Review article

Long-term effects of organic amendments on soil fertility. A review

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Abstract – Common agricultural practices such as excessive use of agro-chemicals, deep tillage and luxury irrigation have degraded soils, polluted water resources and contaminated the atmosphere. There is increasing concern about interrelated environmental problems such as soil degradation, desertification, erosion, and accelerated greenhouse effects and climate change. The decline in organic matter content of many soils is becoming a major process of soil degradation, particularly in European semi-arid Mediterranean regions. Degraded soils are not fertile and thus cannot maintain sustainable production. At the same time, the production of urban and industrial organic waste materials is widespread. Therefore, strategies for recycling such organic waste in agriculture must be developed. Here, we review long-term experiments (3–60 years) on the effects of organic amendments used both for organic matter replenishment and to avoid the application of high levels of chemical fertilizers. The major points of our analysis are: (1) many effects, e.g. carbon sequestration in the soil and possible build-up of toxic elements, evolve slowly, so it is necessary to refer to long-term trials. (2) Repeated application of exogenous organic matter to cropland led to an improvement in soil biological functions. For instance, microbial biomass carbon increased by up to 100% using high-rate compost treatments, and enzymatic activity increased by 30% with sludge addition. (3) Long-lasting application of organic amendments increased organic carbon by up to 90% versus unfertilized soil, and up to 100% versus chemical fertilizer treatments. (4) Regular addition of organic residues, particularly the composted ones, increased soil physical fertility, mainly by improving aggregate stability and decreasing soil bulk density. (5) The best agronomic performance of compost is often obtained with the highest rates and frequency of applications. Furthermore, applying these strategies, there were additional beneficial effects such as the slow release of nitrogen fertilizer. (6) Crop yield increased by up to 250% by long-term applications of high rates of municipal solid waste compost. Stabilized organic amendments do not reduce the crop yield quality, but improve it. (7) Organic amendments play a positive role in climate change mitigation by soil carbon sequestration, the size of which is dependent on their type, the rates and the frequency of application. (8) There is no tangible evidence demonstrating negative impacts of heavy metals applied to soil, particularly when high-quality compost was used for long periods. (9) Repeated application of composted materials enhances soil organic nitrogen content by up to 90%, storing it for mineralization in future cropping seasons, often without inducing nitrate leaching to groundwater.

soil fertility / soil carbon and organic matter / organic amendments / long-term experiments

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1. INTRODUCTION

Indiscriminate use of agro-chemicals, excessive and deep tillage, and luxury irrigation have degraded soils, particularly in semi-arid Mediterranean areas, as well as polluted surface and groundwaters, and contaminated air (Lal, 2008). Soil is an essential non-renewable resource with potentially rapid degradation rates and extremely slow formation and regeneration processes (Van-Camp et al., 2004). Soil degradation is as old as agriculture itself, its impact on human food production and the environment becoming more serious than ever before, because of its extent and intensity (Durán Zuazo and Rodríguez Pleguezuelo, 2008). There is a strong link between soil degradation and desertification on the one hand, and risks of accelerated greenhouse effects and climate change on the other (Komatsuzaki and Ohta, 2007). Durán Zuazo and Rodríguez Pleguezuelo (2008), confirmed that reduced precipitation or increased temperature accelerates land degradation through the loss of plant cover, biomass turnover, nutrient cycling and soil organic carbon storage, accompanied by higher greenhouse emissions. The reason for the earth's increased temperature along with change in rainfall amount and distribution, must be sought in the use of fossil fuel, that has drastically disturbed the global carbon cycle with its attendant impact on climate change (Lal, 2008). According to Komatsuzaki and Ohta (2007), there is also evidence that continuous cropping and inadequate replacement of nutrients, removed in harvested materials or lost through erosion, leaching, and gaseous emissions, degrade soil physical, chemical and biological properties, intensifying global warming. Moreover, the production of urban and industrial organic wastes is increasing worldwide, and strategies for disposal in such a way that these do not further degrade soil, contaminate water or pollute air must be developed and optimized (Düring and Gäth, 2002; Lal, 2008).

Soil fertility can be defined as the capacity of soil to provide physical, chemical and biological needs for the growth of plants for productivity, reproduction and quality, relevant to plant and soil type, land use and climatic conditions (Abbott and Murphy, 2007). It is becoming understandable that the proper agricultural use of soil resources requires equal consideration for biological, chemical and physical components of soil fertility, thus attaining a sustainable agricultural system.

The term "sustainable agriculture" is used in this review with the meaning given by Tilman et al. (2002), as referring to practices that meet current and future society needs for food and feed, ecosystem services and human health, maximizing the net benefit for people. Namely, sustainability implies both high yields, that can be maintained, and acceptable environmental impact of agricultural management.

It is relevant to note that organic farming is the only sustainable form of agriculture legally defined. According to the current legislation (EC Council Regulation N. 834, 2007), soil fertility management relies on a complex long-term integrated approach rather than the more short-term one of conventional agriculture. One of the possible main tools for the maintenance and the improvement of soil fertility in organic farming is to adopt crop rotations, including a mixture of leguminous fertility-building crops and plants with different rooting depths (Watson et al., 2002). Furthermore, organic wastes such as animal manures, by-products of several kinds and composted residues can be used as amendments to increase soil fertility, since they are important sources of nutrients for growing crops and means for enhancing the overall soil quality (Davies and Lennartsson, 2005).

1.1. Soil management strategies for a sustainable agriculture

Soil organic matter plays an important role in long-term soil conservation and/or restoration by sustaining its fertility, and hence in sustainable agricultural production, due to the improvement of physical, chemical and biological properties of soils (Sequi, 1989). The organic matter content is the result of the inputs by plant, animal and microbial residues, and the rate of decomposition through mineralization of both added and existing organic matter. More specifically, the generic term "organic matter" refers to the sum of all organic substances present in the soil. This sum comes from residues at various stages of decomposition, substances synthesized through microbial-chemical reactions and biomass of soil microorganisms as well as other fauna, along with their metabolic products (Lal, 2007). Decomposition of organic matter is chiefly carried out by heterotrophic microorganisms. This process is under the influence of temperature, moisture and ambient soil conditions and leads to the release and cycling of plant nutrients, especially nitrogen (N), sulfur and phosphorus (Murphy et al., 2007).

The different fractions of organic matter undergo the "humification" process, which is the changing from recognizable parts and pieces of plants or animals into an amorphous, rotted dark mass. The products of humification are the humic substances that in soil are dark brown and fully decomposed, i.e. humified (Fig. 1). The humic substances are one of the most chemically active compounds in soils, with cation and anion exchange capacities far exceeding those of clays. They are long-lasting critical components of natural soil systems, persisting for hundreds or even thousands of years (Mayhew, 2004). In fact, the turnover rate of organic materials varies considerably, from less than 1 year, as for microbial biomass, to more than 1 thousand years of stable humus (Van-Camp et al., 2004). The organic matter is being progressively depleted, particularly in the Mediterranean area, where the warm climate

Figure 1. The diagnostic horizons of a Vertisol (Sparacia experimental farm - Department of Agronomy, University of Palermo) showing the presence of well-transformed, dark-colored humified organic matter in the topsoil.

and the intensity of cultivation increase the rate of decomposition (Montemurro et al., 2007). By contrast, the build-up of organic matter in soils is a process much slower and more complex than its decline (Van-Camp et al., 2004). Since organic matter contents are difficult to measure directly, a great number of methods measure the soil organic carbon level, multiplying it by conversion factors ranging from 1.7 to 2.0 to obtain organic matter values (Baldock and Nelson, 2000).

Several investigations have demonstrated that soil organic matter is a very reactive and ubiquitous soil quality indicator that influences the productivity and physical well-being of soils (Lal, 2006; Komatsuzaki and Ohta, 2007). As a consequence, agricultural management practices that enhance soil organic matter content are used for preserving farming output and environmental quality; thereby they can be considered as sustainable activities (Lal, 2004).

Conservative soil tillage systems, e.g. no-till, which leaves more residues on the surface because the soil is not turned over, can maintain or improve the organic carbon content and the related soil fertility properties (Ismail et al., 1994; Johnson et al., 2005). Crop rotations usually increase organic matter and prompt changes in N sources, affecting their availability for plants and, as a consequence, the N efficiency is greater when a crop rotation is adopted (Montemurro and Maiorana, 2008).

The inclusion in a rotation of cover crops or green manures can also enhance the efficient use of nutrients by plants, mainly owing to the increase in soil microbial population and activity (Watson et al., 2002). Cover crops are generally grown to provide soil cover during the winter months, thus preventing soil erosion by wind and rainwater strength, which reduces organic matter content in the long run. Moreover, Komatsuzaki (2004) indicated that cover crop utilization is a technique that limits nutrient leaching, scavenging the soil residual N and making it available for subsequent cultivation.

In addition, the summer green manures are field crops or forage ones, such as leguminous and non-leguminous plants, usually incorporated into the soil soon after flowering, to improve soil fertility. In particular, leguminous green manures can fix large quantities of atmospheric N_2. They also provide useful amounts of organic matter, as well as non-leguminous crops which, nevertheless, cannot fix atmospheric N_2 (Davies and Lennartsson, 2005). During 32 years of winter wheat cropping, Procházková et al. (2003) found higher average yields with green manuring compared with straw incorporation into the soil, probably due to a slower decomposition and following release of nutrients by the latter.

There is increasing interest in the alternative fertility building strategies previously described, because conventional inputs, such as synthetic fertilizers, should be excluded or reduced in sustainable agricultural management. Within this context, soil fertility could also be improved with organic waste application such as by-products of farming, or municipal activities including animal manures, food processing wastes and municipal biosolids, wastes from some industries, such as sewage sludges, wastewaters, husks and vinasse. Both groups of wastes present generally notable contents of organic matter and substantial quantities of nutrients and their use in agriculture can contribute to closing the natural ecological cycles (Montemurro et al., 2004; Montemurro and Maiorana, 2008). Increased recycling of organic residues as fertilizers and soil amendments on cropland avoids both utilization of non-renewable resources, e.g., fossil fuel and peat, and excess of energy expenses, i.e., production of chemical fertilizers and pesticides, treatment and landfill disposal of such organic wastes (Mondini and Sequi, 2008). Biodegradable wastes can also be considered valuable resources to promote soil fertility. However, this benefit occurred only if they were applied according to good practices, taking into account the needs of the soil, its use and the climatic conditions (Van-Camp et al., 2004). Moreover, it is necessary to adopt waste management strategies, such as controlled biodegradation processes, able to both minimize their potentially negative environmental impact and increase agricultural utilization (Montemurro et al., 2009).

Despite the fact that manure characteristics are influenced by many factors such as species and age of the animal, ration fed, and collection and storage method, it can be generally assumed that their ratio of nutrients are different from those removed by common crops (Edmeades, 2003). As a consequence, soil manure application, often in excess of crop requirements, can cause a significant build-up of phosphorus (P), N and salt. Nowadays, the industrialization of livestock enterprises has led to other problems linked to the land distribution

(a)

(b)

Figure 2. Aerobic biodegradation can enhance the quality of wastes which will be applied to soils. Figure 2a shows a composting windrow stirred mechanically by a turning machine, while Figure 2b shows an experimental field with compost application.

of solid and liquid animal manures, enhancing the interest in pretreatment technologies, which can convert manure into a more valuable and easily usable resource called "compost" (Figs. 2a and 2b).

Compost is a stabilized and sanitized product of composting, which is the biodegradation process of a mixture of organic substrates carried out by a microbial community composed of various populations, both in aerobic conditions and solid state (Insam and de Bertoldi, 2007). During the composting process, the simple carbonaceous and nitrogenous compounds are transformed through the activity of microorganisms into more stable complex organic forms, which chemically resemble soil humic substances (Epstein, 1997).

The soil application of co-composted manure has several advantages over fresh manure, such as reduced numbers of viable weed seeds, reduced volume and particle size, which facilitates land distribution, a better balanced nutrient composition, stabilized organic matter and a slower release of nutrients. This topic has recently been reviewed by Moral et al. (2009).

From all the above, it can be summarized that the environmental impact of conventional farming practices and global concerns about soil degradation have increased the interest in sustainable agricultural strategies such as land application of waste materials. This is a way to avoid disposal costs and recycle nutrients into soil, unlike commercial fertilizers (Miller and Miller, 2000; Van-Camp et al., 2004). However, it is necessary to point out that the utilization of various organic residues in agriculture depends on several factors, including the characteristics of the waste, such as nutrient and toxic element content, availability, the transportation costs and the environmental regulations, as reviewed in detail by Westerman and Bicudo (2005).

1.2. Purpose of this review article

The Rothamsted experiments, lasting for more than 100 years, are the oldest and most continuous agronomic trials in the world, that measure the effects on crop yields of inorganic fertilizers in comparison with farmyard manure and other organic materials. Since their results are well summarized in the "Guide to the classical and other long-term experiments, datasets and sample archive", they will not be discussed further in this review (Rothamsted Research, 2006).

This paper, focusing on recently published data, gives emphasis to long-term field trials, particularly regarding raw and composted agro-industrial and municipal waste application. Although there is a large amount of literature relating to the influence of raw and composted organic materials on soil fertility, only a few published studies have focused on studies about long-term effects of these amendments on the soil-plant system, for a sustainable crop production. The present work attempts to address this issue by using the results from long-lasting fertility trials. Long-term research on organic amendment use on cropland is particularly relevant because many effects, e.g. organic matter enrichment and possible soil toxic element accumulation, evolve slowly and are difficult to predict.

We have collected published literature, investigating a broad array of organic residues, composts and experimental conditions, especially analyzing their impact on soils and crops in relation to modern sustainable agriculture. Experimental data of field trials were selected lasting for at least 3 years up to 60 years, stressing longer-term research. Therefore, experimental designs considered in this review ranged from those usually known as mid- to long-term ones. Summaries of the essential data for the longest duration trials are given in Table I.

The organic amendments covered in this paper are defined in Section 2 along with their effects on the soil-plant system,

Table I. Summary of the main data of long-term trials (selected data from experiments of $\geqslant$ 10 years).

Site	Organic materials	Application rate	Crop	Trial period	Reference
Punjab, India	Rice straw compost	8 t ha^{-1}	Rice–wheat rotation	10 years	Sodhi et al. (2009)
Obere Lobau near Vienna, Austria	Biowaste compost	9, 16 and 23 t ha^{-1}	Cereals and potatoes	10 years	Erhart et al. (2005); Hartl and Erhart (2005); Erhart et al. (2008)
Turin, Italy	(1) Cattle slurry; (2) Composted farmyard manure	(1) 100 t ha^{-1}; (2) 40 t ha^{-1}	Maize for silage	11 years	Monaco et al. (2008)
Linz, Austria	Composts of: urban organic waste; green waste; cattle manure or sewage sludge	175 kg N ha^{-1}	Maize, summer-wheat and winter-barley rotation	12 years	Ros et al. (2006a)
Bennett, CO, USA	Anaerobically digested biosolids	2.2, 4.5, 6.7, 8.9 and 11.2 t ha^{-1}	Two-year wheat–fallow rotation	12 years	Barbarick and Ippolito (2007)
Ravenna, Italy	Municipal-industrial wastewater sludge: (1) Anaerobically digested (liquid slurry); (2) belt filtered (dewatered sludge); (3) composted with wheat straw	(1)–(3) 5 and 10 t ha^{-1}	Winter wheat–maize–sugarbeet rotation	12 years	Mantovi et al. (2005)
Toledo, Spain	(1) Barley straw and crop waste; (2) two-year-old cattle manure	(1) 3 and 2.5 t ha^{-1}; (2) 30 t ha^{-1}	Barley, wheat and sorghum	16 years	Dorado et al. (2003)
Murcia, Spain	Municipal solid waste	65, 130, 195 and 260 t ha^{-1}	none	17 years	Bastida et al. (2008)
Orange, VA, USA	Aerobically digested sewage sludge	42, 84, 126,168 and 210 t ha^{-1}	Barley, radish and romaine lettuce	19 years	Sukkariyah et al. (2005)
Tanashi City, Tokyo, Japan	(1) Dried sewage sludge; 2) rice husk compost; (3) sawdust compost	(1) 259.8 t ha^{-1}; (2) 82.5 t ha^{-1}; (3) 77.2 t ha^{-1}	Maize, barley and rye	19 years	Kunito et al. (2001)

Table I. Continued.

Site	Organic materials	Application rate	Crop	Trial period	Reference
Tokyo, Japan	(1) Sewage sludge composted with rice husk; (2) sewage sludge composted with sawdust	(1)–(2) 240 kg N ha^{-1}	Maize and barley	23 years	Zaman et al. (2004)
Alberta, Canada	Solid beef cattle manure	30, 60 and 90 t ha^{-1} in dryland soils and 60, 120 and 180 t ha^{-1} in irrigated soils	Barley, canola, triticale and maize	25 years	Whalen and Chang (2002)
Yamaguchi, Japan	Rice straw–cow dung compost	15 t ha^{-1}	Double cropping (paddy rice and barley)	25 years	Shindo et al. (2006)
Czech Republic	(1) Straw harvest; (2) straw harvest + green manuring; (3) straw incorporation; (4) straw incorporation + green manuring; (5) straw burning; (6) farmyard manure	(6) 10 t ha^{-1}	Winter wheat continuous cropping	32 years	Procházková et al. (2003)
Punjab,India	Farmyard manure	20 t ha^{-1}	Rice–wheat and maize–wheat systems	34 years	Kukal et al. (2009)
Gumpenstein, Austria	(1) Cattle slurry+straw; (2) animal manure (solid); (3) animal manure (liquid); (4) cattle slurry (semi-liquid)	(1) 120 kg N ha^{-1}+ 0.2 kg m^{-2}; (2)–(4) 240 kg N ha^{-1}	Cereals; rape; pea; flax	38 years	Antil et al. (2005)
Fidenza, Italy	(1) Farmyard manure; (2) aerobically digested sewage sludge	(1)–(2) 5 t ha^{-1} digested sewage maize and wheat	Two-year rotation consisting mainly of	(1) 40 years; (2) 12 years	Saviozzi et al. (1999)
Legnaro, Italy	(1) Farmyard manure; (2) liquid manure	(1) 20 and 60 t ha^{-1}; (2) 120 t ha^{-1}	Maize	40 years	Nardi et al. (2004)

Table I. Continued.

Site	Organic materials	Application rate	Crop	Trial period	Reference
Bologna, Italy	Cattle manure, cattle slurry, wheat or corn residues	6 t ha^{-1} after wheat and 7.5 t ha^{-1} after maize crops	Two-year maize-winter wheat rotation	34 years	Triberti et al. (2008)
Central Sweden	Farmyard manure	4 t carbon ha^{-1}	Maize	47 years	Elfstrand et al. (2007)
Martonvásár and Keszthely Hungary	Farmyard manure	35, 40, 80 and 104 t ha^{-1}	Martonvásár: wheat–wheat–maize–maize; Keszthely:wheat–wheat–sugar beet–maize–maize	Martonvásár: 54 years; Keszthely: 41 years	Sleutel et al. (2006)
Towada, Japan	Rice straw compost	11 t ha^{-1}	Potato, maize and soybean in rotation	60 years	Takeda et al. (2005)

whereas the environmental impact and sustainability are outlined in Section 3.

2. EFFECTS OF ORGANIC AMENDMENTS ON THE SOIL-PLANT SYSTEM

Miller and Miller (2000) highlighted that organic material application to cropland could affect soil properties, but the effects generally may not be apparent over a short time period. More specifically, Tittarelli et al. (2007) pointed out that the simplest method of examining the agronomic value of stabilized organic materials is the calculation both of organic matter supply and plant nutrients. The slow release of these nutrients is responsible for the increase in crop yields in the subsequent years, thus determining the difficulty of quickly evaluating the true agronomic value of these organic materials as amendments. However, there is a considerable variability between experimental techniques, climate, soil type and organic material characteristics, and therefore attention must be paid to generalizing the effects of composts and raw waste application on the soil-plant system.

2.1. Effects on soil biological, chemical and physical fertility

Van-Camp et al. (2004) found that organic amendments influence soil characteristics by the interdependent modification of biological, chemical and physical properties (Fig. 3). Also, fertility improvement through an effective management of these properties has the capability of optimizing crop production. In this subsection, we selected papers whose primary purpose was to examine the effect of different organic amendments on overall soil fertility. However, it is necessary to take into account that sometimes it was difficult to compare the results, because of the different assessment methods used in the studies.

2.1.1. Biological fertility

Microbiological and biochemical soil properties are very reactive to small changes occurring in management practices. Therefore, it is possible to use them in a basic analysis for evaluating the effects of the application of different sources and amount of organic matter on soil characteristics during experimental trials. Microorganisms, e.g. bacteria, fungi, actinomycetes and microalgae, play a key role in organic matter decomposition, nutrient cycling and other chemical transformations in soil (Murphy et al., 2007). Since organic carbon (C) is utilized for energy by decomposer microorganisms, its fate is to be either assimilated into their tissues, released as metabolic products, or respired as carbon dioxide (CO_2). The macronutrients N, P and sulfur (S), present in the organic chemical structures, are converted into inorganic forms. Subsequently, they are either immobilized and used in the synthesis of new microbial tissues or mineralized and released into the soil mineral nutrient pool (Baldock and Nelson, 2000). For assimilation by microorganisms of decomposing organic residues, the N has to be assimilated in an amount determined by the C/N ratio of the microbial biomass. More specifically, the amount of N required by the microorganisms is 20 times smaller than that of C. If there are both a low concentration of easily decomposable C compounds and a larger N quantity in respect to that required by the microbial biomass, there will be net N mineralization with release of inorganic N. On the contrary, Corbeels et al. (1999) found that if the amount of N present in the residues is smaller than that required by the
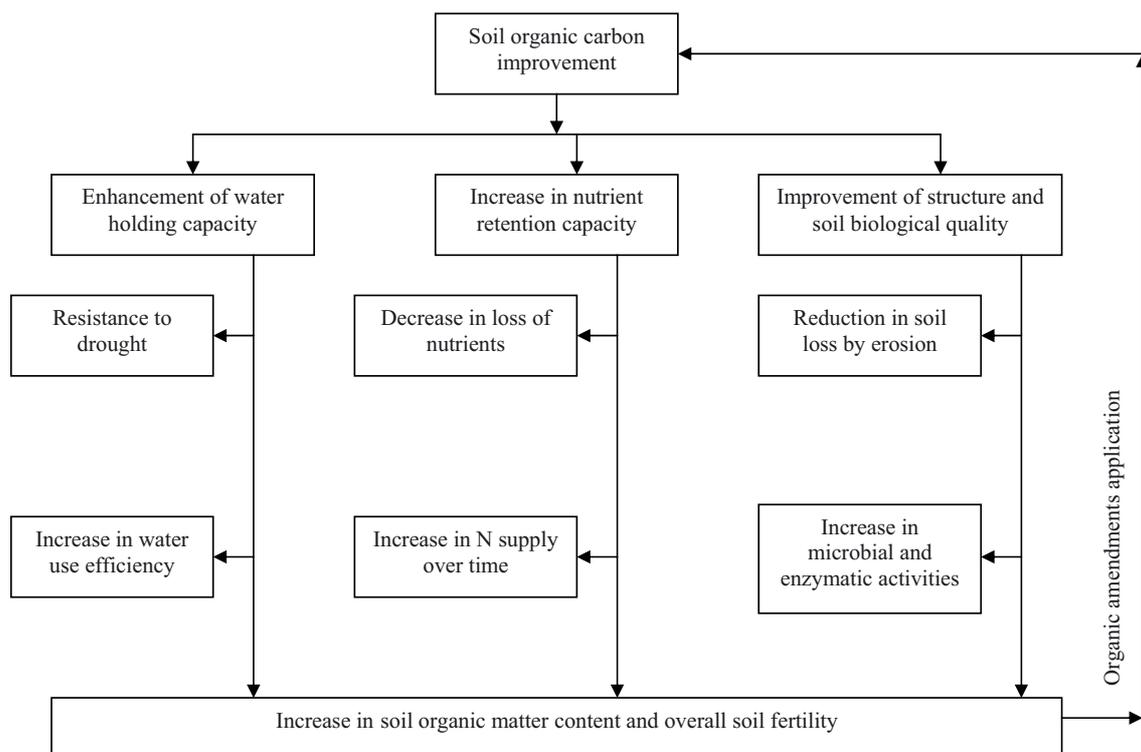
Figure 3. Effects of increasing soil organic matter content and overall soil fertility by soil organic carbon improvement (adapted from Lal, 2006).

microbial biomass, further inorganic N will need to be immobilized from the soil to complete the decomposition process.

It is difficult to distinguish between the direct and the indirect effects of an amendment on the behavior of soil microorganisms. In soils amended with compost or other raw organic materials, even in association with mineral fertilizer N, autochthonous microbiological activity and growth can be stimulated. However, different authors (Ros et al., 2006a; Kaur et al., 2008) suggest that a direct effect from microorganisms introduced with the compost is detectable. Several long-lasting experiments have demonstrated that soil biological properties, such as microbial biomass C, basal respiration and some enzymatic activities, are significantly improved by compost treatments. This is particularly evident in the upper layers of the soil because of the added labile fraction of organic matter, which is the most degradable one (Zaman et al., 2004; Ros et al., 2006a, b; Tejada et al., 2006, 2009). Since generally the composts are slowly decomposed in the soil, the continuous release of nutrients can sustain the microbial biomass population for longer periods of time, compared with mineral fertilizers (Murphy et al., 2007). In fact, an interesting residual effect of composts on the microbial activity has often been observed in many experimental seasons after their application, which also results in a longer availability of plant nutrients. Ginting et al. (2003), for example, found 4 years after the last application of compost and manure that the residual effects resulted in 20 to 40% higher soil microbial biomass C compared with the N fertilizer treatment. Research

on the effect of different doses of raw municipal solid waste in Mediterranean semi-arid conditions, ranging between 65 and 260 t ha^{-1}, demonstrated 17 years after a single application of this organic amendment an average increase of 70% in organic matter content. The water-soluble C fractions also increased by up to 195 t ha^{-1} application rate, above which they leveled off (Bastida et al., 2008). The authors also found that the enzymatic activities of urease, β-glucosidase, alkaline phosphatase and o-diphenyloxidase associated with humic substances increased significantly in all the amended plots, thus improving soil biochemical quality.

Sixteen years after 1 and 3 t ha^{-1} year^{-1} sludge application, in a field situated close to Lund in the southern part of Sweden, an increasing trend for substrate induced respiration was found, ranging from 20 to 22%, due to the organic material inputs, and enhanced by from 11 up to 33% acid phosphatase activity involved in the mineralization of organically-bound P (Mats and Lennart, 1999). This behavior follows the increasing rates of sludge addition.

As a general rule, the quantity and quality of organic material added to soils are the major factors in controlling the abundance of different microbial groups and the activity of microorganisms involved in nutrient cycling. Enzyme activity and microbial biomass analysis indicated that microbial properties were stimulated, e.g. microbial biomass C increased to about 100%, more by high rates and composted than by low rates and fresh paper mill residuals (78 t ha^{-1} and 22 t ha^{-1}, respectively) (Leon et al., 2006).
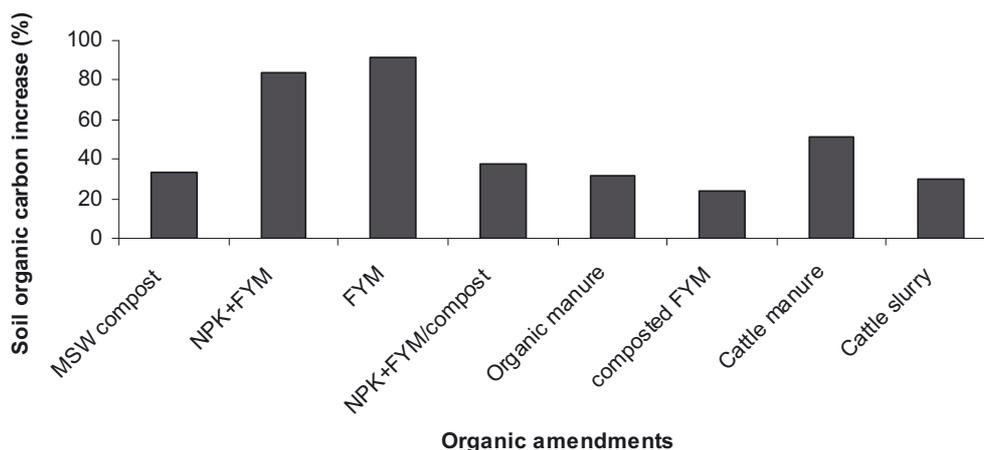
Figure 4. Soil organic carbon increases after different long-term organic amendment applications.
Note: data taken from: Montemurro et al. (2006) (means of crops); Kaur et al. (2008) (at 0–15 cm depth); Kukal et al. (2009) (means of crops; at 0–15 cm depth); Mandal et al. (2007) (means of 5 trials' data); Meng et al. (2005); Monaco et al. (2008); Triberti et al. (2008). SOC = soil organic carbon; MSW = municipal solid waste; FYM = farmyard manure.

As regards the effects of the quality of amendment, Monaco et al. (2008) pointed out that microbial activity, measured by the potential soil respiration parameter, gave a reliable and useful indication of the amount of easily decomposable organic C, and this parameter was lower when the C was partially humified before soil input. In fact, after 11 years of repeated applications of different organic materials, soil respiration was in the order of $640.9 < 682.1 < 755.1$ mg C-CO_2 kg^{-1} for farmyard manure, cattle slurry and straw, respectively. The effect of green manure amendments was studied in a 47-year field experiment (Elfstrand et al., 2007). The authors found a higher abundance of bacteria and fungi in the green manure treatment, i.e. 34.3 and 1.8 nmol g soil^{-1}, respectively, in respect to the unfertilized one (20.3 and 0.9 nmol g soil^{-1}), measured before maize sowing. Furthermore, a higher fungal/bacterial ratio was noticed, equal to 0.054 compared with farmyard manure (0.036) and sawdust (0.046) application. This behavior might be attributed to differences in the quality of the organic matter added.

The reviewed results suggest that exogenous organic matter applications to cropland lead to an improvement in soil biological functions, depending on the quantity and type of materials applied.

2.1.2. Chemical fertility

A considerable number of studies, concerning long-term fertility trials, pointed out that soil organic material applications increased the organic carbon stock and, therefore, increased the cation exchange capacity. This effect was due to the high negative charge of organic matter. This is important for retaining nutrients and making them available to plants (García-Gil et al., 2004; Ros et al., 2006b; Weber et al., 2007; Kaur et al., 2008). Figure 4 shows the organic carbon increase,

as a consequence of several organic amendments' long-lasting application, ranging from 24 to 92%.

Habteselassie et al. (2006a) found that, over a 5-year period, the C pool was enhanced by 115% in dairy-waste compost-treated soil. Moreover, the dairy-waste compost increased organic carbon by 143 and 54% as compared with ammonium sulfate and liquid dairy-waste treatments, respectively, applied at the same available N level (200 kg Nha^{-1}). This C stored in the soil organic matter accounts for approximately 11% of the total amount of C applied.

After 3 years of municipal solid waste compost and olive pomace compost application, the total organic carbon significantly increased by 24.0 and 43.2% for cocksfoot and alfalfa plots, respectively, in respect to the unfertilized control, indicating that these amendments positively affected the organic matter (Montemurro et al., 2006). Other authors also showed that municipal-industrial wastes stimulate plant growth, indirectly and with a long-term effect, by improving organic matter (Mantovi et al., 2005; Cherif et al., 2009).

Under 7–36-year fertility experiments in five different rice-based cropping systems, the application of organic amendments at 5–10 t ha^{-1}year^{-1}, through farmyard manure or compost combined with balanced mineral NPK, increased organic carbon by 10.7% (Mandal et al., 2007).

In a rice–wheat system, farmyard manure application at 20 t ha^{-1} showed, after a period of 32 years, higher organic carbon concentration of 17% compared with NPK fertilizers in the 0–15 cm soil layer (Kukal et al., 2009). Nevertheless, the results of repeated applications of either digested sewage sludge over 12 years or farmyard manure for 40 years indicated that such organic amendments were inadequate for restoration of organic matter lost as a consequence of cultivation (Saviozzi et al., 1999). In fact, the amount of organic carbon in the undisturbed site was 120 and 156% higher than that in farmyard and sludge cultivated soils, respectively. On the other hand, contrary to common belief, over a 25-year period

of intensive rice-wheat cropping, a depletion of organic carbon did not occur, but rather an improved organic carbon concentration of 38% (Benbi and Brar, 2009).

In terms of sustainability, only farmyard manure fertilization maintained the total organic carbon level of 40 t C ha^{-1}, measured in the top soil layers at the start of a 40-year experiment, while the average total organic C depletion was 23% with liquid manure and mixed fertilization treatments, 43% with mineral fertilizers alone and 51% in the control (Nardi et al., 2004). Furthermore, the presence of weakly acidic chemical functional groups on organic molecules makes organic matter an effective buffer, as supported by the findings of García-Gil et al. (2004). These authors observed a long- (9 years) and short-term improvement in the soil humic acid buffering capacity in municipal solid waste compost-amended soils, derived from a residual effect of a single application and cumulative effects from repeated ones. These distributions will favor the general soil fertility status and crop production.

There are reports in the literature of long-term compost and manure application both increasing (Eghball, 2002; García-Gil et al., 2004; Butler and Muir, 2006) and decreasing (Meng et al., 2005; Bastida et al., 2008; Bi et al., 2008) the pH of soils, depending on their initial pH and organic residues. Butler and Muir (2006) observed that soil pH increased on average by 0.5 units as the dairy manure compost rate doubled in magnitude from 11.2 to 179.2 t ha^{-1}.

As previously explained, with long-term compost use the residual effects on crop production and soil properties can last for several years, since only a fraction of the N and other nutrients becomes available for plants in the first year after spreading (Hartl et al., 2003; Eghball et al., 2004). As an estimation of the the available N from compost treatment in the first year of application, Tittarelli et al. (2007) mentioned a release of only 30–35% of the total N content. The N release from compost will mostly occur in the first two years after application, suggesting that a distribution frequency of once in every second year may be better than other application strategies, especially with higher rates (Zhang et al., 2006).

More specifically, it is well known that many microorganisms convert organic N into inorganic N forms by mineralization. A large number of authors confirmed that N mineralization from compost is very limited in the short term. However, there is a significant residual effect from the cumulative applications which becomes visible later after 4–5 years, resulting in deferred higher N availability and yields (Eghball, 2002; Blackshaw et al., 2005; Barbarick and Ippolito, 2007; Leroy et al., 2007). Regular addition of organic material to soil for more than 10 years, through compost or manures, enhanced both soil C and N stocks and resulted in build-up of N, indicating a physical protection of this nutrient within macroaggregates (Whalen and Chang, 2002; Meng et al., 2005; Mallory and Griffin, 2007; Sodhi et al., 2009). According to Hartl and Erhart (2005), the organic N content increases by about 10% compared with the control, in the upper 30 cm of soil, after 10 years of compost treatments. This result was complemented by significant increases in organic C, of 22%, indicating that the organic N was tied up in organic matter. After 4 years of vegetable compost applications, significantly higher soil total N

concentration was observed on compost plots compared with plots without it (Nevens and Reheul, 2003).

The C/N ratio of organic material can be used as a good indicator of nutrient supply. Tejada et al. (2009) showed an optimum balanced C/N ratio (10–12) for soils amended with composts originating from leguminous residues, due to organic matter mineralization overcoming immobilization. These findings were not in accordance with those of Weber et al. (2007), who found the C/N ratio clearly increased, from 10.7 up to 22.2, in the third year after municipal solid waste compost application. This behavior can be explained by a depletion of N reserve, probably because of plant N uptake. However, there are often other explanations for such an increase in the C/N ratio. In fact, it is well known that when a compost that has a high C/N ratio is added to soil, the microbial population competes with plants for soil N, thus immobilizing it (Amlinger et al., 2003).

Soil available potassium (K) content increased on average by 26%, as compared with control, in 5-year compost treatments derived from organic household wastes and yard trimmings (Hartl et al., 2003). These treatments are a rich source of K, probably due to the large proportion of woody plant material and kitchen refuse in the raw material.

As regards the P from organic amendments, He et al. (2001) reported that compost applications can increase plant-available P in the soil. The biosolids-municipal solid waste co-compost, applied once in 4 years, has also been found to effectively supply P to soil at 0–15 cm depth. The soil extractable P concentration increased on average from 7.2 to 86 mg kg^{-1} soil with enhanced application rates from 0 to 200 t ha^{-1} (Zhang et al., 2006). Furthermore, Eghball (2002) suggested that 4-year beef cattle manure and composted manure application based on N needs of corn could eventually result in soil accumulation of P, since the manure or compost N/P ratio is usually smaller than the corn N/P uptake ratio.

Our overall literature analysis demonstrates that several organic amendments' long-lasting applications enhanced soil available potassium, extractable phosphorous and organic carbon content, and resulted in deferred N availability.

2.1.3. Physical fertility

Aggregate stability is a keystone factor in questions of soil physical fertility and can be enhanced by means of an appropriate management of organic amendments, which can maintain an appropriate soil structure. This agronomic procedure could improve pore space suitable for gas exchange, water retention, root growth and microbial activity (Van-Camp et al., 2004). Soils rich in organic matter are less prone to erosion processes than soils with low content, such as those which predominate in arid and semi-arid areas (Durán Zuazo and Rodríguez Pleguezuelo, 2008).

The topic of soil structural stability has been reviewed recently by Abiven et al. (2008). Their literature analysis validated the conceptual model proposed by Monnier (1965). This author considers different patterns of temporal effects on

aggregate stability, depending on the nature of the organic inputs. Easily decomposable products have an intense and transient effect on aggregate stability, while more recalcitrant ones, such as lignin and cellulose, have a lower but longer-lasting effect.

Results of Albiach et al. (2001) pointed out that organic matter and carbohydrates appeared to be the parameters most closely related to structural stability of soil aggregates obtained with five applications of a municipal solid waste compost. Another 5-year field trial confirmed these findings, suggesting that municipal solid waste compost, applied every 2 years, can be used to increase soil aggregate stability by 29.3% in respect to the control, thus improving soil resistance to water erosion (Annabi et al., 2006).

The organic matter stabilizes soil structure by at least two different mechanisms: by increasing the inter-particle cohesion within aggregates and by enhancing their hydrophobicity, thus decreasing their breakdown, e.g. by slaking. More specifically, the increase in soil microbial activity, especially due to the addition of composted residues, could be responsible for the increase in soil structural stability (Van-Camp et al., 2004). The relationships between soil biological activity and the functioning of soil are very complex. According to Abiven et al. (2008), several biological binding agents have been recognized as accountable for aggregation and aggregate stability. Polysaccharides synthesized by microorganisms, particularly at the beginning of the organic matter decomposition, tend to adsorb the mineral particles and increase their inter-cohesion. Conversely, products rich in humic compounds, such as manures or composts, would also be expected to increase aggregate hydrophobicity of clays. This has mainly been proved in long-term trials. In fact, after 16 years of either farmyard manure or crop waste applications, substantial improvements in soil physical properties have been noticed, markedly aggregate stability and water retention, due to the increased concentration of humic colloids in soil (Dorado et al., 2003). In particular, the authors found that the structural instability index decreased by 2.5 units with respect to control plots.

Tejada et al. (2009) observed that three different composts, consisting of leguminous plants, non-leguminous plants and the combination of both plant residues, applied at rates of 7.2 and 14.4 t organic matter ha^{-1} during a period of 4 years, had a positive effect on soil physical properties. More specifically, at the end of the experimental period and at the highest rate, the soil structural stability was the highest in the non-leguminous plant compost treatment (28.3%), followed by the combined one (22.4%). This result was due to greater amounts of humic acids provided to the soil, 63.6 and 59.5 g kg^{-1}, respectively, which are then directly involved in clay–organic complex formation.

Another recent study showed that, after 10 cycles of rice–wheat cropping, the amount of water-stable aggregates was significantly higher in plots amended with rice straw compost at 8 t ha^{-1} to both rice and wheat, as compared with inorganic fertilizers (Sodhi et al., 2009). The authors also suggested that this higher amount of water-stable aggregates can be ascribed to the regular addition of organic matter to soil, resulting in enhanced microbial activity and production of microbial de-

composition products, which helps with binding of aggregates. Leon et al. (2006) found that the application of medium and high rates, equal to 38.1 and 78.4 t ha^{-1}, of composted paper mill residuals over 4 years, caused an increase in amounts of water-stable aggregates on average of 25% compared with the control. There was no significant difference ($P \leqslant 0.05$) between the two compost rates tested, suggesting that the lowest amount of amendment was enough to maximize water-stable aggregation.

These positive results of long-term compost application agreed with the findings reported by Tejada et al. (2008). The authors observed that composted leguminous plants, alone or mixed with beet vinasse, an agro-industrial by-product, had a positive impact on soil structural stability, which increased by 5.9 and 10.5% compared with the unfertilized treatment, respectively. Conversely, fresh beet vinasse application decreased soil structural stability by 16.5% in respect to the control, probably because high quantities of destabilizing monovalent cations were introduced into the soil by this organic material.

Whalen and Chang (2002) noted that 25 years of annual beef cattle manure applications, at rates of more than 30 t ha^{-1} year^{-1} to dry land soils and at more than 60 t ha^{-1} year^{-1} to irrigated soils, can shift the aggregate size distribution from larger (> 12.1 mm) to smaller (< 2.0 mm) dry-sieved aggregates, because of dispersive agents in the manure. Consequently, many years of continuous manure applications could raise the risk of wind erosion because of a greater proportion of the soil small aggregates. Moreover, different authors have shown typical decreases in soil bulk density, on average of 15%, after long-term compost, farmyard manure or digested sewage sludge agricultural use, suggesting that the addition of composted and fresh organic matter facilitated, as a consequence, the soil porosity connected to soil bulk density (Saviozzi et al. 1999; Meng et al., 2005; Tejada et al., 2008; 2009). Porosity is a measure of the size and system of voids in the soil matrix, affecting both aeration and water movement. On the other hand, Eghball (2002) reported that soil bulk density was unaffected by 4-year manure or compost application.

Leon et al. (2006) found a strong correlation (r = 0.65, $P \leqslant 0.001$) of total C with soil moisture content after application of paper mill residual by-products, corroborating that high C level in soils increases the water-holding capacity because of the effect of organic matter on soil aggregation. This increase provides more available water to plants, also helping with resistance to drought.

On the basis of the information presented in this subsection, it can be summarized that repeated applications of organic amendments can increase soil physical fertility, mainly by improving aggregate stability. In general, a rise in the above investigated overall soil fertility influences crop yield response, as framed in the following subsection. Selected studies are summarized in Table II, focusing on the effects of organic amendments on yields.

Table II. Summary of the effects of organic amendments on crop yields (selected data).

Crop and trial period	Amendments and application rate	Sub-treatment or comment	Highest yield (t ha^{-1})	Yield increase [*] (% t^{-1} of total C applied)	Reference
Wheat (5 years)	MSW composts C1 (40 t ha^{-1}) and C2 (80 t ha^{-1}); FYM (40 t ha^{-1}); MSW+Cf; FYM+Cf	Higher HM content in MSW compost treatments	C2[**]: 60.2 t ha^{-1}; C2Cf: 61.9 t ha^{-1}	17	Cherif et al. (2009)
Wheat– maize– sugarbeet rotation (12 years)	Municipal-industrial wastewater sludge: (I) anaerobically digested, (II) dewatered and (III) composted (two rates: 5 and 10 t ha^{-1} year^{-1})	Mineral fertilizer dressings: four increasing rates of urea, plus superphosphate	I (at 10 t ha^{-1}year^{-1}) for sugarbeet: 60.5 t ha^{-1} II (at 5 t ha^{-1} year^{-1}) for wheat: 6.23 t ha^{-1};	10; 11	Mantovi et al. (2005)
Cereals and potatoes (10 years)	Biowaste compost: C1 (9 t ha^{-1} year^{-1}), C2 (16 t ha^{-1} year^{-1}) and C3 (23 t ha^{-1} year^{-1}) plus 5 treatments with combined fertilization	Mineral fertilizer: three increasing rates (N1; N2; N3)	N3+C1: 5.2 t ha^{-1}[**]; N2+C1: 4.9 t ha^{-1}	15	Erhart (2005)
Maize (7 years)	VFG compost: C1 (22.5 t ha^{-1}) and C2 (45 t ha^{-1}); cattle slurry	Mineral fertilizer	C2 plus cattle slurry: 22.4 t ha^{-1}	5 (from compost C applied)	Leroy (2007)
Tall fescue (7 years)	Three food waste compost with: (1) yard trimmings; (2) yard trimmings + mixed paper waste; 3) Wood waste + sawdust (each at 155 t ha^{-1}rate)	Two composting methods: (I) aerated static pile; (II) aerated turned windrow	(1) 79 t ha^{-1}	0.2[***]	Sullivan et al. (2003)
Silage cornfield (5 years)	(1) Low dairy-waste compost rate (to provide 100 kg ha^{-1} of available N); (2) high dairy-waste compost rate (200 kg N ha^{-1}); (3) low liquid dairy-waste rate (100 kg N ha^{-1}); (4) high liquid dairy-waste rate (200 kg N ha^{-1})	Other treatments: ammonium sulfate at 100 kg N ha^{-1} and 200 kg N ha^{-1}	(1) 24.6 t ha^{-1}	9.7 (in the last year of the experiment)	Habteselassie et al. (2006a)

Note: MSW = municipal solid waste; HMs = heavy metals; Cx = compost (x = 1, 2, etc.); Cf = chemical fertilizer; (*) in respect to the control and regarding the yield indicated as (**); VFG = vegetable-fruit-garden waste; (***) in respect to the lowest yield, found in wood waste + sawdust, and for the second method.

2.2. Effects of organic amendments on plant nutrition and yielding responses

The N dynamics in compost-amended soils could be affected by different site-specific factors, e.g. compost matrices, composting conditions, climate, soil properties and management practices. It can be generally assumed that the prompt availability of N to plants is low, as already explained in this review, since the majority of total compost N is bound to the organic N-pool (Amlinger et al., 2003). In fact, the greatest total N content in compost is not readily available, but it can be mineralized and subsequently taken up by plants or immobilized, denitrified and/or leached.

It is important to take into account that the slow release of nutrients from compost or green manures should be adequately controlled to match temporal crop demand with nutrient supply. The increase in the N-use efficiency decreases loss to leaching when there is wide drainage, e.g. during the fall-winter period, or volatilization (Tilman et al., 2002). The plant-available N in the application year was expected to be higher for fresh manure than for stable composted manure. In fact, in a 4-year experiment, it ranged from 26 to 67 and from 12 to 18 kg ha^{-1} for fresh and stabilized manure, respectively (Blackshaw et al., 2005). Furthermore, Zhang et al. (2006) reported that the amount of N used by crops from municipal solid waste compost for barley, wheat and canola, at two different sites, was 11, 3, 1 and 2% for the first and subsequent 3 years. These results indicate the complexity of estimating N release from different composts and its relationship with plant N uptake. Barbarick and Ippolito (2007) showed that six applications once every second year of anaerobically digested biosolids, in a 2-year wheat–fallow rotation, provided about 9 kg N t^{-1} biosolids. Sullivan et al. (2003) noted that 7 years of one-time food waste compost application consistently increased tall fescue N uptake by a total of 294 to 527 kg ha^{-1}. Therefore, the increase in grass uptake due to amendment was 15 to 20% of compost N applied. However, compost N immobilization/mobilization is predominantly linked to the degradability and balance of soil C pools, as will be better explained in Subsection 3.3 of this review.

Moreover, Eghball et al. (2004) found that the lowest rate of P (125 kg ha^{-1}) was applied for the annual P-based beef cattle manure whilst the greatest amount (594 kg P ha^{-1}) was applied for the biennial N-based cattle manure compost treatment. The latter resulted in P leaching to a soil depth of 45 to 60 cm. On the contrary, the P-based application was environmentally sound, since it provided nutrients for the crop, while maintaining the amended soil P at a level similar to the untreated control.

2.2.1. Yield response

There are three possible scenarios relating crop yield or agronomic productivity to organic C content of soil: (i) increase in crop yield as a consequence of organic carbon pool enhancement; (ii) no or little decrease in crop yield with reduction in the organic carbon pool, and (iii) increase in crop yield with decrease in the organic carbon pool (Lal, 2006). These apparently conflicting responses depend on several factors such as the previous organic carbon pool, soil management, and use of chemical fertilizers and organic amendments.

As demonstrated by several long-term experiments on crop nutrition and yielding responses, the benefits of increased organic matter content will differ on the basis of the rate supplied. In a 5-year trial, Hartl et al. (2003) found that every second year spreading of 40 t ha^{-1} biowaste compost, from source-separated organic household waste and yard trimmings, resulted in slightly higher (9%) rye yields than other rates. This result suggested that beneficial use depends on choosing the best amount and frequency of compost application.

Frequently, the best rate is the highest, as supported by Butler and Muir (2006), who observed the greatest tall wheatgrass dry matter yield with the highest composted dairy manure rate of about 180 t ha^{-1}. More specifically, forage yield increased from 32 to 96% with 11.2 and 179.2 t compost ha^{-1}, respectively, in the first of two growing seasons. Sullivan et al. (2003) highlighted the long-lasting effect of a one-time high rate (155 t ha^{-1}) food waste compost application in providing slow-release N for crop growth, over a 7-year period. These results agreed with the findings of Habteselassie et al. (2006a), who found that soils with about 100 t ha^{-1} dairy-waste compost maintained N supply to the plants through continuous mineralization, as shown by available inorganic N pools, silage corn yield and plant N content analysis.

Wheat grain yield was enhanced on average by 246%, in respect to the control, with a high rate (80 t ha^{-1}) of municipal solid waste compost applied annually over 5 years, alone or combined with mineral fertilizer, reaching 60.2 and 61.9 t ha^{-1}, respectively (Cherif et al., 2009). Similarly, Erhart et al. (2005) investigated the agronomic performance of biowaste compost, on cereals and potatoes, showing that the highest application rate equal to 23 t ha^{-1}year^{-1} increased crop yields by 10% compared with the unfertilized control, on the average of 10 years. These findings are in contrast with those of Mantovi et al. (2005). In repeated sewage sludge applications for 12 years on a winter wheat–maize–sugarbeet rotation, the composted sludge gave a significantly lower yield, equal to 51.8 t ha^{-1}, for sugarbeet with higher dose spreading compared with non-composted biosolid treatment yield (60 t ha^{-1}, on average). Moreover, residual effects of amendments on both soil properties and crop production can last for several years, as referred to in the preceding subsection of this review. For instance, in a 7-year trial Eghball et al. (2004) confirmed that available P concentration in the soil surface can contribute to corn crop P uptake for more than 4 years after the last biennial N-based compost application, being 241% higher than the control.

The examined literature pointed out that the use of composts or of other organic amendments in combination with mineral fertilizers enhanced crop yield in many cropping systems over more than 10 years, compared with compost and amendments alone (Ros et al., 2006a; Bi et al., 2008). The subject has recently been discussed by Montemurro (2009), who found that the multiple application of municipal solid waste

compost associated with mineral fertilizer increased wheat yield by 8% compared with mineral N alone and induced a more productive stability and N uptake throughout the years. Furthermore, maize grain yield was the highest where farmyard manure at 10 t ha^{-1} was applied along with recommended NPK fertilizer for 34 years, under a maize–wheat cropping system (Kaur et al., 2008). In a study by Sleutel et al. (2006), 41 years of application of 35 t farmyard manure ha^{-1}, plus an equivalent amount of NPK in mineral fertilizer, every 5 years in a wheat–wheat–sugarbeet–maize–maize crop rotation, increased grain yield by 124 and 55% for maize and wheat in respect to the control. Moreover, in a 7-year study, Leroy et al. (2007) investigated vegetable-fruit-garden-waste compost combined with cattle slurry applied at both 22.5 t ha^{-1} yearly and 45 t ha^{-1} every other year. Both the application strategies resulted in 25 to 43% higher maize yields in respect to the two organic amendments provided alone. On the contrary, Edmeades (2003), after reviewing 14 long-term soil fertility trials, concluded that, despite the positive effects of organic manures on soil biological and physical properties, no advantage to crop yields with respect to the application of the same amounts of nutrients as mineral fertilizers was found. However, it is necessary to note that in organic farming systems the use of mineral fertilizers is not a possible alternative. After all, the analyzed soil management practices used in sustainable farming systems have potential for producing comparable yields to conventional farming ones. Poudel et al. (2002) reported that the average tomato fruit and corn grain yields, for a 5-year trial period, were 71.0 and 11.6 t ha^{-1}, respectively, both not significantly different among organic, low-input and conventional farming systems.

From all the above discussion, there is clear evidence that the best agronomic performance of compost, particularly if combined with mineral fertilizers, is often obtained with both high rates and frequency of applications, leading to residual effects as a slow-release nitrogen fertilizer.

2.2.2. Quality response

From the yield quality viewpoint, the reviewed long-term research showed, for example, that source-separated organic waste compost as well as mixtures of sugarbeet vinasse composted with other agro-industrial solid wastes did not adversely affect the quality of products (Madejón et al., 2001; Erhart et al., 2005). In particular, winter rye protein concentration was similar in compost and mineral fertilized treatments, and the nitrate concentration of potato tubers in compost treatments was not significantly higher than in the unfertilized control (Erhart et al., 2005). The crop quality in some cases was even improved by compost fertilization. In one above-mentioned study, the partial substitution of mineral with organic N not only did not reduce the quality of wheat, with respect to mineral fertilizer, but also increased the protein content by 6% in comparison with the unfertilized control (Montemurro, 2009). In another study the wheat grain quality, expressed by its apparent specific weight as means of 12 cropping years, was worsened by excessive N supply, so high

rates (10 t ha^{-1} year^{-1}) of liquid and dewatered sludge were particularly detrimental, while compost was safer (Mantovi et al., 2005). In fact, a downward trend was observed as 74.7 > 73.5 > 72.8 kg hL^{-1} for composted, dewatered and liquid sludge, respectively.

Therefore, considering that stabilized organic amendment application does not reduce the crop yield quality, as reviewed here, but can even enhance it, their use can appear more profitable.

3. ENVIRONMENTAL IMPACT AND SUSTAINABILITY OF ORGANIC AMENDMENTS

As recently highlighted by Lichtfouse et al. (2009), while conventional agriculture is driven almost solely by productivity and profit, sustainable agricultural systems aim at developing new farming practices that are also safe and do not degrade the environment. By taking this into account, and from the previous discussions, it is possible to suggest that appropriate organic matter management is a fully sustainable pattern, because it fulfils three requisites: sustainability of resources, human health and economic sustainability. Conversely, organic amendments that can improve organic matter and the linked soil fertility can also be a source of environmental pollution, especially when they are improperly used. In fact, when the application rates of manure are calculated on the N crop requirement, the amount of P added often exceeds the plant P requirement, resulting in soil P accumulation (Miller and Miller, 2000). According to Komatsuzaki and Ohta (2007), soil management strategies for sustainable agriculture should focus not only on increasing organic matter in the soil, but also on the uptake or stocking of soil residual nutrients in such a way to prevent excess nutrient leaching into the groundwater.

The cropland application of immature compost can produce environmental and agronomic problems. In fact, if the organic material has not been sufficiently stabilized, its application increases ammonia volatilization, decreases the soil oxygen concentration, produces some phytotoxic compounds and immobilizes soil mineral N. Therefore, organic products of high quality must be produced and their stability must be accurately assessed.

With regard to toxic elements, e.g. heavy metals, their accumulation in soils is the most often cited potential risk, particularly for biosolid waste compost use. On the other hand, there is increasing positive evidence of the impact that composts and wastes can have on soil C sequestration, as we will discuss in the following pages.

3.1. Organic matter evolution and soil carbon sequestration

In recent years, global concern over increased atmospheric CO_2 and methane (CH_4) emissions has raised interest about the potential role of soils as a source or sink of C and in studying organic matter dynamics and related C sequestration capacity. In fact, organic matter varies in both decomposition

rate and turnover time. and the soil C pool can be a source or sink for the atmospheric pool, depending on land use and management (Van-Camp et al., 2004). When organic materials, such as composted wastes, are added to soil, at least a share of their organic C is decomposed producing CO_2, which is a good indicator of the decomposition rate, while another part is sequestered in the soil.

For the purpose of this review, the term "carbon sequestration" is used according to Lal (2004, 2007), implying the transfer of atmospheric CO_2 into the soil C pool through: (i) humification of crop residues and other wastes added to the soil, (ii) formation, in arid and semi-arid regions, of secondary carbonates or leaching of bicarbonates into the groundwater, so CO_2 thus adsorbed is not immediately re-emitted, (iii) formation of organo-mineral complexes which encapsulate C and protect it against microbial activities, and (iv) translocation of organic carbon into the sub-soil, that can move it away from the zone of disturbance by plowing and other agronomic practices, minimizing the risks of being removed by erosional processes.

Article 3.4 of the Kyoto Protocol emphasizes the agricultural role in CO_2 sequestration in tilled soils and advocates sustainable cropping techniques for this purpose. These practices primarily include the reduction of soil disturbance and the optimization of water-use efficiency. However, soil incorporation of organic materials and N fertilization can also influence C dynamics (Triberti et al., 2008). Any attempt to enrich the organic carbon reservoir through sequestration of atmospheric C will help to manage global warming.

According to Feller and Bernoux's (2008) findings, it is essential to consider that when an organic waste contains a high percentage of fossil carbon, the C in soils originating from this fraction should not be referred to as sequestered C, i.e. originating from the atmosphere, but as "stored C".

As explained by Mondini and Sequi (2008), it is also important to consider that the reduction in the soil of the C pool contributes both to an atmospheric enrichment in CO_2 concentration and an involution in soil fertility. This reduction also induced the onset of degradative processes such as erosion, salinization, desertification, compaction, nutrient deficiency, etc. However, whereas the exact magnitude of the historic loss of organic carbon may be debatable, Lal (2004) suggested that the troubling process of organic carbon depletion can be reversed.

The effects of organic amendments on organic carbon increase should be studied through long-term field experiments, as already seen in Subsection 2.1.2. of this review, because of the long time needed to attain a new equilibrium after environmental change in the organic matter.

Triberti et al. (2008) reported that 29 years after the start of a trial comparing cattle manure, cattle slurry and crop residues with mineral fertilization, the cattle manure gave the quickest organic carbon stock build-up, 0.26 t organic carbon ha^{-1} year^{-1}. Each t dry matter ha^{-1} of applied cattle manure, containing 33.1% of organic C, increased the organic carbon stock by 27 kg C ha^{-1} in the 0–0.4 m soil layer. This increase corresponded to the highest sequestration efficiency, equal to 8.1% of the C added, due to its low degradability, as compared with

3.8 and 3.7% in the instances of cattle slurry and cereal crop residues. On the whole, the recycling of cattle farming by-products for CO_2 sequestration purposes poses environmental risks, such as pollution by nitrate N (NO_3–N), that can limit its sustainability in fertile cropland of developed countries.

About 25 and 36% of applied manure and compost C remained in the soil after 4 years of application, indicating greater C sequestration with composted than non-composted manure (Eghball, 2002). According to Sodhi et al. (2009), a 10-year application of rice straw compost, either alone or in combination with inorganic fertilizers, results in C sequestration in macroaggregates. In fact, with the application of 8 t compost ha^{-1}, the C concentration in the 1–2 mm size fraction increased by 180 to 191%, respectively, over unfertilized control. From trials still in progress for more than 10 years, there is evidence that the organic carbon sequestration rate increased more due to farmyard manure and composted farmyard manure in comparison with mineral fertilizers or other organic materials (Monaco et al., 2008; Kukal et al., 2009).

Mandal et al. (2007) observed that the total quantity of soil C sequestered over a long period was linearly related to the cumulative crop residue C inputs, and the rate of the conversion to organic carbon was higher in the presence of added organic materials, i.e. 6.9% of each additional t C input ha^{-1}, than in their absence (4.2%). Indeed, it has been calculated that the rate of organic carbon sequestration is on average 0.3 to 0.5 t C ha^{-1} year^{-1} under intensive agricultural practices (Lal, 2007). As reported by Mondini and Sequi (2008) organic matter is the largest C stock of the continental biosphere, with 1550 billion tons. On the time scale of several decades, in arable soils which receive high organic materials, relatively less organic matter is stabilized either by association with the silt plus clay mineral fractions, or by its inherent biochemical recalcitrance (Sleutel et al., 2006).

Shindo et al. (2006) reported that continuous compost application in a field subjected to 25 years of double cropping could increase both the amounts of fulvic and humic acids, and the total humus content. From the organic carbon sequestered quality standpoint, Nardi et al. (2004) found that, over 40 years, farmyard manure fertilization improved by 116% the production of humus with a high degree of polycondensation, a high-quality fraction usually linked to soil fertility. Conversely, the absence of organic fertilizer inputs determined the opposite, with a higher percentage of non-complex and lightweight humus.

Besides, the soil C sequestration should not be restricted to a mere quantification of C storage or CO_2 balance. All greenhouse gas fluxes must be computed at the plot level in C–CO_2 or CO_2 equivalents, incorporating as many emission sources and sinks as possible across the entire soil-plant system (Feller and Bernoux, 2008). For example, results of Ginting et al. (2003) showed that fluxes of CH_4 and nitrous oxide (N_2O) were nearly zero after 4 years of manure and compost applications. This evidence indicates that the residual effects had no negative influence either on soil C and N storage, or global warming. However, there is a lack of information and a strong need to further understand the greenhouse gas fluxes as related to organic material input dynamics in the soil.

The reviewed results suggest that the process of organic carbon depletion can be reversed by long-term organic amendment application. Soil carbon sequestration should be considered as a "win–win" strategy for increasing soil fertility and preventing soil erosion processes (Sánchez-Monedero et al., 2008).

3.2. Heavy metal concentration in the agro-ecosystem

Despite the numerous benefits, the agricultural utilization of raw and composted wastes could also induce adverse impacts on the environment. This is particularly due to the types of toxic elements contained in these organic materials that might enter the food chain, since they may be taken up by plants from soil.

The concentration of heavy metals in compost is generally higher than the normal concentration in soil, so the possibility exists of metal accumulation when the compost is repeatedly applied (Zhang et al., 2006). On the other hand, little research is available from studies lasting decades and longer about the availability of metals applied as constituents of composted organic matter. Over a 10-year trial period, the most abundant metals in the uppermost soil horizon were copper (Cu), zinc (Zn) and lead (Pb). Cadmium (Cd) was the least plentiful, corresponding to the mean metal concentrations in the municipal solid waste compost applied (Businelli et al., 2009). This is supported by the opposite findings of Bergkvist et al. (2003) who found, during a period of 41 years, 92% of applied Cd was recovered in the topsoil in sludge treatment, indicating measurable losses by both downward movement and crop uptake.

Six-year consecutive applications of a swine compost resulted in significantly higher concentrations of Cu and Zn at 10–20 cm depth of the compost-amended soil, relative to the control, with an increase from 102.8 to 127.4 mg kg^{-1} for Cu and from 111.9 to 165.7 mg kg^{-1} for Zn (Zhao et al., 2006). On the other hand, Bartl et al. (2002) found that 32t ha^{-1} of biowaste compost did not influence the total contents of Cd, manganese (Mn), molybdenum (Mo) or nickel (Ni) in soil, in 5 years. The total soil contents of Zn and Pb were significantly higher in soils with compost treatment than in the unfertilized soils.

From experiments longer than 10 years, it is possible to suggest that sludge and composted sludge showed a high accumulation of Zn, Cu and chromium (Cr), probably due to the notably higher concentration of these metals in the raw materials (Saviozzi et al., 1999; Kunito et al., 2001). The soil enzyme activities, dehydrogenase, urease and β-D-glucosidase were also found to be adversely affected by the metals derived from the addition of sewage sludge (Kunito et al., 2001).

Notwithstanding, the concentration of pollutants in composts may be reduced through the correct separation of organic wastes at source, which offers the opportunity of high-quality input material for aerobic biodegradation (Montemurro et al., 2009). For the long-term protection of the environment, it is also necessary to develop and implement other preliminary treatments for potentially polluting wastes. Erhart et al.

(2008) showed that, after 10 years of application, the use of high-quality biowaste compost gives no variation in either total heavy metal concentrations or available fractions. In particular, with total applications of 95, 175 and 255 t biowaste compost ha^{-1}, no heavy metal significant increase was measurable, except for Zn in the treatment with the highest application rate.

However, the environmental hazard is strictly linked to the mobility of metals, and to their concentration in the soil solution rather than to the total soil concentration. According to Businelli et al. (2009), metal mobilization is not an immediate process, but it involves various equilibria that control their adsorption and desorption. These behaviors depend on soil characteristics and climatic conditions and they involve biochemical processes responsible for the microbial degradation of autochthonous and compost-derived organic matter. This highlights the importance of long-term experimentation when studying the environmental fate of heavy metals, particularly in compost-amended soils on large scales (Businelli et al., 2009).

Within this context, according to Tittarelli et al. (2007), the main factors that affect the environmental behavior of heavy metals are: (i) cation exchange capacity, as an index of the soil capacity to adsorb and hold metal cations; (ii) humic substances, that can interact with heavy metals, forming complexes with different solubility, and consequently mobility, and (iii) the water and thermic regime of the soil, which affect the organic matter decomposition.

It can also be generally assumed that extractability and uptake of heavy metals decline as the soil pH becomes more alkaline, especially after repeated compost application. By contrast, low pH in the soil, caused by more than 60 years of rice straw compost applications, may have enhanced the concentration of metals in the water-soluble fraction (Takeda et al., 2005).

The aerobic composting processes increase the complexation of heavy metals in organic waste residues. In this condition the metals are strongly bound to the compost matrix and organic matter, limiting their solubility and potential bioavailability in soil (Smith, 2009). However, 10 years after municipal solid waste compost application, a share of the heavy metals was further re-mobilized in the soil profile, also leading to a decrease in the percentage distribution of organically-bound heavy metals with time. According to Businelli et al. (2009), this metal mobilization was primarily influenced by organic matter dynamics. On the contrary, Sukkariyah et al. (2005) reported that in aerobically digested sewage sludge-amended soils, the extractability of the heavy metals steadily declined over 17 years, despite a significant decline in organic matter concentration in the amended plots. This outcome showed that the mineralization of exogenous applied organic matter did not increase heavy metal availability due to loss in metal binding capacity associated with organic matter.

Monitoring concentrations of various heavy metals, their fractionation and the percentage contribution of each fraction to the total concentration are important analytical tools. In fact, in soil receiving long-term application of compost or other organic materials with relatively high concentrations of metals, these determinations can produce important information at the

present time and help to determine what might happen in the future (Zhao et al., 2006; Businelli et al., 2009).

In any case, moderate compost doses applied in current agriculture will not cause any risk of toxicity for plants or animals, and therefore it is reasonable that application rates always have to be chosen on the basis of limited heavy metal loadings. However, no adverse effect on plant growth or excessive amounts of plant metal uptake were noted 17 to 19 years after biosolid application, despite the high application rate, equal to 210 t ha^{-1}, containing concentrations of Cu and Zn that exceeded the pollutant concentration limits (Sukkariyah et al., 2005).

In general, heavy metal uptake by crops increases in leafy plants and it is higher in cereal leaves than in grain. Lettuce, for example, had higher assimilative capacity for Zn and Cd uptake than other non-leafy crops (Sukkariyah et al., 2005). Mantovi et al. (2005) reported that biosolid applications significantly increased the content of Zn and Cu in wheat grain and of only Cu in both sugarbeet roots and maize grain. Cadmium is one of the most significant potential contaminants of food supplies on arable lands and may limit sewage sludge suitability for soil amendment, because this organic material presents a large amount of this metal (Singh and Pandeya, 1998). Being relatively soluble in soils, it is readily taken up by crops and it is quite toxic to humans (Miller and Miller, 2000). This behavior is particularly evident at low soil pH. Cd solubility in equilibrium extracts of $Ca(NO_3)_2$ increased, during the 41-year trial above mentioned, by a factor of 20 in the sludge treatment compared with the control (Bergkvist et al., 2003). This was reflected in the Cd concentration of the straw fraction in barley, which was almost doubled in the sewage sludge treatment, compared with the control. The grain fraction, on the other hand, showed no significant increase in Cd concentration.

It can be concluded that there is no tangible evidence demonstrating negative impacts of heavy metals applied to soil, particularly when high-quality compost was used for a long period. Composting processes also inherently reduce metal availability compared with other organic waste stabilization methods (Smith, 2009).

3.3. N pool fate

Proper use of organic amendments requires the capacity to predict the release in the soil of inorganic nutrients from organic forms. Sikora and Szmidt (2001) suggested that a better understanding of coupled mineralization-nitrification is essential to manage the soil N pool with an environmentally sound application of amendments.

The C/N ratio, which is an important tool of amendment evaluation, cannot explain all differences in N mineralization, since organic materials with similar C/N ratios may mineralize different amounts of N. This behavior is probably due to other differences in their chemical compositions. Repeated long-term applications of organic amendments not only generally increase the size of the soil organic N pool, but also cause remarkable changes in soil characteristics, that influence N dynamics and can lead to a residual effect.

Habteselassie et al. (2006a) found an 89% increase in total soil N content after 5 years when dairy-waste compost at 200 kg N ha^{-1} was applied. Conversely, Zaman et al. (2004) observed, after 23 years of 240 kg Nha^{-1} sewage sludge plus sawdust compost application, an increase in total N content of approximately 14%, as compared with a chemical fertilizer supply. The increase in total soil N after compost, biosolids or compost-plus-N was closely related to the build-up of organic matter in the soil over time and may be attributed to the direct effect of organic inputs (Mantovi et al., 2005; Ros et al., 2006a). After 7 years of application, the soil N concentration in the topsoil accounted for 33% of compost N applied (Sullivan et al., 2003). Antil et al. (2005) showed that the highest total soil N content increase, by 70% in respect to NPK mineral fertilizer, was found after 38 years of animal-manure liquid applications, as compared with solid animal-manure, cattle slurry and half cattle slurry plus straw. Moreover, in the plots after 13 years of cropping, compared with those kept fallow for the same period, there was a clear impact of N removal due to both the harvest and N losses, following enhanced mineralization due to tilling.

The N uptake by crops depends on several factors such as the N content and C/N ratio of the amendment, soil characteristics, climatic conditions and, obviously, on the plant's N requirements. Research on an average of 10 years by Hartl and Erhart (2005) pointed out that the ratio of N output by harvested plant parts to total N input in the source-separated organic waste compost treatments ranged from 3 to 7% of the applied N. This result was lower compared with mineral fertilization (11 to 15%), even if it was not reflected by a higher proportion of NO_3–N in the soil profile at the end of the growing season.

Data collected on N recovery from different composts, related to N uptake or yield, showed that the N effect of compost application does not generally exceed 15–20% of total N supply in the first year, while the residual compost N pool is mineralized at rates of 3–8% in following years. Continuous compost amendments and crop rotations with high nutrient demand may increase N mineralization (Amlinger et al., 2003). Eghball (2000) found that of the organic N applied to provide corn N requirements, 151 kg available N ha^{-1} for an expected 9.4 t ha^{-1} grain yield, about 11% was mineralized from composted beef cattle manure and 21% from non-composted manure during the succeeding growing season. A lower N availability from compost reflects the presence of stable N compounds.

The organic matter mineralization process increases the amount of ammonium and nitrate in the soil. However, the NO_3–N is minimally adsorbed by the soil particles because it is very mobile and is susceptible to losses into ground- and surface waters by infiltrating water. Within this context, it is essential to remember that the synchronization of N supply with crop N demand, together with a proper application rate, is the best way to avoid the accumulation of soil mineral N, thus reducing the risk of NO_3–N leaching (Montemurro and Maiorana, 2008).

The long-term application effects of raw and composted organic materials on nitrate leaching have been evaluated by several researchers, but the results of the studies are often discordant. In fact, Mallory and Griffin (2007) in a 13-year experiment found that, despite similar NH_4–N inputs and rates of NH_4–N consumption for manure and fertilizer N treatments, NO_3–N accumulation was slower in the manure treatment. This is because the N from manure became available more slowly than fertilizer N. On the contrary, Basso and Ritchie (2005), in a 6-year maize–alfalfa rotation, observed the highest amount of NO_3–N leaching of 681 kg ha^{-1} in the manure treatment, followed by compost (390 kg ha^{-1}), inorganic N (348 kg ha^{-1}) and control (311 kg ha^{-1}). They suggest that, although manure applications can be valuable for organic matter increase, attention needs to be given to the possible environmental impact without benefiting from yield increase.

From several experiments longer than 8 years conducted under different soil and climate conditions, it might be concluded that compost fertilization resulted in equal or lower NO_3–N leaching losses to groundwater than corresponding mineral supply (Hartl et al., 2001; Hartl and Erhart, 2005; Erhart et al., 2007). These findings are observed even with higher amounts of amendments than used in practical farming. Nevens and Reheul (2003) reported that, at the end of a 4-year trial, the increase in residual soil NO_3–N was smaller with vegetable-fruit-garden waste compost and compost plus cattle slurry applications, in respect to mineral fertilizer treatment.

Regarding the effect of the application rates, over a 5-year field trial with permanent rye, the treatments receiving 20 to 40 t ha^{-1} of biowaste compost per single application showed smaller amplitudes in the soil NO_3–N levels in fall than the treatments receiving 60 t ha^{-1} (Hartl et al., 2003). Other studies have noted that compost produced more nitrate than needed for plant use throughout a 5-year period. This is particularly evident at a high rate of application. The continuing mineralization of the organic material, even after harvest, led to postharvest nitrate production and a consequent downward movement (Habteselassie et al., 2006a). Furthermore, measurements of gross N transformation rates are important to properly understand N cycling in agricultural soils, where both productive and consumptive processes occur. Habteselassie et al. (2006b) reported that, by applying dairy-waste compost and liquid dairy-waste annually for 6 years, the mean gross N mineralization rates were about 5.7 and 2.9 mg N kg^{-1} day^{-1}. Conversely, the gross nitrification rates were 10.2 and 1.6 mg N kg^{-1} day^{-1}, respectively, and the net mineralization rates were less than 35% of gross rates. The ratio of gross nitrification to mineralization for dairy-waste compost-treated plots were more than 100%, indicating a large increase in nitrifying capacity of the soil following repeated applications, which is undesirable due to the known high mobility of nitrate.

Zaman et al. (2004) found that the long-term application of sewage sludge, composted with rice husk or sawdust, has showed a positive effect on gross and net rates of N mineralization, and net nitrification rates, probably due to high levels of microbial and enzyme activities. The same authors also found that chemical fertilizer-treated soils showed negative net N mineralization rates, which is indicative of N immobilization. These assessments are contradicted by Poudel et al. (2002), who observed that organic systems managed with cover crops and composted animal manure showed 112% greater potentially mineralizable N pools than conventional systems. They also showed N mineralization rates to be lower by 100% throughout the growing season, as compared with conventional systems. This reduction corresponds to a reduced risk for NO_3–N leaching and groundwater pollution.

The valuation of the potentially mineralizable organic N pool for soils that have received organic amendments is important for estimating the capacity of these soils to provide N over time. For example, residual effects of 4-year compost and manure application resulted in 42 to 74% higher potentially mineralizable N compared with synthetic N fertilizer treatment (Ginting et al., 2003). Furthermore, when both organic amendments are added to soil and biological oxygen demand by decomposer microorganisms exceeds the supply, the anaerobic microenvironment necessary for denitrification is created and the intermediate product N_2O gas is formed. This gas is a strong "greenhouse gas" and can also be emitted into the atmosphere (Epstein, 1997). The long-term application of stabilized organic materials at 300 kg N ha^{-1} year^{-1} significantly increased N_2O emissions from 150 g N_2O–N ha^{-1} year^{-1} in the control treatment soil to 856 g N_2O–N ha^{-1} year^{-1} in the organic ones (Meng et al., 2005). N_2O production was also significantly higher in the 0–15 and 15–20 cm layers of the compost-treated soils than in the respective layers of the chemical fertilizer-treated ones (Zaman et al., 2004). The higher N_2O emissions from some compost-treated soils highlight the need for quantifying N_2O emissions from agricultural land. This is particularly important where composts are used instead of chemical fertilizers (Sikora and Szmidt, 2001).

In summary, the repeated application of composted materials can enhance soil organic N content, storing it for mineralization in the following cropping seasons.

4. CONCLUSION

Only a few published studies have focused on the long-term effects of organic amendments on the soil-plant system for sustainable crop production. Therefore, our work attempted to address this issue by using the results from long-lasting fertility trials, providing a useful platform for future research.

The basic reflections of this review include:

(i) long-term trials are the best indicators of both organic material utilization and sustainability. In fact, many effects, e.g. release of nutrients, carbon sequestration and possible build-up of toxic elements in the soil, evolve slowly, thus needing time to be tested. These effects are present only when repeated applications occurred;

(ii) addition of exogenous organic matter to cropland can lead to an improvement in soil biological functions, even more than 15 years after spreading, depending on the quantity and quality of materials applied. For example, microbial

biomass C increased up to 100% with high rate compost treatments, while enzymatic activity was enhanced by up to about 30% with sludge additions;

(iii) several organic amendments' long-lasting application can enhance soil available potassium, extractable phosphorous and, particularly, organic carbon. Soil organic carbon increased by about 90%, in respect to unfertilized soil, and by more than 100% as compared with chemical fertilizers;

(iv) regular addition of organic amendments increased soil physical fertility, mainly by improving aggregate stability and decreasing soil bulk density;

(v) the best agronomic performance of compost is obtained with the highest rates and frequency of utilization. This is particularly evident if the amendment is combined with mineral fertilizers. Furthermore, there were residual effects because it is a slow-release nitrogen fertilizer;

(vi) crop yield was enhanced by about 250%, with high rates of municipal solid waste compost repeated applications. There is also some evidence that stabilized organic amendments do not reduce the crop yield quality, but even enhance it;

(vii) long-term organic amendment application can play a positive role in climate change mitigation by soil carbon sequestration, which in turn can reverse the process of soil degradation;

(viii) agricultural utilization of raw and composted wastes could induce adverse environmental impacts. However, there is no tangible evidence demonstrating negative impacts of heavy metals applied to soil, particularly when high-quality compost was used for a long period. Composting processes also reduce metal availability;

(ix) repeated application of composted materials can enhance soil organic N content, by up to 90%, storing it for mineralization in the following cropping seasons, often without raising the nitrate leaching to groundwater.

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