The Role of Compost in Bio-waste Management and Circular Economy

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Abstract The increase of separate collections of bio-waste, largely represented by food waste, and their biological treatment is an essential feature of the waste management strategy. The aim of this paper was to highlight the role of compost in the circular economy, and its use in the agricultural sector. An annual time-step model for estimating soil organic matter (SOM) stock dynamics in a 22-year time frame was developed and tested on cardoon cropping system. The model took into account few soil parameters, mean annual temperature, and the cultural systems management, in particular organic fertilizers and crop residues. This work indicates that compost use in agriculture would be beneficial both for SOM increase and GHG reduction. The results showed how high-quality compost could represents the actual driving force of this change able to connect food, waste, economy and environment.

1 Introduction

In the EU between 118 and 138 million tonnes of bio-waste are produced every year, of which about 88 million tonnes come from municipal waste [1] which corresponds at about 170 kg of bio-waste per capita per year and about 150 kg per capita per year of realistic potentials [2]. Of the overall bio-waste amount, only 25% (i.e. 30 million tonnes per year) is recycled into digestate or high-quality compost [3]. The latter must

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E. Benetto et al. (eds.), *Designing Sustainable Technologies, Products and Policies*, https://doi.org/10.1007/978-3-319-66981-6_16

meet several requirements like: allowable heavy metals contents, absence of pathogenic bacteriology and phytopathogens, absence of plastic materials >10 mm etc.

Composting predominates over anaerobic digestion for the bio-waste separately collected, resulting over 90% of food and garden waste being processed into compost. For the most part, food waste is still landfilled within Europe, leading to the release of uncontrolled greenhouse gases [4].

The Circular Economy Package, published by the EU Commission in December 2015, paved the way for a resource-efficient society and sustainable recycling industry across Europe and it contains also proposals addressing the EU waste legislation with the aim of avoiding, reusing and recycling more waste in the future [4]. Of particular relevance, for bio-waste treatment in Europe, is the proposed changes to the EU Landfill Directive [5] whose aim is to reduce the landfill of municipal waste to 10% by 2030. In this ambit food waste fraction plays an important role in recycling and in raising circular economy since up to 50% of municipal solid waste is biogenic. Therefore, the 10% landfill target can be only achieved through sustainable bio-waste management, including composting and anaerobic digestion. In this paper, it is addressed the valuable effects of compost use in agriculture on Soil organic matter (SOM) management and GHG emissions balance of an industrial oil crop pointing out its role in the circular economy.

The SOM is primarily composed of carbon (C), and in soil plays a role in providing four important ecosystem services: (i) resistance to soil erosion, (ii) soil water retention, (iii) soil fertility for plants and (iv) soil biodiversity. SOM is therefore the main indicator of soil quality. Even small changes of the soil C pool could have strong effects both on agricultural yield and on global greenhouse gas cycle. Maintaining organic C-rich soils, restoring and improving degraded agricultural lands and, in general terms, increasing the soil C, could play a fundamental role in addressing food security and in mitigating the anthropogenic GHG emissions [6]. Organic matter (OM) in compost is rich in humifiable and humified materials and so it provides and improve SOM pool and consequently soil fertility. A specific SOM model has been developed and applied within BIT3G Italian project funded by MIUR (Ministry of Education, Universities and Research) as part of the National Technology Cluster of Green Chemistry SPRING with the aim of defining a predictive tool suitable for estimating the site- specific SOM dynamics in function both of pedoclimatic conditions and agricultural practices. Here are reported the experimental results defined on cardoon industrial crop (*Cynara cardunculus* var Altilis DC) cultivated in the North-West of Sardinia following two agricultural protocols: with and without compost application. In addition, this study shows how compost can help to reach the objective of the '4 per 1000' initiative launched at the COP21 that aspires to increase global soil organic matter stocks (SOMS) by 0.4% per year as a compensation for the global emissions of greenhouse gas (GHG) by anthropogenic sources [7].

The final aim is to point out the valuable role of compost which represents the bridge between bio-waste strategy targets and sustainable agriculture principles as qualitatively described through a virtuous circular economy model reported in the discussion.

2 Materials and Methods

An annual time-step model for estimating SOM dynamics was developed and tested [8, 9] in a 22-year time frame. Indeed, C stock changes are generally calculated in a duration longer than 20 years. The model takes into account the main soil characteristics, annual mean temperature, and management of cropping systems and in particular organic fertilizers and crop residues. The analysed agricultural system consists in a not irrigated 8-years rotation repeated until 22 years: 6-year cardoon, one-year durum wheat (*Triticum durum* Desf.) one year field bean (*Vicia faba* cv Minor) and so on.

The model implements the Hénin-Dupuis equation [10–12] which apply two different kinetic constants (k_1 and k_2) on annual step in the above complex cropping system.

$$\Delta \mathrm{SOM} = \mathrm{k}_1 * \mathrm{M} - \mathrm{k}_2 * \mathrm{SOM} \tag{1}$$

where M (dry matter, Mg/ha) stands for raw OM, exogenous OM and/or crop residues, k_1 (% w/w) as the humification constant (i.e. the organic matter that arrive to become humus) and k_2 (% w/w) as the mineralisation constant (i.e. how much humus is mineralised in CO_2). Soil type did not affect significantly the mineralisation behaviour of M according to Noirot-Cosson et al. [13], rather constant k_1 is specific for each M, and it is correlated to specific biological stability index (BSI, % w/w), calculated after a laboratory measurement of biochemical fractions [14], and OM, calculated as M without ashes content, by Eq. (2)

$$\mathrm{k}_1 = \mathrm{BSI} * \mathrm{OM/M} \tag{2}$$

One gross estimate of the mineralisation constant k_2 depends on agricultural practices (P, i.e. tillage frequency and depth, irrigation, crop residues and organic fertilizer frequency), clay content (A, g/kg), total carbonates (g/kg $CaCO_3$), site mean annual air temperature (T, °C):

$$k_2 = \frac{1200 * 0.2 * (T - 5)}{(200 + A) * (200 * 0.3 * \mathrm{CaCO_3})} \tag{3}$$

In addition, specific residual biomasses, agricultural practices (i.e. tillage frequency and depth, irrigation, crop residues and organic fertilizer frequency), were considered [8]. The SOM stock (SOMS, Mg/ha) in 30 cm topsoil (h, m) were estimated taking into account soil organic carbon (SOC, % w/w), bulk density (BD, Mg/m^3), coarse materials (CM, % v/v):

$$SOMS = \frac{SOC}{0.58} * BD * (1 - CM) * h \tag{4}$$

Six soils cultivated with cardoon were sampled within 10 km of Porto Torres area, (Sassari, Sardinia Region, Italy) and assessed for required parameters to make possible the model running (Table 1).

The mineralisation coefficient (k_2) for a "derived soil" from parameter averages, was calculated according to Castoldi and Bechini [11], considering the lack of irrigation (I = 1). The amount of resistant SOM fraction was estimated according to Boiffin et al. [15] or applying BSI [10,14] on cardoon above-ground residues: wheat 0.08, bean 0.1, and roots 0.15; above-ground cardoon was 0.18 experimentally estimated from compositional analysis. Even contribution of cardoon basal leaves and renewal of roots was calculated and computed in the model. This issue will be the subject of a specific forthcoming publication.

Cardoon residues were harvested leaving on the ground 10% of above-ground biomass (w/w as dry matter).

Two scenarios were considered: "compost" and "no compost". Compost scenario planned for 20 Mg/ha compost application before cardoon sowing and 15 Mg/ha on the crop during the 4th year of cultivation. Compost incorporation applied dry matter (dm) 50% (w/w), Nitrogen (N) content 1.8% (w/w dm), organic carbon 48% (w/w dm), BSI 0.53, k_1 0.25 [16]. In "no compost" scenario the contribution of OM is represented only from the cardoon above-ground biomass (i.e. 10%) that remains in soil after harvesting.

Cardoon C footprint was estimated using BioGrace tool [17] and IPCC [18] methodology applying 20-year time-horizon to assess global warming potential for CO_2 CH_4 and N_2O [19]. In particular following IPCC [18], GHG emissions fixed in the industrial production process of urea was taken into account along with direct and indirect N_2O emissions due to N-synthetic and organic fertilisers, crop residues

Table 1 Parameters implemented in the model for different soil samples (from 1 to 6) and if their contribution in increasing (+) or containing (−) the SOM stock mineralisation rate, according to the model

Sample/parameter	SOMS correlation	1	2	3	4	5	6	Mean ± st. dev.
Mean annual temperature (°C)	+	16.7	16.7	16.6	16.7	16.8	16.7	16.7 ± 0.1
Soil organic matter (% w/w)	+	2.10	2.45	2.03	2.59	2.76	2.38	2.39 ± 0.31
Bulk density (g/cm^3)	+	1.32	1.28	1.31	1.26	1.26	1.26	1.28 ± 0.03
Coarse materials (% v/v)	−	0.00	0.13	0.17	0.17	0.12	0.02	0.10 ± 0.07
Clay (g/kg)	−	367	517	458	567	400	121	405 ± 82
Carbonates (g/kg)	−	163	37	3	79	9	616	151 ± 66

and N mineralisation associated with eventual SOM loss. Agricultural supplies were experimentally estimated for each year of cardoon cultivation and then averaged out; so, for example, the CO_2 equivalents needed for seed production to grow one hectare of cardoon was divided by six.

3 Results and Discussions

The model was firstly applied to cardoon cropping system, but it could be applied even to any other crop system (i.e. food and non-food) [8, 9]. Assessed scenarios showed that SOM increased by the supply of exogenous OM rich in humifiable materials, such as high-quality compost. The magnitude of GHG emissions or sequestrations caused by SOM variation depended on soil characteristics (Table 1). The results obtained by the soil model with mean characteristic are reported in Fig. 1. Error bars show the variation due to the soil variability. For both compost and no-compost scenarios the upper SOMS values above the curves set a “C sink layout”, built implementing a “derived soil” having values obtained by mean plus standard deviation of parameters that contain mineralisation and mean minus standard deviation of parameters that increase mineralisation (Eqs. 3 and 4). On the contrary, the lower SOMS values below the curves in Fig. 1 set a “C source layout”, built considering the mean plus standard deviation of parameters that increase mineralisation and mean minus standard deviation of parameters that contain mineralisation (see Table 1).

Compost application allows to reach, on average, a 6.2 Mg/ha organic matter sequestration in 22 years, a value that corresponds to about 160 kg of C per year. This SOM improvement will corresponds to reach more or less a SOMS increase of around 0.4% per year requested by ‘4 per 1000’ initiative [7]. Instead, in the “no compost” scenario, is expected to deplete 3.9 Mg/ha SOMS (around 100 kg C lost per year).

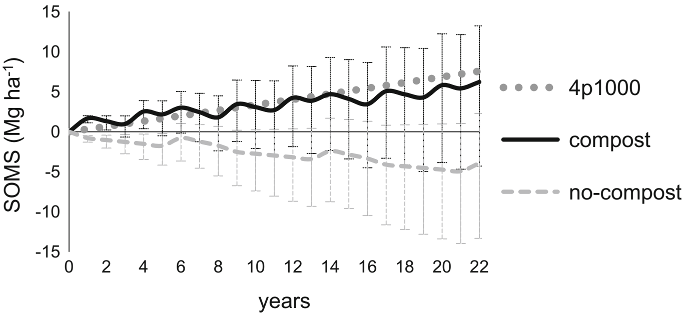

Fig. 1 Soil Organic Matter Stock (SOMS) variation on average soil (out of 6 soil samples) in 22-years cardoon-durum wheat-field bean cropping system simulation. Error bars shows C sink and source layout obtained by standard deviations of soil parameters. Compost application allows to increase, on average, the SOMS by the ≈0.4% per year

In addition, the cropping system allows for maintaining a roughly high level of OM, mainly by virtuous release by cardoon roots decay at the end of every production cycle. Nevertheless, in soil with higher mineralisation (e.g. with lower content of clay and/or carbonates), the supply of appropriate compost amounts is necessary to maintain, or at least to minimise, SOMS losses. Indeed, an exogenous SOM supply increases biogenic C mineralisation, as well as pool of recalcitrant C in soil [13]. Therefore, compost amounts need to be appropriate also because the supply of excessive amounts of compost, i.e. 30 t/ha dry matter in Mediterranean condition, declines the C conversion efficiency [20], and some threats might occur (i.e. metals and excess nutrients into groundwater and increase in soil salinity) depending on compost quality [21].

SOC sequestrations or depletions can be fundamental in greenhouse gases (GHG) crop management as demonstrated by the Life Cycle Assessment focused on cardoon agricultural phase.

The GHG balance of one year for cardoon cultivation is reported in Fig. 2. Among the cardoon cultivation inputs, the main C footprint were due to the chemical fertilizers (i.e. urea) and diesel according to Cocco et al. [22]. Moreover, the use of compost cut down on N_2O emissions according to Aguilera et al. [23]. However, the contribution of SOMS dynamic is preponderant. Carbon source and sink from soils play a fundamental role in C footprint assessment of agricultural phase: the net balance of GHG emissions in the "no compost" scenario accounts for 1710 kg CO_2eq per hectare, whereas the same crop system where compost was applied resulted to be characterised by 490 kg CO_2eq per hectare, with an over 70% reduction.

The promoting of a sustainable agriculture has a huge relevance since agricultural sector represents the ground of bio-economy. High quality compost availability, even assuming a notable increase of bio waste recycling (i.e. 60 million of metric tonnes per year of bio waste) would result much lower if compared to potential demand: according to a rough estimation of the authors, the annual amount of compost (potentially) produced would be enough to be used in the 1–3% of the EU-28 agricultural land. Consequently, SOM management shall be pursued with the aim of innovative agricultural practices (e.g. intercropping, green manure, incorporation of higher amount of biomass in soil etc.). Nevertheless, the authors agree to the EU Landfill Directive proposal that will oblige EU Member States to introduce the separate collection of bio-waste as far as is technically, ecologically and economically feasible. This change, in fact, would activate a series of virtuous mechanisms whose benefits can be summarise as follows:

1. 10% landfill target achievement and reduction of GHG emissions from inappropriate disposal (i.e. landfill)
2. Increase labour market (i.e. food waste management and composting)
3. Reduction of greenhouse gas emissions from crops cultivation (i.e. CO_2 uptake linked to SOM increase, Fig. 2)
4. Sustainable agriculture (i.e. no SOM depletion).

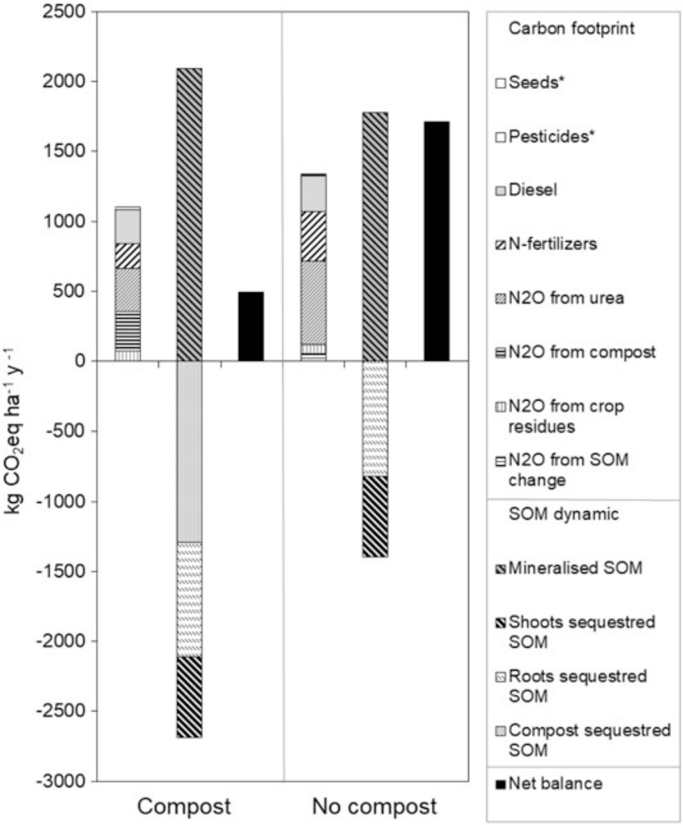

Fig. 2 Yearly average GHG balance for one hectare of cardoon cultivation, with or without compost, * stands for negligible contribution

Figure 3 describes an ideal model of circular economy where food-waste are able to bring the benefits described in 1–4.

In order to put into practice this model and make real the social, economic and environmental benefit of bio-economy, specific incentives could be introduced for those farmers that apply compost in their agricultural fields. This would increase the demand of high quality compost which could/should be the driving force of the whole system. It is worth to point out that sustainable SOM management is a requisite of emerging standards on the sustainable biomass production like the European EN16751 [24].

Another important aspect for the success of this circular economy model is the execution of an appropriate separate collection of bio-waste by the consumers as a key prerequisite to (i) ensure high quality compost and (ii) reduce the bio-waste management costs of Citizen should be more and more informed about the importance of their behaviour on the success of bio waste management chain. This

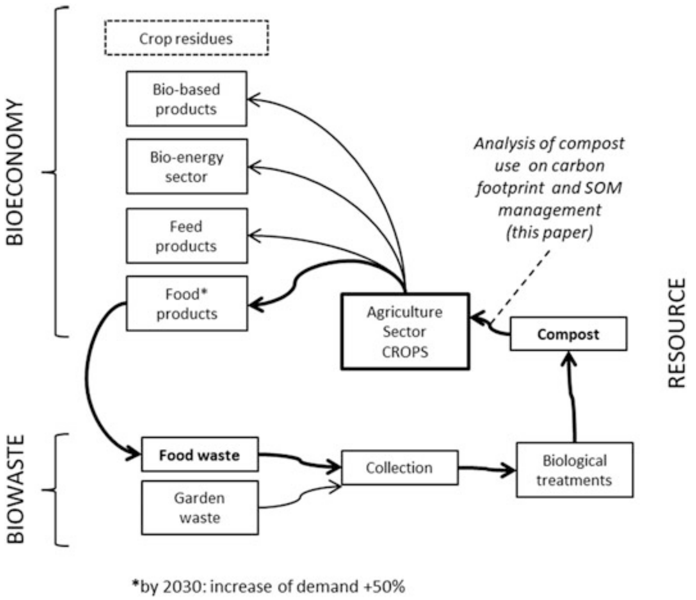

Fig. 3 Virtuous circular economy model for food waste (rows in bold). Above-ground biomass (crop residues) could be exploited to produce bio-based or bio-energy, or partially/totally returned to the soil

aim could be achieved through informative and formative campaigns performed at local level by municipal authorities, NGOs, scholar programmes etc. A real case study of a positive achievement is the experimental program introduced by Agenzia Milanese Servizi Ambientali (AMSA) [25] in 2016 related to the collection of biogenic waste produced at street markets level in Milan. The implementation of ad hoc organic waste collection system [26], along with an effective informative campaign have allowed to reach valuable results: in the five months of experimentation in the fifteen street markets passed from 60 metric tonnes (2015) to 260 metric tonnes (2016) in the same period, with an increase of around +320% (AMSA, personal communication).

In reference to labour market increase linked to bio waste chain (point 2), it was estimated by the European Compost Network that up to 50,000 [4] new jobs in Europe could be created if additional 60 million tonnes of municipal bio-waste would be collected and composted/anaerobically digested across Europe.

4 Conclusions

It has become clear that globally the issue of food waste has significant social, economic and environmental impacts. The Circular Economy Package, published by the EU Commission in December 2015, contains specific proposals addressing the EU waste legislation with the aim of avoiding, reusing and recycling more waste in the future in order to save resources within Europe. One of the targets contained in the proposals is the maximum percentage of municipal solid waste to be disposed in landfill set equal to 10% by 2030. Food waste management is therefore a key topic of the expected strategic action plan since up to 50% of municipal solid waste is biogenic. Biological treatments are well established in Europe with about 3500 treatment plants across Europe, nevertheless, still 25% of bio waste is recycled into high quality compost [3]. These figures suggest e considerable potential for expansion, especially in the southern Europe areas where the treatment capacity is still limited [4]. In this way, sustainable bio-waste management could also be used to strengthen the economy of rural areas and, at the same time, could benefit of compost application in agricultural fields. The SOM model developed within BIT3G Italian projects, suggested that compost use in agricultural sector is meaningful from a SOM management and carbon footprint perspectives as well. The SOMS after 22 years of cardoon cropping system with compost application resulted incremented of 6.2 metric tonnes per ha (first 30 cm of soil) whereas the scenario with zero inputs resulted decremented of 3.9 metric tonnes per hectare. In terms of GHG balance it was observed that average CO_2 uptake has the same order of magnitude of the overall emissions coming from cardoon cultivation. In specific circumstances the CO_2 uptake overcomes GHG emissions making cardoon crop cultivation GHG balance neutral or even negative.

The link between food waste management, compost production/use and food/biomass sustainable production is therefore a key element of both for circular economy and bio-economy to be further investigated by decision makers for its valuable implications in the medium and long term on social, economic and environmental pillars.

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