the relative contribution of individual life cycle processes to the selected midpoint impact categories, namely GWP and PMFP, for both the BaU and the TS scenarios across the full implementation area (200.38 ha).

TS shows overall higher midpoint burdens than those from BaU for the two impact categories considered. For GWP, the dominant contributors in TS are technosol production, accounting for approximately 151,000 t CO_2-eq., and the management of excavated inert material, contributing about 61,000 t CO_2-eq. (an amount around 90% higher than that generated with the BaU scenario). Additional contributions are associated with compost processing, technosol application, and NbS management during the years from the 4th to the 60th, reflecting recurring maintenance activities represented in the CLCA model.

The end-of-life (EoL) phase generates a counterbalancing credit of about −2791 t CO_2-eq., based on the weighted mix of alternative EoL routes assumed in the scenario analysis. These consist of CHP (co-generation of heat and electricity, ~35%), composting (~50%), biomethanation (~0%), and chipping and reutilisation (~15%), with the latter being the only route associated with a net positive GWP contribution (further information are reported in Section S3 of the SM1). Overall, EoL processes contribute less than 1% to the total GWP relative in the TS.

A similar pattern emerges for PMFP. This category is overwhelmingly dominated by technosol production in TS, with an impact of approximately 423,000 kg $PM_{2.5}$-eq., followed by excavated inert material flows for an amount around 86% lower in absolute terms. In BaU, excavation-related flows instead generate an avoided burden of more than 5000 kg $PM_{2.5}$-eq. EoL processes further provide an additional avoided PM burden of more than 7000 kg $PM_{2.5}$-eq., although this credit remains limited relative to the dominant contribution from technosol production, corresponding to an estimated reduction of only about 1–2% of the total PMFP score. Overall, when only life cycle material and process flows are considered, large scale technosol-based NbS implementation is associated with substantial upstream GHGs burden, while PM formation impacts are largely driven by material production and transport-related processes.

3.2 Ecosystem service assessment

To assess the overall environmental performance of the TS scenario beyond its material and energy consumptions, and thus related

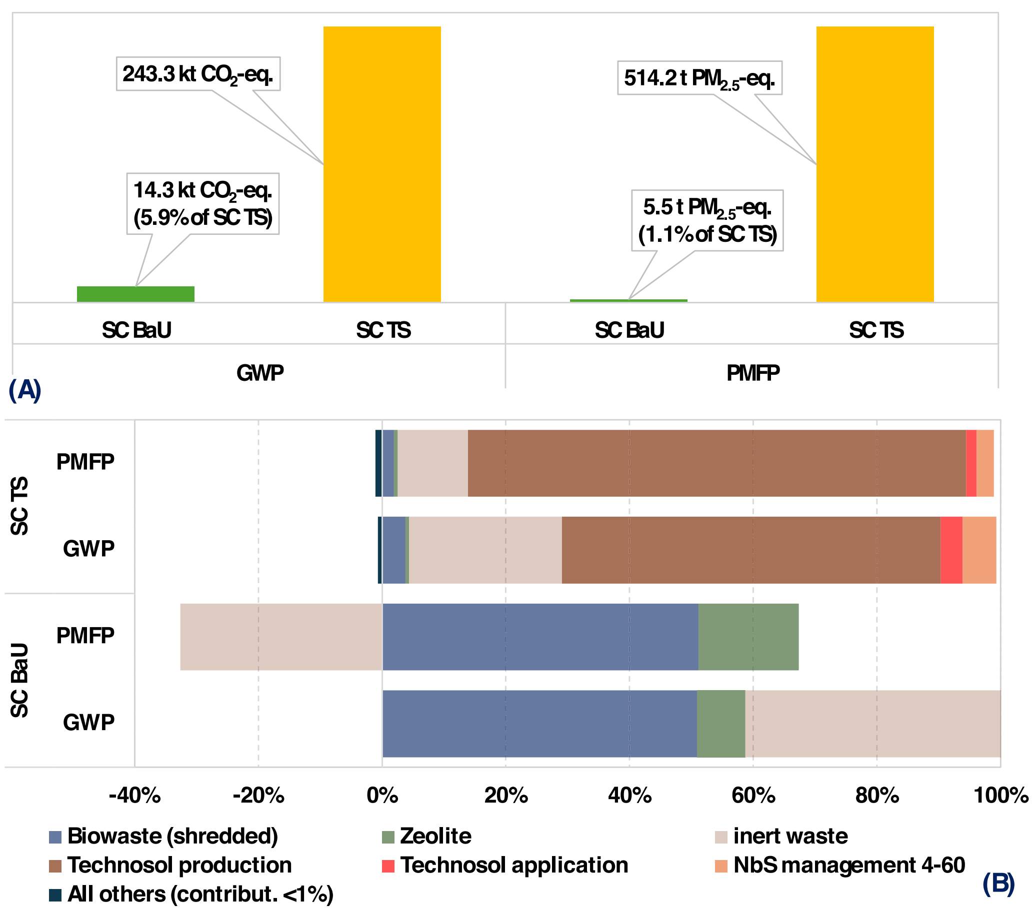


Fig. 3. (A) Comparison of absolute impact scores obtained for the two scenarios and environmental impact categories; (B) relative contribution of each life cycle activity to the total impact score in every scenario; within the category of "all others": biostimulants, mix coconut fibers and polymers, hydroretention compound, irrigation, tree nursery, tree planting, NbS management third year, end-of-life (EoL). GWP = global warming potential; PMFP = particulate matter formation potential; SC BaU = business-as-usual scenario (without NbS implementation); SC TS = alternative scenario implementing technosol-based NbS over ~200 ha.

environmental burdens, life cycle impact scores are compared and balanced against the ES benefits generated during the operational phase. Specifically, annual and cumulative net balances for climate change (ΔCO_2-eq.) and particulate matter ($\Delta PM_{2.5}$-eq.) are calculated as the difference between TS and BaU over the entire 75-year project time frame (Fig. 4). The temporal framework includes:

(i) the 15-year phased rollout period, during which technosol production, application, and tree planting occur and associated environmental burdens are generated (further information reported in Sections S3 and S6 of the SM1), and
(ii) a subsequent 60-year ecosystem operation phase, during which no additional technosol production is assumed and only vegetation growth, carbon sequestration, soil carbon recovery, and PM removal contribute to the balance.

For each year *t*, the net balance is computed as (Eq. 1):

$$\Delta Impact(t) = [LCA_{TS}(t) - LCA_{BaU}(t)] + ES_{benefits}(t) \qquad (1)$$

where $ES_{benefits}(t)$ include annual tree and shrub carbon sequestration, PM removal, and soil carbon recovery, modelled as avoided burdens and therefore expressed as negative contributions in midpoint impact score units (see Sections S4–S6 in the SM1 for further details).

As shown in Fig. 4a, during the rollout phase (years 1–15) the annual ΔCO_2-eq. remains positive and reaches a peak of approximately 20,000 net t CO_2-eq. year^{-1}. After year 15, once implementation is completed, the trend becomes consistently negative, with values ranging roughly in between −6000 and −8000 t CO_2-eq. year^{-1}. In the final period of the modelling horizon, the annual balance gradually approaches zero. Similarly, the cumulative ΔCO_2-eq. trajectory rose sharply during the first 15 years (Fig. 4b), reaching a maximum of approximately 185,000 net t CO_2-eq. After this peak, the curve declines progressively, and the carbon break-even point is reached at around year 45. By the end of the 75-year horizon, the cumulative carbon balance reaches approximately −130,000 net t CO_2-eq. of carbon stock.

For particulate matter, annual $\Delta PM_{2.5}$-eq. follows a similar pattern (Figs. 4c and 4d). During the first 15 years (Fig. 4c), annual impacts are positive, peaking at around 50 t $PM_{2.5}$-eq. year^{-1}. After year 15, annual $\Delta PM_{2.5}$-eq. becomes consistently negative, with values in between −10 and −30 t $PM_{2.5}$-eq. year^{-1}. The cumulative PM trajectory (Fig. 4d) increases to approximately 500 t $PM_{2.5}$-eq. during the implementation phase and then decreases continuously. By year 75, cumulative $\Delta PM_{2.5}$-eq. reaches about −350 t $PM_{2.5}$-eq. *of net removed pollutants.* The air quality break-even point occurred at approximately year 61.

3.3. Endpoint impact assessment

Following the assessment of annual and cumulative net climate and PM balances over 75 years, results were translated into human health impact outcomes using endpoint impact indicators expressed in DALYs (Fig. 5).

When all endpoint impact pathways are aggregated, the TS scenario generates a net burden of approximately 50.5 DALYs relative to BaU, corresponding to an overall loss of about 51 healthy life years over the full assessment period. This burden is mainly associated with upstream and operational impacts related to human toxicity (carcinogenic and non-carcinogenic) and other non-climate stressors linked to technosol production, material supply, inert waste handling, and technosol production operations.

In contrast, when the analysis is restricted to the climate change–human health (CC_hh) and particulate matter formation–human health (PMF_hh) impact pathways, including the avoided DALYs associated with vegetation-driven ecosystem service supply, the TS scenario delivers a net human health benefit of approximately 296 DALYs over the 75-year period. In other words, considering only climate- and PM-related endpoint effects, the restoration scenario produces an estimated saving of about 296 healthy life years relative to the counterfactual BaU condition.

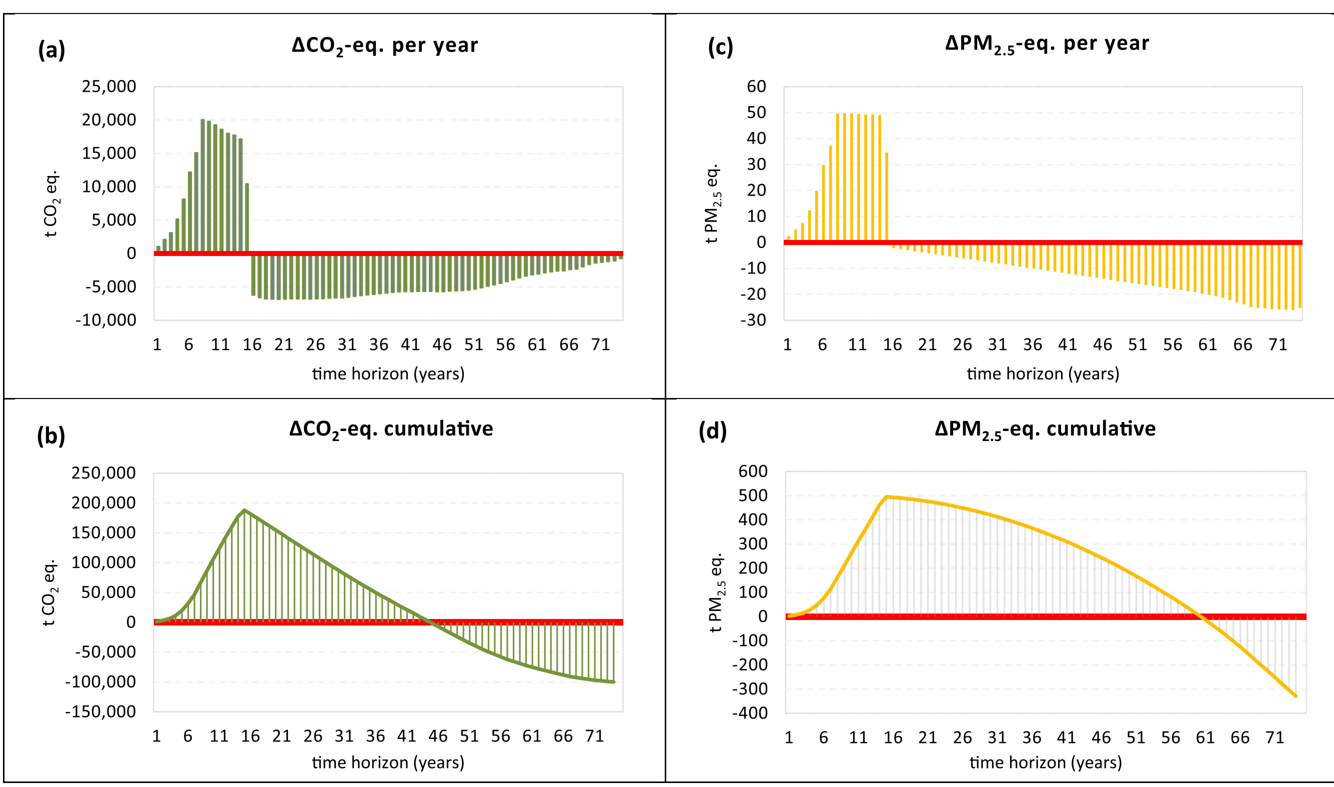


Fig. 4. Annual (a, c) and cumulative (b, d) net impacts calculated as the difference between TS and BAU scenarios (Δ) over the 75-year NbS project timeframe (15 years of implementation phase + 60 years of system operation).

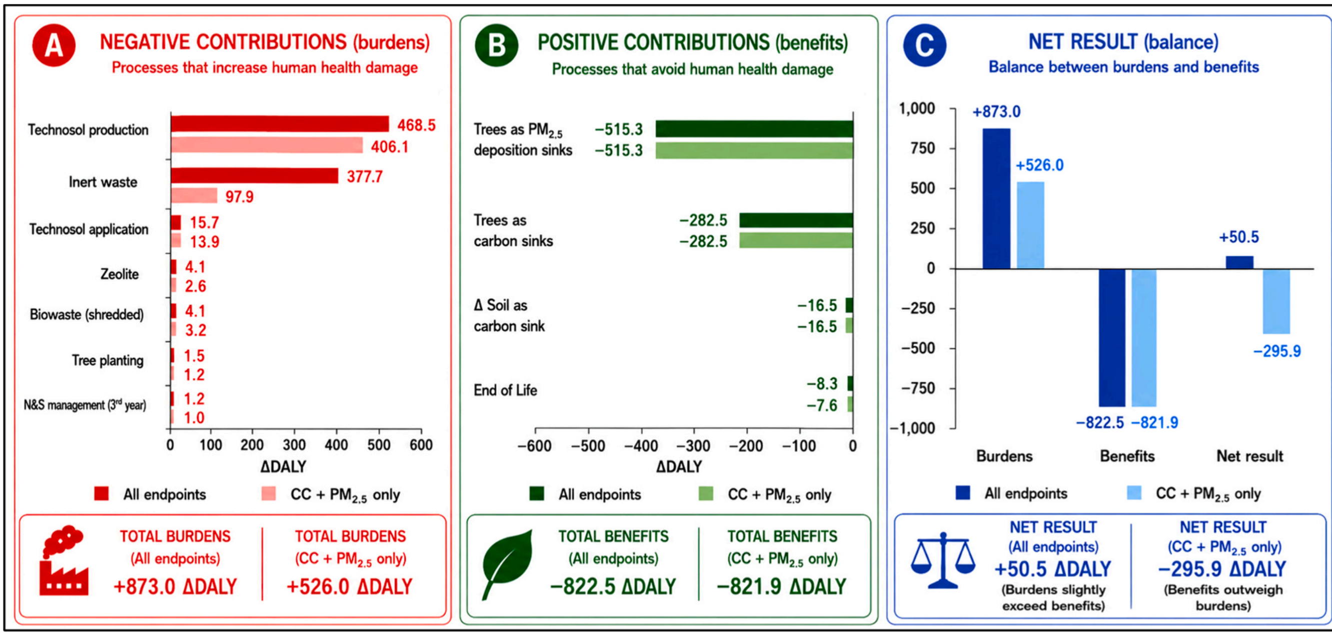


Fig. 5. Decomposition of human health endpoint impacts expressed as disability-adjusted life years (ΔDALY= $DALY_{TS}$ $-DALY_{BaU}$) associated with the large scale implementation of the Nature-based Solution (NbS). Panel A: contribution of the life cycle activities to burdens on human health burdens (expressed as positive ΔDALY). Panel B: contribution of the life cycle activities to benefits on human health (expressed as negative ΔDALY). Panel C: overall balance between burdens and benefits. Impact scores capture information about all human health impact categories as well as only Climate Change (CC_hh) and Particulate Matter Formation (PMF_hh), i.e., the two pathways most directly related to ecosystem service provision by the NbS. Processes contributing ≤ 0.1 ΔDALY are not shown for clarity in the visualisation. Negative ΔDALY values indicate avoided health damage, whereas positive ΔDALY values indicate additional health damage.

Taken together, the endpoint results suggest a meaningful difference between impact-specific and fully aggregated health outcomes: the NbS intervention performs strongly positively in relation to climate- and PM-related health endpoints, but this benefit is partly offset by additional burdens arising from toxicity- and resource-related pathways included in the full endpoint aggregation.

3.4. Uncertainty analysis and sensitivity analysis

Monte Carlo uncertainty propagation and OAT sensitivity analyses are conducted to assess the robustness of the endpoint indicator on climate change (CC_hh, DALY) for the main life cycle activities. The PMFP indicator has not been further investigated as its results are strongly dominated by technosol production, leading to a near-proportional scaling of results under parameter perturbations. Consequently, uncertainty analysis is not expected to yield qualitatively different conclusions compared to GWP, given the highly skewed contribution structure observed for this impact category, as shown in Fig. 3.

Across all modules (Compost, Excavation, and Zeolite), Monte Carlo results show a systematic positive shift in the TS configuration relative to BaU, indicating that the additional CC_hh burdens associated with technosol material provisioning persist under stochastic propagation of background and parameter uncertainty (Fig. 6).

While the absolute magnitude of the difference between the two scenarios (i.e., Δ = TS – BaU) varies among the life cycle activities, the direction of change remains stable across iterations. Excavation-related impact represents one of the main contributors to the additional CC_hh burden, whereas the production of compost (from biowaste) and zeolite still contributes positively but with lower absolute magnitudes.

The OAT analysis (Fig. 7) shows that a $\pm$ 20% perturbation of the technosol production parameter (k1) can produce a $\pm$ 17.5% variation in CC_hh, identifying technosol production as the dominant source of the model sensitivity. The excavation-related parameter (k3) produces a $\pm$ 12.2% variation, making excavation material supply the second most influential parameter. By contrast, the technosol application parameter

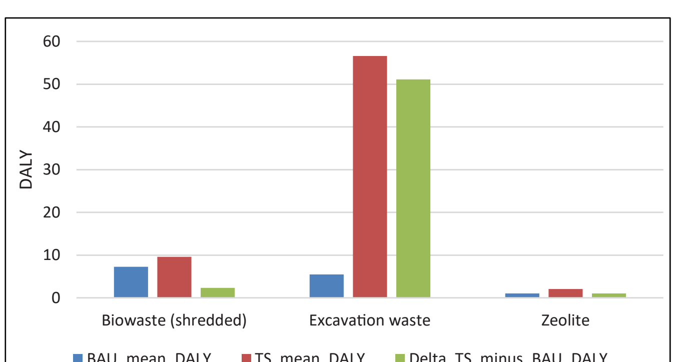


Fig. 6. Monte Carlo mean results for the human health climate change endpoint (CC_hh, in DALYs) at life cycle activity level. Bars represent the average impacts under BaU and TS scenarios, while Δ denotes the mean difference (TS − BaU) obtained from stochastic simulations.

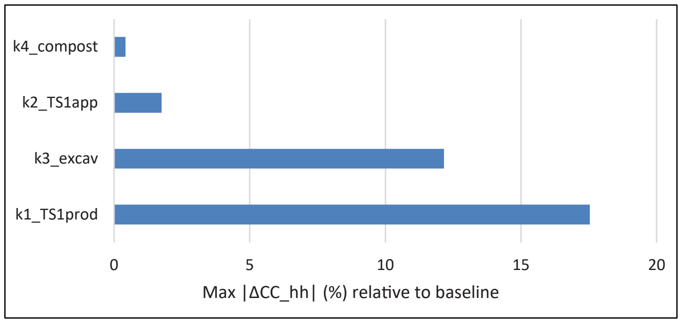


Fig. 7. One-at-a-Time (OAT) sensitivity analysis of key foreground parameters (k1–k4) on the human health climate change endpoint (CC_hh, in DALYs), based on a $\pm$ 20% variation around their central values. Results are expressed as the maximum absolute percentage deviation from the baseline scenario (BaU). The mixing stage of technosol production (k1_TS1prod) emerges as the dominant driver of uncertainty, whereas application (k2_TS1app), excavation waste (k3_excav), and compost from biowaste shredded (k4_compost) contribute to a lesser extent to the overall variability.

(k2) and the compost-related parameter (k4) produce much smaller variations, limited to $\pm$1.75% and $\pm$0.42%, respectively.

Overall, the uncertainty analysis indicates that stochastic propagation can primarily affect the magnitude and dispersion of results, whereas the sensitivity analysis highlights the dominant leverage of technosol production and excavation-related foreground parameters on the impact to human health associated with climate change.

4. Discussion

4.1. Environmental and human health implications

The present study demonstrates that large scale technosol-based NbS generates a clear temporal trade-off between short-term environmental burdens and long-term ES benefits.

The implementation phase is associated with most of the environmental burdens. This is evident both at midpoint level, where technosol production and excavation-related activities dominate GWP and PMFP indicators, and in the temporal profiles, with positive annual ΔCO_2-eq. and $\Delta PM_{2.5}$-eq. throughout the 15-year rollout period. In the present CLCA configuration, this burden-intensive phase reflects not only direct technosol production and field application, but also the activation of additional supply chains, transport requirements, inert-material handling, and recurring management operations represented in the foreground system.

This finding is important because it shows that the environmental performance of urban soil-restoration NbS cannot be inferred from ES outputs alone. At metropolitan scale, the intervention requires substantial material mobilisation before ecological gains emerge. In this respect, the study expands the outcomes of a pilot scale assessment of an urban forestry and soil restoration LCA application by showing how rollout-dependent provisioning burdens can dominate the initial balance when NbS are implemented over more than 200 ha following a consequential approach. The impacts profile over time is also coherent with the ex-ante CLCA structure adopted in the manuscript, in which annual intervention cohorts trigger marginal supplier activation, supplier switching, and transport scaling over time.

Although the intervention is initially impact-intensive, the temporal balance changes substantially as ES begin to accrue with vegetation growth. Following the completion of the rollout phase, annual net carbon footprint and air pollution balances become consistently negative, indicating that vegetation growth, PM removal, and soil and biomass carbon sequestration progressively outweigh the remaining life cycle burdens. Cumulative trajectories at midpoint level confirm this transition, with climate regulation break-even occurring after approximately 45years and air quality break-even after approximately 61 years. Beyond these thresholds, the restored system functions as a long-term net carbon sink and air pollution-removal system within the 75-year modelling horizon. Similar patterns were reported by Babí Almenar et al. (2023) in an urban forestry case study conducted in Madrid, Spain. The gradual flattening of annual carbon removal towards the end of the modelling horizon reflects the biological system maturation rather than a reversal of benefits. As extensively reported in the literature, tree growth slows with age, mortality occurs after approximately 60 years, and soil carbon recovery approaches steady-state conditions (e.g., Köhl et al., 2017; Ruiz et al., 2023). Since no replanting cycles or additional soil amendments are assumed in the model beyond the ecosystem operation phase, the annual net balance converges toward equilibrium rather than entering a new burden phase.

These timelines are broadly consistent with previous urban tree LCA studies, which report that implementation-related impacts are mainly concentrated in the early stages of the project, ES benefits accumulate gradually over time and net carbon sink status may be reached only after several decades (e.g., Petri et al. 2016; Nicese et al., 2021; Antenucci et al., 2025; Manzini et al., 2025). Petri et al. (2016), and Antenucci et al. (2025), in particular, have estimated break-even or net sink conditions from 25 to 26 years post-planting in attributional settings (further information are provided in Section S7, Table S6, SM1). The later break-even points observed in the present analysis is plausible because the study explicitly accounts for technosol production and application, large scale material provisioning, phased implementation, and consequential supply-chain effects, which cannot be fully represented in simpler planting-focused studies.

One of the strongest scientific contributions of this study lies in the contrast between pathway-specific and aggregated endpoint health results. At the endpoint level, when attention is restricted to climate change and PM formation, including avoided DALYs from $PM_{2.5}$ removal, the NbS intervention delivers a substantial net health benefit of ~296 DALYs. However, when all human health damage pathways included in ReCiPe 2016 are estimated and aggregated, the net balance becomes a burden of ~50.5 DALYs. This difference shows that the same NbS intervention can appear strongly beneficial or modestly burdensome depending on whether the analysis focuses only on targeted ES or adopts a full life cycle human health perspective. This also means that climate regulation and PM removal alone do not fully capture the health implications of technosol-based restoration. Upstream human toxicity and other non-climate pathways associated with material production, waste handling, and technosol production operations can partly erode otherwise large ES-related gains. These findings highlight the importance of adopting long-term and system-wide perspectives when evaluating the sustainability of urban land restoration programmes.

4.2. Robustness and methodological contributions of the CLCA framework

Uncertainty and sensitivity analyses confirm the structural robustness of the results. Monte Carlo propagation indicates that the intervention remains more burdensome than in the BaU during the material supply phase across the explored parameter space. While sensitivity analysis identifies technosol production and excavation processes as the dominant drivers of climate-related health impacts. This indicates that the upstream life cycle burden observed in the model is not an artefact of parameter selection but a structural property of such large scale technosol deployment.

At the same time, robustness does not imply immutability of magnitude. The relative importance of technosol production, excavation supply, and transport confirms that improvements in upstream material sourcing, processing, and logistics could substantially enhance early-stage performances. From a decision-making perspective, this suggests that the break-even trajectory is not only a function of ecological maturation, but also of how efficiently the material phase is organised.

Methodologically, the study advances CLCA applications for urban NbS by combining phased implementation, explicit counterfactual modelling, system expansion by substitution, marginal supplier activation under capacity constraints, dynamic transport scaling, and endpoint human health benefits from ecosystem service supply. Together, these features move the analysis beyond conventional static attributional assessments and make it effective for evaluating large scale urban restoration policies.

A second methodological contribution concerns the alignment between the selected midpoint categories and the ES quantified in the study. Impact indicators of GWP and PMFP have not been chosen generically, but because they are directly linked to the core ES being modelled, namely carbon sequestration, soil carbon recovery, and $PM_{2.5}$ removal. At endpoint level, these ecological functions have been translated into DALYs within the ReCiPe 2016 human health framework, improving metric consistency between burdens and benefits. This is particularly valuable in NbS assessment, where environmental gains are often reported in biophysical terms without being integrated into a common life cycle damage metric (Babí Almenar et al., 2023).

4.3. *Limitations and future perspectives*

4.3.1. *Methodological and modelling limitations*

The study has not included a scenario of tree planting without prior soil regeneration. Although such a configuration could theoretically be modelled, local empirical evidence indicates that degraded urban soils in the assessed areas are associated with reduced tree survival and limited ES delivery (Layman et al., 2016; Petrova et al., 2025; Rezapour et al., 2025). Under these conditions, a planting-only scenario would not represent a stable counterfactual pathway in the absence of soil restoration. Future research could explore intermediate configurations involving partial soil improvement or adaptive planting strategies to assess transitional restoration pathways. Moreover, despite the adoption of a comprehensive time-dependent CLCA framework, which allows to advance the representativeness of the NbS life cycle model at the scale of a city, this study is subject to several limitations that are intrinsic to large scale assessments of NbS as well as to specific modelling assumptions and data constraints.

A first limitation concerns the uncertainty surrounding long-term tree-based ES. Projections of carbon sequestration and PM removal over the 75-year assessment horizon rely primarily on i-Tree Eco growth curves and generalized allometric equations. Although widely applied, these models may not fully capture (Yang et al., 2024; Sokolova et al., 2025):

- site-specific stressors such as heat extremes, drought, soil compaction, and chronic air pollution;
- non-linear and threshold-driven climate change impacts on tree growth, physiological stress, and mortality over multi-decadal timescales;
- long-term variability in municipal management and maintenance intensity, which can substantially influence tree survival and ES delivery.

These uncertainties propagate into the estimated timing of climate and air quality break-even points, which are inherently sensitive to assumptions on tree growth, mortality, and pollutant removal parameters. The lack of long-term empirical data for degraded urban soils in Turin further increases uncertainty regarding soil carbon stability and long-term pollutant removal.

A second limitation concerns the representation of market responses within the CLCA framework. Marginal suppliers have been modelled exclusively within the intervention scenario (TS) through:

- a phased annual roll-out over 15 years (on ∼200 ha);
- a hierarchical distance-based sourcing structure defined ex-ante within the scenario design, whereby marginal suppliers are allocated sequentially from local to regional and, if required, to extra-regional fallback sources once predefined annual capacity thresholds were reached;
- explicit marginal activation for excavation soil, compost, and zeolite;
- explicit modelling of landfill diversion effects, whereby a defined share of excavation soil, compost, and zeolite that would otherwise be disposed of under BaU conditions is redirected to producing technosol, resulting in partial avoidance of landfill treatment burdens attributable to the intervention.

While this approach captures non-marginal dynamics more realistically than static attributional models, future market responses remain inherently uncertain. Changes in infrastructure development, regulatory frameworks, industrial investments, or waste-management practices could likely alter long-term supply–demand balances for compost, excavated soil, and mineral amendments. Estimates of avoided burdens are therefore contingent on current market behaviour and may diverge from future elasticities, particularly over a 75-year horizon. This represents a structural limitation of any ex-ante CLCA for NbS. Similar sensitivity to scenario assumptions has also been observed in LCA applications to land restoration (e.g., Rodrigues et al., 2019), although these studies do not implement a full consequential framework.

The present approach further assumes static land use conditions in the BaU scenario, whereas future urban densification or redevelopment could modify technosol feasibility, ES potential, and supply-chain logistics. Coupling CLCA with spatially explicit urban planning scenarios could provide more robust long-term insights for decision-makers. Besides, as proven in recent territorial LCA studies on excavated soil management and NbS implementation (e.g., Rugani & Petucco, 2025), the adoption of spatially aggregated representations of transport and material flows could offer a more realistic ground to model market dynamics and technosol application feasibility.

On top of this, it is worth mentioning that the technology datasets used in both scenarios to model their process life cycles refer to average production systems of current years. They do not capture any future change in energy supply mix, waste management or industrial optimization processes, further introducing uncertainty in the prospective assessments. In other words, the model assumes static background technology performance, while substantial decarbonisation and efficiency improvements (e.g., electrified transport, low-carbon composting, cleaner mineral extraction) may expectedly occur over the assessment horizon. Moreover, transport distances are spatially explicit but do not account for future infrastructure evolution or traffic conditions. Incorporating technological learning curves would refine the long-term impact estimates. Moreover, the 75-year horizon implicitly assumes stable governance and consistent municipal management across multiple political cycles, which may not hold in practice.

4.3.2. Uncertainty associated with ecosystem service and human health metrics

A major source of uncertainty arises from parameters for which site-specific empirical information was unavailable at the metropolitan scale, including long-term SOC trajectories, future marginal supply responses, supplier-switching thresholds, landfill diversion fractions, and long-term ES persistence. Nevertheless, several core model components were parameterized using empirical data collected within the New Soil pilot project, including technosol composition, planting densities, mortality rates, $PM_{2.5}$ deposition measurements, vegetation growth estimates, and GIS-based implementation areas and transport distances (Rugani et al., 2024; Della Casa et al., 2025). Therefore, uncertainty primarily affects the long-term extrapolation of system dynamics rather than the characterization of the pilot intervention itself. Future studies should incorporate probabilistic uncertainty analyses and alternative scenario pathways to further evaluate the robustness of long-term outcomes.

Large scale NbS implementation may indeed generate long-term urban lock-in effects (e.g., modified zoning, mobility, or real-estate dynamics) that extend beyond the system boundaries of this CLCA. Such city-scale feedback could amplify or counteract the quantified net benefits but remain outside the present methodological scope. The BaU scenario also assumes no active restoration of degraded areas, whereas in practice some land transformation efforts may occur, potentially increasing baseline environmental and health burdens.

A key methodological frontier concerns the integration of ES related benefits, particularly $PM_{2.5}$ removal, into DALY-based LCIA metrics. The analysis focused exclusively on carbon sequestration and $PM_{2.5}$ removal because these services could be quantified using site-specific experimental measurements, ES modelling, and characterization approaches. These were more directly compatible with the consequential LCA framework and the human health damage indicators adopted in this study. Yet, ES-based health benefits have been quantified separately from the LCIA results, harmonizing empirical outputs with ReCiPe 2016 endpoint (H) characterisation through a consistent avoided-disease-burden pathway even if:

- existing LCIA methods were not designed to incorporate avoided ES damage;
- dose–response relationships differ between vegetation-level PM removal and city-scale ambient exposure changes;
- without standard integration rules, avoided DALYs may overlap with conventional LCIA pathways if aggregated without alignment to exposure assumptions embedded in endpoint characterisation factors. In this study, this risk is reduced by treating $PM_{2.5}$ removal as an avoided emission and applying the same ReCiPe 2016 endpoint framework used for life cycle PM emissions, ensuring internal consistency.

Broader methodological guidance is still required to ensure conceptual coherence when combining ES-based health benefits with endpoint LCIA indicators. The focus on $PM_{2.5}$ excludes interactions with other pollutants (e.g., NO_2, O_3), which vegetation may reduce or increase depending on species and urban morphology. Other potential human-health pathways in ReCiPe 2016 were also not quantified. For example, vegetation can reduce photochemical oxidant formation (POF_hh) by removing ozone precursors, and soil processes may mitigate toxic exposures (Olszyk et al., 1989; Paoletti et al., 2025). Vegetated soils may also improve infiltration and water retention, influencing water use impacts (WU_hh) (Chávez-Collantes et al., 2025). However, these processes require spatially explicit fate-and-transport models and region-specific characterisation factors, which remain limited (Verones et al., 2017; Miller, 2022). Urban NbS can also contribute to urban heat island mitigation, stormwater regulation, biodiversity enhancement, recreational opportunities, noise reduction, and mental health improvements. Consequently, the overall health gains from technosol-based NbS have been potentially underestimated. Future research should explore the possibility to integrate those additional ES within consequential LCA frameworks to provide a more comprehensive assessment of the environmental and societal value of large scale urban restoration interventions. Additionally, as the absence of detailed exposure and benefit mapping represents a limitation, (as intra-urban heterogeneity in pollution and population vulnerability is not captured), future work could integrate CLCA outputs with high-resolution GIS layers to visualize $PM_{2.5}$ removal, avoided exposure, and associated health benefits. Such spatialisation would not aim at full regionalization but would clarify how burdens and benefits are distributed across the urban area, increasing policy relevance. The assumption of additive ES flows also neglects potential synergy or saturation at large scales (e.g., boundary-layer modifications affecting PM deposition; Nemitz et al., 2020; Huszar et al., 2024), which this framework does not capture.

Future research could couple the proposed CLCA with partial or general equilibrium models to represent non-marginal market responses such as price-mediated displacements, waste-valorisation capacity constraints, or substitution dynamics for mineral amendments (Suh and Yang, 2014; Yang and Heijungs, 2019; Almeida et al., 2020; Bartelings et al., 2024). NbS-oriented LCAs could also expand the assessment to biodiversity enhancement, urban heat island mitigation, non-material well-being, and long-term soil fertility recovery. Integrating these dimensions within multi-criteria or hybrid frameworks would enable more comprehensive evaluation of urban NbS, despite the lack of standard characterisation factors for these benefits in current LCIA methods.

5. Conclusions

This study demonstrates that NbS based on technosol-supported urban forests, when assessed through a consequential, multi-decadal and ecosystem service-integrated LCA framework, can operate as interventions to secure durable vegetation establishment and generate long-term environmental and public health benefits.

Despite generating substantial initial environmental burdens, their ability to deliver climate mitigation and air pollution exposure reduction potentials, as well as associated health benefits for people, position those NbS as transformative tools for ecological restoration in highly urbanized regions. The nuanced trade-offs identified, particularly between climate and air quality benefits and toxicity- and resource-related burdens, highlight the importance of implementing a holistic assessment framework and adaptive NbS design. Furthermore, by addressing certain methodological frontiers, particularly the integration of spatially explicit ecosystem benefits, dynamic supply chain modelling, and harmonized human health metrics, future research can substantially improve the robustness and decision-making relevance of consequential LCA for large scale NbS implementation in urban environments. Economic cost-benefit analysis should also support such follow-up research in order to ensure full sustainability of the urban NbS systems.

Overall, the proposed approach provides a decision-support foundation for cities seeking to reconcile land restoration, climate neutrality, and public health protection, while also outlining key methodological frontiers for further strengthening the role of scenario analysis in large scale urban NbS planning.

CRediT authorship contribution statement

Martina Della Casa: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlo Calfapietra:** Supervision, Project administration, Funding acquisition, Conceptualization. **Chiara Baldacchini:** Writing – review & editing, Supervision. **Gabriele Guidolotti:** Writing – review & editing, Data curation. **Benedetto Rugani:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Copilot in order to assist with the revision of the English language. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study has been conducted in the framework of the international project "proGIreg", which has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement no. 776528. BR, GG, CC and CB further acknowledge the support of NBFC (National Biodiversity Future Centre) funded by the Italian Ministry of University and Research, P.N.R.R., Missione 4 Componente 2, "Dalla ricerca all'impresa", Investimento 46, Project CN00000033.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2026.129593.

References

Almeida, D.T.L., Charbuillet, C., Heslouin, C., Lebert, A., Perry, N., 2020. Economic models used in CLCA: a literature review. Procedia CIRP 90, 187–191. https://doi.org/10.1016/j.procir.2020.01.057.

Alshehri, K., Harbottle, M., Sapsford, D., Beames, A., Cleall, P., 2023. Integration of ecosystem services and life cycle assessment allows improved accounting of sustainability benefits of nature-based solutions for brownfield redevelopment. J. Clean. Prod. 413, 137352. https://doi.org/10.1016/j.jclepro.2023.137352.

Antenucci, E., Di Pirro, E., di Cristofaro, M., Garfì, V., Marchetti, M., Lasserre, B., 2025. Beneficial or impactful management? Life cycle assessment and i-Tree Canopy to evaluate the net environmental benefits of Mediterranean urban forests. Urban. For. & Urban. Green. 107, 128800. https://doi.org/10.1016/j.ufug.2025.128800.

Ascione, G.S., Cuomo, F., Mariotti, N., Corazza, L., 2021. Urban living labs, circular economy and nature-based solutions: Ideation and testing of a new soil in the city of Turin using a multi-stakeholder perspective. Circ. Econ. Sustain. 1, 545–562. https://doi.org/10.1007/s43615-021-00011-6.

Babí Almenar, J., Petucco, C., Sonnemann, G., Geneletti, D., Elliot, T., Rugani, B., 2023. Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle thinking: An application to urban forests'. Ecosyst. Serv. 60, 101506. https://doi.org/10.1016/j.ecoser.2023.101506.

Baldacchini, C., Calfapietra, C., 2023. Living Labs impact at the NBS level (Deliverable No. 4.9). proGIreg Horiz. 2020 Grant. Agreem. No. 776528. European Commission.

Bartelings, H., van den Bos-Verma, M., van Meijl, H., 2024. Introducing municipal solid waste streams in a CGE framework: A step in the direction of circular economy analysis. J. Glob. Econ. Anal. 9 (1), 1–44. https://doi.org/10.21642/JGEA.090101AF.

Bernstad Saraiva, A., Souza, R.G., Mahler, C.F., Valle, R.A.B., 2018. Consequential lifecycle modelling of solid waste management systems – Reviewing choices and exploring their consequences. J. Clean. Prod. 201, 1109–1117. https://doi.org/10.1016/j.jclepro.2018.08.038.

Biasin, A., Masiero, M., Amato, G., Pettenella, D., 2023. Nature-based solutions modeling and cost-benefit analysis to face climate change risks in an urban area: The case of Turin (Italy). Land 12 (2), 280. https://doi.org/10.3390/land12020280.

Brandão, M., Clift, R., Cowie, A., Greenhalgh, S., 2014. The Use of Life Cycle Assessment in the Support of Robust (Climate) Policy Making: Comment on "Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation. J. Ind. Ecol. 18 (3), 461–463. https://doi.org/10.1111/jiec.12152.

Brandão, M., Weidema, B.P., Martin, M., Cowie, A., Hamelin, L., Zamagni, A., 2024. CLCA: What, why and how? In In: Encyclopedia of Sustainable Technologies, 2nd ed., 1. Elsevier, pp. 181–189. https://doi.org/10.1016/B978-0-323-90386-8.00001-2.

Bruni, C., Akyol, Ç., Cipolletta, G., Eusebi, A.L., Caniani, D., Masi, S., Colón, J., Fatone, F., 2020. Decentralized community composting: Past, present and future aspects of Italy. Sustainability 12 (8), 3319. https://doi.org/10.3390/su12083319.

Calfapietra, C., Di Lonardo, S., Peruzzi, E., Doni, S., Masciandaro, G., 2025. Perspectives from nature-based solutions to restore soil and ecosystems. Eur. J. Soil. Sci. 76 (6), e70134. https://doi.org/10.1111/ejss.70134.

Celletti, S., Poreba, L., Wawer, R., Padoan, E., Comis, S., Bartosiewicz, B., Schiavon, M., 2025. The potential of nature-based solutions for urban soils: Focus on green infrastructure and bioremediation. Front. Environ. Sci. 13, 1634662. https://doi.org/10.3389/fenvs.2025.1634662.

Chávez-Collantes, A., Vásquez Lozano, D.J., Velarde-Apaza, L.D., Cuevas, J.-P., Solórzano, R., Flores-Marquez, R., 2025. Influence of vegetation cover and soil properties on water infiltration: A study in high-Andean ecosystems of Peru. Water 17 (15), 2280. https://doi.org/10.3390/w17152280.

Chialva, M., Masson, S., Bongiovanni, D., Votta, C., Barni, E., Padoan, E., Stefanini, I., Fiorilli, V., Larcher, F., Lanfranco, L., 2026. Effect of a constructed technosol on the microbial functional diversity in an urban afforestation site. Urban. For. & Urban. Green. 115, 129179. https://doi.org/10.1016/j.ufug.2026.129179.

Cristóbal, J., Foster, G., Caro, D., Yunta, F., Manfredi, S., Tonini, D., 2024. Management of excavated soil and dredging spoil waste from construction and demolition within the EU: Practices, impacts and perspectives. Sci. Total. Environ. 944, 173859. https://doi.org/10.1016/j.scitotenv.2024.173859.

Della Casa, M., Hirabayashi, S., Rugani, B., Guidolotti, G., Gullino, P., Larcher, F., Calfapietra, C., Baldacchini, C., 2025. City-scale health benefits from experimental results at the tree canopy level: Insights from a nature-based solution case study. Urban. Clim. 64, 102648. https://doi.org/10.1016/j.uclim.2025.102648.

di Cristofaro, M., Moresi, F.V., Maesano, M., Salvati, R., Cimini, D., Cecca, D., Bonella, G., Scarascia-Mugnozza, G., 2026. From tree loss to climate gains: Rethinking carbon flows, payoffs, and trade-offs of forest landscape restoration. Sci. Total. Environ. 1014, 181369. https://doi.org/10.1016/j.scitotenv.2026.181369.

Dogan, E., Cuomo, F., Battisti, L., 2023. Reviving urban greening in post-industrial landscapes: The case of Turin. Sustainability 15 (17), 12760. https://doi.org/10.3390/su151712760.

Edmondson, J.L., Davies, Z.G., McHugh, N., Gaston, K.J., Leake, J.R., 2012. Organic carbon hidden in urban ecosystems. Sci. Rep. 2, 963. https://doi.org/10.1038/srep00963.

Ekvall, T., 2019. Attributional and consequential life cycle assessment. In: Bastante-Ceca, M.J., Fuentes-Bargues, J.L., Hufnagel, L., Mihai, F.-C., Iatu, C. (Eds.), Sustainability assessment at the 21st century. IntechOpen, London, UK. https://doi.org/10.5772/intechopen.89202.

Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. Life Ccycle Assess. 9 (3), 161–171. https://doi.org/10.1007/BF02994190.

European Commission, 2010. ILCD Handbook: General guide for life cycle assessment – Detailed guidance. EUR 24708 EN. Joint Research Centre (JRC) of the European Commission. Publications Office of the European Union, Luxembourg.

European Environment Agency, 2024. Imperviousness and imperviousness change in Europe. European Environment Agency. ⟨https://www.eea.europa.eu/en/analysis/indicators/imperviousness-and-imperviousness-change-in-europe⟩. Retrieved February 17, 2026, from.

Favaretto, L., Rugani, B., Calfapietra, C., Labra, M., Guidi Nissim, W., 2025. Modelling the environmental implications of phytoremediation in urban settings: A review of the integration of life cycle assessment and ES approaches. Urban. For. & Urban. Green. 107, 128788. https://doi.org/10.1016/j.ufug.2025.128788.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91 (1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Greening Cities Partnership, 2024. Urban Agenda for the EU: Greening Cities Partnership – Action Plan. October 2024. European Union, Brussels.

Hamby, D.M., 1994. A comparison of sensitivity analysis techniques. Health Phys. 68 (2), 195–204. https://doi.org/10.1097/00004032-199502000-00005.

Hardaker, A., Styles, D., Williams, P., Chadwick, D., Dandy, N., 2022. A framework for integrating ES as endpoint impacts in life cycle assessment. J. Clean. Prod. 370, 133450. https://doi.org/10.1016/j.jclepro.2022.133450.

Heijungs, R., Allacker, K., Benetto, E., Brandão, M., Guinée, J., Schaubroeck, S., Schaubroeck, T., Zamagni, A., 2021. System expansion and substitution in LCA: A lost opportunity of ISO 14044 Amendment 2. Front. Sustain. 2, 692055. https://doi.org/10.3389/frsus.2021.692055.

Heijungs, R., Huijbregts, M.A.J., 2004. A review of approaches to treat uncertainty in life cycle assessment. Int. J. Life Cycle Assess. 9, 302–311. https://doi.org/10.1007/BF02979806.

Hosseini, S., 2025. Environmental assessment of nature-based solutions in Turin, Italy: A case study within the GREEN-INC European project. Master's thesis. Master's Degree Programme in Territorial. Urban, Environmental and Landscape Planning.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., van Zelm, R., 2016. ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. RIVM Report 2016-0104. National Institute for Public Health and the Environment, Bilthoven, The Netherlands.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., van Zelm, R., 2017. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Huszar, P., Prieto Perez, A.P., Bartík, L., Karlický, J., Villalba-Pradas, A., 2024. Impact of urbanization on fine particulate matter concentrations over central Europe. Atmos. Chem. Phys. 24, 397–425. https://doi.org/10.5194/acp-24-397-2024.

ICLEI Europe, 2021. Cities for an integrated landscape approach: Curbing land degradation and restoring Europe's soil ecosystems. ICLEI – Local Governments for

Sustainability, Europe, Brussels. Available at: ⟨https://iclei-europe.org/en/publications/ICLEI-ES-position-paper-SOIL.pdf⟩ (accessed 14 October 2025).
Imbrenda, V., Quaranta, G., Salvia, R., Egidi, G., Salviati, L., Prokopová, M., 2021. Land degradation and metropolitan expansion in a peri-urban environment. Int. J. Sustain. Dev. & World Ecol. 28 (8), 1797–1818. https://doi.org/10.1080/19475705.2021.1951363.
ISPRA, 2022. Report on waste from economic activities 2022: Summary data. Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma.
Köhl, M., Neupane, P.R., Lotfiomran, N., 2017. The impact of tree age on biomass growth and carbon accumulation capacity: A retrospective analysis using tree ring data of tropical tree species grown in natural forests of Suriname. PLOS ONE 12 (8), e0181187. https://doi.org/10.1371/journal.pone.0181187.
Layman, R.M., Day, S.D., Mitchell, D.K., Chen, Y., Harris, J.R., Daniels, W.L., 2016. Below ground matters: Urban soil rehabilitation increases tree canopy and speeds establishment. Urban. For. & Urban. Green. 16, 25–35. https://doi.org/10.1016/j.ufug.2016.01.004.
Larrey-Lassalle, P., Armand Decker, S., Perfido, D., Naneci, S., Rugani, B., 2022. Life cycle assessment applied to nature-based solutions: Learnings, methodological challenges, and perspectives from a critical analysis of the literature. Land 11 (5), 649. https://doi.org/10.3390/land11050649.
Lesage, P., Ekvall, T., Deschênes, L., Samson, R., 2007. Environmental assessment of brownfield rehabilitation using two different life cycle inventory models – Part 2: Case study. Int. J. Life Cycle Assess. 12, 497–513. https://doi.org/10.1065/lca2006.10.279.2.
Liao, D., 2025. Element system of industrial heritage transformation in Turin: Collaborative assessment and design strategies. Master's thesis. Tsinghua University.
Liu, W., Zhao, H., Sun, S., Xu, X., Huang, T., Zhu, J., 2022. Green space cooling effect and contribution to mitigate heat island effect of surrounding communities in Beijing metropolitan area. Front. Public. Health 10, 870403. https://doi.org/10.3389/fpubh.2022.870403.
Lozano, J.E., Nainggolan, D., Kofler, V., Kernitzky, M., Staccione, A., Bidoli, C., Mysiak, J., Zandersen, M., 2025. Nature-based solutions: Typologies, ecological processes and benefit valuation approaches across landscapes. Nat. -Based Solut. 8, 100268. https://doi.org/10.1016/j.nbsj.2025.100268.
Maes, B., Audenaert, A., Craeye, B., Buyle, M., 2021. Consequential ex-ante life cycle assessment on clinker production in the EU: How will the future influence its environmental impact? J. Clean. Prod. 315, 128081. https://doi.org/10.1016/j.jclepro.2021.128081.
Maes, B., Sacchi, R., Steubing, B., Pizzol, M., Audenaert, A., Craeye, B., Buyle, M., 2023. Prospective consequential life cycle assessment: Identifying the future marginal suppliers using integrated assessment models. Renew. Sustain. Energy Rev. 188, 113830. https://doi.org/10.1016/j.rser.2023.113830.
Manzini, J., Hoshika, Y., Sicard, P., Anav, A., De Marco, A., Sorrentino, B., Trentani, G., Baesso Moura, B., Ferrini, F., Azzini, L., Nicese, F.P., Paoletti, E., 2025. Life cycle analysis and species-specific net CO_2 assimilation model to assess when a new urban forest becomes a carbon sink in a Mediterranean city. Sci. Total. Environ. 959, 178267. https://doi.org/10.1016/j.scitotenv.2024.178267.
Market Reports World, 2025. Zeolite market size, share and forecast analysis. Available at: ⟨https://www.marketreportsworld.com/market-reports/zeolite-market-14719309⟩.
McPherson, E.G., Kendall, A., 2014. A life cycle carbon dioxide inventory of the Million Trees Los Angeles program. Int. J. Life Cycle Assess. 19, 1653–1665. https://doi.org/10.1007/s11367-014-0772-8.
Miller, S.A., 2022. The capabilities and deficiencies of life cycle assessment to address the plastic problem. Front. Sustain. 3, 1007060. https://doi.org/10.3389/frsus.2022.1007060.
Moinel, C., Kuittinen, M., Hautamäki, R., 2024. Estimating CO_2 flows in urban parks: knowns and unknowns. Front. Sustain. Cities 6, 1452403. https://doi.org/10.3389/frsc.2024.1452403.
Montanarella, L., Panagos, P., 2021. The relevance of sustainable soil management within the European Green Deal. Land. Use Policy 100, 104950. https://doi.org/10.1016/j.landusepol.2020.104950.
Morel, J.L., Chenu, C., Lorenz, K., 2015. *Ecosystem services* provided by soils of urban, industrial, traffic, mining, and military areas. J. Soils Sediment. 15, 1659–1676. https://doi.org/10.1007/s11368-014-0926-0.
Mueller, W., Milner, J., Loh, M., Vardoulakis, S., Wilkinson, P., 2022. Exposure to urban greenspace and pathways to respiratory health: An exploratory systematic review. Sci. Total. Environ. 829, 154447. https://doi.org/10.1016/j.scitotenv.2022.154447.
Mutel, C.L., 2017. Brightway: An open source framework for life cycle assessment. J. Open. Source Softw. 2 (12), 236. https://doi.org/10.21105/joss.00236.
Nemitz, E., Vieno, M., Carnell, E., Fitch, A., Steadman, C., Cryle, P., Holland, M., Morton, R.D., Hall, J., Mills, G., Hayes, F., Dickie, I., Carruthers, D., Fowler, D., Reis, S., Jones, L., 2020. Potential and limitation of air pollution mitigation by vegetation and uncertainties of deposition-based evaluations. Philos. Trans. R. Soc. A 378 (2183), 20190320. https://doi.org/10.1098/rsta.2019.0320.
Nicese, F.P., Colangelo, G., Comolli, R., Azzini, L., Lucchetti, S., Marziliano, P.A., Sanesi, G., 2021. Estimating CO_2 balance through the life cycle assessment prism: A case study in an urban park. Urban. For. & Urban. Green. 57, 126869. https://doi.org/10.1016/j.ufug.2020.126869.
Nazish, A., Abbas, K., Sattar, E., 2024. Health impact of urban green spaces: A systematic review of heat-related morbidity and mortality. BMJ Open. 14 (9), e081632. https://doi.org/10.1136/bmjopen-2023-081632.
Nurdiwati, A., Mir, B.A., Al-Ghamdi, S.G., 2025. Recent advancements in prospective life cycle assessment: Current practices, trends, and implications for future research. Resour. Environ. Sustain. 20, 100203. https://doi.org/10.1016/j.resenv.2025.100203.
Olszyk, D.M., Bytnerowicz, A., Takemoto, B.K., 1989. Photochemical oxidant pollution and vegetation: Effects of mixtures of gases, fog and particles. Environ. Pollut. 61 (1), 11–29. https://doi.org/10.1016/0269-7491(89)90259-5.
Paoletti, E., Sicard, P., De Marco, A., Baesso Moura, B., Manzini, J., 2025. Ozone pollution and urban greening. Stresses 5 (4), 65. https://doi.org/10.3390/stresses5040065.
Petri, A.C., Koeser, A.K., Lovell, S.T., Ingram, D., 2016. How green are trees?—Using life cycle assessment methods to assess net environmental benefits. J. Environ. Hortic. 34 (4), 101–110. https://doi.org/10.24266/0738-2898-34.4.101.
Petrova, A., Michael, R.N., Pratt, C., 2025. What kills mature street and park trees in cities? Systematic quantitative review of published case studies. Environ. Manag. 75 (6), 1538–1558. https://doi.org/10.1007/s00267-025-02116-2.
Pizzol, M., Sacchi, R., Köhler, S., Anderson Erjavec, A., 2021. Non-linearity in the life cycle assessment of scalable and emerging technologies. Front. Sustain. 1, 611593. https://doi.org/10.3389/frsus.2020.611593.
Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon storage by urban soils in the United States. J. Environ. Qual. 35 (4), 1566–1575. https://doi.org/10.2134/jeq2005.0215.
QGIS Development Team, 2023. QGIS geographic information system. Open Source Geospatial Foundation Project. Available at: ⟨https://qgis.org⟩.
Rehl, T., Lansche, J., Müller, J., 2012. Life cycle assessment of energy generation from biogas—Attributional vs. consequential approach. Renew. Sustain. Energy Rev. 16 (6), 3766–3775. https://doi.org/10.1016/j.rser.2012.02.072.
Reinhard, S., Naranjo, M.A., Polman, N., Hennen, W., 2022. Modelling choices and social interactions with a threshold public good: Investment decisions in a polder in Bangladesh. Land. Use Policy 113, 105886. https://doi.org/10.1016/j.landusepol.2021.105886.
Rezapour, S., Nouri, A., Shokoohi, M., Alamdari, P., 2025. Urbanization accelerates soil degradation in peri-urban compared to rural farms. Sci. Rep. 16, 3878. https://doi.org/10.1038/s41598-025-33995-4.
Ridlington, E., Weissman, G., & Folger, M. 2020. *Trouble in the air: Millions of Americans breathed polluted air in 2018* (White paper). Environment America Research & Policy Center; U.S. PIRG Education Fund; Frontier Group. ⟨https://environmentamerica.org/wp-content/uploads/2022/07/EnvironmentAmerica_TroubleintheAir_scrn-1.pdf⟩.
Rodrigues, J., Gérard, A., Sérec, G., Morel, J.-L., Guimont, S., Simonnot, M.-O., Pons, M.-N., 2019. Life cycle impacts of soil construction, an innovative approach to reclaim brownfields and produce non-edible biomass. J. Clean. Prod. 211, 36–43. https://doi.org/10.1016/j.jclepro.2018.11.152.
Rugani, B., Petucco, C., 2025. Environmental benefits of re-using excavated soil flows: The case of Luxembourg. Sci. Total. Environ. 958, 177867. https://doi.org/10.1016/j.scitotenv.2024.177867.
Rugani, B., Polling, B., Della Casa, M., Guidolotti, G., Baldacchini, C., Timpe, A., Calfapietra, C., 2024. Coupled life cycle assessment and business modelling to estimate the sustainability of using regenerated soils in urban forestry as nature-based solutions. Urban. For. & Urban. Green. 95, 128327. https://doi.org/10.1016/j.ufug.2024.128327.
Ruini, A., Sporchia, F., Niccolucci, V., Pulselli, F.M., Bastianoni, S., 2025. Rethinking environmental benefit allocation in industrial symbiosis. Sci. Total. Environ. 992, 179932. https://doi.org/10.1016/j.scitotenv.2025.179932.
Ruiz, F., Rumpel, C., Marchese Silva, B., Barbosa de Camargo, P., 2023. Soil organic matter stabilization during early stages of Technosol development from Ca-, Mg- and pyrite-rich parent material. CATENA 232, 107435. https://doi.org/10.1016/j.catena.2023.107435.
Sala, S., Reale, F., Cristobal-Garcia, J., Marelli, L., Pant, R., 2016. Life cycle assessment for the impact assessment of policies: Life thinking and assessment in the European policies and for evaluating policy options (EUR 28380 EN). Publ. Off. Eur. Union. https://doi.org/10.2788/318544.
Schaubroeck, T., Alvarenga, R.A.F., Verheyen, K., Muys, B., Dewulf, J., 2013. Quantifying the environmental impact of an integrated human/industrial-natural system using life cycle assessment: A case study on a forest and wood processing chain. Environ. Sci. & Technol. 47 (23), 13578–13586. https://doi.org/10.1021/es4046633.
Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., Benetto, E., 2021. Attributional and consequential life cycle assessment: Definitions, conceptual characteristics and modelling restrictions. Sustainability 13 (13), 7386. https://doi.org/10.3390/su13137386.
Singh, N., Areal, A.T., Breitner, S., Zhang, S., Agewall, S., Chikowski, T., Schneider, A., 2024. Heat and cardiovascular mortality: An epidemiological perspective. Circ. Res. 134 (9), 1098–1112. https://doi.org/10.1161/CIRCRESAHA.123.323615.
SNPA, 2025. *Consumo di suolo, dinamiche territoriali e servizi ecosistemici. Edizione 2025* (Report ambientali SNPA 46/2025). Sistema Nazionale per la Protezione dell'Ambiente. ISBN 978-88-448-1279-9.
Sokolova, M.V., Fath, B.D., Buonocore, E., Franzese, P.P., 2025. Assessment of regulating ecosystem services generated by green infrastructure: A case study of Bolzano, Italy. Urban. Clim. 60, 102324. https://doi.org/10.1016/j.uclim.2025.102324.
Southerland, V.A., Brauer, M., Mohegh, A., Hammer, M.S., van Donkelaar, A., Martin, R. V., Apte, J.S., Anenberg, S.C., 2022. Global urban temporal trends in fine particulate matter ($PM_{2.5}$) and attributable health burdens: Estimates from global datasets. Lancet Planet. Health 6 (2), e139–e146. https://doi.org/10.1016/S2542-5196(21)00350-8.
Suh, S., Yang, Y., 2014. On the uncanny capabilities of consequential LCA. Int. J. Life Cycle Assess. 19, 1179–1184. https://doi.org/10.1007/s11367-014-0739-9.
Taelman, S.E., De Luca Peña, L.V., Préat, N., Bachmann, T.M., Van der Biest, K., Maes, J., Dewulf, J., 2024. Integrating ES and life cycle assessment: A framework accounting for local and global (socio-)environmental impacts. Int. J. Life Cycle Assess. 29, 99–115. https://doi.org/10.1007/s11367-023-02216-3.

Ugolini, F., Baronti, S., Lanini, G.M., Maienza, A., Ungaro, F., Calzolari, C., 2020. Assessing the influence of topsoil and technosol characteristics on plant growth for the green regeneration of urban built sites. J. Environ. Manag. 273, 111168. https://doi.org/10.1016/j.jenvman.2020.111168.

UNEP/SETAC Life Cycle Initiative, 2011. Towards a life cycle sustainability assessment: Making informed choices on products. United Nations Environment Programme.

United Nations Economic Commission for Europe (UNECE), 2025. Promoting nature-based solutions and sustainable infrastructure in the ECE region: Environmental and health co-benefits (ECE/CEP/NONE/2025/2). United Nations.

Van den Auwelant, E., Nimmegeers, P., Naseem Malik, R., Hussain, M., Khan, A., Van Passel, S., 2026. Assessing the environmental sustainability of the billion trees afforestation project through life cycle assessment. Sci. Total. Environ. 1012, 181252. https://doi.org/10.1016/j.scitotenv.2025.181252.

VanderWilde, C.P., Newell, J.P., 2021. ES and life cycle assessment: A bibliometric review. Resour. Conserv. Recycl. 169, 105461. https://doi.org/10.1016/j.resconrec.2021.105461.

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A., Liao, X., Lindner, J.P., de Souza, D.M., Michelsen, O., Patouillard, L., Pfister, S., Posthuma, L., Prado, V., Ridoutt, B., Rosenbaum, R.K., Sala, S., Ugaya, C., Vieira, M., Fantke, P., 2017. LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. J. Clean. Prod. 161, 957–967. https://doi.org/10.1016/j.jclepro.2017.05.206.

World Health Organization (WHO), 2016. Urban green spaces and health: A review of the evidence. WHO Regional Office for Europe, Copenhagen.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B.P., 2016. The ecoinvent database version 3 (part I): Overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Xie, L., Bulkeley, H., Tozer, L., 2022. Mainstreaming sustainable innovation: Unlocking the potential of nature-based solutions for climate change and biodiversity. Environ. Sci. & Policy 132, 119–130. https://doi.org/10.1016/j.envsci.2022.02.012.

Yadav, S., Goyal, V.C., 2022. Current status of ponds in India: A framework for restoration, policies and circular economy. Wetlands 42 (8), 107. https://doi.org/10.1007/s13157-022-01624-9.

Yang, Q., Liu, G., Gonella, F., Wang, Q., Chen, S., Yang, Z., 2024. Revisiting mid–long term ecosystem services projections: Integrating the interaction effects of future climate and land use changes. Fundam. Res. https://doi.org/10.1016/j.fmre.2024.02.017.

Yang, Y., Heijungs, R., 2019. Moving from completing system boundaries to more realistic modelling of the economy in life cycle assessment. Int. J. Life Cycle Assess. 24, 211–218. https://doi.org/10.1007/s11367-018-1532-y.

Zawadzka, J., Harris, J., Corstanje, R., 2021. Assessment of heat mitigation capacity of urban greenspaces with the use of InVEST Urban Cooling Model, verified with day-time land surface temperature data. Landsc. Urban. Plan. 214, 104163. https://doi.org/10.1016/j.landurbplan.2021.104163.