Title

LCA for territorial metabolism analysis: an application to organic waste management planning

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Abstract

The management of biodegradable waste in landfills is associated to a range environmental impacts and refers to a linear model regarded as unsustainable. At the same time, many agricultural and urban soils present low organic matter content. Composting is emerging as a good practice for converting organic waste into a new resource able to improve soil properties, thus providing regulation Ecosystem Services. Considering a territorial metabolism perspective, this work discusses the potential contribution to regional planning of a transferable methodology for quantifying environmental impacts and benefits associated to waste management, based on a combined use of Life Cycle Assessment and Geographic Information Systems, and considering Ecosystem Services deriving from the application of compost in agricultural soils. The approach was tested through a site-dependent analysis based on primary data, referring to year 2019 and focusing on the Veneto Region, Italy. Results indicate that direct benefits associated to the use of compost and the thermal energy to district heating are compensating from 29% to 51% of the impacts associated to compost production, while waste transports represent the largest share of the impacts, covering between 52% and 78% of the total flows considered. The proposed methodology is applied for comparing the reference condition to alternative scenarios, in the perspective of providing support in Strategic Environmental Assessment procedures. In this context, results shown markedly lower impacts associated to compost production, with respect to organic waste treatment, for 5 out of 6 of the considered categories (freshwater eutrophication 100:1, climate change 5:1), with the notable exception of water resource depletion. Scenarios produced are discussed with respect to the choice between centralized and non-centralized plants, and the characterization of potential benefits at the territorial scale associated to compost use for urban green infrastructures. With respect to this latter point, results showed an underdeveloped use of compost-related ES flow, compared to its capacity, suggesting an interest for further research aimed at estimating compost requirements by urban and peri-urban soils.

Keywords: Life cycle assessment, regulation ecosystem services, compost, organic waste, GIS, urban policies

1. Introduction

In 2015 the United Nations (UN) by publishing the Agenda 2030 and the Sustainable Development Goals (SDGs) have brought high on the political agendas the need for management of the organic fraction of municipal solid waste (OFMSW), especially of food fraction, which represents the most consistent waste flow resulting from household (EEA, 2020; Tonini et al., 2020). The SDG 12 “Ensure sustainable consumption and production patterns”, in particular, aims to take urgent effort to enhance resource efficiency and reduce waste (UN, 2015; UNEP, 2017). According to the Europe 2020 Strategy (EC, 2010), the bio-economy could provide an important contribution to the achievement of the green targets in Europe in the upcoming decades (Pergola et al., 2018). A basic principle of the bio-economy is promoting a sustainable and efficient (see e.g. Sepehri and Sarrafzadeh, 2018) resources transformation and conversion into bio-energy and/or bio-based products, reducing the dependency on natural resources (EC, 2012a). In this framework, composting is a moderately easy and inexpensive way for stabilizing and reducing biodegradable waste (Crowe et al., 2002). Compost represents an organic and biologically stabilized soil conditioner, obtained from the treatment of the OFMSW. During the composting process, the microbial community transforms the degradable organic matter into more stable forms, such as water (H_2O), carbon dioxide (CO_2) and ammonia (NH_3), releasing heat as a metabolic waste product (Ciavatta et al., 1993). Composting thus represents a solution to divert OFMSW from landfills, obtaining a new product suitable, in particular, for agricultural purposes (Al-Rumaihi et al., 2020). In addition, integrated composting and anaerobic digestion plants can provide useful resources to other supply chains, such as energy and water recovery (Hannibal et al., 2018). At the European level, it has been estimated that almost 50% of the entire amount of compost produced is used in agriculture (Saveyn and Eder, 2013). Other uses include gardening (13%), horticulture (11%), landscaping (10%), mixture (6%), land restoration and landfill coverage (5%), while the remaining 4% for other uses including export and wholesale (Corden et al., 2019).

Composting can be performed at three different scales: centralized composting acts on vast geographic areas; decentralized composting acts at the community scale; finally, composting in individual housing units acts at home/courtyard scale. Centralized composting, which is the most widespread, involves both positive and negative aspects. On the one hand, it is a system that treats a more significant quantity of waste and guarantees greater control of the compost production processes; on the other, it involves high environmental costs for the waste collection and transport over long distances (Bruni et al., 2020). In this context, an interesting approach supporting the evaluation of costs and benefits associated to centralized composting actions can be identified in Life Cycle Assessment (LCA). European Commission promoted LCA as a useful quantitative tool for assessing the potential environmental impacts of products and processes, capable of supporting producers and stakeholders (COM 302, 2003). LCA looks at the product's entire life cycle (extraction of resources, raw material processing, production, usage, recycling, disposal of remaining waste) and has been frequently used for waste and agricultural assessments. Literature review showed that there is a strong connection between compost and regulation Ecosystem Services (ES) (Martínez-Blanco et al., 2013), including carbon, macronutrients and water cycle regulation, pest and disease control for crops, soil formation, pollination, and mitigation of natural hazards. Compost effectiveness in terms of providing regulation services results from the interaction among multiple variables, including OFMSW quality, compost maturity/stability, crop management, soil texture, soil organic matter concentration (SOM), and soil temperature/humidity (Martínez-Blanco et al., 2013; Adhikari et al., 2016). Although this relationship is widely recognized (e.g. Cortés et al., 2020), benefits from compost application to soil have not been included in many LCA studies of compost, reducing its environmental value (Department of Environment and Conservation, 2006).

The present study focuses on the usability of LCA to support environmental assessment of compost production and utilization at the territorial scale. This topic is of interest within planning processes, and is framed within a territorial metabolism approach, quantifying of negative and positive environmental effects associated to OFMSW recovery, its treatment, and the use of produced compost. This general purpose is pursued through two specific goals: a methodological one, aimed at performing an LCA based on primary data collected at a centralized composting plant, and referring to the year 2019; a second one focused on scenario building, of interest for comparing different management alternatives. In terms of negative environmental effects, the focus is on emissions related to waste collection and transport, and water and energy consumption for the operation of the plant. In terms of benefits, the focus is primarily on regulation ES related to the use of compost, on energy recovery, and on biomethane production (co-product). Data collection and analyses were carried out in the framework of a project financed by the Veneto region (European Social Fund, Call 2020).

2. Methodology and research phases: the LCA approach

The selected case study considered an integrated composting and anaerobic digestion plant located in the municipality of Este, in the district of Padova (Veneto region, Italy). The plant is managed by S.E.S.A. S.p.A., a joint-stock company responsible for the collection, transport, selection, treatment, recovery and disposal of municipal solid waste, the production of compost and energy recovery. This plant represents a large-scale centralized operation and serves vast geographic areas and sectors. The company has provided data related to the vehicle fleet and flows of organic waste, compost, energy and material guaranteeing the operation of the plant.

The approach combined Geographical Information System (GIS) analysis with the Life Cycle Assessment (LCA), coherently with the idea of territorial Life Cycle Assessment (Hiloidhari et al., 2017). While GIS is used for spatial data acquisition, processing and visualization, LCA is a standardized method used to quantify the environmental impacts related to a product or a process. For the construction of the LCA analysis, following the ISO 14040 and 14044 standards (International Organization for Standardization, 2006), the methodology was articulated in four steps:

- the “goal and scope”, which involves the definition of objectives and scope of the LCA study, the functional unit (FU) and system boundaries;

- the “life cycle inventory” (LCI), which includes collecting data for all the processes included in the analysis;

- the “life cycle impact assessment” (LCIA), which evaluates the significance of potential environmental impacts based on the LCI flow results, and includes the selection of characterization model and impact categories;

- the “interpretation”, in which results of the assessment are analyzed to identify processes of the life stages that have relatively high environmental impacts.

GIS was the key tool for the processing of primary data during the LCI construction phase. Based on existing examples (Mutel et al., 2012; Hiloidhari et al., 2017; García-Pérez et al., 2018), GIS was used to set up an area-specific LCA analysis. A spatial analysis of primary data, focusing on OFMSW, compost flows, and soil properties was carried out as a part of the study. Data on waste flows were provided by the partner company, while those concerning the properties of the soils were collected by the Veneto Region environment agency (ARPAV) as part of institutional monitoring activities. The latter data were used for ES quantification. The base year for this analysis is 2019. The following sections will introduce details on the different steps of the LCA methodology (2.1-2.3). Section 2.4 will therefore explain the rationale for scenarios comparison.

2.1. LCA: Goal, functional unit, and system boundaries definition

The goal of this study is to estimate the life cycle assessment (LCA) of compost produced in a composting and anaerobic digestion plant. The functional unit (FU) chosen is the production of a metric ton (t) of compost derived from organic waste processing, which provided a reference to normalise material and energy fluxes in input and output to the system. The performed LCA study (see Figure 1) considered the collection and transport of municipal solid waste, their processing in the plant and the co-production of energy and bio-methane, the transport of compost, and the regulation ES associated with the use of compost in agriculture, which was considered as the main activity using the compost produced by the plant (data provided by the partner company show that the 84% of the compost produced annually is delivered to the agricultural sector). Instead, the main processes excluded from the LCA are construction of the plant infrastructure, and the use of compost in urban areas. The choice of disregarding the first processes was based on the consideration of the difficulty of evaluating properly the building lifespan and on the consideration that many studies considered a long duration, ~ 50 year, for buildings with characteristics similar to the ones considered

(Ji et al., 2021). As for the use of compost in urban areas is concerned, although this accounted for approximately 16% of the total compost produced (on a weight basis), the scarce amount of information available for characterizing the diversity of urban soils prevented from considering it in the baseline LCA, and was therefore considered in the scenario analysis (see par 2.4). Avoided waste disposal in landfill and incineration were considered outside the system boundaries, and included within the subsequent scenario analysis.

< Figure 1>

2.1.1. Analysis and mapping of primary data: the transport system

Based on the primary data provided by the company, an analysis of the transport system, quantities and characterization of waste and compost flows was carried out. All these data were analysed from a spatial point of view, through the software QGIS 3.14, with two main goals: i) obtaining a spatial visualization of the data and mapping all the points of origin (O) of waste and destination (D) of the compost; ii) calculating the mileage related to these flows, using the QGIS “shortest route” tool (Figure 2). As regards the analysis of the transport system, the variables considered are the amount of materials transported (metric tons, here in tons), the distances travelled (km), the type of vehicle differing in terms of capacity (7.5-16 and 16-32 tons) and fuel (diesel or biomethane).

< Figure 2>

2.1.2. Analysis and mapping of primary data: assessing ecosystem services

The characterization of soil parameters allowed to quantify the potential ecosystem services linked to the use of compost in agriculture. This potential is associated with the increase in soil organic carbon

(SOC), sequestered CO_2eq, available water capacity (AWC) and macronutrients (N, P, K) concentration in the soil. The analysis focused on the agricultural area of the 34 municipalities in Veneto Region in which the partner company sold the compost for agriculture use in 2019. Areas were defined based on level II of the Corine Land Cover in 2018 (https://land.copernicus.eu/). Concerning these municipalities, the main soil parameters have been defined, based on the primary data provided by the Veneto Region Environmental Agency data (ARPAV): the type of soil (sand, silt, clay), SOC in the surface layer of the soil (first 50 cm), expressed both as a percentage (%) and in tonnes per hectare (t ha^{-1}), AWC expressed in millimetres (mm) and subsequently converted in kg (figure 3). As regards the sequestered CO_2eq and AWC, this quantification relies on the increase in soil organic carbon (SOC), assuming that the ideal amount of compost, identified as 30 tons per hectare (ECN, 2010 ; ISWA, 2020; Colombani et al., 2020), is applied to the soil each year over 20 years. The prerequisite for this evaluation is that the compost is of quality and therefore does not present physico-chemical contamination due to a mixture of non-organic waste. Estimated SOC increase rates vary depending on two starting soil parameters: the soil texture and the percentage of SOC, differentiated between lower than 2% and higher than 2%, following the European Soil Bureau, which has classified European soils based on their SOC content (Table 1).

<Figure 3>

<Table 1>

Once these percentages of SOC increase for soil texture with different initial organic carbon contents were defined, specific analyses for the 34 municipalities considered were carried out. For each municipality, the agricultural area is defined by the soil texture (sandy, loamy and clayey), distinguishing the areas with low and high SOC (respectively <2% and > 2%), in order to establish the percentage of organic carbon increase, to be applied to the starting SOC value, expressed in tons/hectare (each municipality has multiple parcels of agricultural soil in which these parameters are variable and can be associated with different percentages of SOC increase; therefore, for defining a single percentage of SOC increase per municipality, a weighted average is carried out with respect to the extension of each soil texture). After obtaining an increased value of SOC for each municipality, this was converted into CO_2eq sequestered in the atmosphere (kg of CO_2eq).

The increase in SOC defined for each municipality was then used as a basis to calculate the rise in soil water availability (AWC), applying a corresponding increase of 2.1% of soil AWC to every 1% increase in SOC. To define the rise in soil nutrient macronutrients (N, P, K), different increase values were applied (expressed in kg $tons^{-1}$ of compost) depending on the type of compost applied (Table 2), whether mixed (ACM) or green (ACV). Once these ES were quantified for the agricultural area of the 34 municipalities analysed, the values obtained were compared to the real ha in which the compost was applied. Assuming that the optimal amount of compost for 1 ha is 30 tons, for each municipality the amount of compost delivered by S.E.S.A. was divided by 30. Finally, the quantified ES for each municipality were normalized to the considered period (1 year), and scaled to the functional unit, 1 ton of compost produced (Table 2).

<Table 2>

2.2. Life cycle inventory (LCI)

The processing of primary data related to flows of matter and energy involved in the compost supply chain, allowed to produce the inventory (LCI) reported in Table 3. Inputs, resources, energy and waste associated to each process were quantified based on the Ecoinvent 3 database, allocating waste disposal to the compost production process. All values were scaled to the functional unit of 1 ton of compost. Energy production and consumption of integrated waste treatment systems were the subject of different works (e.g. Colón et al., 2012; Fernández-Rodríguez et al., 2016). The analysis performed here took into consideration biomethane as a compost co-product. Biomethane produced was used in part for transport operation, and therefore introduced in the analysis by constraining the impacts of biomethane vehicles, both small and medium. This was done by setting to 0 the fuel consumption of such vehicles, while leaving all the other emissions associated to transportation (infrastructures, vehicles, combustion). A fraction of biomethane was distributed to the area nearby the plant in the form of district heating. Avoided impacts associated to this practice were quantified by accounting for the impacts associated to methane production. Regulation ES associated to the use of compost were accounted in the model by introducing in the inventory avoided CO_2 emissions in the atmosphere. AWC increase was accounted by considering avoided consumption of groundwater for irrigation, while the N, P and K increase in the soil were accounted as avoided production of N, P, K fertilizers.

<Table 3>

2.3. Life cycle impact assessment (LCIA): impact categories and methods

LCA was performed in SimaPro v. 84 (PRé Sustainability), allowing the classification and characterization phases defined by the ISO regulation (2006). In the classification stage, each burden is linked to one or more impact categories, while in the characterization stage the contribution of each burden to the environmental impact categories (EICs) is calculated by multiplying the burdens by a characterization factor (Guinée, 2001). In accordance with Martínez-Blanco et al. (2009) and Avadí (2020), we considered for the analysis two evaluation methods: the “ILCD 2011 Midpoint”, including climate change (CC), ozone depletion (OD), acidification (AC), freshwater eutrophication (EU), water resource depletion (WD), and the “Cumulative Energy Demand” (CED) including the non-renewable fossil (NF). Emissions to air, soil, surface and groundwater, and resource consumption are considered with respect to their contribution to these EICs and are associated to the different processes. These EICs have been related to the main processes analyzed in the life cycle of compost and included in Table 3.

2.4. Steps of the analysis: reference and scenarios

The quantification of negative and positive environmental effects associated to OFMSW was carried out in three steps. First the reference condition (REF) was assessed, performing LCIA for the base year 2019. As a second step, an exploratory analysis was carried out, by comparing to REF the following three scenarios, here synthetically presented:

1) the substitution of diesel-fueled vehicles with bio-methane vehicles. This comparison was suggested by a recent change in the company fleet, which was partly converted to bio-methane power supply. Being based on company management actions, this scenario analysis was named “company management” (MGM);

2) the alternative treatment of OFMSW by landfill. This is regarded as a worst-case alternative, considering an entirely linear approach in treating the organic matter currently converted into compost. For this reason, this scenario was named “worst case” (WRS);

3) how current ES flows can increase considering the capacity of urban areas (ES-URB). Literature on ecosystem services addresses the difference between flow and capacity, which distinguishes the current ES supply from the potential supply (Burkhard et al., 2012; Baró et al., 2016). The analysis focused on the potential use of compost for the maintenance of existing green infrastructures and the ES related to the management of public green spaces. In fact, green infrastructures in urban contexts can benefit from the application of compost, being urban soils generally low in organic matter (Sæbø et al., 2006). ES-URB was applied to the city of Padova, the closest one to the plant, with the idea of pursuing the utilization of compost within the area of waste production, in order to promote a higher circularity of the biogeochemical flows. Estimation of ES capacity in the urban context, was

performed assuming to apply 30 tons of compost per year for each hectare of urban green infrastructure.

3. Results

Results of the LCIA for REF (reference condition) are illustrated in Figure 4, showing the assessment obtained for the 6 impact categories selected for the analysis (CC, OD, AC, EU, WD, NF). Positive values indicate impacts on the environment, while negative ones stand for avoided emissions, while different colours indicate the contribution of processes to the overall category. Results show how the direct benefits associated to the use of compost and the thermal energy to district heating are compensating, considering an average among all the impact categories, 29% of the impacts, with peaks of 51% for EU and 31% for AC.

<Figure 4>

In all the categories, OFMSW transportation represents the largest share of the impacts, with values ranging between 52% and 78% of the total flows considered. Waste landfill represent the second term in the budget, although its contribution is always below 30% (achieved in the case of climate change). As expected, the renewal of the fleet and its transition to biomethane-fueled vehicles, under the company management scenario, MGM (Figure 5), implied a decrease in all the indicators considered, with higher effects on CC and a more restricted on AC.

Figure 6 compares the net balance given by the sum of positive and negative contributions for each category calculated in REF, to the WRS scenario (impacts associated to OFMSW waste disposal by landfill), showing a markedly lower impact for all the categories, with the notable exception of WD. These differences are more pronounced for EU (~100:1), and CC (~5:1). The difference in impacts for the various categories can be explained based on the combination of processes included in the REF condition and the WRS scenario, and their relative share. Effects on the different matrices and the associated impact categories are ultimately defined by this share.

<Figure 5>

<Figure 6>

ES-URB scenario estimated the potential for ecosystem services associated to the use of compost in the urban context (Table 4). Urban green areas considered (Figure 7), included: uncultivated green areas (23 ha), sports fields (175 ha), green areas associated with viability (100 ha), urban parks and permanent lawn areas with spontaneous grassing (247 ha), for a total of 719 ha. Padova has a silty soil texture and a low SOC percentage (< 2%) homogeneous throughout the territory, which defines an increase of 46% in SOC. This percentage, applied to the current amount of SOC, leads to an estimation of 2.4 10^6 kg of CO_2eq sequestered, 71.9 10^6 kg of AWC, 3.8 10^5 kg of N, 1.4 10^5 kg of P, and 2.1 10^5 kg of K per year.

<Table 4>

<Figure 7>

4. Discussion

The study of biogeochemical fluxes associated to organic matter exchanges in the territory can be framed within the broader context of territorial metabolism (Wolman, 1965), and analysed treating cities as heterotrophic systems (e.g. Odum, 1963; Grimm et al., 2000). In this perspective, compost production and its use pose challenges and opportunities, of interest for territorial planning. CC values obtained in this study for the REF condition, ~ 2000 kg CO_2 eq per ton produced, are higher than previous estimations by Cortes et al. (2020), 472.59 kg CO_2 eq which, nonetheless used as functional unit 1 ton of feedstock mixture fed to the composting facility, thus making difficult the overall comparison. Avadí et al. (2020) in a screening LCA study carried out in France, reported values closer to those found here, ranging between 517 and 3084 kg CO_2 eq for ton of compost produced. Beside the comparison of the absolute values, it is worth nothing that these analyses are referring to territories characterized by different specificities, both in terms of waste production and transport systems (fuel, road infrastructures availability). In order to support territorial planning it seems of relevance, instead, the possibility of remaining site-specific, associating alterative scenarios to the analysis of the reference state. This was attempted in this work with the goal of providing an approach aligned with the requirements of strategic environmental assessment procedures, which in EU are accompanying the development of territorial plans (Directive 2001/42/EC). The REF scenario was first compared with WRS, indicating that, for 5 out of 6 indicators (WD the notable exception), the linear model production-consumption-disposal, is far less efficient than the one based on organic matter re-circulation through compost (differences ~ 100:1 for EU). In this respect, it seems of interest to direct future research efforts at improving the understanding of water metabolism, by performing a water footprint analysis (e.g. Boulay et al., 2018), also in consideration of the expected trends in water scarcity events affecting this specific region (https://cordex.org/).

Results showed how the conversion to bio-methane have led to a reduction of the environmental footprint, quantifiable with an average decrease of 28% considering all the categories, 10% in the case of CC and 58% for OD. This scenario, MGM, allowed to show the potential of an integrated GIS-LCA analysis for supporting the design of management choices aimed at putting the circular economy concept into practice (Sassanelli et al., 2019). On the other hand, the high impact of the transport sector points the attention to the potential limitations of centralized plants operating at a large scale, due to the high costs of collecting and transporting waste over long distances, as also discussed by other studies (De Feo et al., 2016). In this respect, existing literature (Righi et al., 2013; Bruni et al., 2020) highlight how decentralized composting systems, on a community and/or neighbourhood scale, could minimize negative impacts on the environment. This aspect can be regarded as relevant for fostering the development of innovative decentralized models of organic waste valorisation (e.g. Giwa et al, 2022), although territorial-specific considerations must be performed to consider the real applicability of these solutions in alternative contexts. Indeed, decentralized composting is currently not a common practice in Italy and does not benefit from adequate support from local authorities and citizens, who consider this infrastructure unsuitable and dangerous for urban contexts. Sensitizing the population to the waste issue could be the first step to provide information of what happens to waste once they have been collected and raise collective awareness of the real need to reuse waste and transform them into new resources.

Green Public Procurement (EC, 2012b) is part of the strategies identified by the European Union to implement the Integrated Product Policy (COM 68, 2001; COM 302, 2003), which constitutes an approach aimed at reducing the environmental impact of products and services over their entire life cycle, in a broader perspective of sustainable development. Compost, as defined by Italian national legislation, is one of these products defined as recycled goods and should therefore be included in public expenditure. Worldwide, about one-third of the soil is in conditions of degradation due to erosion, decrease in organic matter, waterproofing, salinization, contamination, compaction, decrease in soil biodiversity, floods and landslides (COM 347, 2002). Urban soils in particular can be highly affected by human activities and, therefore, in many cases must receive a pre-treatment, in order to facilitate the supply of ES and meet the needs of urban inhabitants (Morel et al., 2015). Adding compost to urban soil for planting new tree species, leads to improved tree growth, and associated regulation and habitat services, although it may take several years before its benefits could manifest themselves (Oldfield et al. 2015). In some cases, a proper soil restoration intervention is required, before any type of further action can take place – ecosystem restoration actions are receiving increasing attention by policies at the EU-level (COM 304, 2022). Scenario ES-URB, rooted on the distinction between ES flow and capacity, presents a first accounting of the potential regulation services provided within the administrative boundaries of the city of Padova, estimated in 2.41 10^6

kg CO_2 eq, representing approximately 2.7 times the overall flow associated to the current REF condition. It is worth remarking that this scenario is not analysed through a further LCA, and thus not considers the additional quantity of organic matter required to produce more compost, its source location, and the associated transport burdens. It also assumed that urban soils have the same requirements in terms of amendment use than agricultural areas.

Results showed how the production of biogas, which self-feeds the plant and part of the transport fleet, entails additional benefits through the district heating, quantified in 11.6 kg CO_2 eq, which represents almost 12% of the CO_2 eq associated to compost use. This result highlights that compost use has not yet reached a large market within Veneto Region. The current compost flow is associated with a small portion of the agricultural soil, which could potentially be extended, guaranteeing a higher level of CO_2eq sequestration, improving the quality of soils and thus reducing their degradation. An interesting possibility to extend the flow-capacity scenario carried out within this work, would be estimating the potential provision of regulating ES associated with the use of compost in the entire region. ES quantification performed in this work did not consider the type of crops due to the lack of data. This lack did not allow to include additional ES in the analysis, such as crop yield improvement, crop nutritional quality, pest and disease suppression; moreover, knowing the types of crops, it would have been possible to define more realistic ES values since each crop can react differently to the compost. Another limitation concerns the close relationship between the quantification of ES and the quantity and quality of compost (Ramos, 2017). This study assumes a high compost quality, but its parameters (level of humidity, nutrient content, etc.) were not analysed. Another perspective for expanding the present work would therefore be the use of soil biogeochemical models (e.g. Abrahamsen and Hansen, 2000), to study organic matter degradation in different conditions, thus allowing to relate more specifically compost features to its effects. In this case, an attempt should also be made to bridge local modelling efforts (data intensive) to the wide scale picture, which is provided by operational data collected by regional environmental agencies, and used for territorial planning and management purposes. The final aim would be to improve the picture at the territorial scale, rather than obtaining very detailed local-level descriptions.

5. Conclusions

This work allowed to identify and test a novel and transferable methodology for quantifying environmental impacts and benefits associated to compost production and its utilization at the territorial scale, based on the combined use of LCA and GIS, and considering ES deriving from the application of compost in agricultural soils. The proposed comparison of alternative scenarios provide a means for integrating this type of evaluation in Strategic Environmental Assessment procedures, thus supporting regional planning efforts. Results pointed out a lower impact associated to compost production with respect to organic waste treatment, for most of the impact categories considered, with the notable exception of water resource depletion. A major contribution of transports to the overall impact was detected, covering up to 78% of the total flows. Scenario comparison indicate an underdeveloped use of compost-related ES flow, compared to its capacity. Further research in this area should target a more robust estimation of ES capacity of urban soils at the regional scale, and extending the capacity evaluation to agricultural soils, also including considerations on site-specific biogeochemical conditions.

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Figure captions

Figure 1. LCA Analysis. The square represents the system boundaries, i.e. processes, inputs and outputs taken into account in the LCA analysis (what is outside the square is excluded from the present analysis). Processes considered relevant in the present case study are: transport, avoided disposal, waste processing and compost use.

Figure 2. Mapping of analysed organic matter flows within the Veneto Region (north-east of Italy). A) wet waste flows origin and quantity per municipality; B) green waste flows origin and quantity per municipality; C) compost flows, aggregated based on their different use.

Figure 3. Properties of agricultural soils in the municipalities of the Veneto Region where the compost was used in 2019 (Elaboration based on data provided by CLC – 2018 and ARPAV – 2015, 2016). These represent the main soil properties that influence the benefits given by compost (in this case, compared to the quantity of 30 t/ha).

Figure 4. Results of the Life Cycle Impact Assessment for the Reference condition (REF). Contribution analysis showing the weight of each process on the different EICs. Impact categories considered: climate change (CC), ozone depletion (OD), acidification (AC), freshwater eutrophication (EU), water resource depletion (WD), and non-renewable fossil (NF).

Figure 5. MGM scenario: transport processes for the REF condition. The current fleet partly composed by biomethane-fueled vehicles (BT) is compared with a former fleet, fully composed by diesel-fueled traditional vehicles (TV).

Figure 6. Results obtained for REF (reference condition, net balance) compared to impacts associated to WRS (worst case, OFMSW waste disposal by landfill). Impact categories considered: climate change (CC), ozone depletion (OD), acidification (AC), freshwater eutrophication (EU), water resource depletion (WD), and non-renewable fossil (NF).

Figure 7. ES-URB scenario. Mapping of the green infrastructures of the Municipality of Padua, categorized by 5 main types.

Tables

Table 1. Annually increase of Soil Organic Carbon (SOC) and soil macro-elements (N, P, K) with the use of 30 t/ha of mixed and green compost, for different soil textures with different initial SOC contents. Data based on ISWA (2020).

Soil texture	**Increase in SOC percentage in soil with SOC < 2% with 30 t/ha of compost**	**Increase in SOC percentage in soil with SOC > 2% with 30 t/ha of compost**	**Increase in soil macro-elements (kg/t compost)**	**Mixed compost**	**Green compost**
Sand	40 %	20 %	Nitrogen (N)	17.9 kg	13.7 kg
Silt	46 %	23 %	Phosphorus (P)	6.3 kg	5.1 kg
Clay	55 %	27 %	Potassium (K)	9.8 kg	9.9 kg

Table 2. Quantification of regulation ES related to the use of compost, including: CO_2eq sequestration; Increase of available water capacity (AWC); Increase of soil nitrogen (N); soil phosphorus (P) and soil potassium (K).

Ecosystem services	Benefits in one year (kg)	Benefits for one ton of compost (kg)
CO_2eq sequestration	$0.89\ 10^6$	124
Increase of available water capacity (AWC)	$26.55\ 10^6$	$3.7\ 10^3$
Increase of soil nitrogen (N)	$0.13\ 10^6$	17.8
Increase of soil phosphorus (P)	$0.05\ 10^6$	6.3
Increase of soil potassium (K)	$0.07\ 10^6$	9.8

Table 3. Life Cycle Inventory compiled within this work. Processes were aggregated in Transport, Waste to final disposal, Electricity, Thermal energy, Water, Avoided waste to final disposal, and Ecosystem Services from compost use; the LCI reports, for each process, the value corresponding to one ton of compost with a specific unit of measurement.

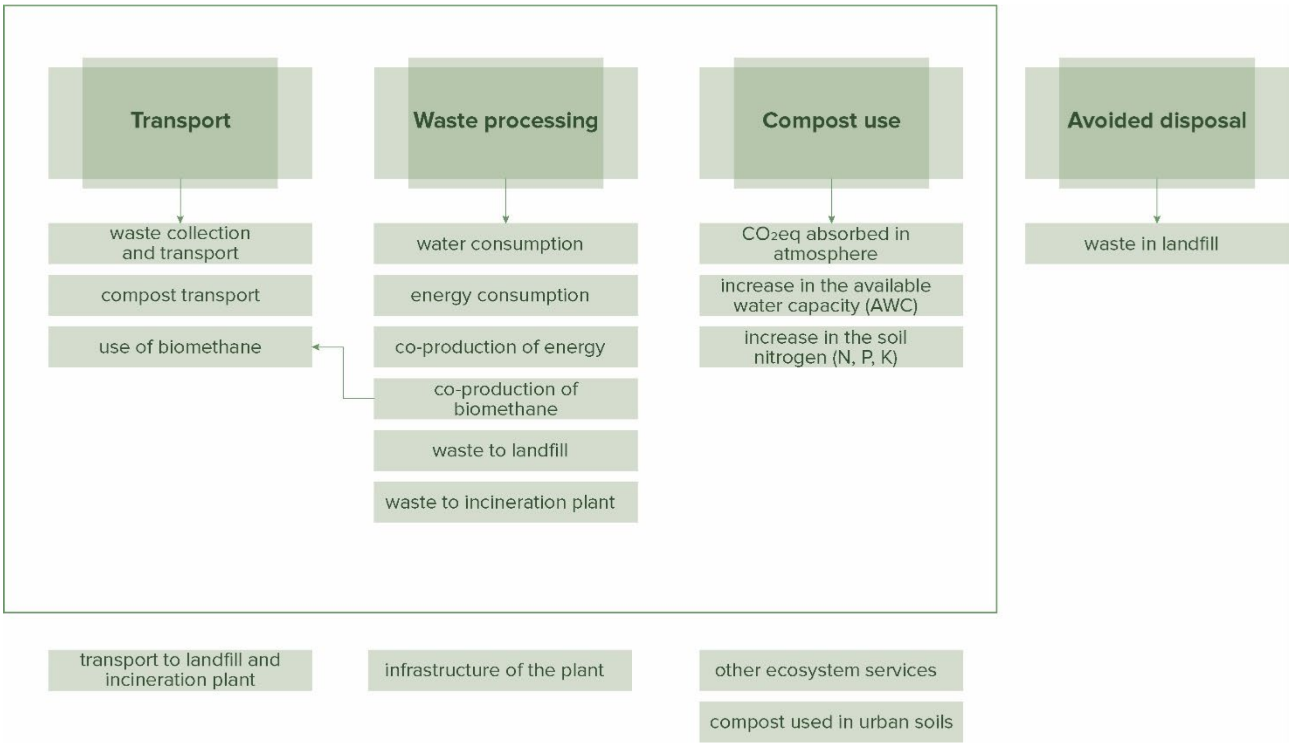
Category	Process	Value	Units
Transport	transport with small biomethane vehicles	2247	tkm
	transport with medium biomethane vehicles	1181	tkm
	transport with small diesel vehicles	627	tkm
	transport with medium diesel vehicles	308	tkm
Waste disposal	landfill	1.77	t
	incineration	0.04	t

Energy	electricity consumption	1540	kWh
	co-production of electricity	3214	kWh
	Thermal energy to district heating	49	m^3
Water	water consumption	985	kg
	Water recovery	3638	kg
Avoided waste to final disposal	avoided waste in landfill	20.03	t
Regulation services	CO_2eq storage	124	kg
	increase in the available water capacity (AWC)	3698	kg
	increase in the soil nitrogen (N)	17.87	kg
	increase in the soil phosphorus (P)	6.30	kg
	increase in the soil potassium (K)	9.80	kg

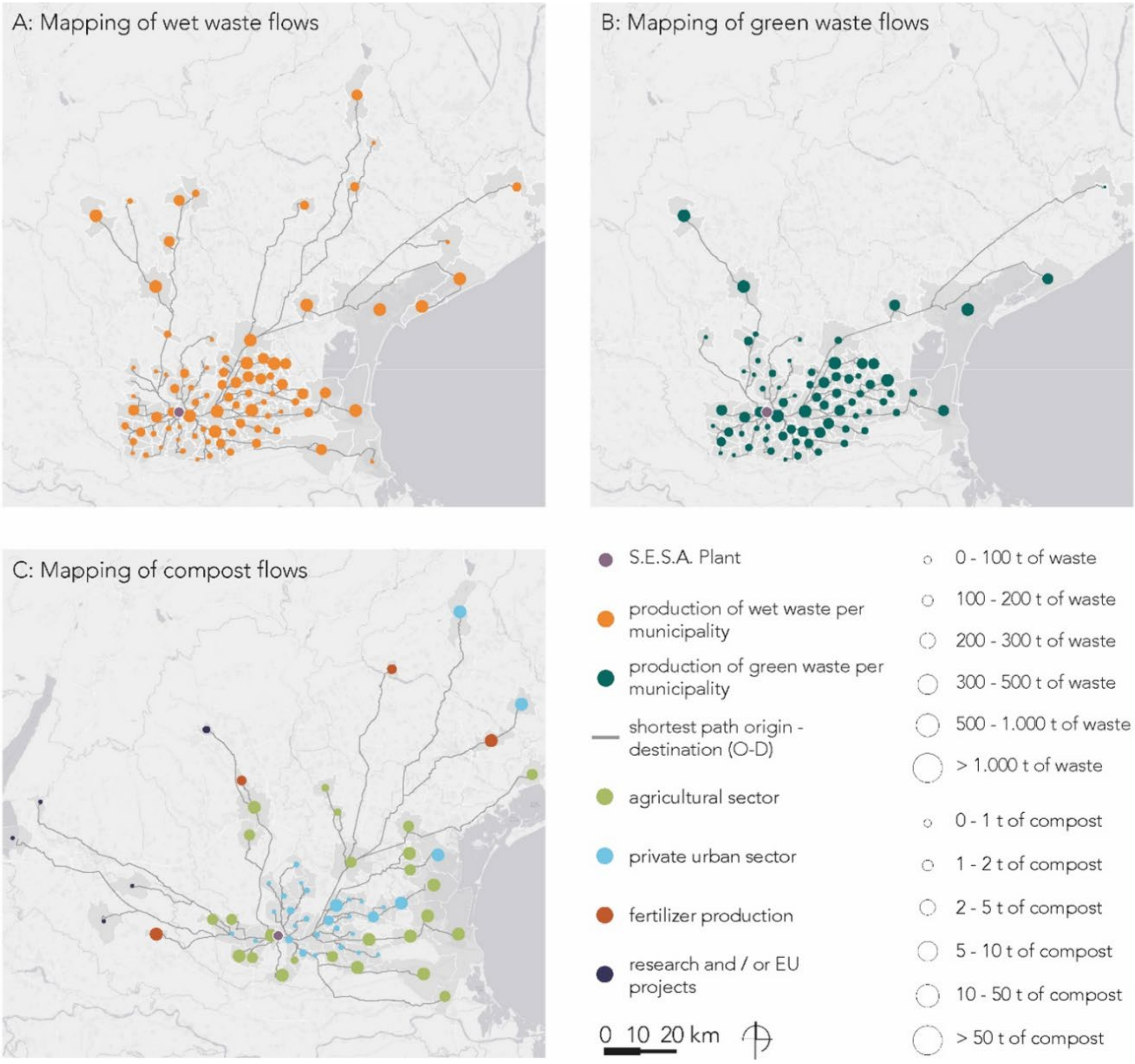
Table 4. REF and ES-URB scenarios: flow and capacity for the 4 regulation ES considered in this work. Capacity estimation was based on the green infrastructures in which compost could be used within the municipality of Padova.

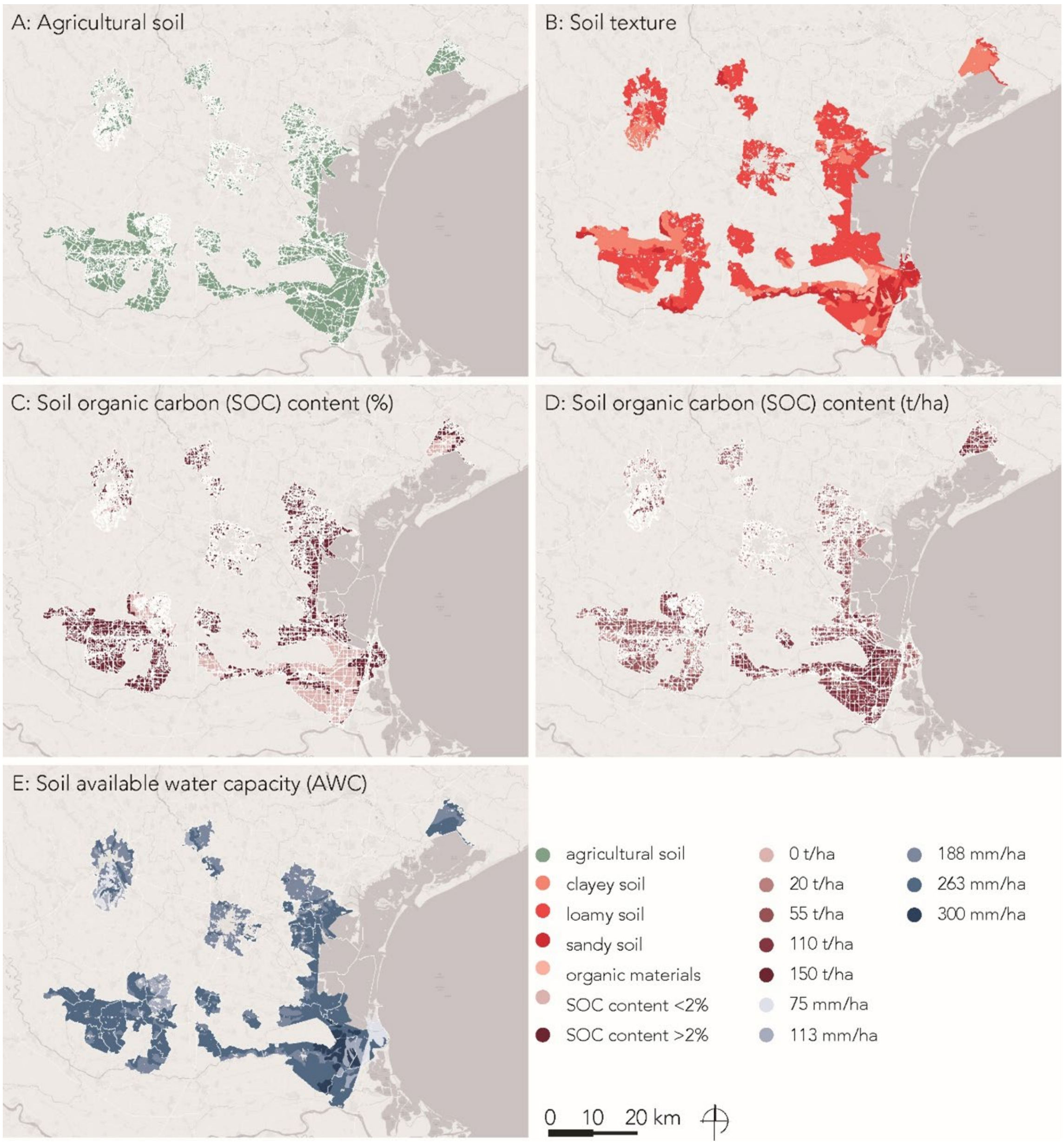
Regulation ES	**REF** **Flow of ecosystem services for one year (kg)**	**ES-URB** **Capacity of ecosystem services for one year (kg)**
CO_2eq storage	$0.89\ 10^6$	$2.41\ 10^6$
Increase of available water capacity	$26.55\ 10^6$	$71.89\ 10^6$
Increase of soil nitrogen (N)	$0.13\ 10^6$	$0.38\ 10^6$
Increase of soil phosphorus (P)	$0.05\ 10^6$	$0.14\ 10^6$
Increase of soil potassium (K)	$0.07\ 10^6$	$0.21\ 10^6$

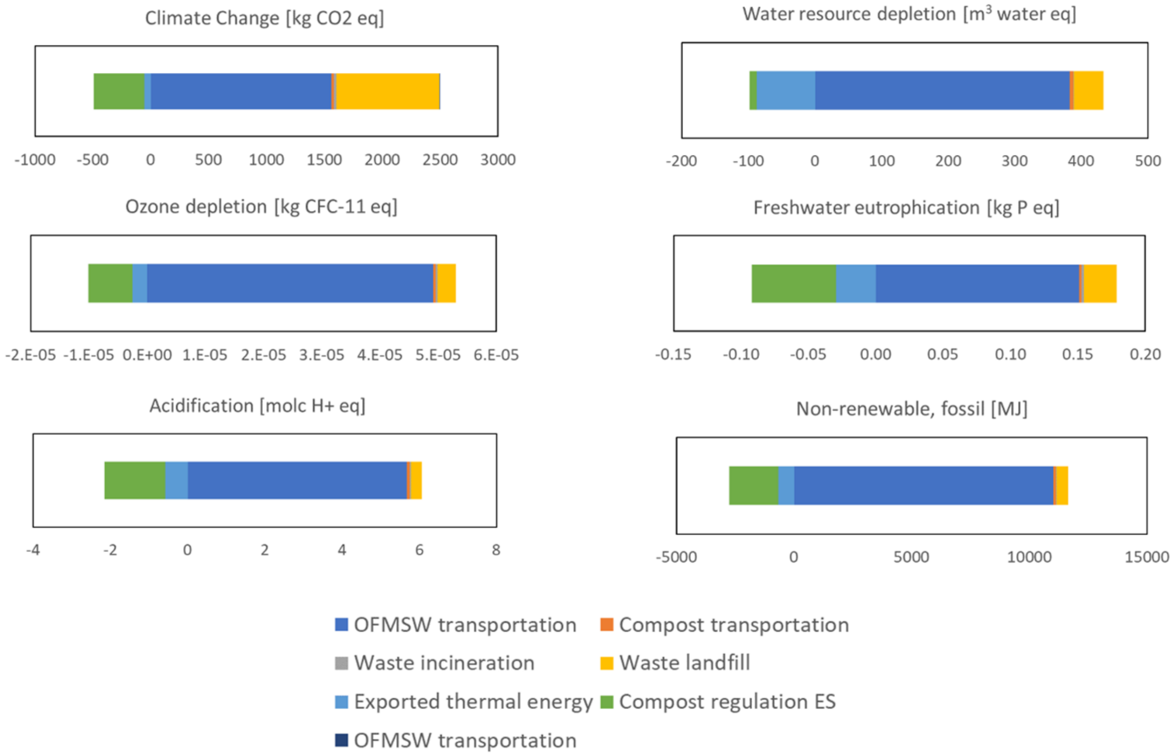
624

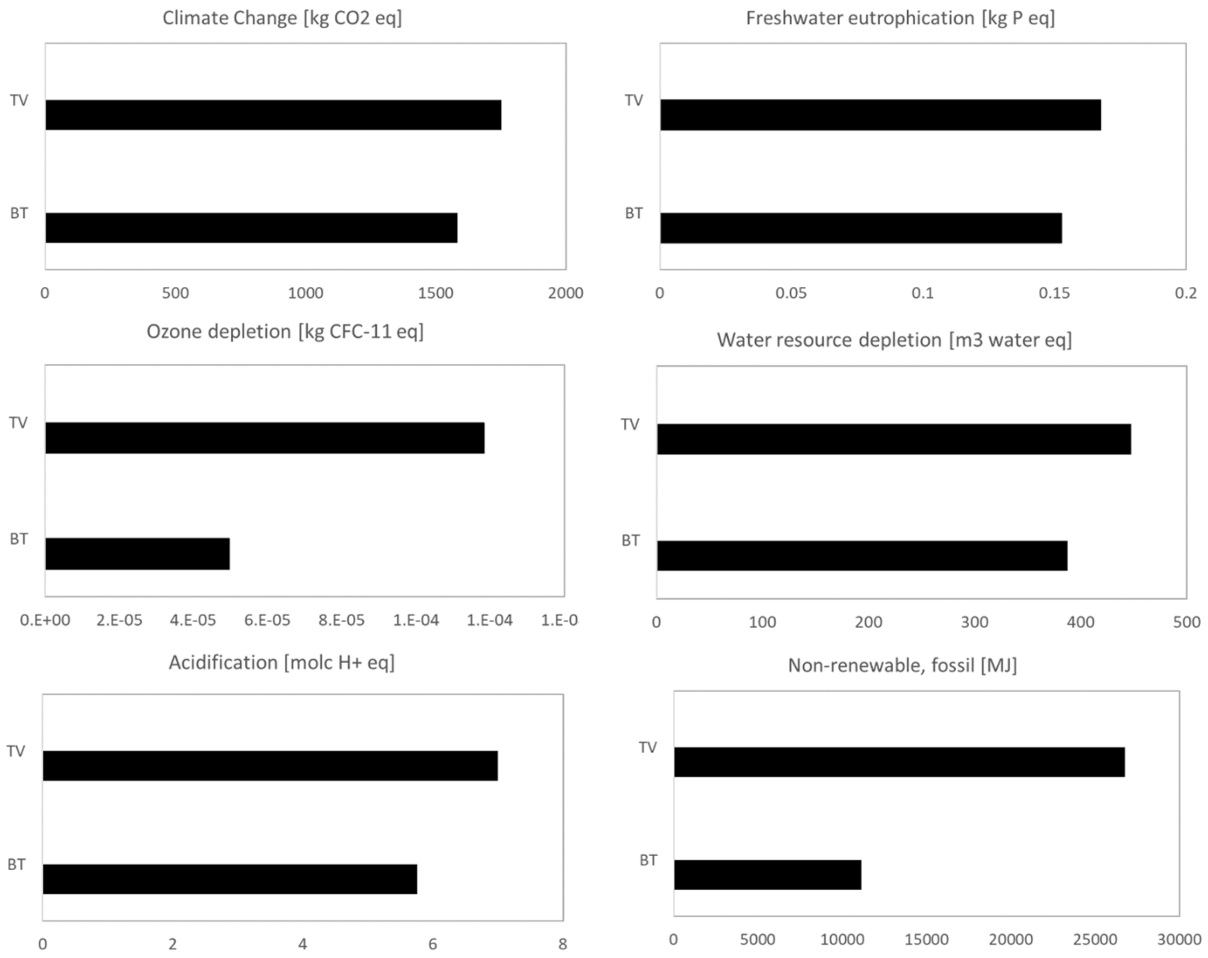

Transport
waste collection and transport
compost transport
use of biomethane
Waste processing
water consumption
energy consumption
co-production of energy
co-production of biomethane
waste to landfill
waste to incineration plant
Compost use
CO₂eq absorbed in atmosphere
increase in the available water capacity (AWC)
increase in the soil nitrogen (N, P, K)
Avoided disposal
waste in landfill
transport to landfill and incineration plant
infrastructure of the plant
other ecosystem services
compost used in urban soils

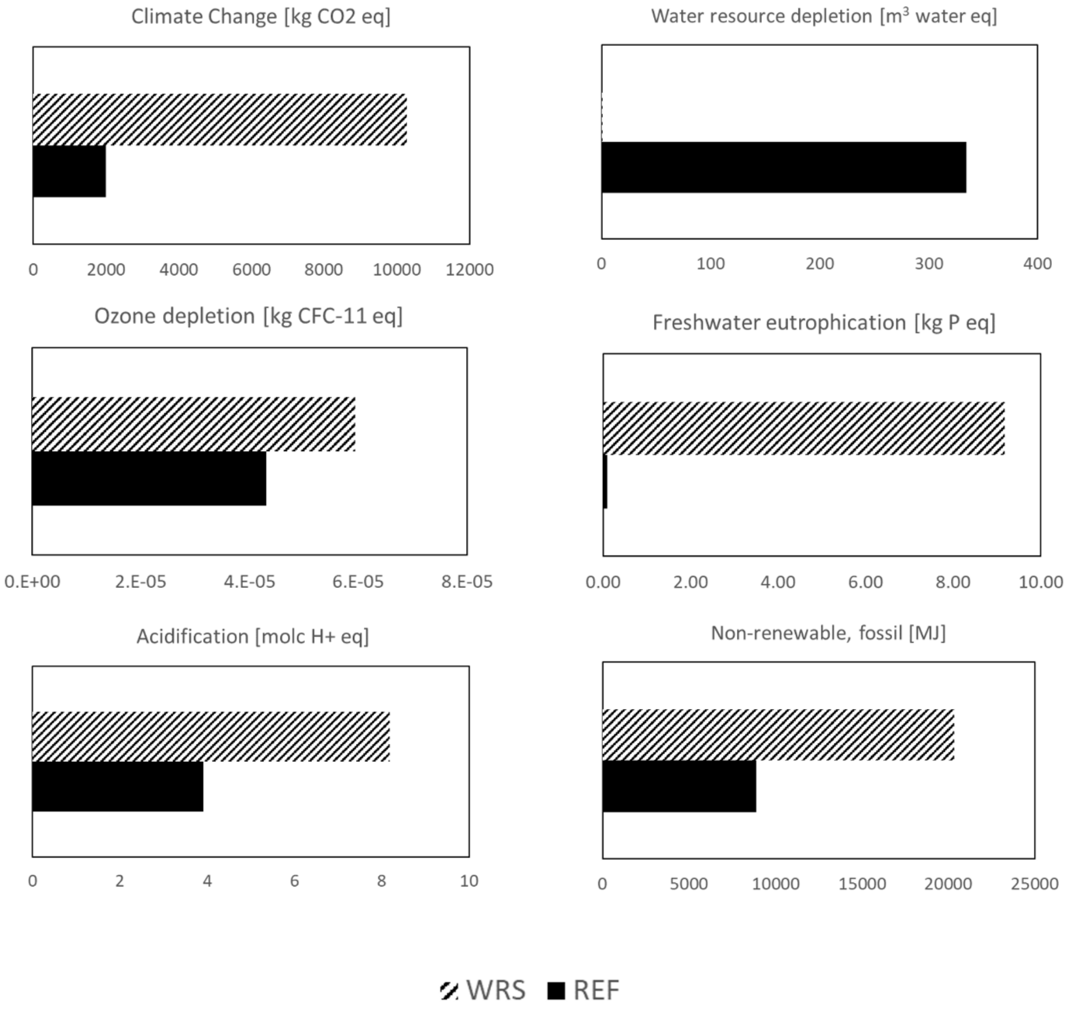
625


A: Mapping of wet waste flows
B: Mapping of green waste flows
C: Mapping of compost flows
S.E.S.A. Plant
production of wet waste per municipality
production of green waste per municipality
shortest path origin - destination (O-D)
agricultural sector
private urban sector
fertilizer production
research and / or EU projects
0 - 100 t of waste
100 - 200 t of waste
200 - 300 t of waste
300 - 500 t of waste
500 - 1.000 t of waste
> 1.000 t of waste
0 - 1 t of compost
1 - 2 t of compost
2 - 5 t of compost
5 - 10 t of compost
10 - 50 t of compost
> 50 t of compost
0 10 20 km


A: Agricultural soil
B: Soil texture
C: Soil organic carbon (SOC) content (%)
D: Soil organic carbon (SOC) content (t/ha)
E: Soil available water capacity (AWC)
agricultural soil
clayey soil
loamy soil
sandy soil
organic materials
SOC content <2%
SOC content >2%
0 t/ha
20 t/ha
55 t/ha
110 t/ha
150 t/ha
75 mm/ha
113 mm/ha
188 mm/ha
263 mm/ha
300 mm/ha
0 10 20 km


Climate Change [kg CO2 eq]
-1000
-500
0
500
1000
1500
2000
2500
3000
Water resource depletion [m³ water eq]
-200
-100
0
100
200
300
400
500
Ozone depletion [kg CFC-11 eq]
-2.E-05
-1.E-05
0.E+00
1.E-05
2.E-05
3.E-05
4.E-05
5.E-05
6.E-05
Freshwater eutrophication [kg P eq]
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
Acidification [molc H+ eq]
-4
-2
0
2
4
6
8
Non-renewable, fossil [MJ]
-5000
0
5000
10000
15000
OFMSW transportation
Compost transportation
Waste incineration
Waste landfill
Exported thermal energy
Compost regulation ES
OFMSW transportation


Climate Change [kg CO2 eq]
TV
BT
0
500
1000
1500
2000
Freshwater eutrophication [kg P eq]
TV
BT
0
0.05
0.1
0.15
0.2
Ozone depletion [kg CFC-11 eq]
TV
BT
0.E+00
2.E-05
4.E-05
6.E-05
8.E-05
1.E-04
1.E-04
1.E-0
Water resource depletion [m3 water eq]
TV
BT
0
100
200
300
400
500
Acidification [molc H+ eq]
TV
BT
0
2
4
6
8
Non-renewable, fossil [MJ]
TV
BT
0
5000
10000
15000
20000
25000
30000


Climate Change [kg CO2 eq]
0
2000
4000
6000
8000
10000
12000
Water resource depletion [m^3 water eq]
0
100
200
300
400
Ozone depletion [kg CFC-11 eq]
0.E+00
2.E-05
4.E-05
6.E-05
8.E-05
Freshwater eutrophication [kg P eq]
0.00
2.00
4.00
6.00
8.00
10.00
Acidification [molc H+ eq]
0
2
4
6
8
10
Non-renewable, fossil [MJ]
0
5000
10000
15000
20000
25000
▨ WRS ■ REF


uncultivated green areas
sports fields
green areas associated with viability
urban parks
permanent lawn areas with spontaneous grassing
0
1
2KM