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REVIEW ARTICLE

Compost benefits for agriculture evaluated by life cycle assessment. A review

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Abstract As compost use in agriculture increases, there is an urgent need to evaluate the specific environmental benefits and impacts as compared with other types of fertilizers and soil amendments. While the environmental impacts associated with compost production have been successfully assessed in previous studies, the assessment of the benefits of compost on plant and soil has been only partially included in few published works. In the present study, we reviewed the recent progresses made in the quantification of the positive effects associated to biowaste compost use on land by using life cycle assessment (LCA). A total of nine environmental benefits were identified in an extensive literature review and quantitative figures for each benefit were drawn and classified into short-, mid-, and long-term. The major findings are the following: (1) for nutrient supply and carbon sequestration, the review showed that both quantification and impact assessment could be performed, meaning that these two benefits should be regularly included in LCA studies. (2) For pest and disease suppression, soil workability, biodiversity, crop nutritional quality, and crop yield, although the benefits were proved, quantitative figures could not be provided, either because of lack of data or because the benefits were highly variable and dependent on specific local conditions. (3) The benefits on soil erosion and soil moisture could be quantitatively addressed, but suitable impact assessment methodologies were not available. (4) Weed suppression was not proved. Different research efforts are required for a full assessment of the benefits, apart from nutrient supply and carbon sequestration; additional impact categories—dealing with phosphorus resources, biodiversity, soil losses, and water depletion—may be needed for a comprehensive assessment of compost application. Several of the natural mechanisms identified and the LCA procedures discussed in the paper could be extensible to other organic fertilizers and compost from other feedstocks.

Keywords Sustainable agriculture · Environmental impact · Organic fertilizer · Biowaste · Soil organic matter · C sequestration · Disease suppression · Soil quality

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1 Introduction

1.1 Background

There is increasing concern about soil interrelated environmental problems such as soil degradation, desertification, erosion, and loss of fertility (European Commission 2006). These problems are partially consequence of the decline in organic matter content in soils. An estimated 45 % of European soils have low soil organic matter (SOM) content, principally in southern Europe, but also in areas of France, the UK, and Germany (European Commission 2006).

A parallel concern is the massive generation of organic waste by human activities, which has led to the proposal of several alternatives to avoid landfilling and promote recycling. Among these alternatives, composting is one of the best-known and well-established processes. Composting allows the stabilization and sanitation of organic waste through accelerated aerobic decomposition under controlled conditions, resulting in a product called compost. Several studies indicate that the use of compost on land may improve several plant and soil parameters, which would make compost an interesting option for soil restoration purposes, as well as take advantage of its fertilizer properties. Compost addition increases SOM content, which enhances aggregation and stability, thereby ameliorating soil structure (Diacono and Montemurro 2010). Stability of soil aggregates prevents surface sealing, improves water infiltration, and enhances water holding capacity, thus reducing runoff generation and soil erosion (ROU 2007). Moreover, increasing SOM levels promotes carbon sequestration (Favoino and Hogg 2008; Marmo 2008). Other potential benefits of compost application are improved biological activity (Bastida et al. 2008; Hargreaves et al. 2008), enhanced nutrient availability for plants (Boldrin et al. 2009), and the suppression of soil borne diseases (Bonanomi et al. 2007). Furthermore, several authors have reported higher yields with compost application and better quality of the harvested crops. On the other hand, the application of compost may also result in environmental and agronomic drawbacks, such as gaseous and leachate emissions, and increase in salt and heavy metal content, etc. (Hargreaves et al. 2008). Nevertheless, these issues are, in general, directly associated to the quality of the final compost.

In recent times, green criteria are increasingly employed in decision-making in response to the growing societal concern regarding environmental issues. Several tools are available to quantify positive and negative environmental impacts of compost in a comprehensive manner. Among them, life cycle assessment (LCA) was promoted in different European directives as a robust quantitative tool and has been widely used for the environmental assessment of the waste and agricultural sectors. While the environmental impacts associated to compost production and transport have been successfully assessed in previous studies (ROU 2007; Boldrin et al. 2009; Martínez-Blanco et al. 2010; Colón et al. 2012), assessment of most of the benefits of compost on plant and soil has not been taken into account. Several recent studies address the inclusion of compost benefits in a partial manner, recommending that further research should be undertaken on the subject (Boldrin et al. 2009; Favoino and Hogg 2008; Hansen et al. 2006; Martínez-Blanco et al. 2011). Carbon sequestration and nutrient supply are, to date, the only environmental benefits taken into account in these studies. Because of the modelling complexity, ROU (2007) is, to our knowledge, the only study where an attempt was made to include most of the abovementioned benefits within LCA of two Australian case studies. The results were however only presented at the inventory stage, and the obtained figures were not included within the impact categories.

1.2 Aims of this review

The main goal of this review paper is to quantitatively address LCA modelling of the positive effects traditionally associated to land application of biowaste compost produced from organic municipal solid waste and garden waste. Here, we have focused only on the implications of compost application to the soil and plant without considering the full life cycle (i.e., production process and transport are not discussed here); see Fig. 1. The specific goals were (1) to identify each environmental and agronomic benefits (from now on, benefit) associated to the use of compost; (2) to provide quantitative data for these benefits (i.e., data that can be later included in an inventory) and to describe the main factors affecting the results for each of them; and finally (3) to describe the existing impact assessment methodologies applicable and future challenges for assessing the benefits within an LCA perspective.

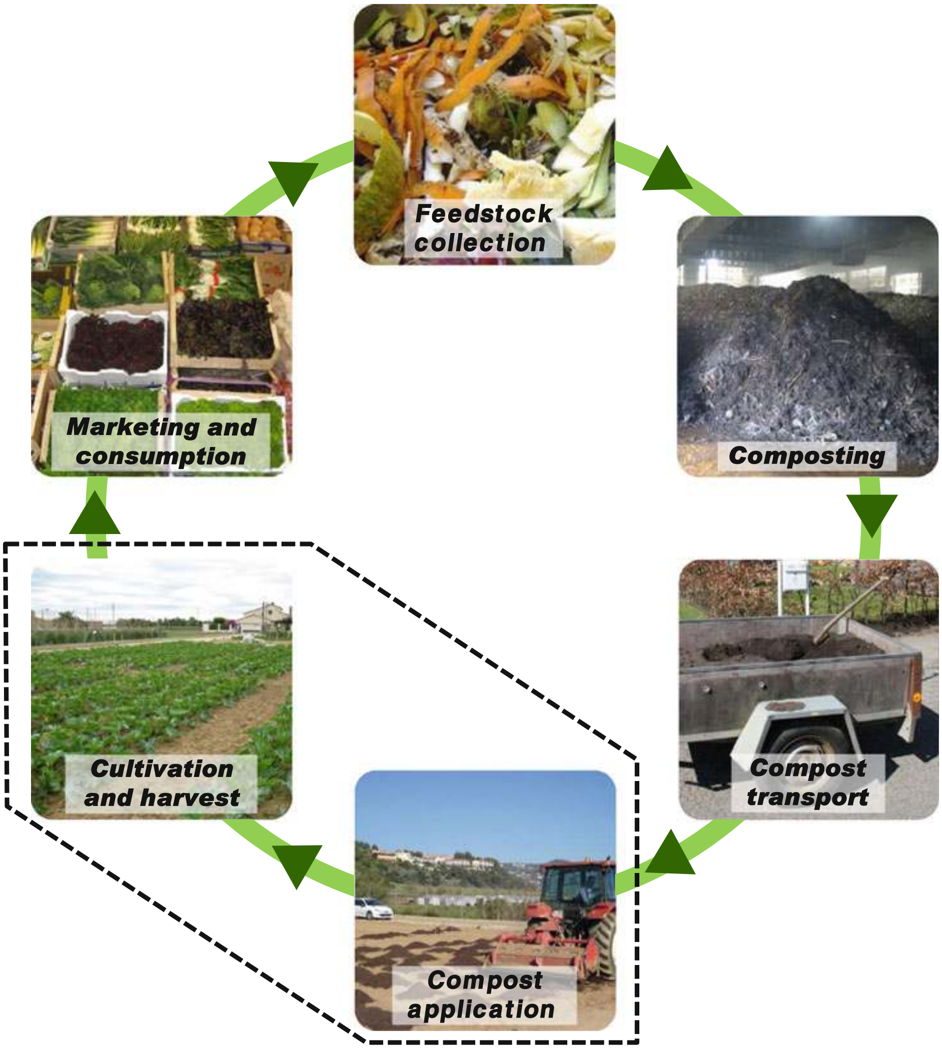

Fig. 1 Overview of the life cycle of compost production and use in agriculture. This review focuses on the environmental benefits produced from the compost application to the harvest stage

2 Methodology

A comprehensive revision of the literature dealing with the potential benefits of compost application, and the current situation of the inclusion of each of these benefits in LCA studies was carried out. First, the most relevant benefits of compost on soil properties and plant growth were identified, and the inventory data were collected. Subsequently, 90 articles (including both reviews and case studies) published later than 1990 were selected. Although similar environmental and agronomical benefits could be observed in compost produced from other types of feedstock and in other organic fertilizers, in this review, field studies considering compost from organic municipal solid waste and green waste (from now on biowaste) were taken into account when possible. The benefits were grouped in nine categories (Fig. 2). According to the literature revision, the benefits were classified into short term (1 year), mid-term (1–10 years), and long term (10–100 years), depending on the time perspective of the agronomic effects.

Later on, the benefits studied were revised, through an LCA perspective, according to: (1) the existing evidences for the effects on soil, plant, environment, farmer, or harvest; (2) the possibility of quantification of the substituted or saved process; and finally, (3) the current availability of tools for their inclusion in LCA, together with the current status of new assessment methodologies.

3 Environmental and agronomic benefits of compost

An outline of the literature review dealing with the nine potential benefits resulting from compost application is provided in Table 1. The full review is available in Martínez-Blanco et al. (2013) where, for each of the agronomic benefits, a discussion of the main factors affecting the performance of the benefit, the degree of proof, and the range of the benefits measured were included.

Regarding the supply of plant nutrients, between 5 and 60 % of the N applied with compost is mineralized,

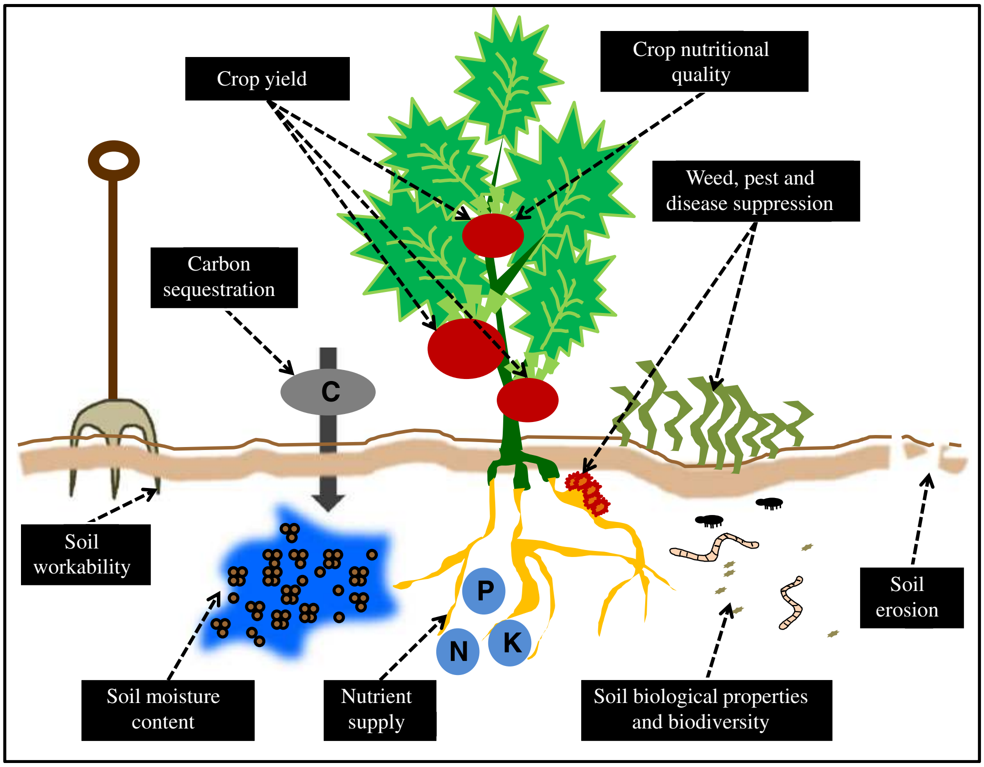

Fig. 2 The nine benefits of compost application assessed in the paper

depending on the time frame considered. Figures range between 35 and 100 % for P and between 75 and 100 % for K. Carbon sequestration rates have shown to be higher in the short term (up to 40 % of the applied C) and decreasing to 2–16 % for a 100-year period. Effects on crop yield vary from decreases of 138 % in crop productivity and in the short term to increases of 52 % in the mid-term. Compost showed to increase soil structural or aggregate stability between 29 and 63 %, reducing soil loss between 5 and 36 %. Soil bulk density is decreased between 0.7 and 23 % after compost application, potentially increasing soil workability. Also, water holding capacity and plant available water can increase by 50 and by 34 %, respectively (see Table 1).

Although we were able to state the magnitude of the effect, for the following three benefits, the share of studies with non-significant results was relevant: Crop nutritional quality was not relevantly different for a third of the case studies included; for crop yield, more than 60 % of the case studies did not report differences when compost was applied, and finally, non-significant benefits were detected for soil moisture content for low rates of compost.

For the benefits pest and disease suppression and crop nutritional quality, although they were proven, it was not feasible to summarize the benefit in a unique data range. These benefits involve several concurring indicators at the same time, and the intensity of the effect is different for each one according to several factors. Relevant pest and disease suppressive effects were reported in most of the studied cases for *Phytium* spp, *Fusarium* spp, *Phytophthora* spp, and *Verticillium dahlia*, although only few experiments resulted in a sufficient suppressive level to justify the replacement of chemical pesticides. Regarding weed suppression, it was not proven when compost is used as a soil amendment. Compost application has been shown to increase the content of a large number of nutritional compounds in crops (such as chlorophylls, carotenoids, sinapic acids, and phenols) while non-significant effects were reported for other compounds.

Data regarding effects of compost application on soil biological properties and biodiversity are scarce and restricted to microorganisms. Table 1 shows the results of the revision for three of the more used microbial indicators: Compost may decrease microbial diversity by 2 % or increase it by 4 %; positive effects are also observed on microbial biomass (3.2–242 % increase after compost application) and microbial activity (43–344 % increase).

On average, positive effects due to compost application were found for all the potential benefits, except for weed suppression. Benefits in the long-term were only reported for nutrient supply, carbon sequestration, soil biodiversity, and soil workability whereas, for the other potential benefits, only mid- or short-term data were found. In addition, quantification of the potential benefits yielded broad ranges in most of the cases.

Table 2 provides an overview of the variables identified in reviewed literature having the largest influence on the magnitude of compost benefits. The original feedstock

Table 1 Summary of the potential benefits of compost use-on-land in the short-, mid-, and long-term retrieved from the literature review (adapted from Martínez-Blanco et al. 2013)

Benefit	Indicator (unit)	Short-term (<1 year)		Mid-term (<10 years)		Long-term (<100)	
		Min.	Max.	Min.	Max.	Min.	Max.
Nutrient supply	N mineralized (% of N applied)	5	22	40	50	20	60
	P mineralized (% of P applied)	35	38	90	100	90	100
	K mineralized (% of K applied)	75	80	100	100		
Carbon sequestration	C sequestered in soil (% of C applied)	40	53		30	2	16
Weed, pest, and disease suppression	Weed suppression (−)	ns	ns	–	–	–	–
	Pest and disease suppression (−)	nad	nad	–	–	–	–
Crop yield	Crop yield gain[a] (% from mineral fertilizers)[b]	−138	0	−71	52	–	–
Soil erosion	Soil loss[a] (%)[b]	–	–	−5	−36	–	–
	Soil structural or aggregate stability[a] (%)	29	41	0	63	–	–
Soil moisture content	WHC[a] (%)	0	50	–	–	–	–
	PAW[a] (%)	0	34	–	–	–	–
Soil workability	Soil bulk density[a] (%)[b]	−2.5	−21	−0.7	−23		−20
Soil biological properties and biodiversity[c]	Microbial diversity[a] (%)[b]	–	–	–	–	−2	4
	Microbial biomass[a] (%)	22	116	10	242	3.2	100
	Microbial activity[a] (%)	0	344	–	264	0	43
Crop nutritional quality	Crop nutritional quality (−)	nad	nad	–	–	–	–

WHC water holding capacity, *PAW* plant available water, *ns* no significant differences, *nad* no average data because of complexity of available dataset, *en dash* no reported benefits

[a] Change in the indicator

[b] Negative value indicates a decrease in the indicator

[c] The ranges of benefit for three of the more used indicators are presented

material, management of the composting process, compost maturity, and crop management are some of the main factors that determine the occurrence of environmental and agronomic benefits. For instance, Boldrin et al. (2009) reported that the typical contents of nutrients in biowaste compost can vary depending on the initial raw waste material. Similarly, the proportion resistant C pool and C sequestration rates can be very variable in different compost materials (Diacono and Montemurro 2010). Susceptibility of these nutrients to mineralization and release might depend on the degree of stability and/or maturity of the compost as well as on the prevailing climatic conditions due to the large influence of temperature and moisture in decomposition and nutrient release (Sikora and Szmidt 2004). The use of heterogeneous input material(s), a correct maturation process, and high dosages were the most important factors influencing compost supressiveness for pests and diseases (Bonanomi et al. 2007; ROU 2007; De Bertoldi 2010). Regarding the impacts of compost on soil moisture, workability, and erosion, several authors reported large positive effects with high-rate compost application on soils with initially low SOC content. Compost quality, including the quality of the original raw material, the maturation degree, C/N ratio, and content of heavy metals are some of the most important factors determining the impacts on soil biological properties and biodiversity, together with the dose applied (Hargreaves et al. 2008; Diacono and Montemurro 2010). Increases in crop nutritional quality when compost is employed largely depend on crop management and climate conditions. The dosages of compost applied as well as the existence of a lag of time between compost application and crop sowing were also key in explaining the strength of the observed benefits.

The benefits identified here are not exclusive of compost as they have also been observed with other types of organic fertilizers. Thus, several of the soil and plant mechanisms described and the LCA procedures discussed in the paper could be extensible to other organic fertilizers and compost from other feedstocks. Yet, we expect that the variability in the observed effects would be much larger than the one observed here due to the different features of the organic fertilizers, thus complicating the elaboration of an inventory.

4 Quantification and impact assessment

In this section, a summary of the state-of-the-art for each of the nine benefits is presented, and, according to this, a

Table 2 Overview of the main factors affecting the potential benefits of biowaste compost application

Potential benefit	Composting process			Compost characteristics				Compost application			Site conditions				Crop management		
	Raw material quality	Composition/heterogeneity	Controlled conditions	Maturity	C/N ratio	Microbial diversity	Heavy metals content	Dosages	Gap application-cultivation	Application method	Climatic conditions	Soil nutrient pool	Type of soil	Saturation level of C	Crop/rotation	Mechanical aeration	Post-harvest management
Nutrient supply	x	x	x	x	x			x	x		x	x	x		x	x	
Carbon sequestration				x				x			x			x			
Weed, pest and disease suppression		x	x	x		x		x	x						x		
Crop yield				x			x	x	x	x		x			x		
Soil erosion								x			x		x				
Soil moisture content								x					x				
Soil workability								x									
Soil biological properties and biodiversity	x	x		x	x		x	x									
Crop nutritional quality											x				x		x

discussion of the quantification model improvement and of the missing or insufficiently developed impact categories is added at the end of the section.

4.1 Benefits of compost application: revision from an LCA perspective

In the following sub-sections, the potential benefits derived from biowaste compost application are quantitatively described within an LCA perspective, including the consequential modeling, the quantification of the substituted or saved process, and finally the impact categories which are most affected when considering compost application.

4.1.1 Nutrient supply

In an LCA context, the supply of nutrients with compost substitutes the use of mineral fertilizers, whose industrial production and transport is thus avoided and would typically result in potential savings on the main impact categories (Fig. 3). The amount of substituted fertilizers depends on the content of nutrients of the compost and their utilization rate. Datasets for N–P–K fertilizers production and transport are reported by different sources (such as Davis and Haglund 1999; Audsley et al. 2003; Hansen et al. 2006). Furthermore, compost is considered as an effective option for phosphorous recycling (Cordell et al. 2009), which is a growing issue as a consequence of the foreseen shortage of mineral P for agriculture fertilization (Syers et al. 2008).

4.1.2 Carbon sequestration

Sequestration of C into soil can be seen as removal of C from atmosphere and translated to saved CO_2 emissions, being directly related to the category "Global warming" (Fig. 3). The time-horizon used in the assessment plays a crucial role when estimating the benefit from carbon sequestration. A time frame of 100 years is considered to be relevant for estimating contributions to global warming (Favoino and Hogg 2008). Large variability was found in the values reported for C retained in soil, most likely due to the synergistic effect of the different abovementioned environmental and site-specific factors, meaning that estimations should be done on a case-to-case basis.

4.1.3 Weed, pest, and disease suppression

When the application of compost reduces the incidence of weeds, pest, and diseases, the use of herbicides and pesticides can be reduced or avoided. The avoided use can consequently be credited to the system as an environmental saving. Nevertheless, although major resistance toward certain diseases has been reported for most cases, benefits are so case-specific that it is not possible to provide any general figure regarding both the amount and the type of pesticides saved.

When pesticides are saved, environmental benefits are related to both the avoided production/transportation (inventories available at databases such as Ecoinvent and GEMIS) and to the avoided use of the pesticides. Assessment of the environmental effects induced by pesticide utilization requires the use of exposure–fate–toxicological models. Unfortunately, dynamic and realistic models are scarce (Birkved and Hauschild 2006) and require exhaustive information, which is in many cases unknown (Antón et al. 2004). Two of the most well-known and used models are PestLCI 2.0 (Dijkman et al. 2012) and USEtox (Rosenbaum et al. 2008). Potential environment impacts from production/transportation and use of pesticides can be

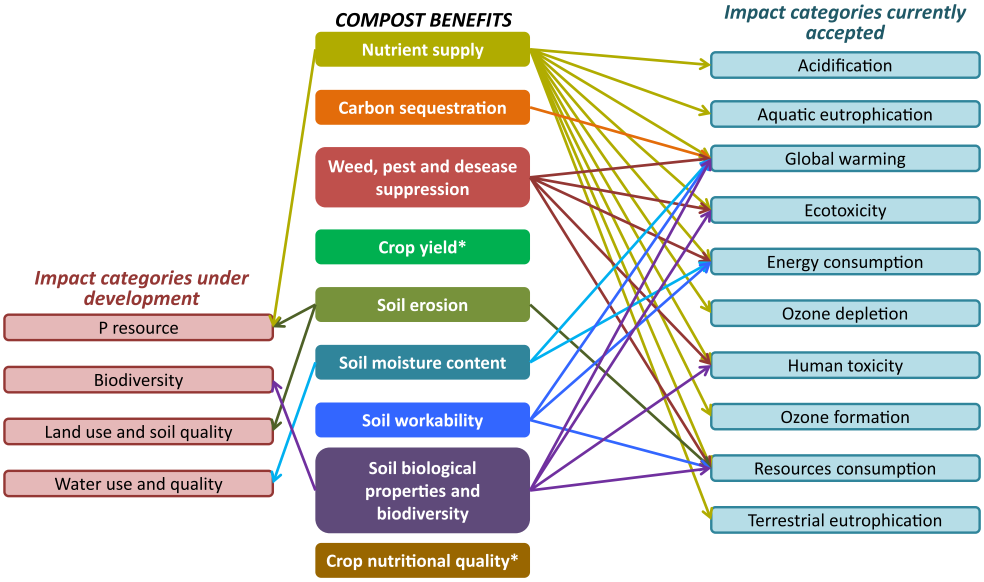

Fig. 3 Midpoint LCA impact categories involved in the evaluation of the potential benefits of biowaste compost use-on-land. *Asterisk:* it has to be included in the LCA using the adequate functional unit

assessed using existing impact categories. The most relevant impact categories related to pesticides use are the Toxicity categories, both Human and Ecotoxicity (Fig. 3).

4.1.4 Crop yield

An increased crop yield as a consequence of compost application could result in avoided agricultural production and thus, the burdens involved. From a consequential LCA point of view, this can have different consequences at a system level, depending on existing agricultural constraints. If arable land in a certain area is not constrained, the benefit is linked to avoided use of material and energy needed for the crop production. In the most likely regime of constrained arable land, the increased yield would have an effect on both intensification and expansion of agricultural production and, ultimately, will prevent indirect land use changes. In turn, reduced crop yield would have the opposite consequences.

The LCA modelling of increased or decreased agricultural productions is typically case-specific regarding both the specific crop directly affected by the increased yield and the indirect changes in land use. For both effects, production inventories can be used to credit the system for the avoided productions. Depending on the specific area and crop, most of the impact categories are influenced when agricultural production is involved (Fig. 3).

4.1.5 Soil erosion

As mentioned earlier, the application of compost could prevent soil erosion and thereby avoid losses of arable land. One approach is to model the avoided losses within traditional LCA impact categories, identifying the agricultural production affected by the losses of arable land and then modelling similarly to “Crop yield” section. A second option is to consider soil as a resource (Fig. 3). Impacts of erosion were recently addressed by Saad et al. (2011), who focused on the degradation of the erosion regulation function due to land transformation and land occupation. Núñez et al. (2012b) focused on impacts of erosion to carbon losses and net primary productivity due to land occupation based on SOC contents. Buratti and Fantozzi (2010) introduced “soil erosion” as an independent endpoint impact category.

4.1.6 Soil moisture content

One potential benefit of compost is to increase the capacity of soil to retain green water, i.e., rainfall and irrigation water stored in the soil as soil moisture, in order to reduce irrigation and consumption of blue water, i.e., water from surface and groundwater resources. This may result in two different consequences: Blue water is saved; and crop yield could increase in those areas where irrigation water is not available. However, the effective amount of water saved would depend on several site and crop conditions.

Environmental burdens from irrigation are linked to water extraction, transport, and distribution in the field and are found in several inventories. Potential impacts from these processes are typically those related to energy supply and consumption (Fig. 3). Furthermore, in recent years, several methods have been developed which propose different freshwater use inventory schemes and impact assessment characterization models considering various cause–effect chain relationships. Kounina et al. (2012) reviewed current methods and indicators for freshwater use potentially applicable in LCA.

4.1.7 Soil workability

Improved soil workability can potentially decrease energy requirements for agricultural operations (Favoino and Hogg 2008; ROU 2007). Notwithstanding, only one study (McLaughlin et al. 2002) was found linking compost application and fuel consumption for agricultural operations, meaning that more comprehensive data are needed to be able to relate, for example, fuel consumption with soil bulk density. Reduced fuel consumptions can be credited to the system as avoided use of diesel, which is available in several databases and published report and mainly affects Global Warming and Resources impact categories, while avoided combustion emissions of nitrogen oxides could also have an influence on Acidification, Eutrophication, and Photochemical oxidant formation (Fig. 3).

4.1.8 Soil biological properties and biodiversity

Changes in soil biodiversity after compost addition might influence either positively or negatively the services delivered by the ecosystem (e.g., hydrological processes, nutrient cycling, and pest incidence), with consequences in terms of impacts associated to the substitution or compensation of those ecosystem services. Alterations in the system service in connection to biodiversity changes could be modelled within the traditional categories if those changes could be quantified in the inventory (Fig. 3). However, data linking compost use, biodiversity, and ecosystem services are nonexisting—apart from a first attempt of establishing a preliminary relation by Nemecek et al. (2011). In addition, the effects of land management practices are highly variable depending on regional and scale-dependent factors (Bengtsson et al. 2005). An alternative approach is to consider biodiversity and ecosystem services as independent endpoint categories (Zhang et al. 2010) (Fig. 3). Some recent initiatives have established baseline biodiversity indices for different soil organisms and under different soil uses that can be used as a reference to evaluate the impacts of compost on soil biodiversity (Cluzeau et al. 2012).

4.1.9 Crop nutritional quality

The differences in the nutrient content of crops do not directly affect resource consumption or emissions per hectare or ton yielded. Furthermore, if the LCA modelling considers functional units based on yield (i.e., mass, volume, surface), no consequences on resource consumption or emissions need to be modelled in the inventory. However, when the functional unit includes qualitative aspects such as nutritional and/or economic value, increased nutritional level of a food product may have as a consequence that lower amounts are needed. In general, terms, including qualitative aspects in the functional unit, would have an effect on the agricultural production, which could be modelled similarly to what is described under the "Crop yield" section (Marshall 2001; Martínez-Blanco et al. 2011).

4.2 Quantification: improved modelling

Review of the existing literature shows that, in the future, modeling of benefits from biowaste compost application should be improved in some areas in order to adequately assess its benefits. First, LCA models are typically linear steady-state models of physical flows (Guinée et al. 2002). Nevertheless, fluxes of nutrients and pollutants after compost application to soil are not linear in most of the cases. This also applies, for instance, to repeated applications of compost, as the cumulative effects on several applications may not be linear with the amount of compost added overtime.

Second, most LCA models assume that impacts depend on the compost characteristics, while models rarely include environmental parameters as determining factors. This links with the necessity of coupling LCA and agronomic models to gain a more precise picture.

Third, the amount of plant nutrients contained in compost is normally modelled for as a benefit. However, the use of compost could in some cases result in excessive application of P and K with respect to N, which is usually used for compost dosage calculation. This could result in impacts to the environment and should be thus included in the LCA modelling through a more thorough mass balancing of the nutrients.

Fourth, there may be a need for a qualitatively more precise definition of system functions when dealing with compost application, especially in those cases where the product quality is affected. This is due to the fact that, besides area used or product yield, different functional units can be used in LCA of the agricultural sector, possibly leading to different results for the same product system. Better definitions could, for example, include the economic value, the nutritional content of a product (Hayashi et al. 2006; Mourad et al. 2007; Reap et al. 2008; Schau and Fet 2008; Martínez-Blanco et al. 2011), or the combination of nutritional quality and yield (Charles et al. 1998; Audsley et al. 2003).

Finally, the choice of the time horizon of the LCA should be harmonized. The studies reviewed showed in fact that such choice is in many cases very important, as both the foreground and background effects of compost application vary largely depending on the time frame.

4.3 Characterization: additional impact categories and proposed modifications

As abovementioned, available impact assessment methodologies may not properly deal with the LCA assessment of many of the benefits derived from compost use-on-land. Thus, new impact categories or modifications of the current ones may be needed in the future to allow for a more holistic assessment. These new categories should deal with depletion of P resources, biodiversity, loss of arable soil, and consumption of water (Fig. 3).

Depletion of P as a resource is currently modelled similarly to other natural resources. However, most resources could be replaced in many of their functions, while this is not the case of phosphate. A revision of the characterization factors is thus needed for the assessment of non-replaceable non-renewable resources such as P. In this respect, the ReCiPe model adds special value to this type of resources (Goedkoop and Spriensma 2000).

Assessment of the impacts of land management on biodiversity can be based, among others, on either particularly endangered species (Nemecek et al. 2011) or the changes of one relevant indicator group (Weidema and Lindeijer 2001; Goedkoop and Spriensma 2000), or the change in the overall number of species per year (Suer and Andersson-Sköld 2011). Other authors have included biodiversity and ecosystem services as midpoint categories within the impact category Land use (Milà i Canals et al. 2007; Udo de Haes 2006). As different options exist, a harmonization may be needed in order to develop a consensus methodology.

Soil loss through erosion involves the loss of cultivable land but also the loss of soil organic carbon, plant nutrients, as well as the associated plant, animal, and microbial biodiversity (Cowell and Clift 2000). The loss of soil mass could be considered as the loss of a resource and included in the inventory as "resource depletion" (Cowell and Clift 2000; Buratti and Fantozzi 2010; Núñez et al. 2012b). However, one of the most used approaches nowadays is that soil erosion can be included within the impact category "land use", whose characterization factors are based on soil quality indicators such as SOM, biodiversity, aesthetic value, etc. (Brentrup 2004; Mattsson et al. 2000).

Regarding the depletion of water resources, there is currently only a preliminary scientific consensus about the parameters to consider and the impact assessment methods to follow (Kounina et al. 2012). They include the types of water use accounted for, the local water scarcity conditions, and the differentiation between watercourses and quality aspects (Berger and Finkbeiner 2010). More emphasis is given to the blue water consumption, although, from an environmental point of view, consumption of green water for crop production is also important because of its influence on ecosystems (Berger and Finkbeiner 2010; Núñez et al. 2012a).

5 Conclusions

Use of biowaste compost on land can have beneficial effects on the plant–soil system. Most of these benefits have been so far excluded from LCA studies, mainly because of scarcity of data or lack of appropriate impact assessment methods. Availability and quality of the data for quantification differed largely among the assessed benefits, with no data or large variability in the observed benefits. Data concerning long-term benefits of compost, which are relevant for LCA purposes, were particularly scarce. Therefore, there is a need for more long-term studies or estimations. When data were available, local conditions and ecosystem complexity were the main obstacles for a precise quantification.

Regarding the specific proof of the benefits and the environmental assessment—including quantification and characterization—for each benefit, four different scenarios were identified:

- Proved, quantifiable, and impact categories available: The positive effects of compost application are proved; benefits are quantifiable, and tools for their consideration with LCA are available. This includes nutrient supply and carbon sequestration.
- Proved, quantifiable but not impact categories available: The benefits are proved and quantifiable. However, corresponding characterization factors and/or impact categories are under development yet. This is the case for soil erosion and soil moisture content.
- Proved but not quantifiable: The benefits are proved, but their magnitude is too variable as a consequence of the synergetic effect of many factors. Thus, inventory data cannot be unambiguously quantified. Impact categories and characterization factors exist for most of the benefits (apart from biodiversity). This is the case of pest and disease suppression, increase in soil workability, biodiversity, crop nutritional quality, and crop yield.
- Not proved: Weed suppression is not proved, and thus, its inclusion in the modeling is not yet feasible.

Therefore, for two of the nine benefits—nutrient supply and carbon sequestration—the review showed that both quantification and impact assessment of the benefits could be performed, meaning that these two benefits should be regularly included in LCA studies, although their quantification needs to be improved. Different research efforts are required in the rest of the benefits for a full assessment. We thus strongly recommend the coupled use of agroecosystem and LCA modeling. Discussion on the suitability of currently available impact assessment methodologies indicated that additional impact categories may be needed for a comprehensive assessment of compost application. The needed impact categories should deal with phosphorus resources, biodiversity, soil losses, and water depletion.

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