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Nitrogen turnover, crop use efficiency and soil fertility in a long-term field experiment amended with different qualities of urban and agricultural waste

Beatriz Gómez-Muñoz, Jakob Magid, Lars Stoumann Jensen*

Section for Plant and Soil Sciences, Department of Plant and Environmental Sciences, Faculty of Science, University of Copenhagen, Thorvaldsensvej 40, DK-1871 Frederiksberg C, Denmark

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ABSTRACT

Organic wastes contain significant amounts of organic matter and nutrients and their recycling into agriculture can potentially contribute to closing the natural ecological cycle. The aim of this study was to evaluate the improvement in overall soil fertility and soil nitrogen (N) supply capacity in a long-term field experiment with repeated application of different urban and agricultural organic waste amendments. Soils from the CRUCIAL field experiment in Denmark, in which diverse types of urban (human urine, sewage sludge, composted household waste) and agricultural wastes (cattle slurry, farmyard manure and deep litter) have been applied annually for 11 years (at normal and accelerated rates), were used to estimate the effects of the different qualities of organic wastes on soil fertility, N turnover and crop N availability. Soil physical fertility parameters, such as water retention and total carbon, improved with the application of organic wastes. Cattle manure, sewage sludge and composted household waste in single or accelerated rates of application increased soil total N by 13–131% compared to the mineral fertiliser NPK treatment. The highest net N mineralisation capacity was observed for the accelerated rate of composted household waste, followed by all the other organic waste amendments and with the lowest net N mineralisation in the NPK-only and the unfertilised treatments. In soils amended for 11 years with NPK, human urine, cattle slurry, sewage sludge, cattle farmyard manure, cattle deep litter and composted household waste, the apparent crop N-use efficiencies (NUE, compared to unfertilised control) were 88, 73, 55, 51, 21, 16 and 11%, respectively. The continuous application of organic wastes generally increased NUE in the last year in comparison with the first year, except for composted household waste where N-use efficiency declined from 27 to 11%. The corresponding long-term mineral fertiliser N-equivalent (MFE) value ranged between 82% (human urine) and 13% (compost). Overall, continuous application of organic wastes improved soil fertility, with low C:N waste improving soil N availability, crop uptake and NUE the most, while the most C-rich and high C:N organic wastes (cattle deep litter and household waste compost) had a negative effect on crop NUE over time.

1. Introduction

Nitrogen (N) is one of the main limiting factors for biomass productivity in terrestrial ecosystems; thus the replacement of N in agricultural land is essential to ensure productivity. There is currently a growing demand for nutrients in agricultural systems. In parallel, the production of urban, agricultural and industrial organic wastes is increasing worldwide. These organic wastes are one of the main sources of reactive nitrogen (N_r) pollution, causing N_r concentrations in the air and water that exceed critical levels for eutrophication, significant greenhouse gas emissions, landscape and biodiversity deterioration, and severe human health impairments (Jensen et al., 2011). The European Commission (2010) is encouraging the recycling of these organic wastes, while endeavouring to reduce waste landfilling and incineration without energy recovery. In this sense, agricultural land application is one possible solution to avoiding disposal costs and recycling nutrients back into the agricultural production, while reducing the use of mineral fertilisers (Miller and Miller, 2000; Van-Camp et al., 2004). Organic wastes contain significant amounts of organic matter and nutrients and their use in agriculture can contribute to closing the natural ecological cycle if used appropriately and cautiously (Montemurro

* Corresponding author.
E-mail address: lsj@plen.ku.dk (L.S. Jensen).

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et al., 2004; Montemurro and Maiorana, 2008). Continuous applications of organic wastes have been shown to increase soil physical fertility, mainly by improving soil porosity (Tejada et al., 2009) and aggregate stability (Diacono and Montemurro, 2010). The application of organic matter into soil also increases the cation exchange capacity due to the negative charge of organic matter, which plays an important role in nutrient retention and buffering availability to plants and therefore increases the chemical fertility of soil (Weber et al., 2007; Kaur et al., 2008). However soil biological fertility also improves after the application of organic wastes such as compost (García-Ruiz et al., 2013), manure (Ginting et al., 2003) and sludge (Mats and Lennart, 1999). Organic waste application typically increases soil biological activity and soil microbial population/biomass, depending on the quality or degradability of the applied carbon, as well as the total soil organic C and Paetsch et al. (2016) found that long-term application of more labile bio-waste and green waste + sewage sludge composts enhanced soil organic C and N stocks and especially the fine mineral associated fraction in a magnitude similar to conventional farmyard manure application, while no such effect was observed with a municipal solid waste compost. However, it has been shown that the functional capacity or diversity is relatively unaffected by the type of organic waste (Poulsen et al., 2013a,b) while biological soil fertility is mainly related to C application rates and contents of nutrients. Typically the improvement in soil fertility after the addition of organic wastes positively influences the crop yields achieved. Montemurro (2009) found that the application of municipal solid waste compost associated with mineral fertiliser increased wheat yield by 8% compared with mineral N alone and induced more stable productivity and N uptake over the years. Borjesson et al. (2014) similarly reported an increase in crop yield and soil organic C and N from repeated applications of sewage sludge.

However, the continuous application of organic wastes in soil could have several environmental impacts. For example, both manures and urban organic wastes may contain high amounts of metals, which could exceed crop requirements and reach potentially harmful or even toxic concentrations (Diacono and Montemurro, 2010), though studies have also shown urban waste products applied for fertilisation purposes in agriculture poses no substantial risks related to potentially toxic elements (López-Rayo et al., 2016). Furthermore, manures and organic wastes may contain organic contaminants and medicinal residues, which may be of concern for promoting the spread of microbial antibiotics resistance (Lekfeldt et al., 2014).

Many waste treatment and management processes (composting or anaerobic digestion) may potentially remove some of the organic contaminants from waste, but are also prone to N loss, may result in the stabilisation of organic C and N (Kätterer et al., 2014) and moreover may change the temporal pattern and magnitude of nutrient release. During the mineralisation of organic matter, significant amounts of ammonium and nitrate may be produced, depending on C:N ratios and degradability of the organic matter. If this available N is not taken up by plants, it could be lost through leaching or gaseous losses. Basso and Ritchie (2005) observed the highest amount of NO_3-N leaching (681 kg ha^{-1}) in the manure treatment, followed by compost (390 kg ha^{-1}), inorganic N (348 kg ha^{-1}) and the control (311 kg ha^{-1}) in a six-year maize-alfalfa (*Zea mays* and *Medicago sativa*, respectively) rotation. Therefore, when fertilisation with organic waste is implemented, it is important to consider the slow and often difficult to predict release of nutrients in the long term to ensure the optimum synchronisation of the supply of N with crop demand, and to reduce the environmental problems associated with an excess of nutrients available in the soil.

Long-term experiments provide the best option for evaluating the effects of organic waste application on soil fertility and how this affects N turnover and crop N availability in order to optimise overall N-use efficiency. The aim of this study was to evaluate the improvement in overall soil fertility and soil N supply capacity as affected by the continuous application of different organic wastes, using a long-term field experiment with urban organic and agricultural waste amendments. We hypothesised that: (1) N availability in the short term in soil amended with different waste-based fertilisers is inversely related to their proportion of organic N and organic matter stabilisation, whereas in the long term residual soil net N availability is closely related to the accumulated soil organic C level; (2) specific soil microbial activity is lowest with the application of more stabilised organic waste such as composted household waste and sewage sludge; and (3) crop N uptake and use

Table 1
Main properties of soil sampled in March 2014 from the different treatments in the CRUCIAL experiment. Values are the means of three true field replicates ± standard deviation. Different letters denote significant differences between different materials for $P < 0.05$.

Treatment[a]	pH	Water content (% WW) at a tension[b] of		TC[c]	TN[c]	C:N ratio	IN[c]	Average annual inputs[d]	
−0.95 kPa	−9.5 kPa	(g kg^{-1} DM)	(g kg^{-1} DM)	(mg kg^{-1} DM)	C (kg ha^{-1} yr^{-1})	N (kg ha^{-1} yr^{-1})	(mg kg^{-1} DM)	C(kg ha^{-1} yr^{-1})	N(kg ha^{-1} yr^{-1})
NPK	6.9 ± 0.2^{ef}	35 ± 1.3^{de}	20 ± 0.8^{de}	16.8 ± 0.49^{def}	1.80 ± 0.05^{de}	9.3 ± 0.0^{bc}	9.6 ± 0.4^{def}	–	100
U	7.2 ± 0.2^{bcde}	31 ± 0.9^{f}	20 ± 0.1^{e}	14.6 ± 0.16^{f}	1.64 ± 0.01^{e}	8.9 ± 0.1^{e}	6.8 ± 0.9^{fg}	–	–
UC	7.4 ± 0.2^{ab}	31 ± 2.0^{f}	20 ± 0.2^{de}	15.2 ± 0.55^{ef}	1.65 ± 0.08^{e}	9.2 ± 0.2^{bcd}	5.9 ± 0.9^{g}	–	–
HU	7.1 ± 0.2^{cde}	33 ± 1.8^{ef}	20 ± 0.4^{de}	16.8 ± 0.80^{def}	1.86 ± 0.13^{de}	9.1 ± 0.2^{de}	8.7 ± 1.2^{efg}	<15	171
DL	7.4 ± 0.2^{abc}	38 ± 2.2^{cd}	23 ± 0.8^{c}	22.0 ± 1.87^{bc}	2.21 ± 0.17^{bcd}	10 ± 0.1^{a}	12.6 ± 5.3^{cd}	5147	232
CS	7.3 ± 0.3^{abcd}	36 ± 2.1^{de}	21 ± 0.7^{cd}	16.6 ± 1.92^{def}	1.83 ± 0.18^{de}	9.1 ± 0.2^{cde}	8.7 ± 1.4^{efg}	1638	119
CMA	7.0 ± 0.1^{def}	42 ± 2.0^{b}	25 ± 1.4^{b}	23.8 ± 2.08^{b}	2.38 ± 0.17^{bc}	10 ± 0.2^{a}	17.4 ± 2.7^{b}	9772	474
S	7.0 ± 0.1^{def}	37 ± 2.5^{cd}	22 ± 0.3^{c}	19.0 ± 1.07^{cde}	2.05 ± 0.12^{cde}	9.3 ± 0.1^{bcd}	12.8 ± 0.7^{cd}	1781	314
SA	6.8 ± 0.2^{f}	40 ± 2.4^{bc}	26 ± 1.3^{b}	20.5 ± 2.79^{bcd}	2.22 ± 0.30^{bcd}	9.2 ± 0.1^{bcd}	15.0 ± 0.4^{bc}	4667	823
CH	7.3 ± 0.1^{abc}	38 ± 1.1^{cd}	23 ± 0.7^{c}	24.1 ± 0.28^{b}	2.57 ± 0.04^{b}	9.4 ± 0.1^{b}	12.0 ± 0.6^{cde}	4650	303
CHA	7.5 ± 0.1^{a}	47 ± 2.1^{a}	29 ± 1.9^{a}	39.3 ± 6.44^{a}	4.16 ± 0.70^{a}	9.4 ± 0.1^{b}	25.8 ± 0.3^{a}	14078	917

[a] Treatment abbreviations are NPK: chemical NPK fertiliser; U: unfertilised; UC: unfertilised, but with undersown clover green manure every autumn; HU: human urine; DL: cattle deep litter; CS: cattle slurry, CMA: cattle farmyard manure accelerated rate; S: sewage sludge normal rate; SA: accelerated rate of S; CH: source-segregated and composted organic household waste, normal rate; CHA: accelerated CH.

[b] Water tension of −0.95 kPa corresponds to −10 cm water column (near saturation) and −9.5 kPa to −100 cm water column (field capacity).

[c] TC: total carbon, TN: total nitrogen, IN: inorganic N (ammonium + nitrate).

[d] Data for annual inputs are from Peltre et al. (2015) and represent estimated inputs with the treatments.