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Coupled life cycle assessment and business modelling to estimate the sustainability of using regenerated soils in urban forestry as nature-based solutions

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ABSTRACT

Using regenerated soils as a planting substrate in newly implemented green infrastructure is considered a circular economy-oriented strategy alternative to traditional ways of depriving fertile soils from agricultural lands, and/or applying fertilizers and soil conditioners. However, knowledge on the environmental footprint of regenerating and applying such excavation soils on urban brownfields is quite fragmented. This study aims to illustrate a coupled application of life cycle assessment (LCA) and business modelling to a pilot nature-based solution (NbS) implemented on a post-industrial area in Turin, Italy. This NbS is configured as urban afforestation intervention on 1200 sqm where trees and shrubs are planted on a layer of excavation soil augmented with organic compost, zeolite powder and biostimulants, called "New Soil". The rationale of combining LCA with a strategic management Business Model Canvas (BMC) is to identify the most relevant socioeconomic and environmental synergies and trade-offs associated with the potential upscaling of a New Soil NbS intervention in the market. On one hand, the use of LCA allowed to estimate the detrimental impacts generated along the entire supply-chain of the NbS implementation, as well as its environmental performances in comparison with hypothetical business-as-usual scenarios. On the other hand, results from expert-based surveys formulated with BMC provided the necessary (and complementary) knowledge for prospecting a sustainable pathway associated with the NbS deployment. It was observed that both life cycle upstream and downstream strategies of reducing environmental impacts can be implemented, which may help saving in between ~70 % to more than 100 % the environmental footprint compared with conventional resource consumption streams. The outcomes of this study are useful to prospect strengths and challenges that land managers need to address for possible deployment of New Soil NbS at large territorial scales.

1. Introduction

The management of soils from excavation activities represents a great sustainability challenge in Europe since they are generally considered waste and therefore moved to landfills. Between 150 and 200 million tonnes of excavated soils were sent in 2018 to disposal in Europe, and, as a consequence of their detrimental impact on drinking water, biodiversity and human health, the EU hardened in 2019 the regulations on their "circular" utilization (EC, 2021; Hale et al., 2021; Heuser, 2022; Panagiotakis and Dermatas, 2022). Yet, despite these changes, the EU Mission Board Soil Health and Food estimated 60–70 % of EU soils to be unhealthy in 2020, with several registered sites still not under remediation (Panagos et al., 2022; Veerman et al., 2020).

Among the EU countries, Germany and France are the largest

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producers of waste soils, representing more than 60 % of the total production of both, contaminated and inert soils in Europe since 2010, followed by a second set of four countries (Austria, Poland, United Kingdom, and Italy) that cover around 25 % of the share (Eurostat, 2023). This means that the majority of waste soils production is concentrated in six countries only in the EU28, which has large effects on land competition for landfill surfaces (MA, 2019; Rizzo et al., 2022).

Because such a risk is expected to grow, mitigation measures have increasingly been proposed and implemented (Alshehri et al., 2023; Liu et al., 2018; Lombi and Hamon, 2005). Among them, the creation of an engineered soil that would not only be environmentally safe but also host and complement other infrastructure strategies to address environmental issues may be considered a sustainable option. This is the case of some types of nature-based solution (NbS), where an artificial ground or technogenic soil is used as manufactured topsoil to grow plants in urban environments (Ascione et al., 2021; Deeb et al., 2020; Minixhofer and Stangl, 2021), further helping to mitigate local environmental impacts such as heavy metal pollution (Egendorf et al., 2018), and enhance biodiversity (Rodríguez-Espinosa et al., 2021). The benefits of combining technogenic parent materials with exogenous materials such as green waste compost and paper mill sludge are well-known (Séré et al., 2008). In the area of green roof infrastructure, for example, the use of so-called "constructed technosols", i.e., mixtures of organic and mineral waste designed to meet specific requirements (Deeb et al., 2020), is considered a profitable solution, both from an environmental and economic perspective to reduce costs of implementation and management. In particular, the use of technosols created from excavated soils, which would otherwise be backfilled with loss of resources, is becoming popular in the field of circular economy (Fabbri et al., 2021). Minixhofer and co-authors have recently investigated such a challenge by focusing on the sustainable allocation of excavated materials for the optimization of soil substitutes in NbS (Minixhofer et al., 2022). Despite promising results have been obtained regarding the yield of plants grown on the investigated technosols, several questions remain open concerning the sustainability of this solution for aspects related to its supply-chain.

For boosting NbS to their full potential to improve city sustainability, all sustainability dimensions have to be considered, including the economic and business dimension (Henriksen et al., 2012; Osterwalder and Pigneur, 2010). Accelerated by Covid-19, NbS implementations are challenged by budget allocation dilemmas for local governments (Lafortezza and Davies, 2023). Their mainstreaming is hampered by insufficient public budgets (Mayor et al., 2021). Thus, new financing and business models considering both private and public sectors alike are needed. Business models explain how companies do businesses (Henriksen et al., 2012); they describe 'the rationale of how an organization creates, delivers and captures value' (Osterwalder and Pigneur, 2010). While market-driven businesses are traditionally oriented primarily towards profit-maximization, in the last years the business model approach has been widened to incorporate also sustainability aspects and NbS. In order to capture the relevant elements of NbS systematically, different scholars with varying backgrounds and vantage points improved the traditional Business Model Canvas (BMC) from Osterwalder and Pigneur (2010).

The aim of this study is to illustrate a coupled application of LCA and BMC approaches to the pilot case study of New Soil NbS in Turin, Italy, which is an urban park close to the Sangone river (peri-urban area of Turin) where trees and shrubs are planted on a layer of regenerated soil, i.e., soil recovered from urban construction sites, and improved mainly with organic compost from urban waste and zeolite powder (Ascione et al., 2021). The rationale of such methodological combination is to identify, ex-ante, the most relevant socioeconomic and environmental factors that generate synergies and trade-offs for a potential upscaling of a typical New Soil NBS implementation in the market. On one hand, the use of LCA can help estimating environmental impacts and damages potentially rising in the NbS life cycle (Larrey-Lassalle et al., 2022). On the other hand, the use of a BMC perspective offers solutions to develop and test sustainability scenarios for NbS deployment. The outcomes of this study are deemed useful to support further investments on the NbS and prospect the potential strengths and challenges that land managers and decision-makers need to address for possible use of the New Soil technologies in renaturation projects at large territorial scales.

2. Materials and methods

2.1. Description of the case study

The New Soil NbS site in Turin (Italy) is represented by an area of "urban forest" of 1500 sqm created from scratch along the banks of the Sangone river (GPS coordinates: 45.009040, 7.641200), built on regenerated soils. It is worth mentioning that, before the tree plantation, 300 sqm of the site were left intact to be used as control site. An additional layer of soil made of regenerated material from excavation processes was integrated in the remaining 1200 sqm, which is the area of reference for life cycle data collection in this study. See Figures S1.1–1.3 in the Supplementary Material 1 (SM1) for further illustrations.

The artificial soil (or technogenic soil) is obtained by mixing earth materials coming from construction sites (i.e., non-living deep excavation material) with compost from the organic fraction of municipal solid waste, natural zeolites and some types of mycorrhizae used as biostimulants. The blend used in the New Soil NbS here was developed in the context of the proGIreg Horizon 2020 innovation action for the sake of testing in urban requalification projects of the City of Turin, (proGIreg, 2023). More details on the composition of the regenerated soil can be found in Ascione et al. (2021) and are summarised in the SM1 (Table S1.1).

The NbS installation was completed in February 2020. The same density (i.e., 1000 units/ha) of a mix of trees and shrubs species was set in both the NbS and control sites, reaching the total number of #150 planted units. More specifically, in the 1200 sqm of land covered by the New Soil, #60 trees and #60 shrubs were settled. Growth analysis to monitor the effect of the regenerated soil on vegetation was performed during the implementation phase and beyond (Zitella, 2021). Number, species and the mortality rate of the plants are reported in the SM1 (Table S1.2). SM1 also reports the list of numerous herbaceous species that were planted in between shrubs and trees to further enrich the local biodiversity (Table S1.3).

Implementation and monitoring works were coordinated by the private-public company Environment Park Spa, located in Turin, with the contribution of several proGIreg consortium and affiliated partners, namely Dual Srl for the creation of the New Soil and the realization of the construction site, the University of Turin and the Italian National Research Council (CNR) for the monitoring activity, Acea Pinerolese organic waste treatment plant as compost provider, CCS Aosta Srl as biotic compound provider, and the City of Turin, Città Metropolitana di Torino and Arpa Piemonte, which assisted in the administrative procedures. Private gardeners of adjacent municipal gardens, as well as representatives of groups of citizens were also involved in the NbS design and implementation (Zitella, 2021).

2.2. Development and application of the LCA model

2.2.1. Goal and scope definition

The LCA method was applied to the NbS case study adopting an attributional approach (Hauschild et al., 2018), which allowed to perform an ex-post analysis of the environmental footprint associated with the NbS implementation and operation stages over the first three years of lifetime starting in 2020. Due to the uncertainty related to management activities foreseen for the next decades, some alternative scenarios were set out to estimate the potential environmental impacts of the NbS (i.e., assessment of environmental costs and benefits in terms of harmful and avoided impacts, respectively) using a prospective (ex-ante) approach (see further details about the setting up of scenarios in Section 2.2.4).

Establish a short- to long-term assessment implied creating a life cycle model of the NbS based on a “from cradle to grave” system boundary, thus preventing the loss of potentially relevant information about the environmental burden generated in all phases of the NbS life cycle. This meant including the most important physical input and output flows of the production activities that are upstream and downstream linked with the operation of the NbS. The unit processes belonging to those activities reflect the activity systems depicted in Fig. 1. The life cycle model was conceived to cover four main phases as follows:

1. *upstream phase*, which included (a) all the activities associated with the regenerated soil production made by excavated soils during construction processes, as well as compost from municipal solid waste, both collected, transported and mixed in the building yard, and ultimately transported to the NbS site in Sangone river, and (b) the production processes and transportation of zeolites to the NbS site as well as the operations needed to prepare this site for the tree plantation;
2. *implementation phase*, which comprised all the trees and shrubs plantation activities and their transportation from the nursery to the NbS site, as well as the production upstream and transportation of the plantation additives (biostimulants, mix of coconut fibers and polymers and hydroretention compounds) and of the seeds used for the ground herbaceous plantation;
3. *management phase*, which included some operations of cleaning, weeds and brushwood mowing, and replanting activity that had been already taking place in the third year, and can therefore expectedly take place on yearly basis all over the lifetime of the NbS;
4. *end-of-life phase*, which was built to model three possible treatment routes for the biowaste generated by the NbS, as suggested in Babí Almenar et al. (2023) for the case of urban forests, plus one potential production chain of renewable energy, namely i) resource for cogeneration of energy, ii) composting, iii) biomethanation, and iv) re-utilisation of dead wood as raw material.

Data for the LCA were collected and elaborated following the criteria described in Section 2.2.2. The functional unit (FU) considered for the analysis was the area of the pilot in the lifetime of the NbS, i.e., 1200 square metres of public urban green space created over a layer of “new regenerated soil” and managed over one reference year. The modelling framework for the analysis considered an initial management of the NbS after three years from its establishment (for the ex-post analysis), and then several possible lifetime projections until an ideal threshold of 50 years (see Section 2.2.4).

2.2.2. *Requirements for the life cycle inventory and impact assessment*

A life cycle inventory (LCI) of the inputs and outputs belonging to the NbS was built according to the second methodological step of the LCA method (ISO, 2006a, b). Table 1 includes the list of data gathered from the proGIreg project consortium in 2022, provided with a data quality check for both “foreground” and “background” process activities, i.e., activities for which data collection and process management is, respectively, “under” and “outside” the control of NbS designers and managers. A detailed explanation of the assumptions adopted to cover some data gaps, as well as a description of the limitations and criteria underpinning the inputs and outputs data requirements are reported in the SM2.

The LCI and the overall life cycle model of the NbS was built in OpenLCA v1.11.0 (https://www.openlca.org/, Accessed on December 2023) using the ecoinvent v3.9 and Agribalyse v3.01 databases as sources of background data (see in the SM2, Table S2.1). For the life cycle impact assessment (LCIA) – third step of the LCA methodology – specific impact category indicators from the ReCiPe method (Huijbregts

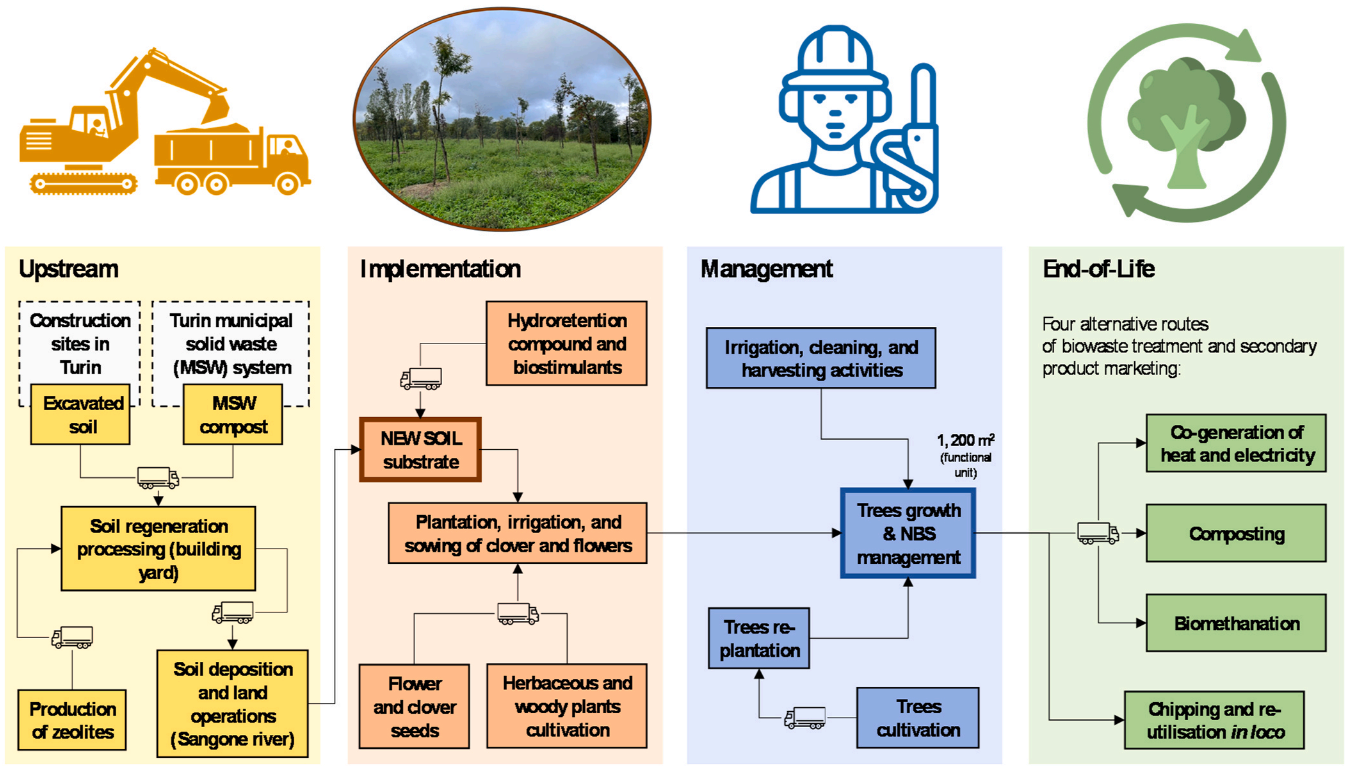


Fig. 1. System boundary of the New Soil NbS life cycle model; activities within the dotted lines are excluded. Icons sourced by Flaticon (www.flaticon.com, Accessed on 1 August 2023). The photo on the top of the image depicts plants in the NbS pilot one year after their plantation proGIreg (2023).

Table 1

Life Cycle Inventory (LCI) and data quality check for the model of New Soil NbS implemented in Turin (Italy), Sangone Park. Data refer to the plantation of #60 trees and #60 shrubs species over 1200 m^2 of land, regenerated with 2647 tons of excavation material recovered from construction sites and managed over one average year (functional unit of the LCA study). Refer to the SM2 (Table S2.1) for further information on the data collection and data sources.

Life cycle activities and processes	Amount	Unit	Foreground data gathering approach	Background data representativeness
1a_New Soil production				
INPUTS (*una tantum*)				
Excavation material, from various construction sites in Turin (Italy)	2541	t	Calculated	*(no link with background database)*
Compost, from organic fraction of municipal solid waste (MSW) in composting plant	106	t	Calculated	High
Operations in the building yard (chemical analysis, primary selection, sieving, mixing with compost, and stocking)	(for) 2647	t	Measured	Low
Distance for the transport of excavated material from construction sites to New Soil production site (use of truck 16–32 metric ton)	15	km	Estimated	High
Distance for the transport of compost from composting plant to New Soil production site (use of truck 16–32 metric ton)	42	km	Measured	
Distance for the transport of New Soil from its production site to the NbS site in Sangone river (use of truck >32 metric ton)	20	km	Measured	
OUTPUT (*una tantum*)				
Regenerated soil	2647	t	Measured	-
1b_Site preparation at Sangone river				
INPUTS (*una tantum*)				
New Soil deposition and land operations (mulching, hoeing, material deposition, tillage etc.)	(various, depending on the dataset used)		Literature	Medium
Zeolite powder	120	kg	Calculated	Medium
Distance for the transport of zeolite powder from production site to the NbS site (use of light commercial vehicle)	250	km	Estimated	High
OUTPUT (*una tantum*)				
Land prepared for plantation	1200	m^{2}a	-	-
2_NbS implementation				
INPUTS (*una tantum*)				
Plants (trees + shrubs), total weight	2100	kg	Measured	-
Trees, total number	60	pcs.	Measured	Medium
Shrubs, total number	60	pcs.	Measured	Low
Dwarf clover, seeds	3.24	kg	Estimated	Medium
Flowering lawn, seeds	0.36	kg	Estimated	Low
Distance for the transport of plants from the nursery to NBS site (use of truck 3.5–7.5 metric ton)	400	km	Measured	High
Distance to NbS site for the transport of all the commodities supporting the plantation (use of light commercial vehicle)	130	km	Estimated	High
Tree planting activity	120	pcs.	Literature	Medium
Sowing of clover and flowers	1200	m^2	Literature	Medium
Mix of coconut fibres and polymers	60	kg	Calculated	Medium
Hydroretention compound	3.6	kg	Calculated	Low
Biostimulants	6	kg	Calculated	Medium
Freshwater, for irrigation	600	litres	Estimated	Medium
OUTPUT (*una tantum*)				
Implemented urban green space	1200	m^{2}a	-	-
3a_NbS management at the 3rd year from NbS implementation				
INPUTS (*on yearly basis*)				
Land occupation (forest land use, extensive)	1200	m^{2}a	Measured	*(no link with background database)*
Land transformation (land use change from grassland to forest land), at 3rd year	400	m^2	Estimated	
Use of machineries (gasoline fuelled), for maintenance	68	hours	Estimated	Medium
Freshwater, for distress irrigation, at 3rd year	235	litres	Estimated	Medium

(*continued on next page*)

Table 1 (*continued*)

Life cycle activities and processes	Amount	Unit	Foreground data gathering approach	Background data representativeness
Amount of total replanted trees and shrubs (produced and transported on site) at the third year	822.5	kg	Calculated	Medium & Low (same datasets of Phase 2)
OUTPUT (*una tantum*)				
Managed urban green area after three years	1200	m^2a	-	-
3b_Hypothetical yearly NbS management from the 4th to the 50th year of NbS lifetime				
Land occupation (forest land use, extensive)	1200	m^2a	Measured	*(no link with background database)*
Biomass harvesting activities	4.8	m^3	Estimated	Medium
Use of machineries (gasoline fuelled), for maintenance	23	hours	Estimated	Medium
OUTPUTS				
Yearly functioning of the NbS (average over 47 years)	1200	m^2a	-	-
Biowaste, wet matter, for recovery (annual average over 47 years)[a]	3.34	t	Calculated	-
4_Hypothetical End-of-Life (EoL) phase of the NbS				
INPUTS (*on yearly basis*)				
Annually recoverable biowaste, wet matter, from NbS[a]	3.34	t	Calculated	*(no link with background database)*
Distance for the transport of plants from the nursery to NBS site (use of truck 7.5–16 metric ton)	25	km	Estimated	High
ALTERNATIVE OUTPUTS (four biowaste treatment options):				
Route 1_Co-generation of heat and electricity, from wood chips	3969.1	kWh	Estimated	High
Route 2_Compost, from composting process	1002	t	Estimated	High
Route 3_Biomethane, high pressure, from syngas methanation	505	Nm^3	Estimated	Medium
Route 4_Re-utilisation of dead wood as raw material	3.34	t	Estimated	High

[a] This value is obtained through *iTree* based simulations over 50 years of future biomass growing dynamics, then averaged on a yearly basis. Refer to Section 2.2.4 and to the SM1 for further details.

et al., 2016) were selected because considered the most pertinent ones to describe the mechanisms and drivers of environmental footprint possibly generated by the NbS' life cycle phases. More specifically, out of the eighteen midpoint impact categories available in ReCiPe, only eight were characterized in this study, i.e., global warming potential (GWP); fine particulate matter formation potential (PMFP); photochemical oxidant formation potential, humans (HOFP); agricultural land occupation potential (LOP); terrestrial acidification potential (TAP); mineral resource scarcity (MRS); fossil resource scarcity (FRS); water consumption potential (WCP). Those eight categories and their related indicators are further described in Table S2.2 of the SM2, with an explanation of their pertinence for the present analysis.

2.2.3. Development and application of the Business Model Canvas

A business model catalogue was developed in the proGIreg project with the aim to highlight market opportunities and public-private-partnership models to be used in the private sector, social entrepreneurship, and public actions. Based on scientific assessments of the multiple benefits NbS provide for social, ecological and economic regeneration, proGIreg's overarching objective of demonstrating NbS-integration into (partly) self-sustained business models required emphasising upon possible bottlenecks for NbS when entering the market (Pölling et al., 2020). Accordingly, both technological and non-technological barriers hindering the broad implementation of NbS, including the pilot investigated in this paper, were identified by engaging with key project stakeholders via questionnaires, as well as by gathering information from cities external to the project (Arbau, 2021; Latinos, 2021; Zitella et al., 2021).

More specifically, a NbS-tailored and adjusted strategic management template building on the original Business Model Canvas (BMC) was developed and used within the proGIreg project (Stork et al., 2023), see Fig. 2. This NbS BMC builds on previous business models for NbS and sustainability-oriented activities. An increasing number of studies matches business model thinking with ecosystem services (Bishop et al., 2009; Van Oijstaeijen et al., 2023), Life Cycle Thinking (Goffetti et al., 2022), sustainability (Broccardo and Zicari, 2020), and NbS (Egusquiza et al., 2021; Mayor et al., 2021). It collates pivotal elements that serve to characterize the NbS for its capability to create value for the society, on one hand, and, to capture value from exogenous sources on the other hand. Assembling information about those themes, called "building blocks", can provide decision-makers with a diagnostic qualitative tool to prospect both negative and positive impacts generated by the implementation and management of the NbS.In total, 14 blocks build the NbS-tailored BMC (see Fig. 2). The right half of the template focuses on value capturing, while the left part on value creation. Centrally positioned are the value proposition and governance of the NbS concerned. While businesses focus on customers, NbS target groups include not only customers, but also beneficiaries (Egusquiza et al., 2021; Stork et al., 2023). The bottom four building blocks allow insights into the financial situation of the NbS, including possible direct revenue streams, but also financing and cost reduction options as well as main cost categories. The top building blocks emphasize on the wider societal and environmental affects; both positive and negative. The NbS-tailored BMC widens the usability beyond business-oriented interventions, especially NbS which are planned, implemented, and maintained by a wide range of stakeholders with various objectives going beyond primary profit-orientation. This proposed NbS BMC allows to differentiate between revenue streams originating from sales, fees, etc. and financing. This is not possible when applying the original BMC. It establishes a logic link between target groups and financial sources: customers are mainly connected with revenue streams, while beneficiaries, who are not directly paying for a value, take advantage of other means of remuneration; often public funds. Additionally, the demonstration of positive societal and environmental impacts substantiating why public funds are reasonable. Furthermore, all the beneficiaries are neglected when using the original BMC and the successful application for public

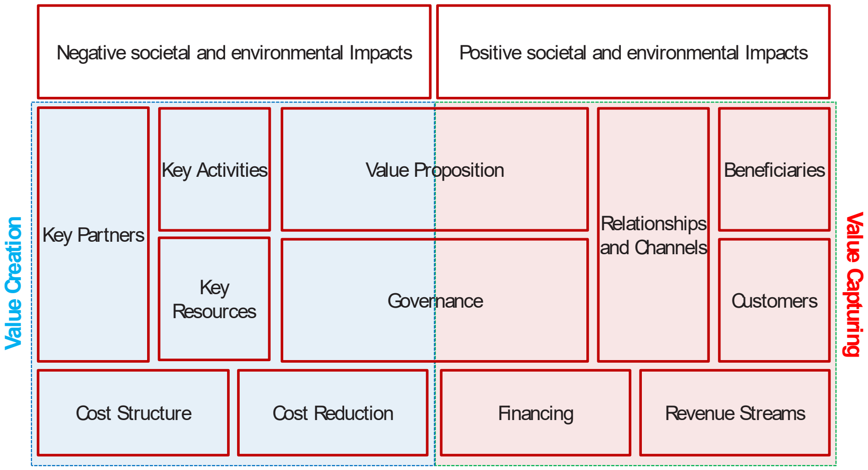


Fig. 2. Building blocks of the Business Model Canvas (BMC) used for the qualitative assessment of the social, economic, and environmental sustainability aspects associated with the New Soil NbS.

funds, including proGIreg, as well as measures for cost reduction can only be highlighted by usage this NbS-tailored BMC.

For each of the 14 building blocks of the NbS-tailored Business Model Canvas a set of guiding questions was developed for allowing comparability of NbS information. These questions are reported in the SM3. The questions, which were asked to the main NbS contact persons via personal interviews, asked for today's situation, but also what is predicted for the future. This concerned in particular the definition of circular economy strategies for the recovery of biomass from the NbS.

2.2.4. *Formulation of environmental performance scenarios*

Because of the uncertainty associated with the plants mortality rates and the volume of biomass growing in the NbS over the next decades, several alternative routes of biowaste treatment were conceived as introduced in Fig. 1 and illustrated in the SM1. Those helped to estimate a potential interval of variability under which the environmental footprint of the NbS can be confined in the future. To this end, the *i-Tree Eco* model (Hirabayashi et al., 2022) was applied to model biomass growth dynamics of trees and shrubs as follows: clear-cutting of the #60 shrub units and removal of their related aboveground biomass on every five years; and clear-cutting of the #60 tree units and removal of their related aboveground biomass after 50 years from the NbS implementation.

Simulating the growth dynamics of the species planted in the NbS was crucial to estimate the yearly potential biowaste outflow associated with the management operations until the hypothetical time horizon of 2070, taken as a long-term reference (the average annual value of this output is included in Table 1). Such an output flow was used as input to model the life cycle activities of the abovementioned four end-of-life alternative scenarios of biowaste treatment, set out trying to meet the BMC requisites of reducing economic costs and increasing circularity (see in the SM1 for further descriptions):

- Scenario 1 (CO-GENERATION): recovery of biomass material for electricity and heat production;
- Scenario 2 (COMPOST): composting of extractable biomass;
- Scenario 3 (METHANE): biomethanation of recovered biomass;
- Scenario 4 (RE-USE): re-utilisation of dead wood as raw material.

The rationale to model scenarios 1, 2 and 3 in relation to the BMC was that those activities may represent additional circular economy-oriented revenue streams in the future. In this case, new or secondary values (goods like resources, products, namely i) electricity and heat, ii) methane, and iii) compost) can be created as it were market commodities ready to be used, in turn, to compensate or mitigate the unavoidable environmental and economic costs associated with biowaste disposal, as well as compared against the environmental performance of conventional market products. In contrast, scenario 4 (mulching material) does not aim to generate direct financial revenues. It can be considered a valuable alternative to avoid any biowaste disposal costs while increasing the supply of ecosystem services (ES) locally, namely the soil organic carbon content and nutrient cycling.

The assessment of the four scenarios was limited to the characterisation of environmental footprint, which allowed to compare their impact performance and create a preliminary baseline for future studies. To this end, the same biowaste input flow estimated with *i-Tree Eco* was implemented in the LCI model of the four scenarios. The LCIA was then run in OpenLCA.

3. Results

3.1. *Ex-post life cycle impact assessment*

This section reports the results of the LCIA related to the New Soil NbS construction and management over the first three years from its implementation, i.e., environmental footprint potentially generated by the NbS at the pilot scale, from the end of the first plantation in 2020 until the end of replantation of death units in 2023. In this regard, Fig. 3 shows the relative contribution of the main life cycle phases of the NbS to the global impact score for each selected indicator, estimated for 1200 sqm of NbS area in the Sangone Park. The total absolute value of each environmental impact category indicator is reported in Table 2 for the sake of completeness.

The model suggests that, after three years, the operations necessary for developing the New Soil and laying it as plantation substrate in the NbS site at Sangone Park (Phases 1a and 1b) are those undoubtedly most responsible for impacts, reaching together the relative contribution of around 88 % on average. Those impacts are mainly due to air emissions and fossil fuel consumptions. More specifically, Phase 1a dominates across all environmental impacts, starting from a lowest contribution of ~25 % with the LOP indicator, and reaching the highest share of ~97 % with the WCP indicator. The phases of site preparation (Phase 1b) and of first plantation (Phase 2), instead, shows a relatively low but meaningful score only for the MRS indicator (with values up to ~3 % and ~11 %, respectively), because of the fairly high amount of minerals indirectly used in the supply-chain of the seeds production. In contrast, when compared to the other life cycle phases, the activities of NbS management (Phase 3) contribute in a negligible manner to each environmental impact (relative contributions between ~1 %, recorded for WCP, and ~5 %, recorded for MRS), with the exception of the LOP indicator. For

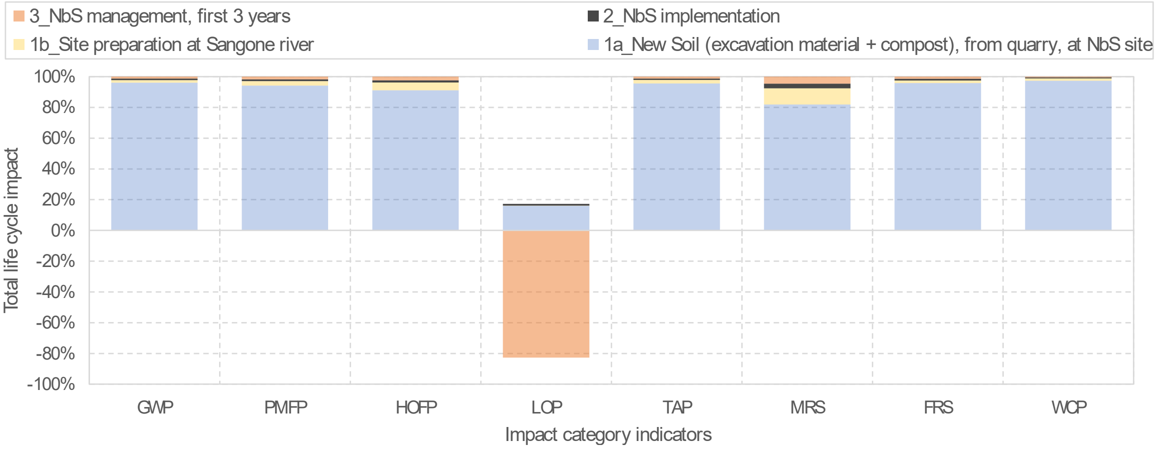


Fig. 3. Distribution of the potential environmental impacts across the life cycle phases of the New Soil NbS (for an area of 1200 sqm) observed after three years from its implementation in Sangone Park (Turin, Italy). GWP = global warming potential; PMFP = fine particulate matter formation potential; HOFP = photochemical oxidant formation potential, humans; LOP = agricultural land occupation potential; TAP = terrestrial acidification potential; MRS = mineral resource scarcity; FRS = fossil resource scarcity; WCP = water consumption potential.

the latter, a net gain of around 1 ha of equivalent crop land is recorded because of the conversion from "abandoned" grassland to urban forest land.

The impact of each selected environmental indicator can be further disaggregated per single process to identify the life cycle activities that should be investigated with priority, to ensure that sound decisions are made for improving the system environmental sustainability performances.

Table 2 displays the distribution of each impact indicator across those life cycle phases and related activities. The highest contributions to the total environmental footprint across the eight categories are due to the operations in the building yard to produce the New Soil (Phase 1a), with values in between ~70 % (for MRS) and ~96 % (for WCP) to the total impact. Those impacts are mainly due, indirectly, to the consumptions of energy (electricity and heat) needed for operations of chemical analysis, primary selection, sieving, mixing with compost and stocking (on average, around 57 kWh per ton of material are estimated to be used in all these processes). Other relevant impacts are associated with the production and transport of compost from the organic fraction of municipal solid waste (still Phase 1a), with contributions in between 2 % (for LOP and WCP) and 17 % (for the HOFP) to the total impact. The transportation of the excavated soils and the generated New Soil product are also relevant processes for the overall impact score in each indicator.

Apart from these life cycle hotspots – although their substantially lower contributions to the total impacts – other activities do also show some criticalities. For example, the production of zeolite, which is used for enriching the regenerated soil on site in Phase 1b, shows to substantially contribute to the impact of that phase across four out of eight categories, namely GWP, LOP, MRS and WCP. In line with previous observations, the production of zeolite in the upstream supply-chain is the major responsible for impacts linked to resource depletion, in particular with regard to water and minerals consumptions. Instead, the use of diesel in the New Soil deposition activities and land operations (Phase 1b), as well as in Phase 2, represents the main source of environmental pressure in both transportation processes of materials and the plantation of trees and shrubs. Notably, the combustion of diesel is directly associated with impacts on crude oil scarcity as well as with impacts due to the release of GHGs, particulate matter, nitrogen and sulphur oxides.

Ultimately, it is worth mentioning that some impact scores are associated with re-plantation processes occurring at the third year of NbS lifetime, after an observed high mortality rate of ~13 % for woody plants, and ~26 % for herbaceous plants (see in the SM1 for further details). Other substantial contributions observed in Phase 3 concern the impact scores generated by the mowing activity performed to clean the area, where, again, fossil fuels are consumed (mainly petrol combusted when using manual harvesting and chipping tools).

3.2. Application of the NbS-tailored Business Model Canvas

The new soil business model is summarized in Fig. 4 by presenting the fourteen building blocks. By applying the NbS-tailored BMC the offered values, the (internal) organization, the target groups, the key resources, activities, and partners, but also the financial aspect can be summarized. Additionally, the wider impact on society and environment are listed reflecting the nature of NbS going beyond primarily profit-oriented activities. A deeper understanding of the BMC exercise is offered in the SM1.

3.3. Ex-ante analysis of the environmental footprint associated with the NbS

Outcomes from the BMC survey synthetized in Fig. 4 suggest that circular economy strategies are best solutions to mitigate high economic costs and provide environmental benefits in synergy. To offer a quantitative estimate of such environmental benefits, four possible end-of-life (EoL) routes for biomass recovery were investigated in this study and compared in terms of impact savings at different times and according to four EoL routes: EoL route 1, i.e., co-generation of heat and electricity from green waste; EoL route 2, i.e., production of green waste compost; EoL route 3, i.e., production of biomethane; and EoL route 4: chipping and re-use of biomass in situ.

The NbS area is supposed to become an urban park for recreational services, where plants are not clear-cut as it were for a coppice management. Despite the NbS aims to become a standing forest with a lifetime of at least 50 years, projections allow to forecast a potential environment footprint as if a sort of "coppice" management were occurring by modelling a clear-cutting for the #60 shrub units, ideally at every 5th year. On top of that, it is supposed to harvest the biomass from the remaining #60 trees after fifty years from the NbS implementation, in order to have an extent of the potential wooden resource generation. Finally, manual cutting of the grass is considered crucial for the maintenance of the overall NbS, and thus modelled at every 3-years interval for 50 years.

As shown in Fig. 5, after 50 years from the NbS implementation the impacts distribution would still be dominated by the relative contribution of the first phases of New Soil production and land preparation, with values that range between ~56 % (for PMFP) and ~78 % (for

Table 2

Gravity Analysis: detailed distribution of the potential environmental impact across the four main life cycle phases of the New Soil NbS and related process activities (for 2647 tons of New Soil layered over an area of 1200 sqm); values refer to the NbS life cycle after three years from its implementation, and do not include any long-term management and end-of-life activity of harvested biomass residues.

	Midpoint impact category indicators							
	Global warming potential (GWP)	**Fine particulate matter formation potential (PMFP)**	**Photochemical oxidant formation potential, humans (HOFP)**	**Agricultural land occupation potential (LOP)**	**Terrestrial acidification potential (TAP)**	**Mineral resource scarcity (MRS)**	**Fossil resource scarcity (FRS)**	**Water consumption potential (WCP)**
	Infra-red radiative forcing increase	$PM_{2.5}$ population intake increase	Tropospheric ozone pop. intake increase	Land occupation and time integrated transformation	Proton increase in natural soils	Ore grade decrease	Upper heating value	Increase of water consumed
Phases and processes	kg CO_2 eq.	kg $PM_{2.5}$ eq.	kg NO_x eq.	m^2a crop eq.	kg SO_2 eq.	kg Cu eq.	kg oil eq.	m^3
1a_New Soil, from building yard, at NbS site								
Inputs:								
Production and transport of compost, from organic fraction of MSW	6.4 %	7.9 %	17.0 %	2.2 %	6.2 %	15.5 %	7.1 %	1.7%
Excavation material, from various construction sites in Turin (IT)	8.7 %	6.0 %	6.5 %	10.5 %	4.5 %	9.9 %	10.3 %	1.5 %
Operations in the building yard	**78.4 %**	**80.7 %**	**70.5 %**	**73.0 %**	**85.6 %**	**68.6 %**	**74.4 %**	**95.5%**
Transportation processes, to NbS site (Sangone river, Turin, IT)	6.5 %	5.4 %	6.0 %	14.4 %	3.7 %	6.0 %	8.2 %	1.3 %
Output: New Soil (excavated material mixed with compost)	7.10E+04	8.94E+01	1.52E+02	2.46E+03	2.51E+02	1.18E+02	2.08E+04	6.86E+02
1b_Site preparation at Sangone Park (Turin, IT)								
Inputs:								
New Soil deposition and land operations	45.8 %	**55.9 %**	**79.2 %**	11.6 %	**52.5 %**	7.2 %	**50.9 %**	10.5 %
Zeolite powder production	**49.6%**	41.1 %	17.8 %	**77.0 %**	44.3 %	**91.5 %**	43.9 %	**87.6 %**
Transportation processes	4.5 %	3.0 %	3.0 %	11.4 %	3.2 %	1.3 %	5.2 %	1.9 %
Output: Land prepared for plantation, at Sangone river	1.21E+03	2.79E+00	8.37E+00	1.29E+01	5.92E+00	1.52E+01	3.61E+02	1.10E+01
2_NbS implementation								
Inputs:								
Tree seedling production	7.1 %	6.8 %	6.2 %	28.8 %	8.6 %	11.6 %	5.5 %	19.3 %
Trees and shrubs planting activity	29.4 %	**50.2 %**	**54.6 %**	8.2 %	**43.8 %**	**56.2 %**	26.4 %	**29.9 %**
Mix of coconut fibres and polymers	2.7 %	5.6 %	5.9 %	0.2 %	7.7 %	0.4 %	3.6 %	3.9 %
Protein hydrolysate-based biostimulant	1.1 %	0.9 %	1.1 %	**31.1 %**	1.3 %	0.2 %	1.0 %	1.7 %
Hydro-retention compound (wooden chips)	0.0 %	0.0 %	0.0 %	0.3 %	0.0 %	0.0 %	0.0 %	0.0 %
Dwarf clover seed production	0.6 %	0.9 %	1.2 %	23.7 %	1.0 %	1.0 %	0.6 %	1.3 %
Flowering lawn production, seeds	0.1 %	0.2 %	0.1 %	0.7 %	0.7 %	0.0 %	0.0 %	0.0 %
Sowing of clover and flowers	0.4 %	0.7 %	1.1 %	0.1 %	0.6 %	0.6 %	0.4 %	0.3 %

(*continued on next page*)

Table 2 (*continued*)

	Midpoint impact category indicators							
	Global warming potential (GWP)	**Fine particulate matter formation potential (PMFP)**	**Photochemical oxidant formation potential, humans (HOFP)**	**Agricultural land occupation potential (LOP)**	**Terrestrial acidification potential (TAP)**	**Mineral resource scarcity (MRS)**	**Fossil resource scarcity (FRS)**	**Water consumption potential (WCP)**
	Infra-red radiative forcing increase	$PM_{2.5}$ population intake increase	Tropospheric ozone pop. intake increase	Land occupation and time integrated transformation	Proton increase in natural soils	Ore grade decrease	Upper heating value	Increase of water consumed
Phases and processes	kg CO_2 eq.	kg $PM_{2.5}$ eq.	kg NO_x eq.	m^2a crop eq.	kg SO_2 eq.	kg Cu eq.	kg oil eq.	m^3
Freshwater, for irrigation	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	16.3 %
Transportation processes	**58.5 %**	34.8 %	29.8 %	6.9 %	36.4 %	29.9 %	**62.5 %**	27.1 %
Output: Implemented urban green space, at Sangone river	7.60E+02	1.08E+00	2.33E+00	1.77E+02	2.35E+00	4.49E+00	2.39E+02	3.68E+00
3_NbS management, over 3 years								
Inputs:								
Tree seedling production	3.1 %	2.3 %	1.8 %	0.2 %	3.0 %	4.1 %	2.2 %	9.1 %
Trees and shrubs (re) planting activity	9.9 %	12.8 %	12.4 %	0.0 %	12.0 %	15.2 %	8.4 %	10.9 %
Mowing activity, by motor mower	**68.1 %**	**76.7 %**	**79.8%**	0.4 %	**75.7 %**	**73.0 %**	**70.4 %**	**64.8 %**
Freshwater, for irrigation	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	6.0 %
Transportation processes	19.0 %	8.2 %	6.0 %	0.0 %	9.3 %	7.7 %	19.0 %	9.3 %
	-	-	-	**-100.7 %**	-	-	-	-
Output: Functioning of the NbS, after 3 years of management	8.83E+02	1.66E+00	4.02E+00	-1.27E+04	3.35E+00	6.51E+00	2.96E+02	3.95E+00
Total per functional unit (= 1200 sqm of NbS pilot, after 3 years)	**7.38E+04**	**9.49E+01**	**1.66E+02**	**-1.00E+04**	**2.63E+02**	**1.44E+02**	**2.16E+04**	**7.04E+02**

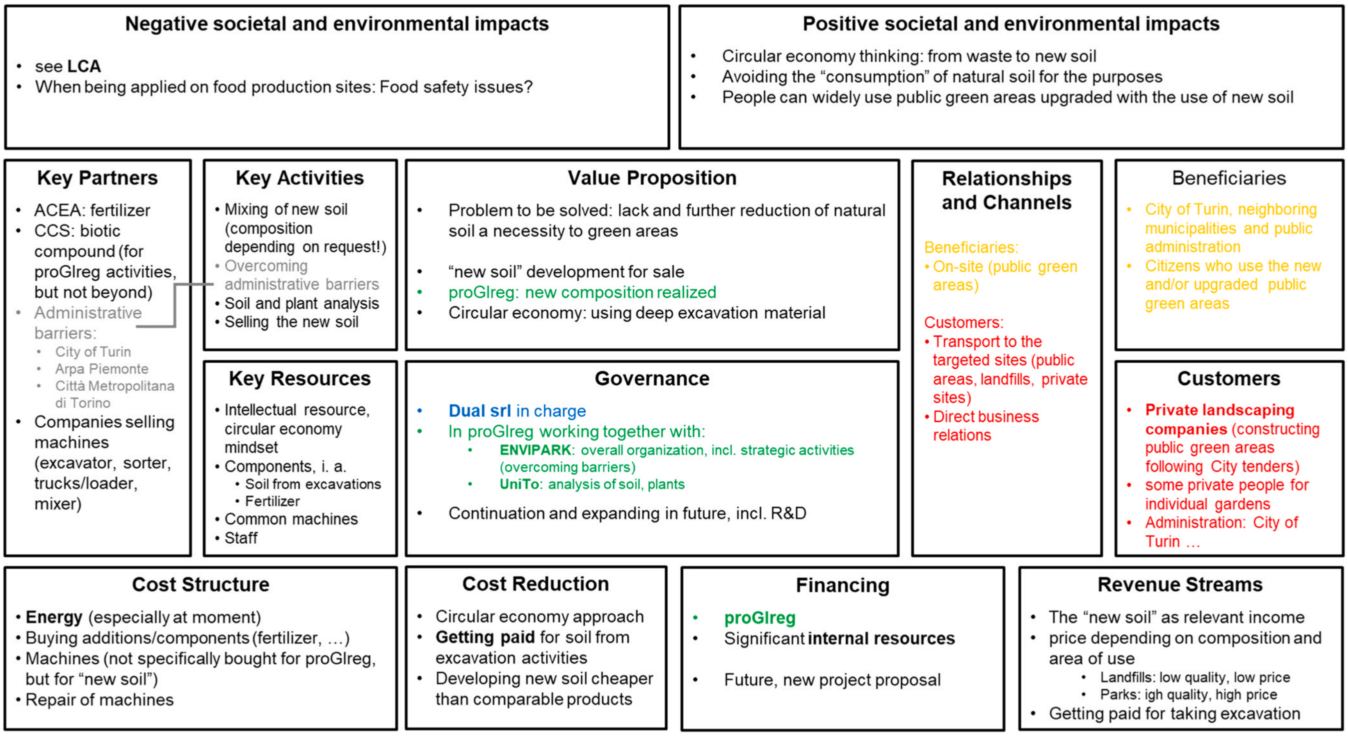
WCP). Only in the case of LOP this contribution decreases to around 9 %, as an effect of the much larger and beneficial impact of equivalent crop land gained through the operations of management (Phase 3). The future management (Phase 3b), instead, may imply a relevant impact in particular with regard to some categories such as MRS (~47 %) and HOFP (~30 %). The estimated impact of the end-of-life stages would also be meaningful because of the activities of biomass removal and treatment (on average among the eight indicators and four biowaste management options, such a contribution is around 14 % of the total impact at the 50th year of NbS lifetime).

More specifically, the future average management operations (Phase 3b of the NbS life cycle) and the EoL processes generate an environmental impact that only slightly accumulates over time, as an effect of the impact allocation occurring at every year. As displayed in Fig. 6, the cumulated impact of both Phases 3b and 4 may grow on average every five years between ~8 % (for MRS) and ~25 % (for WCP), with the exception of LOP which shows decreasing trends (by ~16 %). This is not surprising, considering that the maintenance of the area requires a regular consumption of gasoline and diesel, as well as the supply-chain of biomass recovery demands non-renewable energy and resource flows to support the transformation into electricity and heat, or compost or biomethane. Overall, however, the environmental footprint strongly decreases on every five years by around 19 % on average among the eight indicators. This is mainly due to the allocation effect of the impact associated with Phases 1 and 2. In the model, such impact is diluted over time: already after 10 years it is assumed to lose more than 70 % of the impact occurring at the year of implementation.

Looking more in detail at the Phases 3 and 4, their environmental footprint increases with different extents depending on the impact indicator and the EoL strategy. The environmental footprint due to Phase 3 is slightly dominant in the case of PMFP and MRS, while the contribution of Phase 4 is meaningful mainly at the latest stage, suggesting that the re-use of biomass from the tree species is far from being impact-free.

As reported in the SM4 (Figure S4.1), the EoL route 3 (biomethanation) is the option implying potentially the largest impacts concerning the FRS, LOP, MRS and WCP indicators, because of the biggest consumption of non-renewable resources occurring in the industrial processes needed to produce biomethane. While the production of compost (EoL route 2) would imply the highest GWP mainly because of the release of biogenic methane and N_2O during the aerobic decomposition of the green waste. While the environmental footprint related to the electricity and heat production scenario (EoL route 1) is mostly meaningful for PMFP, HOFP and TAP, which are impacts essentially due to the release of nitrogen oxides, sulphur dioxide and several other air pollutants emitted during the co-generation process at the energy factory. Ultimately, chipping and redistributing the material on site (EoL route 3) has largely the lowest environmental footprint among the four EoL options for all the selected indicators, with exception of FRS, LOP and WCP, where the discrepancy is less apparent.

When looking at all those impact differences, it is worth mentioning that the discrepancies among the EoL models should not be taken as reference for their strict environmental performance comparison, since



Negative societal and environmental impacts

- see **LCA**
- When being applied on food production sites: Food safety issues?

Positive societal and environmental impacts

- Circular economy thinking: from waste to new soil
- Avoiding the "consumption" of natural soil for the purposes
- People can widely use public green areas upgraded with the use of new soil

Key Partners

- ACEA: fertilizer
- CCS: biotic compound (for proGIreg activities, but not beyond)
- Administrative barriers:
  - City of Turin
  - Arpa Piemonte
  - Città Metropolitana di Torino
- Companies selling machines (excavator, sorter, trucks/loader, mixer)

Key Activities

- Mixing of new soil (composition depending on request!)
- Overcoming administrative barriers
- Soil and plant analysis
- Selling the new soil

Key Resources

- Intellectual resource, circular economy mindset
- Components, i. a.
  - Soil from excavations
  - Fertilizer
- Common machines
- Staff

Value Proposition

- Problem to be solved: lack and further reduction of natural soil a necessity to green areas
- "new soil" development for sale
- proGIreg: new composition realized
- Circular economy: using deep excavation material

Governance

- **Dual srl** in charge
- In proGIreg working together with:
  - **ENVIPARK**: overall organization, incl. strategic activities (overcoming barriers)
  - **UniTo**: analysis of soil, plants
- Continuation and expanding in future, incl. R&D

Relationships and Channels

Beneficiaries:
- On-site (public green areas)

Customers:
- Transport to the targeted sites (public areas, landfills, private sites)
- Direct business relations

Beneficiaries

- City of Turin, neighboring municipalities and public administration
- Citizens who use the new and/or upgraded public green areas

Customers

- **Private landscaping companies** (constructing public green areas following City tenders)
- some private people for individual gardens
- Administration: City of Turin …

Cost Structure

- **Energy** (especially at moment)
- Buying additions/components (fertilizer, …)
- Machines (not specifically bought for proGIreg, but for "new soil")
- Repair of machines

Cost Reduction

- Circular economy approach
- **Getting paid** for soil from excavation activities
- Developing new soil cheaper than comparable products

Financing

- **proGIreg**
- Significant **internal resources**
- Future, new project proposal

Revenue Streams

- The "new soil" as relevant income
- price depending on composition and area of use
  - Landfills: low quality, low price
  - Parks: igh quality, high price
- Getting paid for taking excavation

Fig. 4. Core messages derived from the qualitative exercise of applying the NbS-tailored Business Model Canvas for proGIreg NbS 2 "New Soil".

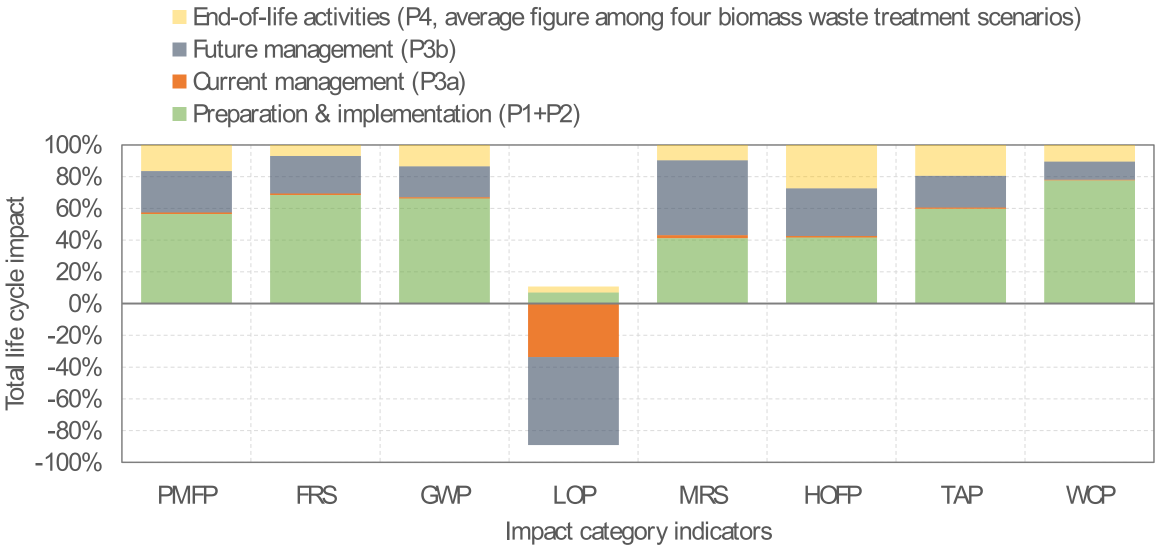


Fig. 5. Estimated distribution of the potential environmental impacts across the life cycle phases of the New Soil NbS (for an area of 1200 sqm) after 50 years from its implementation in Sangone Park (Turin, Italy). Absolute values of each impact score are displayed in Fig. 6 and represent the annually averaged values at a hypothetical total removal of tree biomass in 2070. GWP = global warming potential; PMFP = fine particulate matter formation potential; HOFP = photochemical oxidant formation potential, humans; LOP = agricultural land occupation potential; TAP = terrestrial acidification potential; MRS = mineral resource scarcity; FRS = fossil resource scarcity; WCP = water consumption potential.

the functional units of each EoL activity is not the same or does not have comparable function (e.g., the supply of electricity cannot be compared to the supply of biomethane). Their absolute impact value, however, can offer a parametric overview about the most sustainable EoL solution depending on the scope of the assessment.

In contrast, a comparison with the environmental footprint associated with conventional EoL technologies using virgin material is very pertinent to determining impact saving opportunities associated with the implementation of the four EoL strategies. Fig. 7 shows the difference between the impact generated by the NbS system when considering the EoL routes 1, 2 and 3, and the impact associated with three comparable alternative scenarios that make use of biomass residues collected from hypothetical forest ecosystems placed 25 km far from the EoL factories (same assumption used in the definition of biomass transport distances; see Section 2.2.4). The EoL route 4 was excluded from this analysis because no alternative business-as-usual scenarios exist for which the flow of chipped material may be replaced with.

Results in Fig. 7 suggest that, if the electricity and heat, or the compost or the biomethane produced from the NbS functioning over the next 50 years were to be used in the supply-chains of equivalent

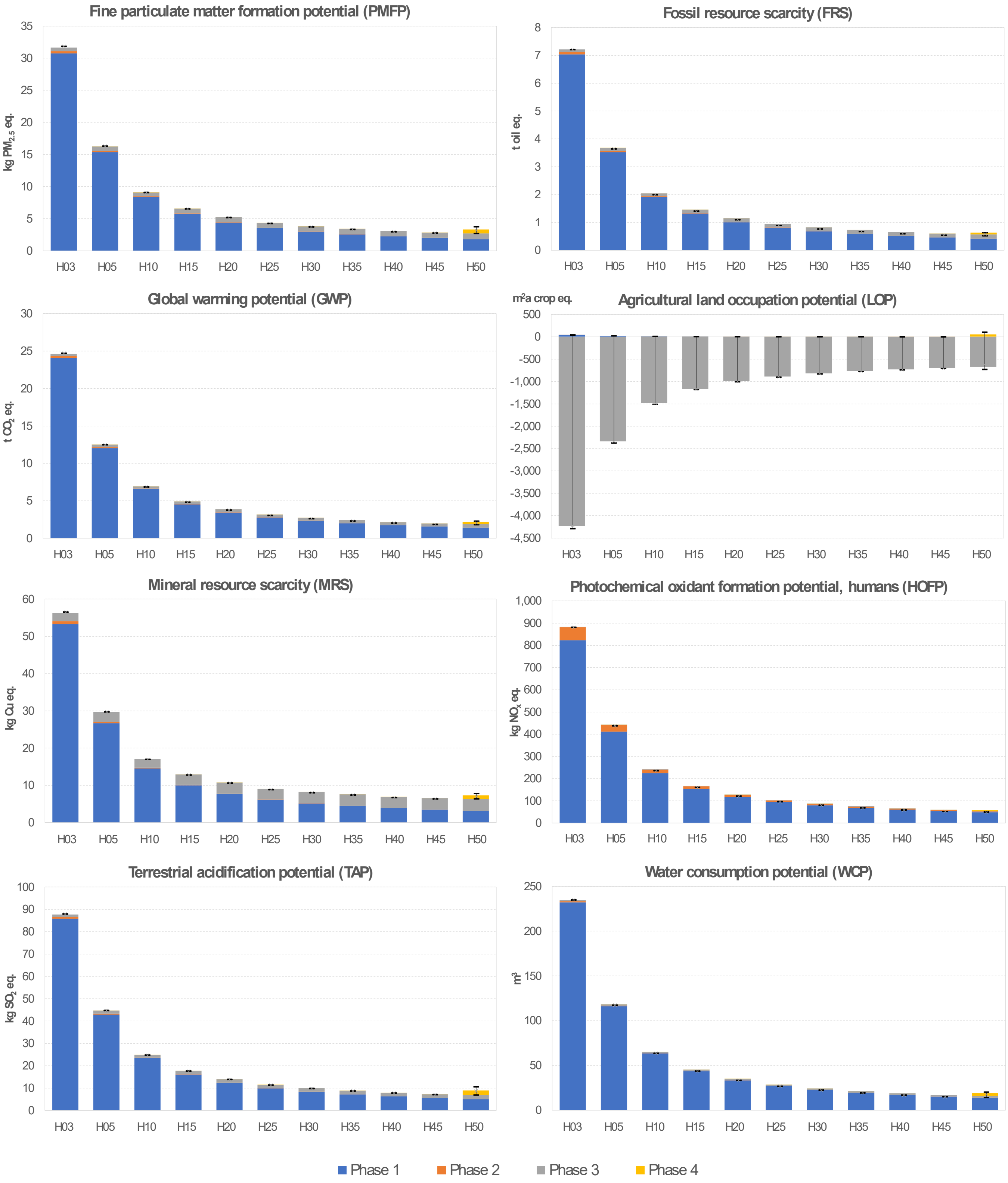


Fig. 6. Potential environmental impacts per life cycle phase of the New Soil NbS at different points in time, considering future time horizons (H) from today's baseline scenario, i.e., NbS after 3 years: H03 (y2020-y2022), H05 (y2023-y2025) until a scenario occurring after 50 years, ideally in 2070: H50); range bars indicate the variability of the impact (from min to max value) observed when varying the end-of-life route, while the relative contribution of Phase 4 is represented by the median value calculated among the min and max impact scores. Impacts allocation is made at one year scale in each time horizon, in order to capture information on the impact at different points in time over the NbS lifespan.

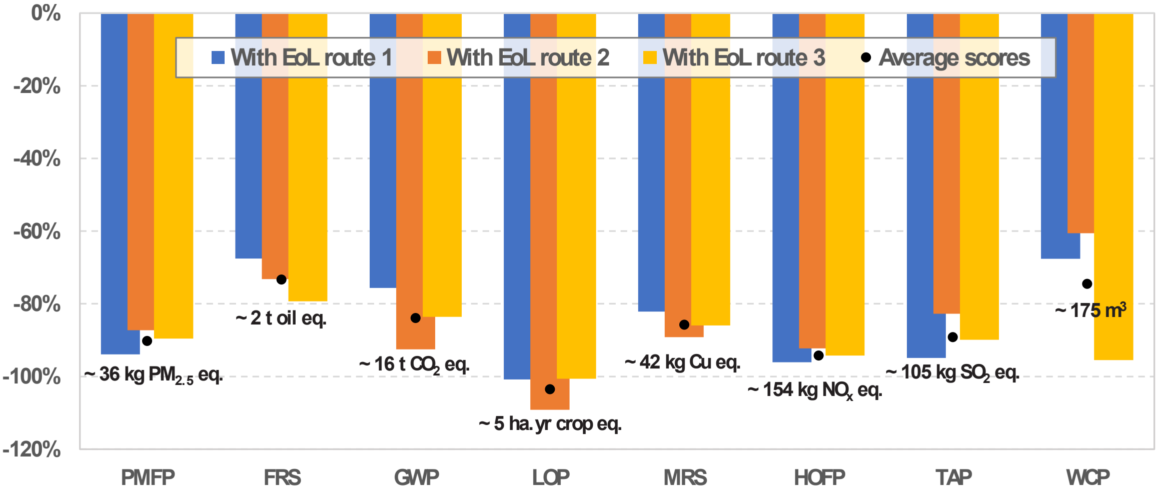


Fig. 7. Potential environmental impact savings generated from recovering biomass under circular economy strategies: differences with business-as-usual practice after 50 years of NbS management; end-of-life (EoL) routes: 1, co-generation; 2, compost; 3, biomethane.

commodities—thus replacing corresponding amounts of the same products supplied from the market—between 73 % (in the case of FRS) and 104 % (in the case of LOP) on average could be considered “avoided impact” as those flows might come from a life cycle system not existing before. To be more specific, for example, if ~157 tons of harvested biomass were collected from the NbS over fifty years and used to produce ~186 MWh of electricity in a co-generation process, around 60 kg $PM_{2.5}$ eq. would be avoided should this biomass replacing chipped material supplied from coppice forests. Such an impact difference, displayed in Fig. 7 with negative percentage values, corresponds on average to around 90 % among the three EoL routes (i.e., ~36 kg $PM_{2.5}$ eq.), with respect to the conventional EoL. Similarly, a carbon footprint between ~6 t CO_2 eq. (through the co-generation scenario) and ~30 t CO_2 eq. (through the compost scenario), which represent on average around 16 % of the carbon footprint of their respective conventional technologies, might be avoided if one of the three alternative EoL options were considered. While such as a modelling scenario cannot be validated at this stage, or might not be fully realistic, it offers an idea of the overall magnitude of the potential benefits linked to the valorisation of by-products from the NbS system.

4. Discussion

4.1. Sensitivity analysis

The ex-post analysis suggests that additional LCA-based analyses looking at the costs and benefits associated with the re-use of soil should be conducted to validate the hypotheses revealed through the qualitative BMC analysis. For example, the New Soil for NbS purposes might not always be favourable from the environmental footprint viewpoint: for certain impact categories, mixing excavated soil with compost may produce higher impacts than business-as-usual landfilling of the inert material (see further details in the SM4). The impact associated with the operations in the building yard to produce the New Soil, and with the production and transportation of the compost derived from the organic fraction of Turin’s solid waste, contribute together by around 70 % (on average across the eight impact categories analysed) to the global environmental footprint. Therefore, specific improvement measures might be undertaken by the producers of the New Soil to increase the environmental sustainability of the recovered product’s supply-chain, e.g., reduce the transportation distances of the recovered material, wherever possible, and change the consumption source from the national electricity mix with a locally produced renewable energy source.

The extent of such improvement potential can be quantified through a sensitivity analysis of the life cycle hotspots. For example, the sole reduction of 20 % of the transportation distances of the recovered material (both compost from the organic fraction of MSW and excavation soils), together with the hypothetical substitution of 50 % of the national electricity consumption mix with locally produced photovoltaic electricity, might help decrease the total environmental footprint of Phase 1 by more than 30 % (on average, across seven impact categories), with values up to 36 % in the case of land use (LOP). Those are two hypothetical improvement measures suggested within the BMC framework, which might be feasible as they would take place under control of the material suppliers. While as a potential tradeoff the MRS indicator might be affected by an increase in consumption of rare earths and other scarce metals should photovoltaic panels be installed for the local production of electricity (see SM4, Figure S4.2).

Most importantly, such a sensitivity analysis has allowed to estimate the potential carbon footprint savings of re-using inert soil and compost to produce a fertile soil as an alternative to depriving virgin soils from agricultural lands or applying fertilizers and soil conditioners. In this case, around 12 kg CO_2-eq./ton of soil can be potentially saved by producing and adopting a New Soil strategy in the creation of urban forests as NbS. This corresponds to around 270 tons of CO_2-eq. avoided per hectare of urban forest. The whole set of results and methodological requirements for the sensitivity analysis exercise are reported in the SM4.

4.2. Limitations and uncertainties

Due to the uncertainty and lack of knowledge concerning future activities occurring in the NbS area, the assumptions undertaken to build the ex-ante analysis model voluntarily followed a conservative approach. This generated a “worse-case” environmental profile both in the determination of key resource consumptions, such as irrigation water, and in the choice of the technologies representing the machineries and tools for the NbS management activities and EoL processing. Next to that, the model did not take into account the benefits in terms of resource use optimisation provided by the possible use of emergent technologies developed to replace the use of traditional (fossil fuel-based) machineries and tools. For example, because the actual activities in life cycle system of Phase 3 were unknown, datasets with average technology information on the use of motor mowers were retrieved from ecoinvent, and then implemented in the model. Despite this is common practice in LCA to address modelling data shortage, such procedure necessarily generates uncertainty, which must be considered when interpreting LCA results. To mitigate the impact of Phase 3 in future management operations, the use of an electric riding lawn mower might be used instead of gasoline-powered lawn mowers, as suggested by Saidani and Kim (2021).

Furthermore, the quality of data implemented for the LCI is low or very low in certain cases, which may affect the robustness of the model and the representativeness and accuracy of the LCA outcomes. As anticipated in Table 1, some key LCI data could only be estimated or retrieved from literature, in particular with regard to process activities that reflected hotspots in the LCIA (e.g., preparation activities of the New Soil in the building yard, or the mowing activities in Phase 3). This certainly increased the overall uncertainty of the environmental footprint scores, which might have been further over-estimated because of the adoption of ecoinvent datasets as source of background data. Compared to other databases such as Agribalyse (also partially used in this study), ecoinvent offers a more and more extensive coverage of life cycle activities, making often "the higher the inventoried inputs and outputs, the higher the associated impact scores" basically a "rule of thumb". While data for an LCA analysis will never be free of uncertainty, the choice done here of using best available technology datasets to model the impacts of the New Soil NbS life cycle might have mitigated the problem of working with uncertain data.

Additional limitations may concern the choice of the impact categories and the lack of an evaluation of the beneficial impact provided by the ES supplied by the plants growing in the NbS area. Further insights on these issues are provided in the SM4.

4.3. *Circular economy related implications and opportunities*

The New Soil NbS represents an innovative test bed where both a novel product and an original methodological approach were investigated for the first time, as anticipated by Ascione et al. (2021). On one hand, regarding the product, the New Soil tested as a substrate for creating a green space in urban settings is supposed to generate multiple social, economic, and environmental benefits, as emerged in the survey for the BMC. However, the qualitative and preliminary outcomes obtained with the BMC approach should be validated with quantitative findings in a few years from now, once the green area in Sangone river will regularly be managed to extract new biomass resources, and people will have benefitted from the recreational services provided by the park. On the other hand, estimations of the environmental footprint associated with the overall life cycle system suggest that the management of the NbS should be done carefully to reduce several potentially harmful impacts and trade-offs, such as the depletion of natural resources.

Urban NbS like green areas and parks are deemed to become a source of ecosystem functions and generate ES for people well-being. Therefore, the original combination between LCA and BMC approaches allows to anticipate that, next to unavoidable environmental and economic costs, several advantages in terms of positive environmental and social impacts can be obtained by the NbS. Those might counter-balance the unfavourable negative impacts. One example above all is represented by the introduction of a circular economy thinking both upstream and downstream to the life cycle. The re-use of waste soil as a new market resource (upstream mechanism), and its further use as a driver for the creation of a system producing additional resources instead of waste biomass (downstream mechanism), do ultimately represent a promising sustainable approach. As illustrated in the SM1 and reported in Fig. 4, some economic cost reduction opportunities were first identified which can potentially answer the question about how to mitigate the New Soil's environmental impacts. Major challenges are related to the energy intensive process in times of high-energy costs or strong fluctuations. Additional costs originate from material inputs (fertilizer and other compounds, …), machineries and tools, including their maintenance. Measures such as i) the re-use of residual biomass material from the management operations occurring in the NbS, ii) the establishment of payment schemes for the soil resources from excavation activities, iii) the decrease of New Soil's price to make it cheaper than comparable products, and, eventually, and iv) the adoption of broader spatial scales and factors to make the impact of scale economy effective, can be promising answers. The latter in particular is expected to reduce the overall life cycle production costs by increasing the amount of New Soil delivered in the market. In this paper, however, only a relatively small area of 1200 sqm was analysed with around 3000 tons of New Soil. Depriving landfill areas from such a little amount of excavation soil recovered for the NbS does not suggest much to decision-makers in the field of waste or territorial management. Realistic business modelling results providing relevant insights for urban planners and NbS managers would rather be generated if the modelling of impacts were done considering 10^1, 10^2, 10^3, or even 10^4 times the available soil waste in Turin (depending on the potential access and availability to regional areas where soil can be recovered). Expectedly, the BMC exercise points out that innovative start-up ventures and policy changes shall be implemented to establish circular economy mechanisms at those scales.

From the mere application viewpoint of the LCA method, the present analysis is novel and original. No similar examples of impact assessments of NbS designed for using regenerated soil currently exist in the literature. Exceptions are a few, although still not comparable studies where LCA is applied to estimate the environmental benefit of recovering inert waste (Capobianco et al., 2018; Karlsson et al., 2017; Petit-Boix et al., 2015; Rodrigues et al., 2019; Zhang et al., 2021). Combining the proposed LCA framework with a quantitative ES assessment would further increase the novelty of such application, since only a limited number of recent NbS-LCA studies have been published so far that also take into account ES quantitatively (Grossi et al., 2023; Larrey-Lassalle et al., 2022; Mihalakakou et al., 2023; Reyhani et al., 2022).

As emerged with the sensitivity analysis, one potential challenge to the widespread use of the New Soil might be represented by the distance between the site of destination and the place where the components of the new soil are extracted. Transport distances may negatively affect the business plan of the New Soil application which, in itself, could economically be advantageous. From a technical point of view, current experiments conducted in Turin to evaluate the TRL (Technology Readiness Level) of the New Soil suggest strategies to introduce the New Soil product on the market (Zitella et al., 2021). It has been observed that the New Soil would be capable of addressing the demand of fertile soil from public authorities in Turin interested in urban green areas implementation, allowing the product entering in regional price lists and in public procurement specifications. Accordingly, outcomes from this paper fit for purpose, since they contribute to address the question about the environmental sustainability of the New Soil.

5. Conclusions

This paper modelled the life cycle impacts of a nature-based solution integrating New Soil as fertile substrate for urban forest developments, setting up and comparing prospective scenarios of resource waste management and recovery through a qualitative business model canvas. The LCA model was conceived for a post-industrial area in Turin (Italy) dedicated to urban afforestation along the banks of the Sangone river. The novelty of such NbS was to plant trees and shrubs on a layer of regenerated soil (New Soil) based on excavation material with the addition of compost from the organic fraction of municipal solid waste, zeolites and innovative biostimulants. Such a composition, defined with the main scope of minimizing maintenance needs, would be suitable for any post-industrial urban areas suffering from poor soil conditions due to the lack of biological activity and humification (Zitella et al., 2021). Further to providing a benefit for soil fertility in brownfield sites, results of the present work suggest that the New Soil may represent a viable solution to decrease the environmental footprint should it replace virgin soil from fertile agriculture land.

One major limitation of this study is represented by the lack of a quantitative assessment of meaningful socioeconomic aspects that may complement the environmental ones evaluated with LCA. The BMC approach proposed here raised several important questions and oriented towards the definition of multiple scenarios for the re-use of biomass from the urban forest. However, financial issues and a quantitative characterisation of relevant ecosystem services for human well-being such as recreation and pollutants removal still need to be addressed. A relevant hypothesis that shall be validated in future research activity concerns the expected advantages of using New Soil at large regional scale in order to cover the three pillars of the sustainability concept.

CRediT authorship contribution statement

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

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128327.

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